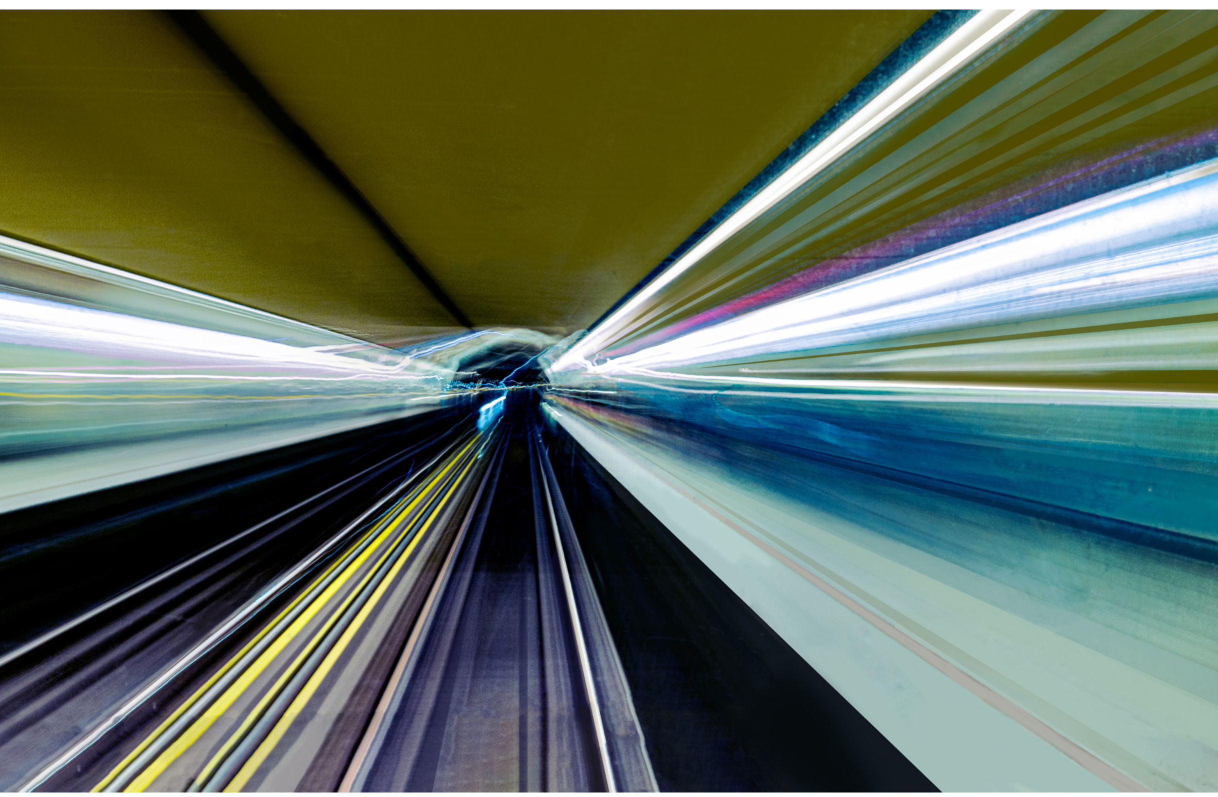
Expanding Underground – Knowledge and Passion to Make a Positive Impact on the World

Proceedings of the ITA-AITES World Tunnel Congress 2023 (WTC 2023), 12-18 May, 2023, Athens, Greece



EDITED BY
Georgios Anagnostou
Andreas Benardos
Vassilis P. Marinos

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EXPANDING UNDERGROUND - KNOWLEDGE AND PASSION TO MAKE A POSITIVE IMPACT ON THE WORLD

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World contains the contributions presented at the ITA-AITES World Tunnel Congress 2023 (Athens, Greece, 12 – 18 May, 2023). Tunnels and underground space are a predominant engineering practice that can provide sustainable, cost-efficient and environmentally friendly solutions to the ever-growing needs of modern societies. This underground expansion in more diverse and challenging infrastructure types or to novel underground uses can foster the changes needed. At the same time, the tunnelling and underground space community needs to be better prepared and equipped with knowledge, tools and experience, to deal with the prevailing conditions, to successfully challenge and overcome adversities on this path. The papers in this book aim at contributing to the analysis of challenging conditions, the presentation and dissemination of good practices, the introduction of new concepts, new tools and innovative elements that can help engineers and all stakeholders to reach their end goals.

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World covers a wide range of aspects and topics related to the whole chain of the underground construction and operation of tunnels of underground structures:

- Knowledge and Passion to Expand Underground for Sustainability and Resilience
- Geological, Geotechnical Site Investigation and Ground Characterization
- Planning and Designing of Tunnels and Underground Structures
- Mechanised Tunnelling and Microtunnelling
- Conventional Tunnelling, Drill-and-Blast Applications
- Tunnelling in Challenging Conditions - Case Histories and Lessons Learned
- Innovation, Robotics and Automation
- BIM, Big Data and Machine Learning Applications in Tunnelling
- Safety, Risk and Operation of Underground Infrastructure, and
- Contractual Practices, Insurance and Project Management

The book is a must-have reference for all professionals and stakeholders involved in tunnelling and underground space development projects.

PROCEEDINGS OF THE ITA-AITES WORLD TUNNEL CONGRESS 2023 (WTC 2023), 12-18 MAY 2023, ATHENS, GREECE

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World

Edited by

Georgios Anagnostou

ETH Zurich, Switzerland

Andreas Benardos

School of Mining and Metallurgical Engineering at the National Technical University of Athens, Greece

Vassilis P. Marinos

School of Civil Engineering at the National Technical University of Athens, Greece

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Preface

Athens, May 2023

The ITA-AITES World Tunnel Congress 2023 (ITA-AITES WTC 2023) and the 49th General Assembly of the International Tunnelling and Underground Association (ITA-AITES), are held from the 12th to the 18th of May 2023 in Athens, Greece. Athens has been selected, for the first time, as the host city of the leading annual event of the International Tunnelling and Underground Space Association.

The Greek Tunnelling Society (GTS) is honoured and proud to host this outstanding event of the tunnelling community that is embraced with the participation of hundreds of consultants, contractors, software producers, machine / equipment manufacturers, investors, as well as operators and owners gathered in Athens to meet, exchange knowledge, promote their expertise / knowhow and define future needs.

The theme of ITA-AITES WTC 2023 Conference "*expanding underground*", focuses on the Knowledge and Passion that our industry offers to Make a Positive Impact on the World, by means of the multiple advantages and solutions that underground space can provide.

The congress theme is fully aligned to support and further promote the new ITA slogan "*underground solutions for a better world*" and ITA's updated vision to "*lead the world in sustainable use and development of tunnels and underground space*", which were both announced last January 2023. Indeed, cities, infrastructure and logistics expansion towards underground provide environmentally friendly, safe and resilient solutions that may facilitate the transformation of millions of people's lives into a more sustainable lifestyle. This is becoming imperative as the globe is facing first-priority demanding challenges, such as (i) rapid urbanization, (ii) climate change and extreme weather phenomena, (iii) other natural hazards, (iv) need for sustainable energy geo-resources and (v) high demands for efficient people's mobility and transportation of goods.

ITA-AITES World Tunnel Congress 2023 provides an ideal opportunity to showcase recent innovations and the perspectives of the new era of smart technologies where sophisticated "digital tools" rapidly change investigation, design, construction and operation methods and strategies to further enhance and efficiently upgrade underground infrastructure assets, transforming the industry and the societies it serves.

The congress covers all "hot" topics of the tunnelling and underground space industry. More than 420 papers from 45 different countries were accepted for publication (out of more than 600 submitted abstracts), ranking ITA-AITES WTC2023 as the second throughout the history of World Tunnel Congresses with the maximum number of papers, since their beginning back in 1974. All accepted papers, each having been peer reviewed by minimum two members of the scientific committee and included in this abstracts volume, are available as Open Access publications and will also be SCI indexed. Such provisions ensure that the research / work / best practice / efforts of the authors will be freely and permanently available, so anyone, anywhere, can read and build upon his / her / their work. The latter, an initiative of the GTS, is applied for the first time in an ITA-AITES WTC conference.

ITA-AITES WTC2023 aim to ensure the highest possible scientific level, was achieved thanks to the contribution of highly skilled professionals and academics from all around the world. The total number of the members of the scientific committee exceeds one hundred fifty (150) coming from 29 countries. Their great effort in the reviewing process is highly acknowledged. Nevertheless, the contents of the papers and opinions expressed are those of the authors.

Timeless Athens, the birthplace of "symposia", provides the ideal conference host city and the meeting hub of the tunnelling and underground space professionals, thanks to its unique blend of history, culture, art, lifestyle and entertainment.

We strongly believe that WTC2023 in Athens (Greece) provides a valuable opportunity and a fertile soil for the international community to, literally, make a positive impact on the world.

Ioannis Fikiris
Chair of the WTC2023 Organizing Committee

Nikolaos Roussos
President of Greek Tunnelling Society

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Knowledge & passion to expand

underground for sustainability and resilience

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A look at embodied carbon in segmental tunnel lining

J.P. Banyai & A. Caspersen
Tunnels Department, Ramboll, Copenhagen, Denmark

ABSTRACT: With the increasing focus on climate changes and sustainability in general, we as civil engineers, have an even greater responsibility to develop innovative sustainable solutions for the projects we are involved in. It is well-known that a significant proportion of the global carbon footprint comes from the production of cement and steel. Historically, the tunnelling industry relies heavily on these two materials to build safe and durable underground structures. Bored tunnels often benefit from highly repetitive construction procedures and the mass production of identical tunnel lining segments, with precision moldings offering excellent build quality and durability. The drawback of this efficient construction process is the fact that any inefficiencies in the design of a segment can be 'locked in' and repeated over vast sections. The aim of this paper is to explore how to construct significantly more sustainable lining in the future with small changes to the well-known procedure.

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Urban underground space use in a climate neutral city

N.G. Bobylev
Saint Petersburg State University, Russia

D. Guo
Army Engineering University of PLA, China

A. Benardos
National Technical University of Athens, Greece

ABSTRACT: Sustainable, compact, green and climate neutral urbanization is essential in the context of tackling global environmental challenges such as biodiversity conservation and climate change. Cities are expanding in both developed and developing countries; the rate of this growth is much higher than the growth of population. Responsible cities are pursuing a compact city policy, striving to exclude new construction in undeveloped and green areas. The three-dimensional development of cities, and the use of underground space in particular, is a complex, multidimensional and interdisciplinary task. Urban climate agenda widens the above research area further, requiring detailing climate adaptation and mitigation issues. The paper will present analysis of opportunities and drawbacks that the urban underground space brings to an urban transition towards climate neutrality. This research contributes to a vision for urban underground space and integrated urban planning that enhance the quality of urban life while pursuing climate responsible development agenda.

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ATG Ceneri Base Tunnel: Driving method and production of concrete aggregates

E. Catelli & P. Lanfranchi
Pagani + Lanfranchi SA, Bellinzona, Switzerland

ABSTRACT: The inclusion of the idea of reuse into the overall process from planning to implementation is a central concern in underground projects. The maximum reuse of excavated tunnel material is important for several reasons. It can save material resources, reduce transport distances and landfill volumes and, last but not least, construction costs on a large scale. Aggregates for concrete can be produced with raw material resulting from both mechanized and drill and blast driving methods. The different production yields and quantities of waste materials have a major influence on the supply rate and on the requirements for the deposit sites. Using an extensive database constructed for the AlpTransit Ceneri Base Tunnel (15.4 km), the influence of the driving method and the production process of aggregates for concrete was analysed to predict the expected aggregate quantities and waste materials, such as sludge, polluted material or excess aggregate fractions. This information is useful both for quantifying the material recycling rate and for optimizing processing and disposal costs.

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BIM-enabled carbon accounting and integrated design of underground infrastructures

X.L. Chen, M.Q. Huang & Q.B. Zhang
Monash University, Australia

R. Wang
Arup, Australia

ABSTRACT: The underground infrastructure construction has lacked progress towards decarbonization and sustainability due to inconsistency of practice, uniqueness of ground conditions, and independency of disciplines, urging to transition the way we design, construct, and operate tunnels. This paper reviews current internationally accepted guidelines of carbon accounting methodologies, namely the module-based method from EN 15978 and the scoped-based method from Greenhouse Gas Protocol, then seeks to digitally implement these methods to account emissions sources in tunnelling, enabled by parametric modelling in Building Information Modelling (BIM) with a case study of prefabricated station. Furthermore, to fundamentally integrate carbon assessments with geotechnical design, a multi-objective optimization algorithm is implemented to generate the optimal solutions resolving the conflicted goals of stability and carbon reductions for TBM tunnel support design. This paper proposes a BIM-enabled carbon-integrated design workflow for underground infrastructures.

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What might be our vision of the ecological transition in tunnels and underground spaces for the years to come?

L. D'Aloia Schwartzentruber
Center for tunnel studies (CETU), Bron, France

ABSTRACT: When considering the main challenges of the ecological transition in underground structures, several points of view are possible. First, the underground structure can be seen as part of the transportation infrastructure and can therefore be one of the solutions to reduce the carbon intensity of transportation and achieve a more sustainable mobility. Besides, it may also refer to underground space offering new opportunities in terms of usages for the sustainable city. Whenever possible, multifunctionality, resilience and mutability should be part of the design criteria. Finally, the ecological transition must also be at the heart of the design, construction and operation of underground structures, by reducing the carbon footprint and the consumption of natural and energy resources. This article intends to develop and illustrate all these aspects, which might form the bedrock of a certain vision of the ecological transition in tunnels and underground spaces.

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Low carbon lining for tunnelling precast segment – How Dramix® fibre reinforced concrete could facilitate this achievement

Benoit De Rivaz
NV Bekaert SA, Zwevegem, Belgium

ABSTRACT: Concrete is recognized as the second most widely consumed commodity on the planet after water. It also contributes approximately 8% of global carbon emissions; the main source of these emissions is the manufacture of Ordinary Portland Cement (CEM I). In a tunneling project, it is generally considered that 60% to 70% of embodied carbon is contained in the concrete linings of the shafts and tunnels. It is paramount, therefore that the tunneling industry does its utmost to significantly reduce or eliminate its use of cement in all applications segmental linings, in-situ linings, sprayed concrete, and annulus grouts. This is the reason why a great challenge for the coming years will be developing solutions for low carbon lining. Recent projects have demonstrated that structural ductility, durability, and sustainability are going hand to hand, this combined approach will be key requirement in all. The use of Fibre Reinforced Concrete (FRC) allows several advantages summarized in the fib bulletin 83 as follows: Cracking control during construction phases; higher impact resistance; durability advantages at final stage; reduction of costs; sustainability advantages (less material usage through minimizing the amount of steel and concrete cover required). The advantages related to the adoption of FRC use should be evaluated according to the project characteristics. The introduction of the Model Code 2010 has promoted the use of FRC segments. This paper underlines the design principle based upon MC2010 and fib bulletin 83. The use of steel to replace all or a part of conventional reinforcement has been demonstrated to lower the embodied CO2 of the segmental lining as well. The return of experience of the Doha Metro as the Grand Paris Linea 16.1 will provide a good recent illustration.

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ADVANTEX: Research of innovative tools to support the logistics of the use of excavation materials produced by the Lyon-Turin railway line for the best sustainability and circular economy of the process

A. Fantilli, A.M. Cardu, A.M. Lingua, P. Marini & J.M. Tulliani
Politecnico di Torino

M. Rocca & R. Scevaroli
Tunnel Euralpin Lyon Turin – TELT

ABSTRACT: The Mont-Cenis Base Tunnel is the key work of the new Lyon-Turin railway line. The project envisages a total volume of 37.2 million tons of excavated material over a period of 10 years: a considerable part of the excavated material will be used for the tunnel lining (concrete or railway embankments) and for the embankments of the open-air sectors, while the remaining part will be transported by rail, conveyor belts, and heavy vehicles to the temporary and permanent storage sites. To maximize the circular economy and the efficiency of the materials logistic, TELT is working with the Politecnico di Torino (Department of Environment, Land, and Infrastructure Engineering, Department of Structural, Geotechnical and Building Engineering, and Department of Applied Science and Technology) and the Interdepartmental Laboratory SISCON - Safety of Infrastructures and Constructions, to study innovative solutions for the characterization and reuse of the excavated materials. Given that the materials are substantially undifferentiated during the excavation and that the geological classification requires long and complex additional verification activities, which can negatively affect the process, a significant sample of materials excavated at the survey tunnel of La Maddalena (place where the base tunnel will be excavated) were analyzed. The objective of this first phase is the search for new technologies and new processes for the early characterization of the excavated material in order to determine its intended use, designing green concretes (defining its sustainability and mechanical characteristics for structural use, through synthetic parameters, including durability analysis) and backfilling, seeking innovative tools for optimal logistics, in order to "industrialize" the identification process and optimal technologies for automatic process control and traceability, in order to give strength and speed to all activities. The subject of this work is the results of the early characterization experimentation process with the application of artificial intelligence and possible innovative circular solutions.

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Final design considerations for the major rehabilitation of the Montreal Lafontaine Tunnel

J. Habimana, B. Amara & R. Showbary
Hatch

L. Rus
Singular Structures

ABSTRACT: The Quebec Ministry of Transportation is undertaking major structural rehabilitation work and systems upgrade on the La Fontaine Tunnel to comply with current codes, standards and best practices in fire life safety and to extend the lifespan of this 55-year-old immersed tube tunnel for another 40 years.

The paper will discuss final design consideration of ongoing works that include structural analyses and repair strategies for the post-tensioned reinforced caissons, the scheme to repair two leaky joints between caissons, the design of passive fire protection that involved in situ and real scale laboratory tests, and other tunnel systems upgrades.

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Carbon footprint emissions of different tunneling construction methods

P. Jarast
AECOM, Massachusetts, USA

M. Bakhshi & V. Nasri
AECOM, New York, USA

ABSTRACT: Construction is a big contributor to carbon footprint emissions. The carbon footprint emissions in the construction stage are mainly from the construction materials and the construction activities. Among various construction processes, tunnel construction produces a significant amount of carbon emissions since it utilizes various types of high energy-consuming equipment. In order to identify and mitigate such carbon emissions of a tunneling project, it is required to reliably estimate carbon footprints of a tunneling project. The CO_2 emissions can be calculated by estimating the consumed fuel of equipment and transport (diesel, electrical energy) and materials, and then using the conversion factors to CO_2, from well recognized organizations. The purpose of this paper is to evaluate carbon footprint emissions of different tunneling construction methods. It includes the material production, different excavation methods (drilling and blasting, road header or hydraulic breaker hammer, TBM), casting and lining, rock support and road work. The contribution of each stage to the total carbon footprint is discussed and different methods are compared. The results of this study can be used as basic data for establishing a CO_2 emission reduction plan at construction sites.

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Preliminary design and socio-economic benefits of a road tunnel construction in the Tzoumerka mountainous area

D. Kaliampakos, A. Benardos, P. Nomikos, V. Marinos, I. Zevgolis & E. Vlahogianni
National Technical University of Athens, Greece

G. Panagiotopoulos
Metsovion Interdischiplinary Research Center, Metsovo, Greece

A. Bougas
Geologist, Arta, Greece

ABSTRACT: The paper analyses the feasibility of a developing a mountainous road tunnel between the Theodoriana and Melissourgoi, two mountainous villages located at the area of Central Tzoumerka, Epirus, Greece. The principle geological, hydrogeological and geotechnical characteristics of the wider area are analyzed, followed by the identification of alternative tunnel alignments to achieve the optimal construction and operational characteristics of the project. The preliminary design of the tunnel follows, including the assessment of the tunnel's layout and overall geometrical characteristics and proposed construction method. Detailed numerical analysis is performed for the design of the tunnel primary support measures and the requirements for the permanent tunnel lining are defined, along with all required E&M installations. A preliminary evaluation of the construction cost is made along with the assessment of the direct and indirect socio-economic benefits that can be created by the proposed solution. The latter is given by taking into account a series of alternatives solutions in terms their respective cost, ability to provide ease of passage, environmental performance and finally socio-economic benefits to the population of the area.

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Managing tunnel infrastructure: A new guideline

Martin Knights - FREng
Chair – London Bridge Associates Ltd

ABSTRACT: The new guide on Tunnel Asset Management is going to be published by the UK industry that reflects current industry advances in technological innovation and evolving tunnel asset owner requirements. This will enable asset owners to have a trusted practical guide that can support technical and commercial decision-making regarding tunnel assets and aging infrastructure and also will provide a guidance for all involved stakeholders to effectively manage the ever-growing infrastructure asset legacy.

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Underground solution for urban resilience: Stormwater management infrastructure

A. Koliji, T. Kazerani, G. Questi & J. Senn
BG Consulting Engineers, Lausanne, Switzerland

ABSTRACT: In past decades, stormwater management has become an essential component of climate-change resilient urban development. Replacement of natural pervious areas with impervious surfaces increases stormwater runoff volumes and peak flows. In the absence of sufficient drainage system, cities are subject to urban flooding with potential loss of life and property damage. Underground solutions with network of smart tunnels and pumping stations are of a central role for urban resilience. The present paper studies a stormwater infrastructure in the city of Jeddah in the Kingdom of Saudi Arabia. In the framework of Jeddah Stormwater Drainage Program and Masterplan, a new pump station known as Al-Salam Pump station, is planned to discharge the incoming flow from the storm water tunnel to the Red Sea via an outfall. The design and construction of the deep large-diameter shafts close to the sea as well as their intersection with the connecting tunnels involved several technical challenges. Geotechnical analyses combined with advanced numerical methods were used for an optimized design. As an overall assessment, a Value Engineering study of the proposed solution was carried out highlighting the Value Engineering Concepts, their technical evaluation and engineering development as well as cost, risk and sustainability impact on the project.

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Advancement of conventional cost benefit for selection of truly sustainable infrastructure alternatives

T. Kondrachova, G. Grasselli & E. Miller
University of Toronto, Toronto, Canada

ABSTRACT: In the 21st century, selection of a best infrastructure alternative became prominent for all public sector projects. Initially, such selection was using the well-established for assessment of most profitable private investments, the cost-benefit approach. Criticized for insufficient inclusion of project social and ecological effects, this approach was later replaced with variety of multi-criteria-based methods. An overview of both approaches identifies their advantages and potential burdens for fair assessment of economical, social, and ecological effects. All analyses are supported by world-wide practical examples with emphasis on historical tunnelling projects from Greater Toronto (Canada). Relying on some findings by Canadian and Australian scholars and the results of their own research, the authors develop an enhancement to the conventional cost-benefit approach to ensure selection of fact-proven most sustainable alternatives. As demonstrated, application of this methodology can reduce infrastructure planning timeline, also working toward its better sustainability and helping with achievement of the United Nations' Sustainable Development Goals.

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Practical countermeasures for road tunnels against collapse of lining caused by earthquake

A. Kusaka
Public Works Research Institute, Tsukuba, Ibaraki, Japan

N. Isago & K. Kawata
Tokyo Metropolitan University, Hachioji, Tokyo, Japan

ABSTRACT: Rock tunnels are generally considered to be strong structures against earthquakes compared to surface structures. In recent years in Japan, however, several severe damages such as the collapse of lining have occurred due to direct earthquakes. For road tunnel owners and users, such damage is unacceptable and countermeasures are required. On the other hand, due to budgetary constraints, it is impossible to take large-scale measures for all tunnels. The authors therefore have reviewed the severe tunnel damage by earthquake, conducted dynamic measurement in actual tunnels, and examined effective countermeasures against large earthquake through laboratory test and numerical analysis. As a result, ground conditions that are prone to be affected by the earthquake are proposed. It is also proposed that reinforcing bar in permanent lining concrete is effective to avoid collapse of a large mass of lining concrete.

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Sustainable and resilient city: The case study of a hypogeum stadium in a desert area

P. Lunardi
Lunardi Geo-Engineering, Milan, Italy

G. Lunardi, G. Cassani, M. Gatti & C.L. Zenti
Rocksoil S.p.A., Milan, Italy

ABSTRACT: As cities have grown denser, it seemed only natural to extend skywards. However, the sky is not the limit: Cities need to start looking downwards to adapt to new circumstances and reach the next level of existence. Earth is our only home and that humankind faces enormous challenges. To overcome these challenges we need to focus on how spaces underground can contribute to more sustainable and resilient cities. At the same time we need to break out of our existing paradigms and transition to new ways for space use. The aim of paper is to describe a case study presenting the project of a Hypogeum stadium located into a desert area. The authors, through this project try to reply to above mentioned requirements.

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Autostrade per l'Italia (ASPI) TRS Tunnel Renewal Strategy: The cases of Castello 1 left, San Fermo right and Colle Marino left tunnels

M. Mazzola
Tunnel Assessment Programme Manager, Autostrade per l'Italia S.p.A. (ASPI)

M. Giordano
Tunnel Assessment Programme Coordinator, Autostrade per l'Italia S.p.A. (ASPI)

C. Alessio & B. Spigarelli
Tunnel Assessment Technical Authority, Tecne Gruppo Autostrade per l'Italia S.p.A

ABSTRACT: The objective of ASPI Network's Tunnel Renewal Strategy is the extension of tunnel linings' life cycle (i.e., additional 50 years) through the construction of new, structurally autonomous shell structures, replacing the original linings and ensuring suitable performance under seismic events. Since there is the need to limit the impact on highway traffic, program implementation requires innovative technical and technological solutions, that is the optimization of structural interventions, the automation and speeding up of operations, the maximization of work productivity and flexibility in terms of sites and logistics in order to allow rapid job site start-up and dismantling, by only closing at night time. For the design of pilot interventions aimed at testing alternative technical solutions, following tunnels - built in the late 1950s and early 1970s - were identified: Castello 1 left (Highway A10 Genoa - Ventimiglia), San Fermo right (Highway A09 Milan - Como) and Colle Marino left (Highway A14 Bologna - Taranto). In all the cases, preservation of original intrados profile was planned (crown radius and platform width). In Castello 1 left and San Fermo right tunnels, the new shells remain within the original lining intrados profile, after partial milling or hydrodemolition (required in presence of temporary nailing or concrete containing asbestos fibers), while in Colle Marino left the new crown is inscribed in the existing one thanks to platform lowering 65cm, which was made possible by the absence of altimetric constraints at tunnel portals. New shells consist of Steel Liner Plates in Castello 1 left, a high-performing shotcrete arch integrated with three-dimensional steel mesh panels (Ram-Arch system) in San Fermo right, and prefabricated arch slabs with rear concrete casting (on new cast in place invert) in Colle Marino left.

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Resins filling injections of an extensive system of voids behind the final lining of Monte Baldo highway tunnel

M. Mazzola & M. Giordano
Autostrade per l'Italia S.p.A. (ASPI)

C. Alessio, B. Spigarelli & C. Ghilardi
Tecne Gruppo Autostrade per l'Italia S.p.A

ABSTRACT: The Monte Baldo twin bore tunnel, along the A27 Highway linking Venice to Cadore, was excavated during the 1970s in marls, with partial section advancing system, systematically installing metal ribs as a temporary support. The final lining consists of unreinforced concrete with average thicknesses of 90cm. As part of Autostrade per l'Italia (ASPI) Tunnel Assessment Programme, the southbound tube has recently undergone major temporary safety works, consisting mainly of crown supporting with steel-welded wire mesh and self-drilling bolts. At the same time, an extensive investigation plan was put in place in order to identify the actual thickness of the linings and the extent of back voids due to over-excavation and casting flaws. The investigation, based on video-endoscopy and phorometric techniques, showed an extensive system of interconnected cavities being almost a meter deep. The extent of the volumes involved determined the need to study specific design criteria, based on the seismic response of the shell lining in the presence of cavities on its back, in order to identify priority sectors for filling as well as the suitable material to be used. It was deemed appropriate to proceed with the injection of expansive epoxy resins of high mechanical properties in the hardened state (strength and dynamic stiffness have been investigated, varying the expansion factor). Resin injection proved to be an optimal solution to minimize impacts in terms of site logistics and time incidence of secondary works (perforations diameter, injection equipment). This paper discusses the evidence gathered from the experimentation of this pilot solution in the field of systematic filling of back cavities on existing tunnel linings, specifically in the conditions of implementation during night-time traffic closures.

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Shafts and spiral tunnels for large heat storages – an economic study on ideal geometries

S. Messerklinger
Research Center Wels, University of Applied Sciences Upper Austria, Wels, Austria

M. Smaadahl
OST - Eastern Switzerland University of Applied Sciences, Rapperswil-Jona, Switzerland

E. Saurer
Skava consulting ZT GmbH, Salzburg, Austria

ABSTRACT: Large heat storages are playing a key role in district heating networks in the future. They allow for a broad integration of renewable energy sources and industrial waste heat by providing producers and consumers with the necessary flexibility. Currently, insulated steel tanks with volumes of around 30,000 m^3 and heights of around 60 meters are frequently used by district heating providers in Austria for this purpose. However, due to the limited storage volume and the significant heat loss of around 23 kWh/m^3 to 73 kWh/m^3 storage volume, particularly during the cold season, further developments are required. The use of large rock caverns allow for large storage volumes of more than 100,000 m^3 and a reasonably steady temperature profile of the boundary conditions over the year with significantly reduced heat losses during winter seasons as compared with conventional strorages. Heat storages for this purpose need a minimum height of 60 m to provide the pressures needed in directly connected district heating systems. In this paper, varying geometries of rock caverns with a vertical dimension of in minimum 60 meter are analyzed with respect to efficient and economic construction methods for typical rock conditions in Alpine regions. The costs per cubic meter storage volume are estimated considering in particular (i) construction costs of caverns and access structures; (ii) costs for annual heat losses; (iii) operating costs. The results of this analysis show that the storage cost per cubic meter in rock caverns built in sound rock are in the range of 120 €/m^3 to 170 €/m^3 approximately for storage volumes of > 100,000 m^3 to 500,000 m^3. This is lower than the current costs per m^3 for conventional insulated steel tanks. Concurrently large storage volumes have the additional advantages of reduced heat losses and a long service life with limited maintenance costs. This is of particular relevance for seasonal storages and for the application of the storage caverns for a service life of more than 100 years.

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Waterproof sprayed concrete with improved sustainability performance

E.S. Moe
Norwegian University of Science and Technology, Trondheim, Norway

K.G. Holter
Norwegian Geotechnical Institute, Oslo, Norway

H. Strømsvik
SINTEF, Trondheim, Norway

ABSTRACT: Sprayed concrete in combination with rock bolts has successfully been used for permanent rock support in tunnels for decades. The main shortcoming is that sprayed concrete alone is unable to function as permanent waterproofing in tunnels that requires a dry interior tunnel surface. Therefore, the trend is final inner linings of cast-in-place concrete or waterproof pre-cast segmental lining. In hard rock conditions such concrete linings often represent an excessive structural design, resulting in unnecessary costs, excavated volume, construction time and CO_2 emissions. The research project SUPERCON, aims to develop a waterproof sprayed concrete, as an alternative to the currently used linings. The research results indicate the feasibility of a waterproof sprayed concrete. The concept is presented and discussed. To emphasize the effect of the concept, a comparison is made on CO_2 emissions from cement and excavated volume of rock for four different lining types used in road and railroad tunnels.

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Environmental profile of bentonite drilling fluids for civil engineering applications

S. Padulosi, D.F. Putzu & N. Bartolini
ITALFERR S.p.A., Rome, Italy

D. Sebastiani, M. Cinelli & S. Mangifesta
GEEG, Geotechnical and Environmental Engineering Group, Rome, Italy

I. Bavasso
Sapienza, University of Rome, Italy

ABSTRACT: Bentonite is the commercial name of a class of materials composed mainly of montmorillonite, which may also contain kaolinite, feldspars, micas, cristobalite and quartz. Such product is widely used for different civil engineering applications such as foundations (piles and diaphragm) and tunnel excavations (TBM, Micro-TBM and other no-dig technologies). This paper presents the results of a Research program developed by ITALFERR and GEEG including an experimental investigation based on the analysis of geotechnical and chemical properties of bentonite-based slurries in order to compare and identify the main properties of fluids prepared either with natural or polymer-modified bentonites. The interaction of the drilling fluids with the environment is an extremely delicate issue that must be carefully addressed during the design and construction phases. This study aimed at acquiring knowledge and defining best practices for the proper management of drilling fluids and the sustainable reuse of soils and rocks during and after the excavation.

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Experimental study on cyclic shear behavior of biopolymer-treated soil as a tunnel backfill material

D.Y. Park, M.H. Lee & G.C. Cho
Department of Civil and Environmental Engineering, KAIST, Daejeon, Korea

I.H. Chang
Department of Civil Systems Engineering, Ajou University, Korea

ABSTRACT: The purpose of backfill grout injection is to immediately fill voids left by the TBM body between the tunnel wall and the segmented blocks, preventing subsidence in the surrounding ground structure. The backfill material must resist various shear behaviors during tunnel operation. When cement is used as the primary material for grout, two significant problems can occur. First, the cement-based material has a small damping ratio. Therefore, stability against dynamic loading is low. Second, cement causes serious environmental problems because it causes alkalization due to its direct contact with the ground. Biopolymer-soil treatment improves strength and stiffness and has injection capabilities and permeability reduction effects, showing potential as a tunnel grouting material. However, the performance related to dynamic load has not been evaluated much. Therefore, applying biopolymer-based backfill grouting material will be evaluated through cyclic direct simple shear test by acquiring various types of geotechnical properties of the biopolymer-treated soil.

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Search for potential compressed air energy storage sites in Switzerland

E. Pimentel & G. Anagnostou
ETH Zurich, Zurich, Switzerland

A. Brauchart
ETH Zurich, Zurich, Switzerland
(currently: Rothpletz, Lienhard + Cie AG, Zurich, Switzerland)

ABSTRACT: The energy transition process in Switzerland foresees a move away from nuclear energy. This calls for an expansion of alternative energy sources such as solar or wind. Since these types of energy generation depend on the weather, the energy generated must be stored to be available on demand. In addition to pumped storage plants, compressed air energy storage (CAES) in underground cavities offers a potential solution for this problem. The economic viability of a CAES system depends on the investment costs as well as the overall efficiency of the system, *i.e.*, storage and recovery of the energy. The paper describes the search for a suitable site in Switzerland for an envisioned adiabatic, high pressure (100 bar) CAES with the potential to store 500 MWh of energy. First, the minimum dimensions and possible arrangements of all the cavities required by the CAES facility are determined. Subsequently, relevant hazard scenarios are identified and analysed from the geotechnical viewpoint. A determination is then made of the requirements, such as rock strength, overburden or distance to the valley flanks of the high-pressure underground chamber. In addition, potential damage to the chamber's sealing is analysed and the plug of the high-pressure chamber is dimensioned structurally. Finally, potential sites are selected with the help of a GIS system incorporating the geological and topographical map of Switzerland.

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Mixed use potential of existing road tunnels for conveying water for hydropower generation: A case study of motorway tunnels in Swat, Pakistan

A. Riaz
Frontier Works Organization (FWO), Rawalpindi, Pakistan
Tunneling Institute of Pakistan (TIP), Islamabad, Pakistan

A. Hussain & M. Ajdar
Tunneling Institute of Pakistan (TIP), Islamabad, Pakistan

Z. Ud Din
University of Houston, Houston, Texas, USA

ABSTRACT: The emerging energy crisis is affecting almost everyone in the world. In order to meet energy demands, efforts are being made to harness renewable energy resources. Fossil fuel reserves are depleting, and global warming is caused by the combustion of fossil fuels. Pakistan, with a population of over 220 million people, has been facing an energy shortage for the past two decades due to increased population and industrialization. In Pakistan, hydroelectric energy has been meeting most of the energy demands. When done correctly, hydropower is low-cost, has a little negative environmental impact, and provides numerous economic benefits. In most hydropower generation plants; tunnels are designed to carry water. Several road tunnels have been built in the country's northern region recently, near mountain peaks and bodies of water. The authors propose an innovative use of an existing road tunnel for water conveyance. The hybrid tunnel will result in significant cost savings compared to constructing a tunnel for a hydroelectric facility. The water that runs through the tunnel can also be used to generate power for the tunnel operations, which contributes to achieving the Sustainable Development Goals. Moreover, the outflowing water can be used for irrigation of agricultural fields. The proposed innovation can be implemented at 1.3 kilometers long Tunnel No. 1 on the Swat Motorway, located close to the Swat River. In this research, the authors will perform a detailed investigation study for the tunnels at Swat Motorway to see the feasibility to use existing tunnels traffic and water conveyance.

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The new Line 16 São Paulo Metro and best use of zero-carbon technology

H.C. Rocha, F.M. Pontes & D.L.C. Lima
Companhia do Metropolitano de São Paulo- Metrô, São Paulo, Brasil

ABSTRACT: The Line 16 Project sought to find solutions to reduce its construction and operations costs, with emphasis on solar photovoltaic energy generation, reduced energy consumption and construction costs due to the adoption of high-capacity elevators in deep level and low-ridership stations. A large diameter (14 m) tunnel boring machine (TBM) was adopted, which will house, in addition to the tracks, station platforms, technical equipment rooms and also 23 intermediate train parking spaces, reducing capital costs for construction of surface depots, in addition to operational energy savings due to reduced train shunting distance.

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On the mechanical behavior of underground pipeline with separated joints rehabilitated by cured in place pipe

K.J. Shou & J.M. Hsu
Department of Civil Engineering, National Chung-Hsing University, Taiwan

ABSTRACT: In this study, numerical analysis was applied to investigate the mechanical behavior of separated pipe joint rehabilitated by the Cured In Place Pipe (CIPP). The numerical model was calibrated by the laboratory test results, then applied to simulate the rehabilitated pipelines with various geometries and loading conditions. The influence of control factors, i.e. backfill, interface, etc., on CIPP rehabilitation performance was also analyzed in details. The results of this study suggest that the CIPP could improve the separated joint to certain extent, and the findings could be applied in design optimization and guideline development.

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Low-carbon ground support design for an underground tunnel crossover with a narrow roof pillar in a road tunnel project in Sydney, Australia

S. Thirukumaran
Senior Associate Tunnel Engineer, Jacobs, Sydney, NSW, Australia

D. Oliveira
Technical Director, Rock Engineering and Mined Tunnels, Jacobs, Brisbane, QLD, Australia

M. Sheffield
Technical Director, Tunnelling, Aurecon, Sydney, NSW, Australia

ABSTRACT: This paper presents a study case on how a design solution with lower carbon footprint was achieved at a road tunnel crossover connecting two major stages of Australia's largest road tunnel, the WestConnex Project. There was only a 3 m thick crown rock pillar (i.e., vertical separation) between the crossover ramp and twin mainline tunnels. Two bridging structures were initially designed to be cast in the mainline tunnels. These structures need to be heavily reinforced with concrete thicknesses up to 2 m extending for up to 100 m in length. Constructing these large structures underground is challenging, increasing the use of materials and reducing production rates. A new approach allowed for replacing one of these bridging structures with a Permanent Sprayed Concrete Lining combined with temporary rock reinforcement. Further, extensive in-tunnel monitoring combined with a specific construction sequence was proposed to minimise the risks of roof rock pillar failure. The in-tunnel displacements obtained from the monitoring data were then compared with the numerical predictions. Similar trends were observed between measured and predicted in-tunnel displacements, validating the design.

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Traceability and environmental follow-up of excavated materials Learnings from implementation experiences with bigger projects

C. Villette
CEO, Altaroad, France

T. Dumas
Partner, Business Development, Altaroad, France

ABSTRACT: Whether imposed by owners or proposed by contractors, monitoring correctly the environmental impact of construction works is an increasing concern. This requires a system capable to guaranty the detailed traceability of all waste materials from extraction to final destination, including storage, transformations and reuse, which becomes complicate when trying to collect and synchronize data from distinct systems and stakeholders. Construction in France provides an interesting case study in this respect. In 2017, Grand Paris Express imposed a digital tool to track all movements of soils from its projects. In 2022, the country imposed the same for all hazardous waste, and in 2023 for all construction waste, forcing the industry to adapt. Since 2018, Altaroad developed systems to help meeting these requirements. The paper summarizes how to successfully implement such system to the benefit of all partners.

Geological, geotechnical site investigation and ground characterization

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Televiewer defect aperture logging for detailed model development – A case study from the M8, Sydney, Australia

H. Baxter-Crawford
SMEC, Sydney, Australia

A. Lippet
Jacobs-Aurecon JV, Sydney, Australia

ABSTRACT: The central portion of the 9km long M8 tunnel in Sydney, Australia, was developed under the existing Cooks River and a deep palaeochannel filled with Tertiary and Quaternary sand and clay sediments. The palaeochannel was an artifice of regional scale faulting in the underlying Hawkesbury Sandstone bedrock. Grouting from the surface aimed to reduce water inflows into the tunnels during construction. A primary grid of three parallel rows of boreholes spaced 20 m apart were drilled covering a 1300 m long section of the alignment were drilled via percussion methods. Secondary, angled holes were drilled to target specific water bearing features for pre-grouting. Each hole was logged using an acoustic televiewer probe with the interpretation of defects completed using Wellcad^{TM}. The holes were interpreted geotechnically, focused on open defects, using defect codes commensurate with tradition logging and the Australian Standard at the time. The key parameters logged were defect aperture and void observations. Defects with >100 mm aperture became the focus for modelling and targeting with secondary grouting holes. Regional faulting was expressed as sub-vertical joints, which formed only part of the overall deformation picture at the site. Detailed Design Phase site investigation also suggested accommodation structures in the form of sub-horizontal to shallow dipping bedding plane shears would be prevalent. The televiewer logging confirmed this. Structures were correlated between the boreholes using Vulcan^{TM} as the modelling software. The modelling resulted in significant refinement to the predicted intersection of sub-vertical structures related to the regional fault zone as well as defining 13 individual bedding shear planes that would intersect the tunnel alignment. Subsequent excavation and mapping confirmed the models high accuracy.

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Reliability analysis of discrete fracture network projections from borehole to shaft scale discontinuity data

C. Brueckman
Stantec, Denver, USA

E. Eberhardt
The University of British Columbia, Vancouver, Canada

S. Rogers
WSP, Vancouver, Canada

ABSTRACT: Discrete fracture network (DFN) models allow discontinuity data to be stochastically quantified and used to represent a jointed and faulted rock mass, providing a means to assess potential failure modes for a planned tunnel and the corresponding excavation methods and support design. Required inputs are generally obtained from borehole data to obtain representative values at the tunnel depth, but with limited opportunities for ground truthing and validation. Results are presented from a validation exercise comparing DFN results from discontinuity data sampled across two different spatial scales, first from a deep geotechnical borehole followed by a co-located deep shaft. The results indicate that both under- and over-sampling of different discontinuity sets occurs due to orientation bias and trace visibility. The corrections and workflow developed demonstrate the utility of continuous data collection and updating of DFN analyses as projects transition from investigation and design to construction.

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Which tests for a rapid geotechnical characterization of excavated materials for use as concrete aggregates? Application to the Lyon Turin base Tunnel

A. Cherrey & D. Chamoley
Centre d'Etudes des Tunnels, Bron, France

J. Vennat & P. Schriqui
Lyon Turin Euroalpine Tunnel,Bourget-du-Lac, France

J. Blache
CEREMA, Bron, France

ABSTRACT: Rapid geotechnical characterisation of excavated materials is key to all initiatives aimed at mitigating the impacts of managing the materials excavated during tunnelling in particular by maximizing reuse and re-employement by immediately sorting materials of good geotechnical quality (applications for concrete, subgrade layer……). Rapid characterisation is a materials identification process during the work site phase that is essential given the pace of the tunnel boring machines and the need for significant temporary storage areas pending analysis results. This characterisation can only be performed after geological investigations (soundings, exploration galleries) enabling geological formations of good geotechnical quality to be selected and on which rapid characterisation will be performed. It is not sufficient in itself and requires more advanced tests after the materials have been sorted (L.A./M.D. tests. grain-size characterisation, V.B.E.). At present, contracting authorities, project managers and companies are looking for rapid tests that are fast and easy to put in place on the site. This article gives food for thought for future research by presenting resistance test results carried out on good geotechnical quality materials on the T.E.L.T. site and the correlations between the Point Load Test (Franklin test) and the Los Angeles test on untreated materials and the dynamic fragmentation test and the Los Angeles test on screened materials.

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Geotechnical analysis of adapted permeation and compaction grouting techniques for detailed design and construction of underground structures

T.M.A. Delport, J.A.S. McCosh & K.M. Nowak
hyperTunnel Ltd., UK

ABSTRACT: hyperTunnel's method aims to substantially change tunnelling and underground construction, contributing a solution that is envisaged to be more sustainable and cost effective. The method works by turning convention on its head; building structures prior to excavation and use - in-situ tunnelling. Through a unique combination of proven technologies – including digital twins, robotics, 3D printing and digital underground surveying, supported by AI and VR – hyperTunnel's approach aims to redefine the possibilities in underground construction. Two such existing technologies, permeation and compaction grouting, are established means of ground consolidation and groundwater ingress mitigation. The hyperTunnel method builds on these by tailoring them for a detailed and controlled underground construction process. Geotechnical assessment of the ground's properties, both pre- and post-deployment of grout, is used to evaluate and develop the novel construction process. To generate samples, deployments are conducted in ground chambers of various sizes (≥1 m^3) resulting in grout "plumes". The size, weight and shape of plumes create a unique challenge to traditional cube and cylindrical sampling. Samples of the virgin ground and post-deployment composites are tested for their material properties. Testing includes, but is not limited to, particle size distribution, shear box, consolidation, uniaxial compression, modulus of elasticity, Poisson's, in-direct tensile, density and permeability. The consistency and repeatability of the post-deployment product is evaluated to inform design assumptions and provide insight to computational modelling. Application aside, the overall process and data provide insight into the properties of grouted ground, away from more idealised and controlled desktop environments. The outlined geotechnical process underpins the thorough, empirical approach to design assurance adopted by hyperTunnel in its design and construction methodology.

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Mapping by pictures: A case study of simplified rock mass classification to improve consistency

P. Evins
WSP, Stockholm, Sweden

ABSTRACT: Inherent subjectivity in the most used rock mass classifications often causes accumulated inconsistencies between parameters mapped by different geologists which can lead to classification of the same rock mass into 3 different rock support classes. An alternative approach is to reduce the number of mapping parameters and focus on repeatability and geological consensus for rock mass classification. In this case study, scaled example pictures of the expected levels of blockiness and fracture condition were appended to the Geological Strength Index (GSI) chart. Direct comparison of these pictures to the rock mass determines the parameter values and reduces mapping time. Because the mapping process is quick, it can be repeated and verified more often. This pictorial GSI classification was tested on geologists and engineers and then used for rock support decisions on an open TBM. The resulting streamlined mapping process provided more consistency between all parties.

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Equivalent material modelling of fractured rock mass resonance effects

H.T. Holmes, C. Paraskevopoulou & M. Hildyard
University of Leeds, Leeds, UK

K. Neaupane
AECOM UK&I, Birmingham, UK

D.P. Connolly
University of Leeds, Leeds, UK

ABSTRACT: Resonance effects in parallel fractured rock masses are investigated using equivalent material models. The mechanisms of spring resonance and superposition resonance are considered. Both of these resonance mechanisms give rise to resonant frequencies, which represent bands of high transmission. Three different representations of a fractured rock mass are adopted: discrete fractures using special elements in the finite difference mesh; a homogenous equivalent medium representing the weakening to the material caused by the fractures; and a localised equivalent medium applied in the vicinity of fractures. The models are excited by a wide-band source, the response measured and a transfer function generated from the results. Results are compared to the prediction of spring and superposition resonant frequencies calculated using analytical equations. It is found that the discrete and localised equivalent materials give similar results, which match the predictions from the analytical equations for both resonance mechanisms, while the equivalent homogenous medium does not show any resonance effects. Showing that this effect occurs in the appropriate equivalent material model helps future prediction of ground borne vibrations from underground sources, such as railway tunnels, as it gives a greater scope of models which can accurately model the propagation of stress waves through fractured rock masses.

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Rheological properties of artificial sandy soil conditioned with foam and polymer

B. Hwang, J. Kwak, D. Lee, A. Bae & H. Choi
Korea University, Seoul, Republic of Korea

ABSTRACT: Recently, tunnelling projects using the Tunnel Boring Machine (*TBM*) have been increased in South Korea. As for the Earth Pressure Balance (*EPB*) shield *TBM*, functional additives such as foam or polymer are sprayed and mixed with excavated soil. Conditioned soils by additives show improved flowability and workability, and thus can provide cutter wear reduction, face stability, material hauling facilitation, and other excavation efficiencies. In this study, rheological characteristics related to workability were examined for additive-conditioned soils. An artificially fabricated sandy soil was prepared by mixing silica sand 70% and illite 30%. Two types of additives, foam and polymer, were considered. Rheological characteristics were evaluated by performing the laboratory pressurized vane shear tests varying the Foam Injection Ratio (*FIR*) and the Polymer Injection Ratio (*PIR*). The vane torque, peak strength, and yield stress decreased as *FIR* increased or *PIR* decreased.

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Laboratory experiments for hazardous ground prediction ahead of a TBM tunnel face based on resistivity and induced polarization

M. Kang, J. Lee, S. Park, K. Kwon & H. Choi
Korea University, Seoul, Republic of Korea

ABSTRACT: It is crucial to predict hazardous ground conditions ahead of a Tunnel Boring Machines (TBMs) for stable tunnel construction. In this study, a laboratory chamber test was conducted to simulate the electrical resistivity and Induced Polarization (IP) surveys during the TBM advancement toward risky ground conditions in a soil chamber. In addition, risky geological conditions (i.e., the typical zones of fault, geologic transition, and embedded core-stone) possibly encountered during tunnel excavation were modeled in the soil chamber. The electrical resistivity and chargeability were simultaneously measured at the tunnel face of the model during tunnel excavation. The guideline on accurately predicting various hazardous conditions was proposed by analyzing the variations in resistivity and chargeability measurements during TBM advancement in the experiment. In conclusion, a hybrid method simultaneously implementing the electrical resistivity and the induced polarization surveys can predict hazardous ground conditions ahead of a tunnel, which enables efficient and stable tunnel excavation by minimizing potential risk in advance.

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Tunnel portal design optimisation in tectonically disturbed and weathered gneissic rock masses

F. Kritikou & C. Paraskevopoulou
University of Leeds, Leeds, UK

V. Marinos
National Technical University of Athens, Athens, Greece

ABSTRACT: It is often the case that portal areas are subject to slope instability phenomena related, amongst other factors, to the poor-quality ground conditions, where soil or weathered rock material is present. This weathering is more prominent in specific geological settings. In this paper gneissic formations in a setting where weathering is favoured are studied. Information on several gneissic rock mass types and their potential behaviour in slopes is used to propose a set of guidelines regarding slope geometry focusing on benching for different slope heights and angles. Slope stability analyses were conducted for multiple scenarios per rock mass type. It was observed that for moderately weathered rock masses, steeper slopes (≤3:1) are satisfactory, whereas for weathered types, gentler slopes (~2:1) are suggested, depending on the maximum height of the slope. Through a site-specific study the complexity of gneissic systems and the effect of the weathered zone to stability was highlighted.

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Geostatistical modelling of geotechnical properties in the context of a tunneling project: Application to the Grand Paris Express project (France)

L. Lacherade
BRGM, Direction des Risques et Prévention, Orléans, France
Arts et Métiers Institue of Technology, Université de Bordeaux, CNRS, Bordeaux INP, INRAE, I2M Bordeaux, Talence, France

A. Marache & A. Denis
Arts et Métiers Institue of Technology, Université de Bordeaux, CNRS, Bordeaux INP, INRAE, I2M Bordeaux, Talence, France

I. Halfon, L. Closset & J. Rohmer
BRGM, Direction des Risques et Prévention, Orléans, France

F. Quesnel
Direction des GéoRessources, Orléans, France

ABSTRACT: In the context of underground construction projects, the knowledge of the urban subsoil is of major importance. This article focuses on the development of a 3D geostatistical modelling of the pressuremeter tests applied on a section of the Grand Paris Express. The spatial variability of the geotechnical behavior is studied through a comparison between deterministic geostatistical methods: ordinary kriging and collocated cokriging. They both give quite similar results but collocated cokriging is definitely more accurate. This study also shows that large-scale underground projects are an ideal setting for the application of such 3D modelling.

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Observations on the condition of a hydraulic pressure tunnel through an ROV survey

S. Lopez & F. Micheli
Lombardi Engineering, Quito, Ecuador

M. Buestan
CELEC EP, Cuenca, Ecuador

ABSTRACT: Due to the significant costs and possible risks associated with the dewatering of pressure tunnels, inspections with Remote Operated Vehicles (ROVs) are an economical alternative that can provide valuable insights into their conditions. The headrace tunnel of Paute HPP Phase C is part of Ecuador's largest hydroelectric complex and was inspected with an ROV in 2016 and 2021. A direct comparison was made between the two surveys, showing clear evidence of deterioration within a relatively short period, which complemented with the accurate quantification and location of the anomalies, allowed the planning of extraordinary maintenance works. This paper presents the main observations of the ROV surveys and describes the advantages of preventive monitoring through indirect inspections, which can provide extensive information on the conditions and evolution of pressure tunnels.

Keywords: ROV, pressure tunnel, tunnel dewatering

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Acoustic emission of calcitic and dolomitic rock specimens during uniaxial compression tests

M.A. Lotidis
EDAFOS Engineering Consultants SA, Athens, Greece

P.P. Nomikos
School of Mining and Metallurgical Engineering, National Technical University of Athens, Zografou, Athens, Greece

ABSTRACT: Cylindrical and prismatic rock specimens, subjected to uniaxial compression, are usually studied to assess the material's uniaxial compressive strength, Poisson's ratio and Young's modulus. However, in order to monitor their fracturing, and so to comprehend the fracturing behaviour of the tested material, additional methods should be employed, such as the recording of the acoustic emission activity. Acoustic emission, offer a valuable insight of the rock's fracturing behaviour and of the accompanied phenomena. In the current study, five calcitic and dolomitic rocks are subjected to uniaxial compression, while the acoustic emission activity is recorded and post-processed accordingly. There are apparent differences regarding the acoustic emission activity, for which two different behavioural types are noticed and described, based on the mineralogical composition of the studied specimens. Finally, the ability to predict the upcoming failure of the specimen through the analysis of the basic acoustic emission parameters is evaluated.

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Innovative assessment methodologies to introduce rock mass behaviour into tunnelling - The legacy of Professor Paul Marinos in the Athens Metro

Vassilios Marinos
National Technical University of Athens, Greece

Mania Benissi, Georgios Rovolis, Konstantinos Korkaris & Georgios Stoumpos
ATTIKO METRO S.A, Athens, Greece

Nikolaos Syrtariotis
Gall Zeidler Consultants, Ashburn VA, USA

Kalliopi Aggelidaki
Loudoun County Public Schools, Ashburn VA, USA

Ioannis Papadatos
Balfour Beatty VINCI, Birmingham, UK

Margarita Panteliadou
AVAX S.A, Athens, Greece

Dimitra Papouli
AKTOR S.A., Thessaloniki, Greece

ABSTRACT: The role of Professor Marinos in the Athens Metro was multifarious from the early stages of the Project. During this period, little experience was shared among the Greek technical world with respect to urban tunnelling let alone in complex ground conditions. The technical expertise and scientific knowledge, in terms of engineering geology, was brought to the project by Professor Marinos. He implemented novel methodologies, the most important of which being the introduction of the engineering geological model in terms of behaviour against a given construction method. The work ethics of Professor Marinos is still the tool to approach, address and decipher the interaction between the engineering geology and the construction method. It has permeated through the specifications and contract documents of ATTIKO METRO S.A. and –most importantly– through the collective knowledge of numerous geologists and engineers that were directly or indirectly associated with his work.

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Modelling total convergences in tunneling: An essay on Venda Nova III data

P. Matos
Comsa S.A., Lisbon, Portugal

N. Plasencia
EDP Gestão da Produção de Energia S.A., Porto, Portugal

G. Paneiro
DECivil/CERENA, Técnico, University of Lisbon, Portugal

ABSTRACT: One of the main problems in underground excavations regarding geotechnical monitoring, especially when excavated with drill and blast, is the late installation of the instruments, namely convergence's sections. Due to the applied construction methods, the minimum distance, defined on Monitoring and Observation Plans, to which the convergence profiles must be installed, is usually exceeded. This situation has been repeatedly alerted by the Designers, who refer the loss of information of early and main deformations. A methodology for estimating convergences from the excavation instant to the beginning of the convergences readings is presented, by mathematical modelling of time-history convergence data. The proposed approach is applied to a case study in the North of Portugal: the 1346 m length and 7.4 m diameter Access Tunnel in the Venda Nova III Hydroelectric Scheme. An attempt to correlate these results with the RMR and Q was made. This approach can be used both in the construction phase and in the design phase, to predict the behavior of deformations and optimize production cycles and rock supports.

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The management of excavation data in accordance with the WBS for the Mont Cenis tunnel

M.E. Parisi & A. Rajevich
TELT sas

M. Cussino
gd test srl

ABSTRACT: The GIS represents an effective and useful digital tool for managing various types of information in order to be able to use it as required. In this context, a geological portal has been created within TELT since the beginning of 2000s on a GIS basis in order to classify, sort and record all geotechnical/geological parameters. The IT portal is set up with a database in an SQL Server and a GIS mapping representation. It has been populated over time with data from the different project phases which have characterised the Lyon-Turin project. The database includes data from exploratory investigations, measurements of the water resources in the areas involved in the new railway line and data from the construction of the first underground works (face surveys, excavation progress, geotechnical monitoring, TBM excavation parameters). Within this huge information structure, data is organised with a WBS or Work Breakdown Structure. The breakdown of the base tunnel into smaller, identifiable elements allows the huge mass of data to be better tracked and organised and to make information accessible to all operators on a common dictionary basis. In addition, the possibility of using a single structure allows to avoid duplication and the exponential growth of available data. In conclusion, the organisation of GIS data according to a single WBS becomes particularly important in big projects in order to create lean tools capable of responding in an increasingly efficient and effective manner.

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Hydrogeology of the Brenner Base Tunnel in the Italian section: Observed inflows and forward monitoring procedures

P. Perello
GDP-GEOMIN s.r.l., Torino, Italy

S. Skuk, A. Spaziani & A. Voza
Brenner Basis Tunnel, Tunnel di Base del Brennero BBT SE, Bolzano, Italy

ABSTRACT: The Brenner Base Tunnel (BBT) is a double-tube, high-speed railway line currently under construction between Italy and Austria across the Alpine chain divide. The underground section is 55 km long, is composed of 230 km total tunnels and has a maximum overburden of 1.800m. As from design programs, the realization of main tubes (MT) was continuously preceded by the excavation of an exploration/drainage tunnel (EDT) 27 km long. On the Italian side, the EDT construction is now completed, as well as large portions of MT. The local geological context consists of superposed metamorphic tectonic units having strongly variable lithology, including gneiss, phyllites, micaschists, marbles and gypsum/anhydrites. The hydrogeological conditions observed during the EDT construction are heterogeneous, owing to variable lithology and fracturation state. The relevance of water inflows and the related possible impacts on springs was one of the main concerns in the design phase. The peak of cumulative water discharges during excavation is currently in the order of 250 l/s. Appropriate forward monitoring and investigations were designed to prevent the unexpected drainage of springs aquifers. These procedures, based on the execution of forward boreholes equipped with blowout preventers, had to couple with the double shield TBM operation. The EDT completion provided relevant know-how feedback, in terms of knowledge of groundwater flow systems in Alpine domains and of capability to operate forward hydrogeological monitoring while excavating with a double shield TBM. This experience is here summarized.

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Contribution of twenty years of exploratory work in the complex carboniferous formation of the montcenis base tunnel

J. Senemaud, B. Serrano & C. Salot
Tunnel Euralpin Lyon-Turin, Le Bourget du Lac, France

M.E. Parisi & L. Brino
Tunnel Euralpin Lyon-Turin, Turin, Italie

ABSTRACT: This paper discusses the work undertaken to explore the most geologically complex section of the 57.5 km Lyon-Turin cross-border base tunnel between Susa, Italy and Saint-Jean- de-Maurienne, France. This section, on the French side, has been subject to exploratory work in the Houiller briançonnais fields, between Saint-Martin-La-Porte and La Praz for nearly 20 years. After the realization of two access tunnels which had convergences up to 2 meters, this work, in the axis of the south tube of the base tunnel, was divided into 2 parts: 1.5 km realized using the traditional method to explore and cross the most converging terrain corresponding to the Front du Houiller and 9 km using a TBM for the other Houiller parts. The unknown and extremely difficult geological and geomechanical conditions in these carboniferous formations, under 300 to 1,200 m of covering, have made this work a real technical and human challenge that required a special and adaptive design with the testing and validation of constructive solutions before the launch of the construction of the base tunnel in this sector. This exploratory work has also made it possible to optimise the design and consolidation of economic forecasts and planning for this section.

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Characteristic of ground deformation with unsupported tunnel excavation in a sedimentary soft rock

H. Takase
Metropolitan Expressway Company Limited, Tokyo, Japan

K. Namikawa
Metropolitan Expressway Maintenance East Tokyo Company Limited, Tokyo, Japan

M. Matsumoto
NOM Company Limited, Tokyo, Japan

J. Koseki
The University of Tokyo, Tokyo, Japan

ABSTRACT: New underground infrastructures in Greater Tokyo in Japan are now planned through greater depth space where the sedimentary soft rocks (mudstone) are widely distributed. The sedimentary soft rocks have the strain and confining pressure dependency as deformation characteristics and creep deformation is observed, however, the measurements of detail deformation characteristics of ground during tunneling the sedimentary soft rocks are not enough. This paper describes the test results carried out a following experiment, excavating an unsupported horseshoe-shaped tunnel with 5.0 m in height in the sedimentary soft rocks at a depth of 45 m to obtain basic data on the ground deformation characteristics and deformation behavior of the ground around the tunnel, and the ground deformation during tunnel excavation works by relating to the deformation characteristics and features of sedimentary soft rocks are reported.

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Innovative and conventional geophysical investigations at the Hamza Bey (Alcazar) monument in Thessaloniki, Greece

G.N. Tsokas, P.I. Tsourlos, G. Vargemezis, A. Stampolidis & E. Athanasiou
Exploration Geophysisc Lab., Aristotle University of Thessaloniki, Greece

C. Raptis
Ephoreia of Antiquities of the city of Thessaloniki, Eptapyrgio, Thessaloniki, Greece

ABSTRACT: The current paper describes the conduct and the results of the innovative (for the time of the survey) geophysical investigations carried out in Hamza Bey Mosque (cine Alkazar) in Venizelou station at Thessaloniki. The assessment of the geological structure and the detection of buried antiquities under the monument were accomplished by conventional GPR and ERT techniques and have been reported elsewhere. A fully 3-D survey is presented here. Further, since the investigations aimed also to precisely determine the depth of the foundations of the monument, innovative crosshole ERT was employed to accomplish this task.

The use of geophysics to assess the burial depth of the foundations of buildings is a very difficult task because operating directly over the ground surface is impossible. Further, the manmade noise comprises an additional problem. These are the reasons led to a combination of conventional methods and a cross hole one. Thus, the investigations had a certain degree of innovation. During these investigations we introduced new surveying techniques, specific ways of data treatment and modifications to the mathematical inversion schemes. Practical and theoretical problems had to be faced which were addressed by the collaboration of all involved groups.

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3D Geo-modelling using geophysical tools to aid injection grouting

J. Whittaker, T.M.A. Delport & R.S.A. Al-Harthy
hyperTunnel Limited, UK

ABSTRACT: Geophysical tools are increasingly utilised within the tunnelling and underground construction industry; investigating the extent and properties of physical domains where traditional direct investigation methods encounter restrictions. This paper describes the development and subsequent advanced processing method used by a unique robotic ground penetrating radar (GPR) tool, that is used to survey beyond a pipe-liner installed within an in-ground horizontal direction drilling (HDD) bore. The GPR device assists in the construction of underground structures by hyperTunnel Ltd, who employ adapted grout injection methods to controllably place cementitious and non-cementitious chemistry into porous ground (from installed and lined horizontal bores). The device is shown to use 900 mHz and 2.6 GHz frequency antennas to discern the coincidence of objects both beyond and on the pipe's surface, both in terms of their spatial extent and probable material type. This capacity is utilised by hyperTunnel in two complimenting elements of their construction process; to assess the ground conditions pre- and post-injection of chemistry, and to assess the spatial extent of injections for the purpose of validating construction objectives and identifying ground which requires further injections to meet said objectives. This novel use of GPR provides a key visualisation and verification tool to hyperTunnel's construction method, and its full application continues to be realised in further scenarios.

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Acceleration of soft ground with tunnels near soft-hard strata interface: Longitudinal shaking

Yuan Yong
State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

Li Siming
Department of Geotechnical Engineering, Tongji University, Shanghai, China

Xiao Mingqing
China Railway Siyuan Survey and Design Group Co.,Ltd., Wuhan, China

ABSTRACT: Current aseismic design has seldom considered the effect caused by underlain tunnels. Previous studies of this issue have already dealt with the situation of tunnels embedded in homogeneous soil under transverse seismic excitation. It would be essential to explore the ground response pattern when tunnel crossing the region of soft-hard strata, commonly in river crossing tunnels. A shaking table test of scaled tunnel-strata model was conducted to investigate the influence of the tunnel on the acceleration response of the ground. In this test, harmonic excitations with different frequencies and intensity levels were input from the shaking table, in the direction along the tunnel axis. By comparing the ground acceleration response of the free-field model and the tunnel-strata model, amplification of the ground acceleration caused by tunnels was found with both frequency and intensity of excitation.

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Optimization of electrical resistivity survey utilizing harmony search algorithm to predict anomalous zone ahead of tunnel face

Y. Yoon, M. Kang, J. Lee, Y. Choe & H. Choi
Korea University, Seoul, Republic of Korea

ABSTRACT: Accurate prediction of anomalous zones ahead of a TBM tunnel is essential for stable and efficient construction. This study developed an optimization model to predict characteristics of anomalous zones based on the electrical resistivity survey. The harmony search algorithm (HS) was adopted in the optimization process. An analytical solution of the electrical resistivity corresponding to the anomalous zone was derived for the objective function of the developed model. The HS optimal operators were determined by evaluating the prediction errors of the optimization model. Parametric studies were conducted to validate the reliability of the optimization model in predicting the characteristics of the anomalous zone. The prediction errors between the optimized values and experimental results were less than 10% for all the characteristics. It is concluded that the developed optimization model can accurately predict the anomalous zone ahead of a tunnel face, which enables stable tunnel excavation.

Planning and designing of tunnels and underground structures

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Design aspects of deep water distribution shafts

N. Allahverdi
New York City College of Technology, New York, USA

V. Nasri
AECOM, New York, USA

ABSTRACT: This paper covers aspects of planning and designing of deep shafts with reference to two water distribution shafts under construction in New York City. The new shafts will be sunk into soil and rock to a depth to connect to existing Queens-Brooklyn tunnel section of City Tunnel No. 3 (CT3). The inside diameter of the upper parts of both shafts is 14.9 meter. Artificial ground freezing is specified as preferred method of excavation support for the entire stretch in soil. Excavation in competent rock will be performed using drill and blast technique preceded by a pre-excavation grouting program. Membrane waterproofing with sectioning is prescribed to limit groundwater infiltration to dry chambers.

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Short-term tunnel face stability in clays

G. Anagnostou & Th. Pferdekämper
ETH Zurich, Switzerland

ABSTRACT: On account of their low permeability, clays respond to tunnel excavation with a considerable delay. This is favourable for the interplay between ground, tunnel support and tunnelling equipment and, *inter alia,* also for the stability of the tunnel face. Nevertheless, even when tunnelling through practically impermeable clay deposits, the face may fail under certain conditions. The latter represents the subject of the present paper. Specifically, based upon a simple but accurate face stability model and a well-known empirical relationship, this paper provides generic answers to two important questions: which geotechnical conditions would result in an unstable face, thus necessitating, *e.g*., closed-mode TBM operation? and which conditions would be prohibitive in this respect, *i.e*. the required face support pressure would be beyond today's technical feasibility limits, so that soil improvement measures would become indispensable?

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Preliminary comparison of the life cycle cost and safety of a single bore bidirectional tunnel including semitransverse ventilation, with a twin bore unidirectional tunnel of the same length longitudinally ventilated

Georgios Angistalis
Geological Engineer, EurIng, CEng, MSc, MBA, Attiko Metro S.A.

Angelos Astrantzis
Mechanical Engineer

Aglaia Papamargariti
Geologist, Aegean Motorway S.A.

ABSTRACT: This paper compares the life cycle cost (LLC) and safety level of a single bore bidirectional (SBB) tunnel including semitransverse ventilation and a parallel escape adit (PEA), with a twin bore unidirectional (TBU) tunnel of the same length. The tunnel's length is arbitrarily selected 3800m. The design fire for the SBB tunnel is selected 100MW; the civil works of the SBB tunnel also include a 400m high ventilation shaft with a vent fan room at its top. Two traffic cross sections have been examined, the first including a clearance borderline (CBR) 7,5m wide and 4,5m in height, and the second a CBR 8,5m wide and 5m in height. A PEA either for pedestrians or for emergency vehicles has been examined. LCC costs have been included reinvestment cost, operation & maintenance cost and accidents cost. Within the design life of the structure and under the considered assumptions, the SBB tunnel has been found becoming more expensive than the TBU tunnel in all cases.

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Tomography based method for investigation of steel fibre distribution in tunnel shotcrete

A. Ansell
KTH Royal Institute of Technology, Div. Concrete Structures, Stockholm, Sweden

ABSTRACT: Steel fibre reinforced shotcrete (sprayed concrete) is a vital factor for achieving long technical lifespan and safe performance for the support of hard rock tunnels. A large number of fibres must cross areas with large tensile stresses for the shotcrete to be efficient. Computed tomography (CT) is a laboratory testing technology based on X-ray scanning followed by digital image detection to visualize the material interior. This is here used in a mesoscale approach for investigation of in situ cored shotcrete samples containing full size fibres and aggregates. For investigating the occurrence and orientation of steel fibres in shotcrete this method is much more efficient than the traditionally used electron microscopy studies of sawn thin slices, which is time consuming, costly, destroys the samples and provide limited information. The newly developed method provide a complete and detailed description of the fibre orientation within a cored shotcrete sample.

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3D numerical modelling of a large shallow cavern in densely built-up area for Sydney Metro

S. Azari, D. Tsang & A.R.A. Gomes
SMEC, Sydney, Australia

R. Nair
Mott MacDonald, Sydney, Australia

ABSTRACT: Construction of underground works in densely built-up areas involves dealing with the potential impact of tunnelling-induced displacements on adjacent buildings and infrastructure. This paper presents the methodology and discusses the results of a numerical model analysis carried out at a feasibility stage to assess the stability conditions and displacements caused by the excavation of a large-span shallow underground mined metro station cavern and ancillary tunnels for Sydney Metro in a densely built-up area in Sydney's Central Business District. Emphasis was given to the modelling of the tunnel excavation and support sequence to capture relevant failure mechanisms and potential impact on nearby infrastructure.

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Design and construction sequence of big crossover cavern in Himalayan Geology

V. Bansal
Senior tunnel design Engineer, TUMAS India, Gurgaon, India

S. Patle
Geotechnical Engineer, TUMAS India, Gurgaon, India

H.A. Bhardwaj
Alignment design Engineer, TUMAS India, Gurgaon, India

ABSTRACT: The design and construction of railway tunnels in the Himalayan geology is always a challenging task as the cross-sections of the tunnels are larger, have long lengths, high overburden, and complex geology along the tunnel alignment. The design complexities increased manifold during the planning and design of tunnels as the track center between two tracks of a double-track railway tunnel needed to be increased from 5.9m to 25m in tunnel no 8 of the Rishikesh – Karanprayag railway line leading to a huge width clearance requirement. This paper illustrates the various options explored to finalize the tunnel layouts, cross-section requirements, and the design philosophy of temporary support systems adopted for the finalized layouts considering the three major objectives of high safety, less cost, and less excavation time. Due to the 3-dimensional nature of the problem, the study was made using 3D as well as 2D numerical approaches to understand the ground behavior and the support adequacy of the recommended design support system in line with the construction sequence.

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Parametric analysis of shotcrete lining capacity using an improved compressive membrane action model

E.S. Bernard
Adjunct Fellow, Institute for Sustainable Industries and Liveable Cities (ISILC), Victoria University, Australia

R. Winterberg
Group Chief Engineer, BarChip Inc., Japan

ABSTRACT: An improved method of analysis based on bi-axial compressive membrane action has been developed to assess the peak load and stiffness of flat unbonded Fibre Reinforced Shotcrete (FRS) linings. The predictions of this method are verified against full scale tests conducted on macro-synthetic FRS linings in an underground coal mine. The method of analysis is then used to perform a series of parametric analyses to determine the relative influence of lining thickness, bolt span, radial stiffness, compressive strength of the concrete, and residual tensile strength of the FRS, on peak load and stiffness. The results indicate that thickness and radial stiffness appear to dominate the load resistance of flat unbonded linings acting in bending, largely due to compressive dome action between the point of loading and the perimeter. Compressive strength of the concrete has a more pronounced influence on peak load resistance than the tensile strength of the FRS.

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Pre-cast linings for hydropower tunnels: Advantages and successes

D. Brox
Dean Brox Consulting, Vancouver, Canada

R. Grandori
WeBuild Group, Rome, Italy

ABSTRACT: Pre-cast concrete segmental linings have been increasingly used for the design and construction of long hydropower tunnels around the world as their advantages and successes over the past nearly 50 years have continued to be recognized in the industry as the most cost effective and low risk approach for safe future hydraulic operations without undue maintenance. Key advantages of the use of pre-cast concrete segmental linings include improved hydraulics, durability against abrasion, simple pre-design and construction implementation without decision-making, high quality control of fabrication, rapid installation for overall high productivity and shorter construction durations, greater cost certainty, confident long-term stability for safe and uninterrupted future hydraulic operations for the full range of tunnel sizes generally varying from 3 m to 10 m and improved worker safety. The risks associated with the use of pre-cast tunnel linings are limited as the design and construction practice has become a well-established approach.

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The Traditional Method of Madrid – a 2D SSI approach calibrated via 3D modelling

C. Cabral Dias, A. Gonzalez Villavicencio & J. Masagué Martín
Ayesa

ABSTRACT: The Traditional Method of Madrid (TMM), also known as Belgian Method, is a method for tunnel construction. This method uses a unique excavation sequence in which the crown is divided into a series of pocket excavations which are successively supported using temporary works, and then quickly followed by the permanent lining construction. Due to the complexity of the multiple phases and structures involved, this type of tunnel needs a 3D Soil Structure Interaction (SSI) model to correctly capture all the elements and their contributions, however, a 3D model is not always possible due to project constraints, such as budget and deadlines. This paper aims, firstly, to enhance the current design approaches, via a new 2D approach based on a calibration with a 3D SSI model; secondly, to contribute for a more informed design when a 3D model is not available; and thirdly, to contribute to more sustainable designs without compromising safety and quality.

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Porto Metro Rubi Line – the design of the conventional tunnels in residual soils

C. Cabral Dias, P. Lamas Alvarez & S. Gomez
Ayesa

V. Silva & J. Dores
Metro do Porto

ABSTRACT: Porto Metro has commissioned to Ayesa, the design of the future Rubi Line tunnels. The new line project includes 8 new stations, 4 of which are underground, and approximately 2.6 km of tunnels. These tunnels are double-track railway with an equivalent external diameter of 9 m, and they cover different stretches of the alignment, both in the cities of Porto and Gaia. The tunnels go through different geo and hydrogeological conditions, overburden, topography, and underneath different type of buildings. The foreseen geology is quite complex, including fresh Granite and Schist-Greywacke Complex and their residual soils. Both rocks weathering result in quite deformable and mixed soils, making up a challenging scenario of mixed face conditions. This context has critically conditioned excavations stability, which consequently needed to be fully investigated using advanced 3D modelling. This paper presents how the proposed design solutions tackle the intrinsic challenges of Porto's complex and heterogeneous geology.

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Second tube of the Gotthard Road Tunnel: Tunnel design and challenges after 2 years of construction of the preparatory works

E. Carrera
Lombardi Engineering Ltd., Switzerland

G. Ballacchino
B+S AG, Switzerland

T. Fries
ILF Consulting Engineers AG, Switzerland

T. Ackermann
Emch+Berger AG Bern, Switzerland

ABSTRACT: The existing Gotthard Road Tunnel is one of the most important underground connections in Europe. With a total length of 17 km across the Alps, it connects the German-speaking northern part of Switzerland to its Italian-speaking southern part. After more than 40 years of operation, the existing tunnel must be renovated. In order to avoid interrupting this crucial north-south link, the Swiss electorate decided to build a second tube to ensure road traffic during renovation work of the existing tunnel. The project of the second tube of the Gotthard Road Tunnel includes the construction of a new two-lane tunnel parallel to the existing tube, 5 new underground ventilation caverns, 2 new technical buildings at the tunnel portals and new cross-passages to the existing tunnel every 250 m. Prior to the excavation of the second tube tunnel, numerous underground preparatory works will be carried out, such as two access tunnel of 5 km length each, and two new sections of the service and emergency gallery. The present paper highlights different design aspects of these preparatory works and lessons learned after about two years of construction in the heart of the Alps.

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The Glacier Garden in Lucerne gets a new main underground attraction

S. Cattori & S. Zingg
Lombardi SA, Lucerne, Switzerland

ABSTRACT: "Gletschergarten Luzern" (Glacier Garden Lucerne), one of the oldest and most visited museums in Lucerne, Switzerland, has expanded its museums spaces into the underground called "Die neue Felsenwelt" in 2021. In a spectacular tunnel system through the rock, the museum tells the Earth's history from the formation of the Lucerne sandstone on the seashore, to its unfolding into the Alpine mountains and its modeling by the glaciers of the Ice Age into the future. The innovative concept of the museum aims to connect its contents with the tunnel design by incorporation the natural geological art along the tunnel. The challenge was to build the tunnel safely and present all surfaces as "true to nature" as possible, even in public areas, without any "visual disturbances" of auxiliary measures such as shotcrete or rock bolts. This paper illustrates selected aspects of the design and construction of an underground structure with the unique task of meeting high museum and architectural standards not usually found in traditional infrastructure projects.

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Study of a large opening in a retaining wall by a TBM: Consequences on the ground and the structures, structural reinforcement solutions and impacts on neighboring constructions

E. Charanton
Artelia, Complex and Innovative Structures Division, France

L. Marchese
Artelia, Deputy Director of the Infrastructures Departement, France

N. Noroozipour
Artelia, Director of the Tunneling Division, France

ABSTRACT: This paper analyses the effects of large opening realization on the underground structures and those effects on the neighboring constructions. Firstly, the meaning of a large opening in a retaining wall have been defined and qualified with regard to soil and structural considerations. Secondly, the consequences of the opening on the diaphragm wall/ soil interaction have been studied to define a simplified calculation approach adapted to this issue. This study focuses on the breaking through of the TBM and its effects of the station retaining wall in a dense urban context.

Keywords: Large opening, Ground-structure interaction, TBM break through, Retaining wall, Ground settlement, Dense urban context

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Significance of initial lining on dynamic performance of final lining for large size cavern

S.H.(J.) Choi & W.H. Hansmire
WSP USA, Los Angeles, USA

C. Herranz
Mott MacDonald, Madrid, Spain

ABSTRACT: The Regional Connector Transit Corridor (RCTC) Project is a $1.9B design-build project currently under construction by the Los Angeles County Metropolitan Transportation Authority (Metro). The light rail subway project comprises major underground elements, including Metro's first mined rail crossover cavern, which is horseshoe shaped, 56-ft (17-m) wide by 34-ft (10.4-m) high and nearly 300-ft (91.4-m) long. Located in one of the most active seismic regions of the world, the cavern structure underwent comprehensive seismic design to comply with rigorous seismic design criteria and other design requirements. The construction of the cavern structure was substantially completed in 2020. For the seismic design of the cavern structure, a fully-coupled dynamic time history analysis was performed using FLAC models. During the course of the dynamic analysis, the influence of the initial lining on the dynamic performance of the final lining was particularly evaluated. The numerical model was also used for a sensitivity analysis to assess the impact of different bonding conditions between the initial and final linings during a seismic event. The analysis incorporated stiffness, material properties, inertial effects, and dynamic behavior of the initial lining and the interface between initial and final linings. The analysis and results are discussed in this paper.

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Interaction between underground works and deep foundations: A risk assessment approach

J.V. Cruanyes Gavilà
Typsa, Valencia, Spain

M.Becerril Muñoz & P.Ramírez Rodríguez
Typsa, Madrid, Spain

P. Ingram
Arup, London, UK

ABSTRACT: Complex underground infrastructure projects frequently require, especially in dense urban areas, the need to build concurrently various elements of different nature, in very reduced spaces. It is critical to determine the type of structure, geometry and construction sequence in order to optimise the design as well as to procure a safe and practical construction, minimizing risks. This paper aims to establish a preliminary design approach, for underground works in close proximity to deep foundations, that considers the construction sequence as the key element to assess and derive the optimal method of construction. For this purpose, a simplified systematic strategy, including flow charts, is proposed. Throughout this procedure, potential geotechnical and structural risks associated with the different construction options considered are identified and discussed. This paper is based on the theoretical case of a vent shaft asset construction, with high interaction effects due to the proximity of its various elements, such as, the shaft itself, the ventilation tunnels (adits), the line tunnels and the headhouse building foundation. A vent shaft is a common infrastructure element within underground railway systems in dense urban environments, and its complexity arises from the number and nature of elements to be built in close proximity. To deal with these complexities is a common challenge on many underground infrastructure projects that are becoming more frequent due to urban space limitations. The paper describes potential problems related to the construction processes and proposes design strategies to evaluate them.

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Design methodology for tunnel collars assessment under fire load

M. De Poli & B. Lafarga
Mott MacDonald, Croydon, UK

ABSTRACT: Tunnel structural collars are complex structures often connecting different tunnel elements such as mined tunnels with bored tunnels or shaft openings. The Bromford Tunnel is a twin bored tunnel part of the High Speed 2-Phase 1 project in the UK where over 30 permanent reinforced concrete collars need to be cast. This paper presents the design methodology followed for the assessment of the bored tunnel to cross passage collars under the EUREKA curve fire load.

The main innovation introduced in this assessment is the use of a non-linear staged analysis considering a Mohr-Coulomb concrete material model. This is used to represent the plastic behaviour and captures both the flexural and shear failure of the structure. Such an analysis proved to better represent the fire event and the behaviour and stress redistribution on the structure during the fire. This methodology was able to allow an optimised reinforcement intent design where the full structural capacity of the structure was used.

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Mechanical performance evaluation of operating shield tunnel segment under different ovality induced by underlying tunnel construction

Xiaobin Ding
South China University of Technology, Guangzhou, Guangdong, China
Guangdong Provincial Key Laboratory of Modern Civil Engineering Technology, South China Institute of Geotechnical Engineering, Guangzhou, Guangdong, China

Xufeng Ren* & Donglin Han
South China University of Technology, Guangzhou, Guangdong, China

ABSTRACT: The existing metro shield tunnel structure will be greatly impacted by the improper construction of neighboring underground structures. This research examines the stress of shield segment under different ovality induced by underlying tunnel construciton in Granite residual soil. In this paper, based on the field measurement data, a refined three-dimensional finite element model is established considering the detailed structure components including shield segements, connection bolts, nuts and installation holes. The quantitative relationship between the ovality of the shield segment and the stress of the lining structure is studied. The results show that as the ovality of the shield segment increases, so does the maximum principal stress and maximum shear stress of the segment structure. The maximum shear stress of the structure has a linear relationship with the ovality, whereas the maximum principal stress of the shield structure has a more obvious trend with the ovality and a nonlinear relationship with the ovality.

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The fourth edition of the BTS/ICE specification for tunnelling

C. Eberle
Mott MacDonald, Croydon, UK

ABSTRACT: The *Model Specification for Tunnelling* was produced by the British Tunnelling Society in conjunction with the Ground Board of the Institution of Civil Engineers in order to establish a common standard for tunnelling and first published in 1997. The latest major revision of the *Specification for Tunnelling, Third edition* was issued in 2010 and extensively used on infrastructure projects in the UK and abroad, in particular the mega project Crossrail. The forthcoming fourth edition of this reference standard reflects the further developing maturity of the industry and the increased focus of stakeholders on carbon footprint reduction.

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Structural safety of tunnels in case of fire based on CFD simulations

M. Filus, Th. Pappou & B. Protopsaltis
FIDES DV-Partner GmbH, Munich, Germany

K. Diakakis, A. Gisakis & K. Stokos
SOFiSTiK Hellas S.A., Athens, Greece

ABSTRACT: A unified procedure on the same model and mesh for all simulations, excavation, dimensioning, reinforcement safety, ventilation, fire, in the tunnel design loop is presented. All nonlinear structural calculations are performed using a 3D model which includes elastoplastic behavior of the soil, temporary and permanent lining. The "hot" design carried out checks if sufficient load-bearing capacity is available in case of fire.

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Effect of the rock mass disturbance due to the tunnel excavation on the tunnel loading, based on numerical simulation

D. Georgiou
PhD Mining – Geotechnical Engineer, NTUA Athens, Greece

A. Benardos & P. Nomikos
Professor, School of Mining & Metallurgical Engineering, NTUA Athens, Greece

ABSTRACT: The present research aims to investigate the effect of the rock mass disturbance due to the tunnel excavation method, as incorporated through the disturbance factor (D) in the Generalized Hoek & Brown (2002) rock mass failure criterion, on the tunnel lining loading. Particular emphasis is given on the drill and blast method, which is the most common tunnel excavation method in intact or massive and blocky rock masses, both in civil and in mining engineering. The tunnel perimeter blasting charge determines the tunnel overbreak and the disturbance zone around the tunnel perimeter. Thus, the tunnel lining may be overloaded due to the development of the disturbance zone with higher than the anticipated and designed load values. In order to investigate the disturbance zone's effect on the tunnel support measures, two dimensional numerical analyses are used, based on the RS2 – Rocscience software. Different quality rock masses are examined, with GSI values ranging between 60 and 80 while the disturbance factor D takes values between 0 and 1, incorporating in the analysis all possible blast conditions. From the parametric numerical analysis, it is shown that the increment of the rockmass disturbance due to the tunnel excavation has a significant effect in the tunnel lining's overload, where for low rockmass disturbance the lining load increases higher than 30%, especially on the tunnel perimeter rockbolts. Moreover, the effect of the rockmass disturbance increases the tunnel deformation higher than 10%, in a comparison with non – rockmass disturbance.

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Tunnel design guideline in cases of tunnel face pre-support by fiberglass nails and/or forepoling umbrella

D. Georgiou
PhD Mining – Geotechnical Engineer, NTUA Athens, Greece

G. Georgakopoulos
MSc Mining – Tunnel Engineer, NTUA Athens, Greece

E. Diakoumi
MSc Survey Engineer, NTUA Athens, Greece

A. Malandraki
MSc Civil Engineer, NTUA Athens, Greece

ABSTRACT: The present research aims to investigate the optimal design parameters of the tunnel face pre – support, where the conventional tunnel excavation method is implemented, by using forepoling umbrella and/or fiberglass nails. The research is based on numerical investigation, in both cases of shallow and deep tunnels, by usage of the Simulia ABAQUS FEM. During the numerical analysis, the tunnel face deformation (extrusion) and the tunnel face pre – support measures response were recorded, in occasions of different rockmasses and various tunnel overburden heights. From the results of the several design parameter, was specified the optimal length of the support measures in order to achieve the maximum effectiveness. For both tunnel face reinforcement with fiberglass nails and/or tunnel face pre – support by forepoling umbrella, were exported non – dimensional nomographs and expressions, in order to be useful for the tunnel designer.

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Use of the tunnel face stability factor in unsupported and supported tunnel faces

D. Georgiou
PhD Mining – Geotechnical Engineer, NTUA Athens, Greece

M. Kavvadas
Emeritus Professor, NTUA Athens, Greece

ABSTRACT: The paper studies face stability in shallow and deep tunnels with unsupported and supported faces (using fiberglass nails, forepoling umbrella or a combination of them). Parametric 3D finite element analyses in elasto-plastic ground show that stability of unsupported tunnel faces is controlled by a dimensionless Tunnel Face Stability Factor (Λ_o), defined in terms of ground strength and tunnel geometry. The parameter (Λ_o) is correlated with a dimensionless average tunnel face extrusion (Ω_{h0}) which permits to define face instability. In supported tunnel faces, the numerical analyses calculate the reduced average tunnel face extrusion (Ω_h) due to the beneficial effect of the face support measures. This permits to calculate safety against face instability via the same (Λ_o - Ω_h) empirical correlation, for both unsupported and supported tunnel faces. In shallow tunnels, the parameter (Ω_h) is also correlated with the excavation volume loss (V_L). Finally, the above dimensionless parameters are correlated with the 2D tunnel deconfinement ratio (λ) along the tunnel axis, which permits to calculate (λ) for use in 2D numerical analyses of tunnels with unsupported and supported faces.

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The importance of axisymmetric simulations for the estimation of tunnel support pressure for sequentially supported deep tunnels

V. Gkikas
Tunnelling Laboratory, School of Mining and Metallurgical Engineering, National Technical University of Athens, Athens, Greece
EDAFOS Engineering Consultants S.A., Athens, Greece

P. Nomikos
Tunnelling Laboratory, School of Mining and Metallurgical Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT: Tunneling is a complex three-dimensional problem, especially due to the sequential excavation and primary support installation procedure. The use of three-dimensional numerical methods, that incorporate the construction sequence, derive the best approximation of the anticipated stresses and displacements of the tunnel lining. This approach is time consuming, and it is often avoided in design practice. This study presents the results of axisymmetric numerical simulations that incorporate sequential excavation and support cycles. Those simulations, in combination with plane strain models provide a good approximation of the three-dimensional conditions that prevail at the proximity of the tunnel face. The results of those simulations are compared with other available methods and indicate the influence of the installed support to the rock mass confinement at the support installation position. The importance of axisymmetric simulation for the estimation of tunnel support pressure for deep tunnels is emphasized, particularly in cases where three-dimensional numerical modeling is not practically available.

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Planning of the Tel Aviv Metro Network

T. Grammenos, M. Sims & L. Samama
EGIS RAIL ISRAEL SA, Israel

G. Nacht
NTA Ltd, Israel

ABSTRACT: This paper presents the new state-of-the-art Metro Network to be deployed in Israel. The Gush Dan Metro Network will have three lines covering the metropolitan area of the city of Tel Aviv, and its suburbs. Tel Aviv is one of the most dynamic cities in the Mediterranean and needs an efficient metro transportation system to reduce traffic congestion, improve the environment and enhance a sustainable way of living. Top in the field local and international consultants and design companies have been mobilised to undertake the configuration of the Metro Network characteristics. The Metro Network Programme consist of 3 fully underground lines, M1, M2 and M3. There are challenges to overcome, as the lines passes through the densest urban areas of the City of Tel Aviv. The Programme comprises metro lines of a total of 150 km, 109 stations and 7 hubs, 4 depots, 2 operations centers and other ancillary structures, such as switchboxes, ventilation shafts and emergency exits. Programme procurement has been determined to be executed in at least two main stages. The first stage is expected to start construction in 2025. It includes significant portions of the North-to-South Metro Line 1, the East-to-West Metro Line 2 and the semi-circular Metro Line 3 to provide a core operational network. The paper outlines the basic characteristics of the Metro Network and the main challenges and solutions that are envisaged. The expected hydrogeological conditions are expected to pose difficulty for the construction. The dense urban development, bridges, existing LRT and Israeli Railways lines define additional challenges to be met and overcome.

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TBM excavation under existing operation railway: A practical example applied to the Brenner railway

C. Iasiello, M. Aganetti & D. Maturi
Systra SWS, Trento, Italy

D. Buttafoco
Dolomiti JV Webuild-Implenia, Fortezza, Bozen, Italy

V. Perrotta Orgnani
Petrucco Italia Srl, Udine, Italy

ABSTRACT: TBM (tunneling boring machine) is widely employed in very dense urban area to minimize the risk of possible surface settlements onto the existing structures. The evaluation of the soil structure interaction is undertaken through analytical evaluations in conjunction with finite element analysis. The aim of this paper is showing a quite original approach of this technique to the existing Brenner railway line. The first step was to evaluate the expected settlements through empirical, analytical, and numerical models and, so evaluate the influence of the settlements on railway. Once evaluate the risk, the contractor decided to support the railway in operation with a temporary support constituted by a structural grid of steel beams to create a semi-elastic system during the TBM excavation. In this way, the designer achieved that the possible settlements due to the TBM excavation would not interfere with the operation of the existing railway.

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Thermal performance of a metro station in Turin equipped with energy geostructures

A. Insana & M. Barla
Politecnico di Torino, Torino, Italy

S. Aiassa & F. Antolini
Geosolving srl, Torino, Italy

ABSTRACT: High pollution levels combined with the lack of green spaces are hitting many cities leading to the exploitation of the underground for transportation. Given the need to foster local energy sources with low environmental impact, energy geostructures are more and more being explored. In this context, the promising outcomes of the experimental campaign on the thermal activation of tunnel segments carried out on Turin ML1 South Extension encouraged the authors to investigate applicability of energy geostructures for Turin ML2 project. This paper is intended to focus on the understanding of the thermo-hydraulic behaviour of a metro station equipped with energy diaphragm walls. A 3D FE numerical model reproducing the layout of the planned Mole-Giardini Reali station is used to study the energy exchange potential of the thermoactive walls. The quantification of the exploitable energy to meet the user demands of the station and of buildings above will be discussed on the basis of the results obtained.

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Numerical simulation of the rock cutting process using the discrete element method

A. Kalogeropoulos & T. Michalakopoulos
Laboratory of Excavation Engineering, Department of Mining Engineering, School of Mining Engineering and Metallurgy, National Technical University of Athens, Zographou Campus, Athens, Greece

ABSTRACT: Actual laboratory rock cutting tests were numerically simulated using the discrete element method as implemented by the open-source framework Yade. The objective was to gain a better understanding of how the simulation setup influences the realism of the obtained results, thus providing the basis for developing useful numerical simulation models for solving actual rock engineering problems. The aim is twofold: On the one hand, to realistically simulate the rock medium by considering its inhomogeneous nature. This is achieved through the use of the interaction range coefficient in a model developed in 3D. On the other hand, to examine the combined effects of the microparameters' values on the cutting force history, in terms of the force magnitude and the data series in the time domain and frequency spectrum. In this paper, a four-step calibration process for identifying the optimum set of microparameters' values is presented. The process is based on the 'Design of Experiment' method and optimization techniques. The resulting models were evaluated against the actual laboratory test results both quantitatively and qualitatively. It was concluded that well calibrated numerical simulations of the rock cutting process can provide good approximations regarding the cutting force and energy requirements. Hence, they could be used for the performance prediction of actual rock cutting setups when it is not possible to obtain hard data.

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Ground movement impacts on heritage buildings from trinocular cavern excavation at Town Hall station on the Melbourne Metro Tunnel Project

R. Kaser
WSP Australia, Arcadis | Arup | WSP Design Joint Venture, Melbourne, Australia

R. Storry
Bouygues Construction Australia/Cross Yarra Partnership Design & Construction, Melbourne, Australia

ABSTRACT: The Metro Tunnel Project will deliver twin 9 km rail tunnels from Kensington to South Yarra as part of a new end-to-end Sunshine to Dandenong rail line in Melbourne. In addition to the tunnels, five new underground stations will be constructed. Town Hall station will be located at the southern end of Melbourne's CBD. The station will be constructed within excavated shafts, mined caverns and adits (underground passenger connections). The excavations are bordered by a range of buildings including a number of heritage listed structures. This paper outlines the approach taken to assess ground movement impacts on the buildings, describes the instrumentation installed to monitor building movements during construction and compares some of the predicted and measured movements.

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Influence of construction joints on the mechanical behavior of linings in mountain tunnels acted on by external forces

K. Kawata, R. Okawa, R. Nakazato, T. Natsume & N. Isago
Tokyo Metropolitan University, Hachioji, Tokyo, Japan

A. Fujii
Yokohama City Hall, Yokohama, Kanagawa, Japan

ABSTRACT: Although the construction joints of permanent linings are considered to influence the mechanical behavior of mountain tunnels, their location, surface treatment, and other factors are determined empirically. To propose new tunnel structures and specification concepts in the future, it is necessary to understand the mechanical behavior of linings with construction joints when subjected to external forces. The purpose of this study is to understand the influence of mechanical properties, such as the setting position of the joints, on the fundamental behavior of tunnels subjected to external forces. Therefore, the mechanical behaviors of tunnels with different joint positions under ground heaving or seismic loads were confirmed by numerical analysis and model experiments. The results confirmed that the stress and deformation behaviors differed depending on the position of the joints. These results indicate that certain joints have structurally disadvantageous conditions, and therefore considerations for construction are suggested, such as the need for reinforcement.

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Highway tunnel design under river with shallow overburden-Terzili tunnel example

B. Koçak & I. Sáenz de Santa María Gatón
TMD, Tünel Mühendisliği ve Danişmanlik, Istanbul, Türkiye

C.H. Sentürk
Nurol-Yüksel-YDA-Özka JV, Tunnel Construction Chief, Ordu, Türkiye

ABSTRACT: Terzili tunnel is a double tube highway tunnel with a length of 1180 m each tube. The conventionally excavated tunnel is located in Ordu-Türkiye (Blacksea region) and is constructed mainly in highly weathered, very weak, fractured claystone and clay. Generally, the tunnels are supported by rigid support systems, by means of shotcrete, steel sets, self-drilling IBO bolts and umbrella steel pipes and the excavation has been performed staged by top heading, benching and invert. Between the chainages Ch 32+670 and 32+677, the left tube crown was reaching out of the natural topographical surface due to a river and the overburden above the right tube was around 2 meters. This paper presents the design methodology and successful site construction application of the shallow river passing section.

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A design approach of large diameter surge shaft and passageway connection between headrace tunnels

Ö. Kökten
Temelsu International Engineering Services Inc., Ankara, Republic of Türkiye

ABSTRACT: In order to design a large diameter surge shaft, headrace tunnel and passageway connection, it is required to perform effective numerical analyses to calculate the successive stress distributions and plastic deformations in rock. This paper investigates the structural response of vertical shafts considering interaction with rock mass by a various numerical modeling technique. The main objective of this study is to define a realistic and comprehensive approach to the design of vertical shafts. An axisymmetric and a plain strain nonlinear analyses have been conducted by using finite element codes as Plaxis 2D and Phase 2 to predict the response of rock mass around the shaft. Since geometry is 3-Dimensional, a 3D finite element program called Midas GTS NX has been used to investigate the accurate behavior of shaft excavation. The calculated displacements and plastic zones around the shaft by numerical simulation results have been evaluated and interpreted.

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Holistic largescale planning and optimization of urban subway works

D.C. Konstantakos, P.E.
CEO Deep Excavation LLC, New York, USA
Adj. Prof. New York University, USA

N. Lesgidis, Ph.D.
Software Development Lead, Deep Excavation LLC

ABSTRACT: Planning and deciding on a proposed tunnel alignment in an urban environment presents many challenges involving expertise from different disciplines. The cost of station construction, tunnel, shoring, and impact on existing structures, potential ridership, ideally all need to be considered in initial planning phases by authorities but resource and technological limitations made such a complete approach almost impossible. Continuing advancements in accessible computing power allow engineers to access and utilize large scale data in decision making. This article presents how large-scale urban data can be incorporated with rapid geostructural and transportation modeling in driving better planning decisions for urban subways.

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Ensuring face support and control of surface deformations in soft ground urban tunnels: Verification through international case studies

S. Konstantis
Ruler Consult, London, UK

G. Prountzopoulos
Omikron Kappa Consulting S.A., Athens, Greece

P. Spyridis
Faculty of Architecture and Civil Engineering, TU Dortmund University, Dortmund, Germany

ABSTRACT: One of the key design and construction parameters in urban tunnelling projects with the use of a closed face Tunnel Boring Machines (TBM), is the appropriate range of face pressure to be applied by the TBM, so as to meet all the relevant strict and many times conflicting requirements. On the one hand, the face pressure needs to be high enough to ensure not only the tunnel face stability, but also the control of induced ground deformations within predefined, acceptable limits. On the other hand, maintaining a conservative value of the face pressure that is too high, results in a slow boring process, when all urban tunnel projects face challenges with very demanding construction schedules and may also lead to blow-out risks. Although numerous analytical methodologies provide a satisfactory degree of investigation of the required face pressure for face stability, the estimation of the face pressure that will additionally result in limited deformation around the tunnel and hence on the ground surface, still practically relies only on execution of parametric 3D numerical analyses. This article briefly presents an analytical method that can be applied on soft ground urban tunnels to assess the level of active face support to be considered in numerical analysis in order to ensure elastic relaxation in the advance core and thus effective ground deformation control. The method is then compared with three (3) urban tunnelling case studies from India and Ecuador, where TBMs have successfully underpassed urban areas and structures with EPB machines, through soft soils under small overburden. Available design and construction data from the applied face pressure and the recorded deformational field around the tunnels are presented, followed by a comparative discussion on the results and the applicability range of the method.

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Using a vermiculite-based fire protection mortar to increase the fire resistance of reinforced concrete tunnels

A. Kounadis, N. Anagnostopoulos & P. Douvis
Sika Hellas S.A., Kryoneri, Attica, Greece

P. Nomikos & A. Benardos
National Technical University of Athens (NTUA), Zografou, Attica, Greece

A.N. Tsakiris
ERGOSE SA, Athens, Attica, Greece

E. Katsivelis
Project Director of the project "Panagopoula Tunnel", Achaea, Greece

ABSTRACT: The mechanical properties of reinforced concrete elements tend to be damaged and weakened after they have been exposed to a significant fire, leading to a thinner alkaline protective coating around steel reinforcement, as well as a reduction in the yield and stiffness of the steel. In tunnels, fire can increase the concrete temperature extremely rapidly, as the heat generated cannot escape, resulting in high vapor pressures within the concrete structure, which in turn leads to explosive spalling and a significant loss of strength, potentially endangering human lives. In this study a series of experiments was conducted to evaluate the performance of a specific lightweight fireproofing material in terms of its behavior in fire. Test specimens were produced and tested in accordance with exposure under the RWS fire curve up to a temperature of 1,350 °C as outlined in EFNARC guidelines, then the passive protection provided by the product was evaluated for various layer thicknesses and exposure times. To further substantiate these laboratory findings, a full-scale field test was carried out in an existing reinforced concrete tunnel (Panagopoula twin railway tunnel). The results further contributed to defining and evaluating the parameters in up-scaling this performance under real field conditions, and its influence as a realistic intervention scenario during tunnel service operations.

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Settlement trough estimation over TBM EPB tunnel

R. Kuszyk & A. Siemińska-Lewandowska
Department of Geotechnics, Bridges and Underground Structures, A Warsaw University of Technology, Poland

ABSTRACT: The article presents 13 m in diameter TBM EPB railway tunnel driven in very complex geotechnical conditions - Quaternary soils (Sandy Clays, Fine Sands, Clays). The tunnels are largely located under city historic buildings and the thickness of the overburden above the tunnel top is about one tunnel diameter – as much as 0.8 ÷ 1.1 D. Extensive monitoring system of ground surface settlements, the expansion of settlement trough and displacements of subsoil over the TBM were implemented. In the paper, the results of settlements monitoring including long time settlements are presented. Additionally finite element prediction of settlement trough is discussed and compared with the data obtained from monitoring.

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Effect of rock heterogeneity on the convergence-confinement curve during numerical analysis of underground excavation in discontinuous rock mass

N. Lathourakis & P. Yiouta - Mitra
National Technical University of Athens

ABSTRACT: The presence of discontinuities in strong rock masses creates blocky structures that give an overall different behaviour than an assumed continuous medium with adjusted mechanical properties if the non-jointed rockmass shear strength is higher than that of the rock joint. In this research, numerical simulation is used to investigate the effect of persistent and non-persistent discontinuities in the formation of plastic zone around a deep, circular tunnel. Parametric analyses for persistent joint sets are initially carried out investigating the effect of the presence of up to three joint sets, their spacing with respect to the excavation scale, and their strength parameters, i.e., joint friction angle and joint cohesion with respect to the initial stress field. Then, statistical analysis is used to deepen the understanding of the effects of joint length and spacing for non-persistent discontinuities, i.e., when rock bridges are formed around the excavation. The analyses results are used to identify the critical level of deconfinement in the development of plastic zone around the excavation.

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Curved diaphragm wall construction: A case study on the challenges faced

K.P. Lim, K. Kaliaperumal, X. Zheng & Y. Zheng
Land Transport Authority, Singapore

ABSTRACT: Diaphragm walls are commonly constructed as part of the Earth Retaining Stabilising Structure (ERSS) for deep excavations involving basements, stations and other underground structures. This paper documents the challenges involved during the construction of the curved diaphragm walls due to the varying soil stratigraphy at the Land Transport Authority's (LTA) Contract 883 – Construction of Cantonment Mass Rapid Transit (MRT) Station for Circle Line 6 and analyses the impact of these challenges on quality control. The paper then proposes remedial actions to be taken before and during construction to overcome the challenges through improved planning, which could help to enhance quality and hence improve the construction productivity of curved diaphragm wall construction for future projects in similar soil stratigraphy.

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The excavation of the Brenner Base Tunnel where the Eurasian and Adriatic tectonic plates collide

D. Marini & G. Venditti
BBT-SE, Bolzano, Italy

ABSTRACT: The excavation of the Brenner Base Tunnel requires solutions to multiple challenges. This article explains the methods used to excavate the stretch of the exploratory tunnel running through the Periadriatic Seam, where the Eurasian and Adriatic tectonic plates collide. During excavation, constant monitoring of convergence and tensions within the installed lining and ongoing adjustment of the cavity consolidation measures were of fundamental importance. This allowed us to create a stable balance between the highly tectonised rock mass and the in-stalled lining.

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Design of porous tunnel for ecosystem protection in High Speed Two railway in UK

S. Massinas
COWI UK Ltd, Glasgow, UK

M. O'Sullivan & M. Miller
COWI UK Ltd, York, UK

S. Poulin & B. Kayadan
COWI A/S (DK), Lyngby, Denmark

S. Neno & S. Parr
EKFB (Effiage Kier Ferrovial Bam JV), Birmingham, UK

H. Taivo
High Speed 2 (HS2), Birmingham, UK

ABSTRACT: The C2 Contract of HS2 covers the route from North Portal of Chiltern Tunnels to Brackley and passes through the ancient woodland Sheephouse Wood. This site of special scientific interest includes large colonies of the rare and protected Bechstein's bat. Design aspects of UK's largest-ever porous-tunnel structure (~900m long) to protect the bats from high-speed trains running at 360km/h, the Sheephouse-Wood-Bat-Mitigation-Structure, is presented. Designed to comply with very strict but often conflicting requirements imposed by the licensing and planning authorities, the porous-tunnel structure comprises a series of large prefabricated concrete arch profiles to span over the HS2 and East-West-Rail conventional railway tracks (23m span & 11m height), placed at distances to form large apertures for natural ventilation of smoke during fire event. To protect the superstructure from train derailment, in situ concrete supports are integrated with a combined emergency walkway and robust kerbs. Mesh infill FRP panels are proposed in the formed openings for smoke dissipation and to prevent bats for entering the tunnel. Aerodynamic analyses are carried out to assess the impact of trains' turbulent air speed on bats' flight paths and detailed fire analysis to determine tunnel's structural adequacy. The results confirmed a viable and innovative solution.

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Structural analysis model of joints in steel segment shield tunnel for 3D FEM

Y. Matsumoto, I. Wakui & J. Tamamatsu
NTT Access Network Service Systems Laboratories, Tsukuba, Japan

M. Iwanami
Waseda University, Tokyo, Japan

ABSTRACT: We propose a simple three-dimensional (3D) structural-analysis model for steel segment joints in shield tunnels. Certain types of shield tunnels comprise a primary lining of steel segments and a secondary lining of unreinforced concrete. The 3D finite element method (FEM) is promising as a structural-analysis method that considers the secondary lining. However, there are few examples of 3D FEM analysis applied to such steel segments, and its accuracy has not been thoroughly evaluated. In this paper, as a preliminary step toward establishing an accurate comprehensive analysis method that considers the secondary lining, we propose a structural-analysis model comprising only of steel segments. The aim of this model is to reproduce the behavior of segment joints by adopting a structure in which the joint plates are connected using bolts. We demonstrate that the proposed model accurately reproduces joint bending test results over the range of acting moments that are normally considered.

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Design challenges of underground highway structures in Qatar

Y. Matsuo & G. Sergakis
PARSONS International Limited, Qatar

T. Tzaveas
Public Works Authority 'ASHGHAL', Qatar

ABSTRACT: Driven by Qatar National Vision 2030 and catering to the 2022 FIFA World Cup, Qatar is undertaking an extraordinary and ambitious programme of infrastructure development to deliver a world-class new and upgraded road infrastructure network. Projects designed to improve highway capacity, connectivity, and safety through the urban and rural parts of Qatar and to meet current and future demands of population and economic growth. Underground highway structures form a major part in this modern and integrated road network posing a number of planning and design challenges due to the combination of complex ground conditions, high water table and the need for fast-track construction in congested urban areas with a dense network of existing utilities. In this paper, the authors discuss some of the most critical and challenging considerations in putting a planning and design process on a path to successfully deliver the projects, shifting occasionally from the traditional contracting method to a more collaborative approach. Case studies are presented with an insight in the modelling, numerical analysis, seismic design, temporary and final supports, waterproofing and value engineering. An array of structures are presented consisting of a road underpass built by top-down method to account for traffic constraints, a pedestrian underpass implementing a box-jacking method to ensure undisturbed traffic through soil/hard rock and high water table, and a Cut & Cover tunnel designed in an area of an existing junction including impact assessments of existing utilities and bridge foundations and an evaluation of its seismic performance applying the recommendation of U.S. Department of Transportation FHWA-NHI-10-034 Technical Manual for Design and Construction of Road Tunnels – Civil Elements.

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Permanent secant pile wall for underground transit station

M. Motallebi
AECOM, Montreal, Canada

A. Bhargava & V. Nasri
AECOM, New York, USA

ABSTRACT: Secant piles have been traditionally used as temporary support of excavation for cut-and-cover tunnels and shafts. Alternatively, the secant piles can be integrated into the permanent structure, where it not only provides the excavation support during construction, but also forms the envelope supporting the gravity and lateral loads from the permanent structure. This offers numerous advantages, including reduced excavation cost and time for construction. This was recently used with great success in construction of an approach structure and an underground station as part of the one of the largest transit systems in North America, Réseau Express Métropolitain (REM) located in Montreal, Canada. The current paper presents a case study based on a project where secant piles were used as the permanent liner. Various structural and waterproofing solutions implemented to achieve a cost-effective design are presented along with techniques to ensure water-tight structure with more than 100 years of service life.

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Mechanical behavior of invert structure with new geometries for simplified construction

R. Nakazato, T. Natsume, K. Kawata & N. Isago
Tokyo Metropolitan University, Hachioji, Tokyo, Japan

A. Kusaka & Y. Koizumi
Public Works Research Institute, Tsukuba, Ibaraki, Japan

T. Otsu
East Nippon Expressway Company Limited, Tokyo, Japan

ABSTRACT: One of the possible countermeasures to prevent the heaving of a mountain tunnel in service is the construction of a new inverted arch structure, however the construction activity during the service stage of tunnel has problems in terms of workability and economic efficiency of construction. In this study, we focused on the geometries of an invert arch structure, and through small model test and numerical analysis, we aimed to propose a rational inverted arch structure that contributes to reducing construction time and cost. Some structures were confirmed to exert an effect of reducing construction time as well as maintaining a certain degree of load-bearing capacity.

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REM de l'Est project in Montreal

V. Nasri & M. Sepehrmanesh
AECOM, New York, NY, USA

ABSTRACT: REM de l'Est is a new mega project in Montreal including 32 kilometers of automated light rail and 23 stations with a cost of about $10 billion CAD. The project includes 8.4 kilometers of 9.7 m excavated diameter single bore double track TBM tunnel and 7 underground stations. A hybrid TBM will be used to bore though the limestone and shale rock and alluvium soil of downtown Montreal. One station will be built in cavern and the 6 others using the cut and cover method. REM de l'Est Project is currently under design and will be issued for the design build bid during 2022.

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Rehabilitation of an existing water supply gallery network built in the early 1970s

A. Nicolle, A. Wohnlich, B. Quigley & A. Arigoni
Gruner Stucky SA, Renens, Switzerland

ABSTRACT: The Forces Motrices Hongrin-Léman hydroelectric scheme is a pumped-storage plant in operation between Lake Geneva and Hongrin Reservoir, in Western Switzerland. In addition to the natural catchment area, the upper reservoir is supplied with water drained from 8 different intakes through a large supply network of tunnels. In the eastern part, there is a 8 km long tunnel with a specific 1 km stretch of tunnel showing significant damages which occurred only few years after commissioning. The tunnel cover is about 200 m and the gallery has a 2.5 m internal diameter. A combination of factors leads to this damaged structures, convergence and stability issues. The rehabilitation concept is designed as a new concrete circular lining, with a construction methodology developed together with the Contractor to tackle all tricky logistical issues due to a very narrow underground space and remote access conditions.

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Analysis and numerical simulation of mechanical interaction between ground and elastic supporting elements for circular tunnel

T. Nishimura & M. Kohno
Department of Civil Engineering, Tottori University, Tottori, Japan

ABSTRACT: The activation of the support load of the ground and the interaction with the installed support system must be a key to the stability of the surrounding ground of tunnel. The activation has been illustrated by the Ground Response Curve (GRC) and the Support Response Curve (SRC). GRC is presented as an analytical solution for the problem of stress-displacement around the tunnel in an elasto-perfectly-plastic medium. Displacements are computed from the integration of strains, which are decomposed into elastic and plastic components. A mechanical modeling for shotcrete and steel sets is introduced and the model consists in treating the composite section of a straight beam as a homogenized section of equivalent mechanical properties of the two different materials. SRC is analytically expressed with the force – displacement relation of the composite section. A series of FEM simulation is conducted to represent the interaction between the ground reinforced with rock bolt and the composite liner.

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Comparing the issues, risks and levels of geotechnical investigation for remote hydropower tunnels with urban transportation tunnels

A.G. Noble
WSP Australia

ABSTRACT: Tunnelling for large scale pumped hydro or conventional hydropower projects can be a very challenging component of the overall project development. In contrast to urban transportation tunnelling where the logistics for access during the investigation stage and subsequently the supply of power, water and other essentials are readily available for construction, hydropower projects are usually in very remote locations and all necessary plant, equipment, spares, and materials need to be brought in and the site must function as a self-sufficient unit. This differential also applies to the early geotechnical investigations stage.

This paper explores the differences in the typical levels of geotechnical investigation undertaken for two types of tunnel use: firstly, hydropower and pumped hydro tunnels conveying water for power generation and secondly, those for road or rail passenger tunnels. The paper compares some of the technical and risk management considerations in the planning, design, and construction of tunnels for the conveyance of water vs transportation from the viewpoint of different stakeholders to the project.

The risks categories in urban transportation tunnelling projects are similar to those at remote hydropower projects, but the scale of those risks can differ widely. The frequency of drilled subsurface geotechnical investigations is an order of magnitude larger in the urban shallow transportation tunnel project where typical depths below ground are less than 50m, whereas in large scale and remote hydropower the average depth may be several hundred metres.

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Copenhagen M4 line - safeguarding for future OSD

B. North, M. Abrahamsen & F. Munck
1Rambøll Danmark A/S

E. Paulatto & M. Kjær Jensen
Metroselskabet I/S

ABSTRACT: As part of the construction of Copenhagen Metro M4 line, an underground concourse hall is proposed at Ny Ellebjerg station ("CRSH6"), to enable passenger interchange between the new M4 metro line, commuter train lines ("S-tog" and "Ringbane") and the regional train line ("Øresundståg"). As part of the overall M4 project, a future Over Site Development ("OSD") is planned at this location, extending above and around the newly constructed metro infrastructure. Whilst the design of the OSD was in its very early stages, it was evaluated that some of the foundations for this structure would need to be constructed during the M4 line construction period (within CRSH6) in order to be feasible. The design of these foundations considers different development and loading scenarios from the OSD, and the impact on the M4 line tunnels – both during construction of CRSH6 and in the period during and following the OSD construction.

To maximise the potential footprint of the future OSD, it was necessary to locate some of the foundations within 1 m of the M4 tunnels. Different foundation concepts were considered, and a detailed comparative risk evaluation was undertaken for the options considering the construction of the foundations and their impact on the M4 tunnels. This risk evaluation considered analyses of the likely tunnel movements and their associated impact on watertightness, structural integrity and railway operation. A solution comprising heavily loaded large diameter "conventional" bored piles within Bryozoan Limestone was chosen, with partially-constructed structural columns terminating at ground level to minimise the impact on operations during the OSD construction period.

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Effect of spatial heterogeneity of geomechanical properties on stability of tunnel face

Y. Okazaki, T. Fukuma & M. Ohya
National Institute of Technology, Matsue College, Matsue, Shimane, Japan

S. Morimoto
Dobocreate Corporation, Ube, Yamaguchi, Japan

H. Hayashi & M. Shinji
Yamaguchi University, Ube, Yamaguchi, Japan

ABSTRACT: In the construction of underground openings by the conventional tunnelling, the stability of tunnel face cannot be ensured depending on rock mass conditions, and collapse phenomenon that threatens the safety of workers may occur. For this reason, many studies have been carried out about the stability of tunnel face. However, most of previous studies have been performed without considering the spatial heterogeneity of geomechanical properties. In this study, in order to grasp the effect of spatial heterogeneity of geomechanical properties on the stability of tunnel face, basic stability analyses of tunnel face considering the spatial heterogeneity of geomechanical properties in soft rock mass were carried out based on the random field theory. As a result, it was clear that the effect on maximum shear strain around tunnel face became large depending on heterogeneous condition and ratio of strength of rock and overburden pressure in soft rock mass.

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Longitudinal joints in segmental linings: To spear or not to spear?

D.A.F. Oliveira & A.M. Harding
Technical Director Asia Pacific, Jacobs Engineering Group, Brisbane, Australia

ABSTRACT: Temporary bolting in segmental lining design is usually considered 'good practice' in many parts of the world, but the little guidance that exists usually specifies that bolts be designed to hold the gasket closed. Those guides neither refer to other features of modern lining and TBM operation that more heavily contribute to maintaining the gasket closed nor elements of modern segment geometry that impact the effectiveness of the bolts. This lack of details results in a disconnection between design practice and the reality of modern segmental linings. The actual performance of the bolt-gasket system is rarely investigated, and they are adopted purely based on precedence regardless of whether they can maintain the gasket closed. This paper will show how the routinely ignored geometrical factors of the segments are crucial to the ability of the bolts to restrain segment movement under gasket loads. It will also show, using explicit analysis of joints, how guiding rods have the potential to prevent excessive segment movement under gasket loads better and more reliably than temporary spear bolts.

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Evaluation of subway stations from an architectural point of view

Ö. Öztürk
Faculty of Architecture, Hacettepe University, Turkey

ABSTRACT: Metropolitan cities rely on subway networks for their substantial mass transportation demands. However, the underground has always been regarded as undesirable and as well as being an unpleasant space in different cultures; therefore, one can see that users do not intend to devote more time to an underground facility that lacks natural light and ventilation. From an architectural perspective, the majority of the station design focuses on subjects such as fire safety, pedestrian movement, and building performance analyses under various conditions. Even though it is possible to trace alternative design approaches where designers challenge these issues in specific cases, most of the designers apply the same design templates, regardless of the urban context of the station location. Such actions and design decisions that ignore any potential sustainability or social integration possibilities of the stations end up being concrete boxes that pump people around the city. One can trace their urban significance and possibilities by looking at the impact of stations on our daily lives. From a sociological point of view, these structures, despite being perceived as non-spaces, due to high user demand and ease of access, underground stations will be the optimal solutions for inner-city transportation. Moreover, it is equally important to discuss the notion of space and place in the context of subway stations. As a result, this research will discuss the possibilities of social integration and sustainability of underground spaces, its challenges, and suggestions for a more holistic approach to developing a more balanced understanding to underground station design.

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Design and construction of underground infrastructure at airports

Leslie J. Pakianathan
Tunnelling and Underground Construction Society, Singapore

ABSTRACT: Underground space development as part of airport infrastructure is relatively new but is fast becoming a feature in most of the large airports. This is mainly due to the rapid growth in the numbers of passengers which in turn requires the expansion of existing facilities or building new. The vast above ground space an airport occupies, strict safety and security restrictions to move freely at the ground surface as well as the need for quick access to the aircraft, terminals and in between terminals are other reasons for promoting the construction of facilities underground.

The key underground infrastructure at airports are roads and rail tunnels as well as stormwater, sewer and utility tunnels. Some airports also have tunnels for the pedestrians, baggage handling and people mover systems. Giving due consideration to underground space development and planning these underground infrastructure at the initial master-planning stage will later aid in aerodrome efficiencies and seamless operations.

Construction works below runways and taxiways necessitate careful considerations to prevent ground settlement or sinkholes. The International Civil Aviation Organisation (ICAO) has set standards and recommended practices with respect to permissible runway slopes and surface roughness of pavement. These in turn govern the allowable ground settlement arising from construction of tunnels under runways and taxiways. In addition, there are further considerations that apply to construction works at airports.

The paper covers key and unique challenges related to the planning, design and construction of underground infrastructure at airports together with feasible solutions.

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Surface settlements induced by shallow tunnels- The case of Athens Metro

K.V. Papadopoulou
Dr. Engineer, National Technical University of Athens, Greece

ABSTRACT: The effects of ground displacements on surface structures due to shallow tunnels in urban environment are of great importance. Simplified methods predicting the transverse settlement trough in greenfield conditions are widely used. However, the investigation of the ground movements development is facilitated by the results from numerical analyses and the evaluation of in situ measurements, as well. Firstly, in the present paper, the effect of the most important factors on surface settlements is investigated and commented, applying finite element analyses for the case of TBM tunnels. Extended parametric 3D F.E. analyses are carried out using the Hardening Soil Model for two representative soil types, simulating the cases of a weathered weak rock and a very stiff clay. The geological and geotechnical conditions of the formations encountered during the construction of the Athens (Greece) Metro, driven through weathered weak rock, the so-called Athenian schist are briefly presented and evaluated. The results from back analyses using 3D F.E.M. for representative cases are compared with the corresponding measurements of surface settlements developed during the construction. These measurements are also related with the best fitting curve using the well-known equation after Gauss. Moreover, the distance of the maximum rotation of the surface (inflection point) from the center line, predicted from the 3D F.E. analyses, is compared with this resulted from the measurements.

Keywords: Settlements trough, TBM, F.E. analyses, Athenian schist

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The new major railway lines in Southern Italy: Planning and design approaches towards sustainable solutions

A. Pigorini
Head of Infrastructure Engineering, Italferr, Rome, Italy

A. Sciotti
Head of Tunnelling Department, Italferr, Rome, Italy

A. Corbo, G. Quarzicci & A. Romualdi
Tunnelling Department, Italferr, Rome, Italy

ABSTRACT: The new Messina-Catania-Palermo railway line is the Southern section of the Scandinavian-Mediterranean Core Corridor of the Trans-European Networks-Transport. This alignment, located in Sicily (Italy), has an overall length of 240 km from Giampilieri (Messina) to Fiumetorto (Palermo) crossing known tourist destinations as the coast cities of Taormina and Catania and inland cities as Enna and Caltanissetta.

The project represents one of the major infrastructural investments of the Italian State Railways for the incoming decade (about 10 billion euro) aiming to bring to Sicily an efficient railway system and to partially convert the existent railway line (built in the 19th century) as green ways.

The planning phase focused on the issue of reducing impact on urbanized areas and of facing difficult geomorphological features, thus the alignment is manly located underground with 50% of its total length constituted by tunnels.

Moreover, according to the "Technical Specifications for Interoperability" European regulation for safety in case of single track railway tunnels, safety underground works were planned also with the aim of guaranteeing a sustainable development and exploitation of the infrastructure in the future.

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Fire design analysis for the Green Tunnels at High Speed 2 project (UK)

S. Psomas, N. Al-Haddid & H. Monckton
COWI UK Ltd, London, UK

ABSTRACT: The new High Speed Rail 2 (HS2) connects London (UK) with West Midlands and in its central section includes 3No. twin Cut and Cover precast concrete tunnels ('Green Tunnels'), totaling 6.7km in length with up to 16m of cover. This Paper presents the design methodology adopted to evaluate specifically the Green Tunnels response to the design situation of the accidental fire load. The design approach required firstly a simplified fire assessment, followed by an advanced numerical analysis. The non-linear numerical analysis adopts a transient semi-coupled thermal-mechanical numerical analysis with temperature dependent thermal and structural properties. The results of the two approaches are presented and compared. Finally, the fire test results, conducted at CERIB, France, are presented and validated against the design requirements drawing useful comparisons and conclusions.

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Design and construction of internal structures of Montreal REM Airport Tunnel using precast steel fiber reinforced concrete units

Montazar Rabiei
Senior Structural Engineer, AECOM, Canada

Mehdi Bakhshi
Lead Tunnel Engineer, AECOM, USA

Verya Nasri
Chief Tunnel Engineer, AECOM, USA

ABSTRACT: Once completed, the Montreal Réseau Express Métropolitain (REM) will be the fourth largest automated transportation network in the world. This project involves construction of a 2.5km of single-track bored tunnel made of precast fiber reinforced concrete (FRC) segmental lining which connects Montréal-Pierre Elliott Trudeau International Airport to the rest of light rail network. To accelerate the construction of Airport Tunnel, for the first time, steel fiber reinforced precast concrete units are adopted for building the tunnel internal structures including the separation wall between the egress corridor and the platform walkway, and the slab for egress and platform walkway. Because of higher quality of precast concrete compared to cast-in-place concrete, this solution also results in extending service life of structure. A rigorous geometrical analysis was conducted to size the precast units to allow for the alignment curvatures as well as construction and manufacturing tolerances arising from different sources, including tunnel ring rolls and segment offsets. A three-dimensional model of the internal structures was created using a finite element software to check the precast walls and the precast slabs capacities under design loads, including the train-induced aerodynamic pressure. In addition, to further accelerate the construction of Airport Tunnel and prevent damages to segment due to drilling, a system of embedded sockets in precast segments and prefabricated curved steel channels anchored to these sockets are designed to support train's overhead catenary system (OCS). Before mass production of the precast units, a set of dowel pullout tests was completed by contractor on full-size precast segments to check the capacity of embedded socket/dowel connection system to the segmental lining. This project showed that with close collaboration among designer, contractor, and precast manufacturer, an accelerated and durable construction of bored tunnel's interior structure using innovative precast units can be successfully realized which can have significant benefits for all parties involved.

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Stabilization of a collapsed rock mass and installation of 100 tons permanent strand anchors at the Punatsangchhu-II Hydroelectric project, Bhutan

Piero Roberti
Technical Manager Grouting Techniques, BAUER Spezialtiefbau GmbH Germany

Arvind Kumar Mishra
Managing Director, MHPA, Bhutan

Martin Pielmeier
Team Leader – International Projects and Services, BAUER Spezialtiefbau GmbH Germany

Vidyaranya Bandi
Technical and Tendering Engineer Bauer Engineering India Pvt Limited

ABSTRACT: The Punatsangchhu-II Hydroelectric project (1.020 MW), on the Punatsangchhu river is spread along the Wangdue –Tsirang National Highway in Bhutan in the central Himalayan region, about 80 km east of Bhutan's capital Thimphu. The project includes a complex system of rock tunnels and caverns. The powerhouse complex has been excavated within rocks of the Thimphu Gneissic complex comprising mainly quartz-feldspathic gneiss, biotite micaceous quartzite with leucogranite and pegmatite patches and veins. In March 2016, a huge rock mass collapse occurred in the already excavated downstream surge chamber (DSC) because of an active shear zone. The total volume of muck generated in the collapse was estimated to be approximately 100.000 cum. The designer required the muck fallen into the cavern to be improved to low grade concrete of M10 strength to install 100 T capacity Cable Anchors supporting slender RCC walls. BAUER was entrusted the job as a specialist sub-contractor. The job involves nearly 19.960 m of drilling and systematic grouting followed by 19.900 m of permanent tieback strands anchors with working load up to 1.000 KN each. Along with various equipment for the injection works, up to five new drilling rigs have been mobilized from Europe for this work. The engineering challenges of this project was further compounded due to the cramped working environment and the difficulties related to drilling. With a width of approximately 18 m and a height of 8 m, the work area is extremely small, creating a challenging environment for equipment and personnel, while overcoming the technical challenges. The paper describes the drilling, grouting and anchors solutions adopted and the unique and unprecedented geotechnical challenges of this project.

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Numerical analysis of the effects of grouting on mitigating the risk of hydraulically induced failure during deep shaft excavation

J. Šaponjić, S. Radovanović PhD C.Eng., N. Divac & D. Divac PhD C.Eng.
Jaroslav Černi Water Institute, Belgrade, Serbia

ABSTRACT: Hydraulic failure presents a significant stability and safety issue for deep shaft excavation projects that deal with a high groundwater table in cohesionless soil. In urban environments, the lowering of the groundwater table for deep shaft excavations is usually not an acceptable solution to mitigate these risks due to the surface settlements it may cause, thus jeopardizing the safety of the surrounding structures. In this paper, a case study of an inlet shaft of a TBM-bored wastewater tunnel in Belgrade, Serbia was analyzed in order to show that grouting techniques can be an appropriate measure for reducing hydraulically induced instability. Since the location of the shaft is near the riverbank, the soil stratigraphy consists of granular soils with a high groundwater table. Several different variations of grout curtains around the shaft were modelled by conducting steady state flow analysis using commercial software based on the finite element method, and the obtained results were used to determine the risk of hydraulically induced failure at the bottom of the excavation. Based on the obtained results it is concluded that the application of grout curtains is a suitable solution for increasing the factor of safety for hydraulic heave problems as well as for soil failure problems. However, when encountering an aquitard layer during the earlier phases of excavation, grout curtains have no effect on lowering the pore pressures that are inducing the uplift at the bottom of the aquitard layer.

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Tunnel excavations supported by frozen soil bodies: Lab testing and modelling

U. Schindler, S. Chrisopoulos, W. Yan & R. Cudmani
Zentrum Geotechnik, Technical University of Munich, Munich, Germany

ABSTRACT: The significance of ground freezing is becoming ever more germane, because the design of new urban tunneling systems requires more complex geometries and higher strengths of the improved subsoil, which are limited with conventional construction methods. Therefore, advanced constitutive models for frozen soils must be developed and implemented in commercial Finite Element Analysis (FEA) codes for ground freezing designs under such complex conditions. This study presents a recently proposed elastic-viscoplastic model describing the rate-, stress-, and temperature-dependent mechanical behavior of frozen soils under compressive and tensile loading along with its implementation in a FEA code. After calibrating and validating the model for frozen Fairbanks silt, we simulated the construction of a twin-tunnel excavation supported by frozen soil bodies and compared the numerical results with experimental data from the literature. The good agreement demonstrates the model's ability to predict the stability and evaluate the deformations of frozen soils in tunneling scenarios.

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Circular economy and reuse of excavated materials from TBM excavations

D. Sebastiani, I. Bavasso & M. Amici
GEEG startup of Sapienza, University of Rome, Rome, Italy

N. Valiante, M. Di Nauta, M. Santamicone & G. De Carli
Webuild S.p.A., Milan, Italy

ABSTRACT: The management of excavated materials is one of the major issues for tunnelling projects from environmental, logistical, administrative and economical point of views. Despite the extreme importance of the topic and the huge volumes of materials produced in the context of major works, the excavated materials are too often considered as a waste and therefore their reuse is not a widely established practice. Webuild and GEEG have launched a research activity aimed at developing an integrated management system for excavated soils that involved numerous real tunnelling projects in Italy and abroad and a relevant number of different reuse modality, from the most common, as the morphological re-profiling, up to innovative uses with high added value. This paper, after a general introduction to the topic, intends to provide an overall description of the WE CYCLE Project and an update of the experimental evidences collected on the applicability of several methods of reuse of different soil typologies.

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Single and double tube configuration for transit systems

M. Sepehrmanesh & V. Nasri
AECOM, New York, NY, USA

ABSTRACT: The construction of a new subway line in any urban area is a complex task and typically needs large investment of hundreds of million dollars (in some cases billions) over a few years. Selection of the alignment with low-level risks is usually taken place at the environmental impact statement stage or at the planning design level. It should be proven by the completion of the alignment selection process that the selected alignment is fully feasible and economically cost-effective investment for the client. In almost all mechanized excavation, a circular shape is used with only variable being the dimension of the tunnel diameter. In this paper, a comprehensive comparison of advantages and disadvantages of single tube versus twin tubes for a subway system is outlined. Different aspects such as tunnel diameter (tunnel spaceproofing), configuration of subway line and stations, impacts on passenger safety and evacuation, ventilation system as well as rail system for each solution are evaluated and compared in depth. The practical example of a mega project has been discussed and the details of the decision-making process has been explained. A multi-criterion approach is established in the end to facilitate the decision making for these two different subway systems in any urban areas.

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Planning and positioning of metro station caverns in a heavily urbanised environment

A. Shivasami
Principal Engineer- Tunnels, Mott MacDonald, Sydney, Australia

D. Tsang
Principal Engineer- Tunnels, SMEC, Sydney, Australia

D. Lai
Senior Engineer- Tunnels, Mott MacDonald, Sydney, Australia

S. Azari
Associate Engineer- Tunnels, SMEC, Sydney, Australia

C. Lam & N. Gklotsos
Geotechnical Engineer & Former Technical Director, Mott MacDonald, Sydney, Australia

ABSTRACT: Sydney Metro West is a new 24km metro line with nine underground stations connecting Greater Paramatta and Sydney Central Business District (CBD). Sydney CBD's heavily urbanised environment requires a solution developed to higher levels of maturity at Concept Design than usual. This paper describes the planning process for two underground metro station caverns highlighting the challenges, opportunities, and constraints for the accurate positioning of the double-height caverns during the Concept Design stage. The paper also presents the methods adopted to assist the planning process, including the streamlined coordination work to determine the preferred location, visualisation of interfaces using Building Information Modelling (BIM), assessing the tunnelling impact by numerical modelling, developing a concept level design to inform the cost, schedule and aid the early contractor involvement. The decision process to determine the optimum configuration of the station caverns is outlined by highlighting the balance between the spaceproofing, constructability and external interfaces.

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Effective use of fibres of various types and material for shotcrete in rock support for tunnels

A. Sjölander, A. Ansell & E. Nordström
KTH Royal Institute of Technology, Divison of Concrete Structures, Stockholm, Sweden

ABSTRACT: Large volumes of steel fibre reinforced shotcrete (sprayed concrete) and steel bolts are commonly used to support tunnels in hard rock. This generates a high CO_2-footprint which must be reduced in order to decelerate the continuously increasing average temperature worldwide caused by the emissions of greenhouse gases. Thus, alternative design methods and the possibility to use other materials than steel are currently investigated. Work is ongoing on testing the load-bearing capacity of shotcrete reinforced with fibres of steel, basalt and synthetic materials. This also includes a comparison between tests using Round Determinate Panels (RDP) and four-point bending of beams. Moreover, the practical use of RDP testing as a quality control methodology is also investigated in situ. Here, the goal is to identify several shotcrete mixes suitable for use in tunnelling so that the right material and fibre volume can be used in the right place.

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Reinforcement and bonded block modelling

Georgios Aristeidis Skarvelas
Ove ArupPartners Ltd., London, UK

ABSTRACT: The objective of this paper is to evaluate the use of Bonded Block Modelling (BBM) in 3DEC software combined with hybrid rock bolts, for three different cases. These cases included the Hoek's laboratory rock bolt case, the shearing case, and the blocky rock mass case. The BBM is a relatively new numerical modelling technique. The laboratory rock bolt test was introduced by Hoek and the main idea was to describe the way that rock bolts work. The laboratory rock bolt model validated the results of Hoek. The fragmentation result is examined on the shearing and blocky rock mass cases. The fragmentation of rock pieces was noticeable on the shearing case and followed the fundamentals of the rock mechanics theory.

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Innovative and sustainable precast arch solution for High Speed 2 Green Tunnels

E. Smith & S. Psomas
COWI UK Ltd (Arcadis Setec COWI Design Joint Venture, ASC)

Z. Rostance & J. Martin
EKFB (Eiffage Construction, Kier Infrastructure, Ferrovial, BAM Nuttall, EKFB)

ABSTRACT: EKFB-JV will build the Cut and Cover 'Green Tunnels' (GTs) as part of the High Speed 2 C2 & C3. The design of the GTs was undertaken by ASC-JV. This Paper presents the significant benefits of GTs, in terms of savings in cost, time, waste, reduced safety risk profile and improved sustainability. The design of GTs has a key objective to minimize the maintenance requirements over their total length of 6.6km. This type of construction was selected after a rigorous options assessment. It is efficient and innovative, as this is the first time that has been adopted in the UK for high-speed rail in high overburden (up to 16m). The Paper discusses the benefits that this solution offers covering buildability through reduced complexity in interfaces with other operations and increased level of safety. Other environmental considerations related to construction activities are also presented and discussed.

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Examination of rock reinforcement and stability of the hard rock pillars due to the over-break and blast damage

S. Spasojević
WSP, Belgrade, Serbia

K. Skrobic
WSP Sverige AB

ABSTRACT: The focus of this study is to identify and understand the behavior of the designed pillars and rock reinforcement in hard rock. The analysis is based on the observations during construction of the new underground bus terminal Slussen, blasted underneath the Katarina Mountain, in the City of Stockholm. A two-dimensional, linear elastic-plastic, finite element model (RS2) is created, and numerical analysis was conducted to investigate the stress concentration in the pillars, yield zones and maximal reduction of the pillar area to retain pillar stability.

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Optimizing the climate impact of tunnel structures by advanced numerical simulations

P. Spyridis
TU Dortmund University, Dortmund, Germany

K. Bergmeister
University of Natural Resources and Life Sciences, Vienna, Austria

ABSTRACT: Measurements and analyses in the last decades have confirmed the critical increase of greenhouse gas emissions and global average temperature, and consequently the tendency for irreversible climate disruption. At the moment, very intensified efforts are devoted at European and International levels toward stabilising this phenomenon, moreover with tight target timelines, which is translated to strict measures of reducing CO2 or equivalent emissions in every human activity. The civil – and among them the tunnelling – construction sector contributes to at least 37%. In order to include this important issue, a newly introduced scheme for the assessment of climate compatibility is proposed analogous to the limit states of load-bearing capacity and serviceability. This describes the equivalent CO2 input to achieve a certain load-bearing capacity and considers also the service life. The emission impact over the service life is compared to a limit value derived from climate research and relevant regulations. Therefore, advanced analysis techniques using non-linear finite element calculations and non-elastic design and optimized structural design can vastly contribute to reducing material consumption and facilitating resource-efficient construction layouts. The fundamentals of the newly proposed climate-oriented assessment concept will be presented and a case study on a numerical simulation and pre-design of a realistic tunnel structure is used to exemplify the implementation of this concept and its significance for an ecologically responsible future tunnelling industry.

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Advanced semi-probabilistic methods for the design and assessment of concrete tunnel linings

P. Spyridis
TU Dortmund University, Dortmund, Germany

L. Novák & D. Novák
Brno University of Technology, Brno, Czech Republic

K. Bergmeister
University of Natural Resources and Life Sciences (BOKU), Vienna, Austria

ABSTRACT: Tunnel design is a complex complicated task since it is strongly associated with a great number of load and material uncertainties. Moreover, modelling the soil-structure interaction multiplies the complexity and non-linearity of tunnel engineering problems. Finite Element (FE) stochastic modelling has proven to be a very efficient tool in dealing with such uncertainties. Capturing uncertainties, though, which allows for a more realistic and pragmatic design decision aid, requires probabilistic approaches. The only general tool for probabilistic analysis is represented by Monte Carlo simulation (MC), simulating uncertainties with their complete probability distribution and statistical correlation. The complexity of the FE models renders then such a procedure virtually impossible. The computational burden of MC represents the main obstacle to the approach for time-consuming FE computational models since it is not computationally feasible for industrial applications. Consideration of uncertainties, therefore, remains usually at the level of partial safety factors, the approach which is in most cases on the very conservative side. That is why alternative techniques of so-called safety formats are becoming more and more attractive recently. Methods focused on the Estimation of Coefficient of Variation (ECoV) of structural resistance have been developed and applied recently mainly for concrete structures like bridges. They represent a compromise between the simple and in most cases conservative approach of partial safety factors and highly computationally demanding MC. The paper shows the possibility of application of these methods for tunnels. Selected efficient semi-probabilistic methods based on the ECoV method according to fib Model Code 2010, an improved approach called Eigen ECoV, Taylor Series Expansion and numerical quadrature proposed by Rosenblueth are compared.

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Tunnelling in the Desert, Wakrah and Wukair Tunnel, Doha, Qatar

J.B. Stypulkowski, A.M. Najder Olliver & Khalid Saif F S Al-Khayareen
Public Works Authority (ASHGHAL), Doha, Qatar

ABSTRACT: The Public Works Authority (PWA) of the State of Qatar, or ASHGHAL, has launched the Wakrah and Wukair Drainage Tunnel, which is a 13km-long and 4.5m-ID sewer tunnel serving Doha's growing population in the years to come. The depths range from 50 to 60m, which will make the tunnel entirely in the Rus Calcareous (RUS) and Rus Gypsum (RUSGYP) formations, thus this will be the deepest and most challenging TBM tunnelling project in Qatar to date. Little was known about the ground conditions and the specifics of the deep geological formations along the planned alignment at project inception. Therefore, an extensive ground investigation campaign was launched in several phases to confirm the feasibility of the project, as the key to every successful tunnel project is to properly identify and mitigate the risks. The authors will present the findings of the investigations along with the design considerations for weak/soft rock masses commonly found in Doha, Qatar. The authors will also provide an introduction to the specifics of the PWA's latest project and tunnelling aspects of it.

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A numerical investigation of the lining performance of composite SCL tunnels with debonded sprayed waterproofing membrane

J. Su
Ramboll, London, UK

ABSTRACT: Composite SCL tunnels, comprising two layers of permanent concrete linings and a sandwiched layer of sprayed waterproofing membrane, have been constructed in several major underground construction projects in the UK. The research on composite SCL tunnels has so far been focused on the performance of the permanent concrete lining when the sprayed waterproofing membrane is still bonded to both layers of linings. Recently, research has shifted towards the robustness of the sprayed waterproofing membrane system under external groundwater pressure and the impact of debonded sprayed waterproofing membrane on the concrete lining performance. This paper assesses the second issue by undertaking numerical modelling with various partially and fully debonded sprayed waterproofing membrane scenarios. The lining performance is presented and discussed. Further research on this topic is recommended.

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Stress status of sprayed waterproofing membrane under groundwater pressure within composite SCL tunnels

J. Su
Ramboll, London, UK

ABSTRACT: Groundwater pressure is the main cause of debonding (i.e. tensile failure) of the sprayed waterproofing membrane interface within composite sprayed concrete lined (SCL) tunnels. The debonding could lead to the groundwater pressure being resisted by the thin secondary lining alone, causing concerns about its stability. Therefore, it is critical to understand the stress status and potential failure mechanisms of the sprayed membrane interface and the practical implications of membrane testing methodology. The paper first reviews the status of the composite SCL research and identifies the most critical issue that prevents it from wider application. It then presents a conceptual relationship between the possible groundwater pressure application locations and the stress state and hence potential failure mechanism of the membrane interface in composite SCL tunnels. The current membrane interface tensile strength testing methodology is then reviewed. Suggestions are made for the improvement of the testing methodology.

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Reducing uncertainty in tunnel design

A. Syed & C. Paraskevopoulou
School of Earth and Environment, University of Leeds, UK

V. Marinos
School of Civil Engineering, National Technical University of Athens, Greece

ABSTRACT: A probabilistic approach is undertaken to incorporate uncertainty into the geotechnical design of a tunnel through gneissic environments in Northern Greece to determine optimum support measures. The gneissic unit, part of the Pelagonian formation, varies significantly from fresh to completely weathered and massive intact to disintegrated rock mass. Such geological conditions result from intense tectonic compression and ongoing structural activity. Firstly, the various lithological types for gneissic environments are defined based on literature. Regression analysis is then employed on the raw primary gneissic data to determine the relationship of the intact rock strength parameters (Young Modulus and intact strength). The most probable rock strength parameter values are assessed based on the results of intensive probabilistic analyses. Based on these values, rock mass strength parameters are then determined utilising the generalised Hoek-Brown failure criterion. At the same time, the second series of probabilistic analyses are performed to reduce uncertainty. Finally, the lowest, most probable and mean rock mass parameters, coupled with intact strength parameters, are tabulated through a lognormal distribution. At this stage, various analyses of the structural data (i.e. discontinuity sets, weathering grade, RQD) are carried out to determine Geological Strength Index (GSI) values to assist in defying Rock Mass Types. Moreover, the Rock Mass Behaviour Types are determined based on the expected tunnel behaviour due to the structural and stress environments. These behavioural conclusions and parameters are then used as input data for numerical analysis (2D) using RS2 and Unwedege. Finally, based on the most probable total displacements and the input parameters, a preliminary design of support measures to determine the most optimum combinations possible.

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Design summary and construction considerations for the Nagdhunga Tunnel, Nepal

T. Tomita & J. Mitsuo
Eight-Japan Engineering Consultants Inc. Tokyo, Japan

Y. Nozue & R. Asai
Nippon Koei Co., Ltd., Tokyo, Japan

N.M. Shakya
Government of Nepal Ministry of Physical Infrastructure and Transport Department of Roads

ABSTRACT: This paper describes the Nagdhunga Tunnel project, Nepal's first conventional excavation road tunnel. The tunnel located near the boundary where the Indian Plate subducts into the Eurasian Plate. The geology was complex, with many faults in metamorphic rocks such as phyllite and metamorphic sandstone and alternating permeable and impermeable layers. The design results based on the geological investigation and the current construction status are shown below.

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Large diameter TBM tunnels – Trends in planning and design

S. Vardakos, S. Zlatanic, S.M. Wongkaew & A. Bauer
HNTB, National Tunnel Practice, USA

ABSTRACT: High urbanization and urban migration increase demands for higher capacity transportation projects, underground. Since the mid 90's there has been notable increase in international projects involving large diameter single bore tunnels for transit and roadway applications. The demand has been met by both TBM manufacturers, with the production of reliable TBM units pushing the diameter envelope to the range of 17-18m, and tunnel contractors ready to embark on related construction challenges. Owners and consultants have also embraced these novel approaches and supported selection and subsequent design delivery of a wide range of large diameter tunnel projects needing to meet variety of complex subsurface conditions. The paper presents benefits of large diameter tunnel application and related planning and design considerations; it includes a few examples illustrating emerging challenges, trends and innovations leading to successful implementation of this fast developing methodology.

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The application of DFN modelling to assess the applicability for shaft construction

Ioannis Vazaios & Carmen Hu
Ove Arup & Partners Ltd., UK, London, UK

James Bottomley
Ove Arup & Partners Ltd., NY, USA

Peter Stakne
Strabag UK. Ltd. London, UK

Gareth Williams & Dave Warburton
Anglo American PLC, London, UK

ABSTRACT: Discrete fracture network (DFN) modelling is a state-of-the-art stochastic technique that allows engineers and geologists to provide estimates of the potential rock discontinuity systems within a rockmass that can be acquired through geological mapping of rockmass exposures, boreholes etc. The development of such discontinuity geometry models can provide useful insights in terms of the anticipated rockmass behaviour during excavation as well as assist in determining/optimizing the required support measures to achieve a safe and efficient shaft construction. In this paper DFN modelling has been utilized as a means to assess the applicability of shaft sinking within blocky rockmasses. The implemented workflow aims to assess the potential block size to be encountered in situ based on discontinuity data collected from available rock exposures or boreholes which can be used to feed the decision-making process of the appropriate boring technique and equipment, as well as the adjustments required to provide the necessary support during shaft sinking depending on the unstable block size. A practical example using geo-data from a deep shaft at Lockwood Beck for the Anglo-American North Yorkshire Polyhalite project in the UK will be used to demonstrate the value of the method and its influence on Blind Shaft sinking.

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Consolidation and waterproofing by injection of PU resins. Ilarion Dam - treatment on the spillway tunnel

D. Velez, D. Alumbreros & D. Carpintero
ATEGLOB, Spain

P. Tsakas & E. Tsaka
P.Tsaka Ltd., Greece

K. Sakellariadis & Z.R. Papachatzaki
PPC SA, Greece

ABSTRACT: The behaviour and the actual condition of the strata are variables difficult to define in detail during the design phase. Moreover, during the construction phase of underground works, a disturbance of the natural equilibrium occurs, that may lead to fracturing, ground decompression and water circulation. As a result, the complexity of the ground-construction system increases, and problems are often encountered during the construction and operation phase of the infrastructure. In this field, resins can offer positive results, associated with fast reaction, low viscosity, and adaptable chemistry and may be an effective response to these difficult to solve problems. This paper describes in brief the application of PU resins and the favourable result obtained in the Ilarion Dam spillway No1 tunnel, in Greece.

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Final tunnel design within 24 hours

R.R.E. Vervoorn, A. Santos, A. Khalaf & O. Noureldin
Civil Seven B.V.

ABSTRACT: Delay in underground infrastructure causes great costs. Construction managers know how hard it is to manage one particular aspect: the design time. In practice design teams usually fail to deliver on time. On the contrary scientific presentations have promised to slash design time using buzzwords like parametric design and artificial intelligence. The reason for the failure is simple: behind the scenes, tunnel design is still not automated to handle the complete range of day-to-day nitty-gritty design work: until now nobody has been able to automate the complete chain of tedious tasks for all conditions. For example, manual labour is used for adjusting to local design codes, taking into account construction phasing, tricky thermal and shrinkage effects and reinforcement detailing specials.

This paper cuts out the ‘air’ around artificial intelligence and offers classic design automation - but - for the first time offers the complete preliminary-to-final design package. Three ‘24-hour tunnel designs’ made under different design codes (Netherlands and Sweden) and for different traffic conditions (Road and rail tunnels) will be presented: A9 Highway Tunnel (Amstelveen), West Link Rail tunnel (Gothenburg) and Rail Tunnel (Den Bosch). Then it will demonstrate how to design two new 1 km tunnel segments within 24 hours.

Unique is that two new tunnels will be designed LIVE during the event using just the intended alignment and a few basic inputs. In the paper we will explain the best practices regarding organisational structure, technologies and workflow to achieve this.

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Pillar stress estimation: 3D & 2D numerical analysis vs. Tributary Area Theory

I. Vlachogiannis
School of Mining & Metallurgical Engineering NTUA, Athens, Greece
Geomine J&K, Athens, Greece

A. Benardos
School of MiningMetallurgical Engineering NTUA, Athens, Greece

ABSTRACT: Room-and-pillar is one of the most well-known and widely used underground mining methods worldwide. Even though this method is traditionally linked with mining, its application serves as a cost-effective and versatile construction method for the development of large underground spaces for civil applications as well. The Tributary Area Theory (TAT) has been traditionally used for the estimation of the average pillar stress, the first step in the empirical methodology for the design process. Although TAT and the empirical pillar stress equations have been successfully employed, it is common knowledge that TAT tends to oversimplify and yet overestimate the stress imposed to the pillars.

The main aim of this paper is to analyze and evaluate the pillar stress conditions by directly comparing the TAT values and the pillar induced stresses through FEA. In this effort, a series of 3D and 2D numerical analyses were carried out under a series of various pillars' configurations and initial virgin stress fields in order to properly decode the pillar loading regime and depict the deviation of stresses estimation. The authors suggest two (2) power equations for the direct estimation of the average major principal stresses developed upon the pillars' crest, both for the case of rib & square pillars layout. The performance of the equations was found to provide results within high confidence levels in alignment with the results from 2D & 3D numerical analyses. In general, further room is left for improvement in terms of a more efficient and perhaps more aggressive pillar design maximizing the full potentials of the room-and-pillar method.

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Stress distribution in tunnel openings constructed using the sprayed concrete method in London clay

M.L. Walker
Coffey, Harrogate, UK

C. Paraskevopoulou
University of Leeds, Leeds, UK

J. Su
Ramboll, London, UK

ABSTRACT: Numerical models of tunnel openings constructed using the Sprayed Concrete Method (SCM) typically utilise plate elements to reproduce the concrete lining behavior. Plate elements rely upon the plane stress assumption, which can result in overly conservative values of stress as indicated by the recent fibre optic strain monitoring by De Battista et al. (2015). This study presents an alternative approach to modelling of SCM constructed tunnel openings incorporating discrete volume elements for the primary and thickening layers of concrete. A series of three-dimensional finite element analyses have been completed using model parameters informed by tunnel openings constructed for London Crossrail. Comparison is made between results from models incorporating plate and volume elements. Findings confirm reduced maximum stress values around an opening using the volume element method. The results of the modelling approach corroborate baseline statements made by De Battista et al. (2015) based on field fibre optic strain monitoring.

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Function of reinforcement in concrete tunnel linings

R. Winterberg
Group Chief Engineer, BarChip Inc., Japan

ABSTRACT: An investigation has been carried out on the behaviour and performance of different concrete tunnel lining systems. The reinforcement requirements for their typical structural load-bearing systems have been analysed. Traditional design methods can underestimate the potential of a tunnel lining system when the models ignore parts of the boundary conditions. Experimental investigations have been carried out to provide data to improve the models and to yield more economic designs. The results of the experimental testing program and the academic research demonstrate that in many cases, moderate dose rates of fibre reinforcement can provide the required structural ductility, robustness and safety of tunnel linings while reducing construction cost and time.

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Design of support structure for spatially small-spaced four-tube tunnels: A case study of the He'ao tunnel in China

M.Q. Xiao, C. Xu, Q. Zheng & C.S. Peng
China Railway Siyuan Survey and Design Group Co., Ltd., Wuhan
National & Local Joint Engineering Research Center of Underwater Tunneling Technology, Wuhan

ABSTRACT: The quantitative design and safety analysis of support structure parameters for multi hole space tunnels with small clear distance are a major problem in current design. This paper is aimed at the design of He'ao tunnel in Shenzhen Ji-he Expressway, China. The total safety factor method is used to study and compare the excavation and support modes, excavation sequence and support parameters of the four tunnels. The conclusions are as follows: (1) Based on the principle of total safety factor method, the design method of multi hole space tunnel with small clear distance is proposed; (2) For the spatially small-spaced four-tube tunnels, the excavation and support mode of "excavation of the next tunnel after the secondary lining completion of the first tunnel" shall be adopted, and the excavation sequence shall be tunnel 1 → tunnel 2 → tunnel 3 → tunnel 4. (3) This paper can provide theoretical guidance and reference for similar engineering design.

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Research and application of prefabrication and assembly construction technology for metro station structures

Xiuren Yang & Fang Lin
Beijing Urban Construction Design and Development Group co., Ltd, Beijing, China
National Engineering Research Center for Green & Safe Construction Technology in Urban Rail Transit, Beijing, China

ABSTRACT: In the severe cold areas of northern China, it is impossible to cut and cover underground structures in winter, thus extending the construction period of the project. To address the difficulty of construction in winter, since 2012, the prefabricated construction technology of metro station has been studied and applied in the engineering system of Metro Line 2 in Changchun, Jilin Province, China. This paper briefly introduces the main technical contents and key technical achievements of the research and application of the prefabricated construction technology of metro station structures in the past 10 years, mainly including component joint connection technology, mechanical behaviors of structural system, earthquake resistance behaviors of prefabricated structure, mechanical properties of lightweight structural component, waterproof technology of prefabricated structure, production technology of precast component and construction technology. Engineering practice has proved that the prefabricated assembly construction technology for metro station structures is of high quality, efficient, safe and environmentally friendly. It is not only suitable for the construction of metro stations under various environmental conditions in other cities, but also for the construction of other cut-and-cover underground structures, e.g. metro section, pedestrian passageway, road tunnel and underground pipe rack, with a broad applicability.

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Numerical simulation of the mechanical behaviour and support of laminated discontinuous roof of underground excavations

P. Yiouta-Mitra & E. Vougioukas
National Technical University of Athens

ABSTRACT: Laminated geological formations are often encountered in different environments of underground excavations. This type of rock structure located in underground openings is a key factor in controlling the safety around underground openings in competent rock such as hydropower plants and underground marble and limestone quarries. Their behavior is governed by interbedding low tensile and shear strength which leads to separation and sliding respectively. When the rock layers are internally discontinuous, their behavior significantly diverges from that of a beam succession. In this research, the behavior of multilayered discontinuous roof in underground excavations is numerically investigated and compared to the behavior of single and multiple continuous layers as well as that of single discontinuous layer. A set of numerical analyses with the discrete element method are performed and quantification of the multilayering effect is produced for the unsupported discontinuous roof. Obviously, the control of stresses and displacements by active reinforcement or passive support of the roof is of great interest. A second set of numerical analyses for the quantification of the reinforcement effects of pre-tensioned rockbolting. The cases include up to five layers with ratio of layer thickness to span equal to 0.1 and for ratios of vertical discontinuity distance to span of the opening 0.2, 0.1 and 0.05. Conclusions are drawn with respect to the degree of decrease of vertical displacements for all groups of vertical discontinuities, which interrupt the layers in correlation to the support method. For continuous layers it is observed that the reinforcement of the roof reduces the vertical displacements to a lesser extent. In conclusion, practical guidelines for the planning of an effective reinforcement scheme are produced, which, in combination to careful monitoring of the roof ensures the safety of underground works in laminated environment.

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A 3-D finite element design of a tunnel temporary lining, under archaeological area

E. Zygouri & D. Bairaktaris
D. Bairaktaris and Associates Structural Design Office Ltd, Athens, Greece

ABSTRACT: This tunnel was constructed under the archeological area of Iridanos River, Monastiraki Station, Attiko Metro. The presence of antiquities implies the requirement of minimizing surface settlements. For that reason a presupporting system of microtunnels is provided consisting of longitudinal horizontal steel tubes arranged outside the arch of the temporary lining. The most important scope of the design was to restrict surface settlements at the archeological area. The associated settlements have been carefully investigated using a nonlinear analysis method on a highly sophisticated 3-dimensional FE model, applied for the complete sequence of the steps of excavation and lining construction, insuring the better approximation to the actual performance of the structure. In the model are also introduced soil parameters resulting from the relevant soil borings and the previously executed excavations. A nonlinear elastoplastic analysis applied for the 3-D model of the system by the introduction of the Mohr–Coulomb failure criterion, for the soil 3D finite elements. Rockmass environment consists of: "black Athenian schist" with very low shear strength and deformability parameters. Application was successful and the limitation of settlements at the Iridanos River archaeological area, during the construction to acceptable serviceability, was achieved. The provisions of the study were verified to a large extent, with a deviation not exceeding 8%.

Mechanised tunnelling (and microtunnelling)

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Analysis of annular grouting in tunnels tail void with gap by an interface model

A.H. Ahn & A. Pouya
Laboratoire Navier (Université Gustave Eiffel, CNRS, ENPC), Ecole des Ponts ParisTech, Marne-la-Vallée, France

G.C. Cho
Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea

ABSTRACT: In this analysis study, based on the recognition that the primary volume loss in the construction of the shield tunnel is caused by the tail void gap between the segment lining and the ground skin, the tail void gap is modeled as an interface element to analyze the effect of segment lining by stiffness values and spacing ‘e’ of the interface. These results were evaluated by the member force analysis of a lining and the Convergence Confinement method. If the larger the gap between the tail void interface between the segment lining and the ground and the lower the stiffness value, even if the gap grouting process and the installation of the segment are performed simultaneously, the support stiffness of the actual segment lining is expressed afterward the stiffness combination of the segment lining and the interface. In conclusion, this analysis is required to control the load on the lining.

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Investigation of vibration patterns generated during rock cutting tests and TBM excavation

U. Ates, H. Copur & A. Shaterpour-Mamaghani
Istanbul Technical University, Istanbul, Turkey

M.E. Aymir
Umraniye-Atasehir-Goztepe Metro Construction J.V., Istanbul, Turkey

ABSTRACT: TBMs are widely utilized for infrastructure projects and they should be selected and operated according to the geological conditions to reach favorable excavation rates. Therefore, understanding the geological changes during excavation is very important. With the aim of identification of the geological conditions, three kilometers of vibration data are collected during excavation in adjacent twin tube tunnels from two EPB TBMs. The data is analyzed, compared with geological conditions, geomechanical rock properties, and TBM operational parameters. Laboratory rock cutting tests using a full scale linear rock cutting machine equipped with accelerometers are also performed on the rock samples taken from the same project site. It is seen that the geological condition is the major factor on the vibration characteristics on the most cases and there are relations between the geomechanical properties of rocks and the vibration patterns. Similarly, during the laboratory cutting tests, it is seen that acceleration amplitudes change in relation to the rock type, rock properties, and cutting parameters.

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Design of FRC precast segments for fire in light-rail tunnels

M. Bakhshi
AECOM, New York, USA

M. Partovi
DIANA FEA BV, Delft, The Netherlands

A. Haghighat
AECOM, Oakland, USA

V. Nasri
AECOM, New York, USA

ABSTRACT: Fire is one of the governing load cases for design of precast tunnel segments in transit tunnels. As the best practice, a design procedure is provided based on computational fluid dynamics (CFD) simulation of a light-rail train fire and importing CFD results into a two-dimensional coupled thermo-mechanical finite element analysis (FEA). Application of this procedure to a 6-m diameter tunnel made of Fiber-reinforced concrete (FRC) segments is presented. While use of standard fire curves simplifies the design, it can result in overestimation of fire load on segments. Results show that once the actual fire curve of a light-rail train from CFD analysis used together with a coupled thermo-mechanical FEA, more realistic fire loads can be obtained, resulting in an optimized design of FRC segments.

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Effect of cutting speed on conical pick cutter performance obtained from Portable Linear Rock Cutting Machine (PLCM)

C. Balci, F. Shoaee, D. Tumac & H. Copur
Mining Engineering Department, Istanbul Technical University, Maslak, Istanbul, Turkey

ABSTRACT: Use of mechanical miners (tunnel boring machine, roadheader, continuous miner etc.) in both mining and civil industries has been considerably increased in recent years in the world. If mechanical miners are not properly designed and selected, some problems arise such that advance rates may decrease dramatically and significant economic losses may be encountered. Rock cutting tests in different scales are the most widely used experimental methods for properly selection and design of mechanical miners and optimizing their performances.

Previous studies indicated that the effect of cutting speed on cutting performance was contradictory in both laboratory-scale cutting (lower speeds usually up to ~25 cm/s) and cutting in the field (higher speeds, up to a few meters per second) with real-life mechanical miners. This study investigates the effects of laboratory-scale cutting speeds on cutting performance of a conical pick cutter. A previously developed portable linear rock cutting machine (PLCM), which cuts at a constant speed (3 cm/sec), is modified so that the cutting speed can be adjusted at three levels (3, 12.5 and 25 cm/s). Then, laboratory rock cutting experiments are performed by using PLCM on a rock sample (beige marble) at three different cutting speeds to analyze the effect of cutting speed on cutting performance (mean normal and cutting forces, and specific energy). Depth of cut values used in the tests are 2, 3 and 5 mm in single spiral cutting mode at constant line spacing of 10 mm.

The results indicate that laboratory-scale cutting speeds affect the normal and cutting forces, and specific energy. The studies should be continued with some other rock types, other cutter types, and different experimental conditions.

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Comparison of two identical EPB TBMs under different and complex geological conditions

I.S. Binen
Trakkom Engineering & Industries, Istanbul, Turkey

F. Kara, M. Temur & M. Cinar
Kalyon Construction, Istanbul, Turkey

U. Ates
Istanbul Technical University, Istanbul, Turkey

ABSTRACT: Large metropolitan cities require constant infrastructure investments to fulfill the needs of ever-growing population. With the advancements in mechanized tunneling, utilizing TBMs for infrastructure and utility tunnels has become a very efficient method. However, considering the high initial capital investments, TBM design and selection becomes important for the success of the project. European Potable Water Transmission Project utility tunnels were designed to travel more than 19 km under the densely populated areas of Istanbul. The project crosses complex geological conditions. Based on the complexity of geological conditions, time frame and the operational concerns, the tunnel excavated simultaneously by two identical EPB TBMs. In this study, it was aimed to investigate and compare the performance of both TBMs by analyzing excavation data obtained from the data logging system of the TBMs. In addition, TBMs' reaction under risky or difficult conditions caused by fault lines, excessive hydrostatic pressures, and abrasive sand drives will be presented case by case.

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Challenges experienced during simultaneous backfill grouting using single shield large diameter TBM driven in a sharp negative slope

V.B.M. Braga, J.C.S. Zapico & V. Tyagi
FGJV Future Generation Joint Venture, Webuild Clough Lane, Australia

R. Bono
Webuild, Italy

ABSTRACT: Simultaneously backfill grouting limits the movement due to self-weight and thrust forces generated by the TBM, and the displacement differences between two measurement points, by filling voids left by the TBM between the excavation profile and extrados of the segments, so the system becomes monolithic. On Snowy 2.0, preventing any deviations from construction tolerances of the pre-cast lined tunnel set by the British tunnelling society was a challenge when building a large diameter tunnel in a sharp negative slope using a bi-component backfill grouting and a conventional single shield tunnelling boring machine. Even when injecting grout quite above the theoretical volume per advance, that flowed to the cutting wheel before the gel time formation set by the design specification, and voids were identified during proof drilling, especially in the tunnel crown, even after the secondary grouting had been done. The control of these tolerances constitutes a major challenge in the use of the mechanised tunnelling method. This paper presents the development of the solution on Snowy 2.0 for the Main Access Tunnel through the installation of two auxiliary grouting lines and a manometer, for grouting from the back part of the shield in the tunnel crown, whilst ensuring a grout pressure is maintained in between the acceptable range limits, both above and below the tunnel spring line. After starting the grouting injection from the lines independent from the TBM, the rings built met the tightest construction tolerances set for the Main Access Tunnel.

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An analysis of metal wear in rock excavation by TBM

M. Cardu, A. Di Giovanni & S. Saltarin
DIATI Politecnico di Torino, Italy

C. Todaro
IGG-CNR, Torino, Italy

ABSTRACT: Abrasivity, or its reciprocal concept, "wear resistance", are not intrinsic properties of a material, but rather parameters describing the interaction of two materials, i.e. the wear part and the material exerting the wearing action. Moreover, "wear" or, at least, that part of the wear, which is due to the cumulated effect of minute scratches, is linked to the "hardness disparity" concept: an example is provided by the well-known Mohs hardness scale (the "harder" body wears the "softer" body). In the case of rock-metal interaction, a difficulty arises from the inhomogeneity of the interacting bodies. The paper, after a synthetic explanation of the basic principles, deals first with the problem of measuring and representing the hardness of inhomogeneous bodies; a simple procedure is described, with practical examples. Then, after a review of data on TBM disc service life and rock abrasivity evaluation, cases of TBM used in hydropower tunnel driving in Italy are presented. Data pertaining to the rock bored and to the metal composing the discs, together with machine data, tools consumption and machine productivity are provided and compared to find correlations enabling to forecast tools service life.

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Influence of chip-size on development of adhesion for conditioned clayey soils

A. Carigi, A. Di Giovanni, S. Saltarin & D. Peila
Politecnico di Torino, Torino, Italy

C. Todaro
Consiglio Nazionale delle Ricerche, Torino, Italy

ABSTRACT: In the excavation of clayey soil with Earth Pressure Balance TBMs, the study of soil conditioning is a complex issue. The presence of a mix of water, clay and foam, often added with polymers, makes the resultant mass a material strongly time-dependent and where the internal forces are given both by mass and surface actions. Differently from granular soils, where the time-dependence of the conditioned mass is ruled by the decay of foam, in clays one the rate of adsorption of the liquid phase of the conditioning into the clay chips cannot be neglected since strongly affects the quality of the conditioned mass in time. This paper compares the difference in the adsorption rate through the evaluation of the dynamic adhesion for different chip size. For each studied clay, different chip size distributions are obtained and tested. The difference in the development of adhesion reflects the different rate of adsorption of the liquid phase showing that the dimensions of the chips should be considered in the choice of clay conditioning parameters with reference also to the estimated time spent by the conditioned material to go through the excavation chamber and to exit from the screw conveyor.

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New service tunnel Kerenzerberg: Innovative approach in order to increase the degree of mechanization

F. Carrera-Henke, P. Beeler & G. Gubler
Lombardi SA, Giubiasco, Switzerland

ABSTRACT: The Kerenzerbergtunnel (L = 5.7 km) is part of the highway N03 connecting Zürich with the eastern part of Switzerland. After 37 years of operation it needs a general refurbishment and an upgrading to fulfill with the new safety regulations. The main adjustments include the realization of a new service tunnel, a modification of the ventilation system and the full refurbishment of the road tunnel. The service tunnel has a length of 5.5 km and will be excavated with a double shield TBM. The tunnel design follows an innovative approach: the tunnel acts simultaneously as a safety and ventilation gallery (double function). The main structural elements are realized by precast concrete elements in order to increase the degree of mechanization and reduce the construction time. The TBM supply is carried out by innovative self-driving vehicles, which don't need any mechanical guidance thanks to their modern control sensors.

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Assessment methodology for clogging estimation and soil conditioning in EPB shields

Z. Chen
Ghent University, Ghent, Belgium

A. Bezuijen
Ghent University, Ghent, Belgium and Deltares, Delft, The Netherlands

Y. Fang
Southwest Jiaotong University, Chengdu, China

D.G.G. de Oliveira
TunGeo, São Paulo, Brazil

ABSTRACT: During EPB shield tunnelling, clogging potential could be rather high in soils with high plasticity and at certain consistencies. If not mitigated, clogged material needs to be removed by sending workers inside the soil chamber, which is costly, potentially dangerous and time consuming. A simple methodology, which can be performed in the lab and on the jobsite, is needed to monitor clogging potential and adapt the soil conditioning scheme to changing soil conditions during the tunnel drive. This study introduces a clogging potential assessment device modified from the ATUR device and using an apparatus attached to a regular flow table. The device is straightforward and easy to build, as well as the simplicity of the method itself. Thus, the methodology described in this study can be adopted, repeated, and verified by engineers and scholars around the world. This article includes preliminary results of some tests, investigating the influence of water content and device weight.

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A non-conventional system for TBM recovery: Abandonment of the shield and underground disassembly of the mechanical equipment and inner structures

P. Fernández Coto, F. Domínguez Mayans & P. García de Haro
Tunnelconsult Engineering, Barcelona, Spain

G. Zonghua & Y. Zhuangzhi
CRTG, China Railway Tunnel Group, Tel Aviv, Israel

ABSTRACT: Sometimes the retrieval procedure of the TBM after finishing the drive cannot be the typical vertical shaft extraction; the boundary conditions of the project (schedule, overlapping of activities and/or lack of space among others) may require a different solution. The case presented describes the solution adopted in a metro project where the TBM shield is left buried and becomes a part of the tunnel final lining. To make this possible, a chamber is excavated to disassemble the cutterhead and to recover the main drive, while the rest of the TBM and back-up system are brought back to the launch point through the already built tunnel. Besides, the TBM does not make a conventional breakthrough, but the rotary head and part of the shield are embedded in a block of ground that has previously been improved with ultrafine cement injections. By means of conventional excavation performed from one side of the chamber, the rotary head is reached and released to proceed with its removal.

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Evaluation of the influence of ground conditioning on a large diameter EPB TBM: Performance in the Esme Tunnel, Turkey

Enrico Dal Negro, Alessandro Boscaro & Enrico Barbero
UTT division from Mapei S.p.a

Irfan Serkan Binen & Yasar Yertutan
Trakkom Engineering & Industries

Onur Kansu
Kolin Construction

ABSTRACT: Esme tunnel for the Izmir – Ankara high speed railway project is located in the rural parts of the city called Usak in the mid-west section of Turkey. A 13,77 m diameter Robbins Crossover TBM has been utilized for the construction of the single tube tunnel with a total length of approximately 3 km. The tunnel alignment is developed through two main lithologies which are gneiss and mudstone, respectively. Gneiss was observed right after TBM launch for a few hundred meters, while the dominant lithology was dry mudstone with considerable amount of fine particle. Regarding the hydrogeological aspect, the project area is quite dry and can be considered almost arid. The low water amount and high fine content of the ground make the excavation with the Crossover TBM difficult, thus making the ground conditioning a challenge for the project success. In addition to that, the lack of natural or municipal water resources was a relevant issue in terms of sustainable operation, considering the water requirements of large diameter TBM. To manage all the project aspects and improve the TBM performance, a set of laboratory tests has been conducted on the samples taken from the jobsite to determine the best possible solution for the ground conditioning with a minimum amount of water. A tailor-made product has been developed and tested on site to see the in-situ large scale effects of the developed foaming agent. As a result of the good collaboration with the team on the jobsite, after a few hundred meters, record breaking advance rates and average monthly advances have been recorded for the given diameter. In this paper, preliminary laboratory tests, on-site tests, and TBM performance along with the data extracted from the TBM data logger are analysed and presented.

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Mechanized tunnelling: Improving the environmental impact of chemical products without impacting technical performance

Enrico Dal Negro, Enrico Barbero & Alessandro Boscaro
UTT – Underground Technology Team from Mapei Group

ABSTRACT: Several chemical products are necessary during the mechanized tunnelling with TBM-EPB, mainly for three applications: soil conditioning (important for a fast and safe advance of the EPB), backfill grouting of the annular space that is created between the segmental concrete lining and the surrounding soil or rock mass, and tail brushes sealing (to avoid the ingress of material such as water, foam, soil, etc. into the TBM working area).Each one of these chemical products inevitably brings a certain degree of environmental impact, for example against the underground water or the excavated muck which needs to be disposed in a final destination. MAPEI have been working with its R&D laboratories to develop new products and new technologies that are able to reduce this impact, which can be measured in terms of lower eco-toxicity against terrestrial and watery organisms, quicker biodegradability, and lower emission of CO_2 equivalent gases, which are responsible of the global warming (Carbon Footprint). Several examples will be described where technological and environmental innovations in soil conditioning, backfill grout and tail brushes sealing have allowed a more "environmentally friendly" excavation with EPB machines, without impacting the typical technical performances in any way.

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Single and two-component grout as high-performance backfilling materials

A. Di Giulio & M. Di Felice
GEEG startup of Sapienza, University of Rome, Rome, Italy

N. Valiante & G. De Carli
Webuild S.p.A., Milan, Italy

ABSTRACT: Segmental lining is not usually applied in hydraulic pressure tunnels but may become a viable alternative if it can withstand internal pressure variations and it is possible to fill the tunnel annular gap with high-performance backfilling material, as single-component grout or pea gravel. The research here presented is aimed at studying a mix design for the backfill to be used in a pressure tunnel subjected to severe hydraulic conditions, considering both single and two-component grout. The requirements (high strength and stiffness, cyclic load resistance and durability) are quite common when considering a traditional grout but become challenging for a two-component one. The experimentation consisted in a preliminary phase to find mix designs that conjugated pumpability of the fresh mixture and mechanical properties of the hardened grout, followed by a testing phase on the best recipes, under static and cyclic loads. This paper presents a comparison between the two solutions.

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Dispersion of fine-grained soils in slurry shield tunnel excavation

J. Fillibeck, U. Schindler & R. Cudmani
Zentrum Geotechnik, Technical University of Munich, Munich, Germany

ABSTRACT: In tunnel drives with a slurry-supported face, the excavated soil is necessarily subjected to mechanical and hydraulic actions, both in the excavation chamber and during hydraulic conveyance. Slurry shield tunnel excavation in semi-solid to solid clay and claystone environments can lead to the dispersion (slaking) of the soil aggregates. These become detached as gravel to stone size chips, but in extreme cases, they may separate further into fine particle aggregates. This raises the question of how much effort is required to remove the fines from the slurry. Large chips can be relatively easily removed, for example by sieving, but fine aggregates are much more difficult and costly to eliminate, requiring the use of, for instance, filter chamber presses and centrifuges. To date, few studies have focussed on the dispersion potential of fine-grained soils or rocks during slurry shield excavation, despite the economic urgency of this issue. Our experimental study aims to address this topic and fill the gap.

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The central interceptor project: A complex sewage tunnel network in the city of Auckland

G. Giacomin
Tunnel Division Director, Ghella S.p.A., Roma, Italy

M. Maffucci
Tunnel Division Manager, Ghella S.p.A., Rome, Italy

F. Saibene
Area Manager, Ghella Limited NZ, Auckland, New Zealand

S. Vittor
Construction Manager, G-AJV, Auckland, New Zealand

D. Goudelis
Senior Project Engineer, G-AJV, Auckland, New Zealand

ABSTRACT: The paper describes the complex site logistic and the challenging underground operations for the realization of the 14.7 km long tunnel excavated by the EPB TBM and the 4.3 km of micro tunnels executed by two Pipejacking MTBM. The tunnels are only a part of the Central Interceptor of Auckland, an extended infrastructure that will constitute the largest wastewater project in New Zealand, for stormwater and wastewater control, avoiding the 80% wastewater overflowing in any weather condition. The tunnels are being excavated in geological formations constituted by Kaawa Formation, Tauranga, East Coast Bays Formation (ECBF), Parnell Volcaniclastic Con-glomerate (PVC) and Basalt (with a water pressure up to 3.5 bar). A 1.5 km stretch of the TBM Tunnel will be excavated under Manukau Harbour at a depth of 35 m. One bilobular Shaft constructed with diaphragm walls was built for the launching of the TBM. Additional sixteen circular shafts, excavated with various mining methods, will be crossed by TBM and Micro TBM tunnels. The paper will illustrate the site installation for optimising the tunnelling operation, the selection and configuration of the TBMs in compliance with strict technical specifications, new methodologies for the launching of the TBM and supporting the TBM along the tunnel construction. Special consideration has been given to the treatment and reuse of the extracted material, minimising the environmental impact of the project. All the works have to be carried out with consideration for community and stakeholders in the populated area of the city of Auckland.

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Study on the cutter wear based on the cutterhead working status monitoring system in TBM tunneling

Qiuming Gong, Xingfei Xie, Fan Wu & Junhao Liu
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

Hai Xing
Sinohydro Bureau 6 Co., Ltd., Shenyang, China

Hongzhuan Ren
Sinohydro Bureau 1 Co., Ltd., Changchun, China

Hongwei Zhang
PowerChina Railway Construction Investment Group Co., Ltd, Beijing, China

Yuhang Xiao
China Construction Infrastructure CORP., Ltd., Beijing, China

ABSTRACT: TBM cutters are firmly in contact with the face when TBM is tunneling in the hard rock mass, and the cutter wear rate strongly affects TBM tunneling efficiency. However, the traditional manual measurement of the cutter wear has many limitations, such as the high labor intensity and potential measurement errors, while the most critical one is the manual measurement could not monitor the cutter wear in real-time. Consequently, the excessive and abnormal cutter wear cannot be timely found, which may cause some construction accidents. To tackle this problem, a cutterhead working status monitoring system was applied in several tunnel sites to monitor the cutter wear in real-time. Based on the collected data, three different cutter wear indexes were compared, and the most appropriate one was the loss millimeters in cutter radius per excavated rock mass volume, w_v(mm/m^3). The normal cutter wear process curve was analyzed with the cutter tip shape and was divided into three stages, which were the acceleration wear stage, deceleration wear stage, and uniform wear stage, respectively. Finally, a simple equation was set up to predict the cutter wear based on the obtained datasets.

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Overview of soft ground TBM performance

Pål Drevland Jakobsen, Kim Dae Young, Amund Bruland, Olav Roset &
Dirk van Oosterhout
Norwegian Geotechnical Institute (NGI)

ABSTRACT: The Norwegian University of Science of Technology (NTNU) has a long tradition in preparing empirical prediction models for tunnelling and construction work in rock and soil. Hyundai Engineering and Construction has cooperated with NTNU in gathering TBM production data from recent soft ground tunnelling projects. This research paper aims to present how TBM performance is ranging for various TBM diameters, as well as qualitatively describe how various ground conditions influence the tunnelling performance. The data originates from 9 tunnelling projects, with tunnel diameter from approximately 2 m to more than 12 m. The soil conditions within the collected data range are varying from cohesive soils (clay and silt), to frictions soils mainly consisting of sand and gravel.

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Record-setting large diameter mixed ground tunneling in Turkey: The Eşme-Salihli Railway Tunnel

D. Jordan
Robbins Europe GmbH, Germany

Y. Alpagut
ATES Engineering Construction Ltd., Turkey

Ş. Kiliç
Kolin Construction, Turkey

ABSTRACT: Large diameter tunneling has historically been seen as a challenge. Add into the equation mixed ground conditions, and it becomes a task that may seem insurmountable. However, a recently completed tunnel in Turkey is a flagbearer for changing the mindset towards these challenging tunneling scenarios that are becoming more frequent. A - 13.77 m diameter mixed ground Rock/EPB TBM bored the Eşme-Salihli Railway Tunnel at rates of up to 721.8 m in one month, making it the fastest TBM ever recorded over 13 m in diameter. The machine began its bore in altered gneiss, then passed through mélange consisting of gneiss, sandstone, claystone, mudstone, quartz, and silt. By the end of the bore the machine was excavating in mainly mudstone. Core drillings were taken every 200 m prior to boring.

In this paper, we detail the project as well as analyze factors contributing to the fast advance rates. The factors include TBM choice and system design, ground conditions, TBM utilization rates and downtimes, as well as maintenance practices, crew expertise and technical support, all of which have a part to play in the overall advance rates and successful outcome. Recommendations are made as to best practices in order to achieve good advance rates on similar large diameter, mixed ground tunnels.

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TBM hard rock tunnels projects: Cutter disc wear comparison between estimations and real performance

F. Juárez
Mott MacDonald, Madrid, Spain

L.M. Pinillos
Mott MacDonald, Croydon, UK

J.R. Barajas
Acciona Engineering, Madrid, Spain

ABSTRACT: One of the biggest technical challenges when considering long hard rock tunnels is the estimation of the cutter tools wear, which affects the advance rates, utilization of TBMs and therefore, the overall cost. This challenge also requires a careful TBM design, adapted to the ground conditions, which has an important influence in the cutter tools consumption and TBM maintenance. An accurate estimation is a key element for rock tunnelling analysis and has a relevant impact in the risk evaluation. Those estimations are required to be as close as possible to the actual performance, mostly relevant in long tunnels, at early project stages, when data is scarce. This paper shows estimations undertaken by means of the most widely used predictive methodologies. The article evaluates the main factors affecting the wearing process and presents a comparison analysis of forecasting models versus the actual data in some recent long tunnel projects in hard rocks.

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Shield TBM rock tunnelling: Operational and technical problems due to face instability

G. Kalamaras
AK Ingegneria Geotecnica Srl, Turin, Italy

M. Ortu
GHELLA SpA, Rome, Italy

S. Pelizza
Emeritus Professor Politecnico di Torino, Past President of the ITA, Italy

ABSTRACT: Shield TBM excavation in rock masses prone to face instability results in low advance rates, difficult driving, frequent stops due to high torque demands, overloading of the conveyor system, uneven configuration of the tunnel face similar to mixed-face conditions, excessive cutter wear and damage. Face instability can be discontinuity-related or strength-stress-related including spalling and rock bursting. Frequent variation of face stability conditions and its effect on the machine-geology interface, and thus the TBM performance, generally cannot be defined beforehand. The TBM contractor can do little when dealing with such conditions as systematic face reinforcement is not applicable on TBMs and therefore not a feasible measure for enhancing TBM performance; reducing TBM advance speed, cutter head rotation and the size of cutter head openings are amongst the few driving correction tools that the TBM operator can activate while boring through unstable face conditions.

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Penetration behaviour of slurry in saturated soil – analysis of particle deposition on the basis electrical resistance

S. Kube, B. Schoesser & M. Thewes
Institute for Tunnelling and Construction Management, Ruhr University Bochum, Bochum, Germany

ABSTRACT: In slurry shield tunnelling, detailed understanding of the support mechanism of the slurry interacting with the soil at the tunnel face is of great importance. So far, no precise statements can be made about the depositing of bentonite particles in the process of slurry penetration into the soil structure. In order to investigate the phenomena that occur during face support, an experimental set-up based on electrical resistance measurements was developed to study the penetration of slurry into saturated soil. Various tests showed that particle deposition in the grain structure occurred with almost every combination of soil and slurry. The analysis of the electrical resistance over the penetration depth of the slurry clearly showed this by the dependence of the electrical resistance of the soil-slurry mixture. When considering the penetration depth, it becomes apparent that the properties of the fluid that has penetrated the pores of the soil differs substantially from to the initial slurry due to a decreasing particle content of the slurry with increasing penetration distance.

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Simulation of EPB tunneling using discrete event model: Case study of various grounds in Korea

J.W. Lee, H.B. Kang, Y.J. Shin & J.H. Jung
Hyundai Engineering and Construction, Seoul, South Korea

ABSTRACT: A Tunnel Boring Machine (TBM) tunneling is one of the most recognized methods used for underground construction in urban area as it has many advantages of safety, high speed, high quality, and is environmentally friendly. Thus an accurate estimation of its performance is necessary for the justification and successful use of TBM on any tunneling project. Normally the evaluation of TBM performance uses the rate of penetration and utilization, which are highly affected by geological condition, machine and operation including site setting, various logistics and their interdependencies. Uncertain downtime and the combination of each factors should also be accounts. Some of above factors are hard to quantify and uncertain, making the evaluation inaccurate. To overcome the difficulty, a tunnel simulation technique was introduced. In this study, modelling tunneling activities and downtimes using discrete event simulation approach is applied to predict TBM performance. A railway tunnel project using EPB passing through mixed ground, hard rock and soft soil sections is considered for the development and verification of the model. Probabilistic input parameters are employed to take into unknowns occurred on site such as uncertain downtime and coupling factors. The results show possibility of predicting TBM performance based on good quality of input parameters of tunneling activities.

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Analysis of the disc cutters spacing in the face area of a small diameter TBM

S.Y. Lee & K.I. Song
Inha University, Incheon, The Republic of Korea

H.W. Ryu
Korea Electric Power Research Institute (KEPRI), Daejeon, The Republic of Korea

K.N. Kang & D.G. Lee
Inha University, Incheon, The Republic of Korea

ABSTRACT: When designing a TBM cutter head, Disc cutters spacing is an important design variable because it greatly affects the excavation efficiency of TBM. The excavation efficiency by the disc cutter can be confirmed through the specific energy, and the specific energy can be calculated by dividing the cutting energy by the excavated volume. The specific energy varies according to the disc cutter spacing and the penetration depth. As the spacing between the disc cutters increases, the specific energy decreases and then increases again after a certain value. In this case, the disc cutter spacing in the section showing the minimum specific energy is called the optimal cutter spacing. As a result of investigating the 14-inch disk cutter spacing of the small shield TBM used in Korea, the disk cutter spacing was found between 80 mm and 100 mm. However, the clear basis for this cutter spacing is not known. Therefore, in this study, we investigated the disc cutter spacing of TBM used in Korea and study to verify it through numerical analysis of the discrete element method. As a result of performing the numerical analysis of the discrete element method, it was confirmed that the optimum specific energy was shown between 70 mm and 100 mm the disc cutter spacing. These results show that the cutter spacing of the currently used TBM is reasonable.

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On the way to a better performance prediction for small-diameter hard rock TBMs

G. Lehmann
Technical University of Munich, Munich, Germany
Herrenknecht AG, Schwanau-Allmansweier, Germany

H. Käsling & K. Thuro
Technical University of Munich, Munich, Germany

ABSTRACT: Small diameter tunneling in hard rock gets increasingly widespread due to the surge of renewables energies and the need for new and longer utility tunnels. The large variety in this small diameter range in hard rock includes different TBM types, cutterhead designs, cutter types and most notably geotechnical conditions. Predicting the advance rate for such project conditions in hard rock is an important factor in tunnel project planning and execution. Data from more than 35 small diameter hard rock tunneling pipe jacking and segment lining projects has been compiled and analyzed. Our analysis showed that the achieved performance for such projects varies considerably from the prediction with industry-standard penetration models. This paper will give an insight into the wide variability of small diameter hard rock tunneling and the associated challenges in performance prediction.

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Design of Orange Line project in Austin, Texas

T. Malouf, A. Bhargava & V. Nasri
AECOM, New York, USA

ABSTRACT: The proposed Orange Line project is a 32.2 km light rail transit corridor that will serve downtown Austin in Texas, USA. The project includes 5.2 km of 10.4 m excavation diameter single bore double track TBM tunnel. A hybrid TBM will be used to bore through the limestone and shale rock and alluvium soil of downtown Austin crossing under the Colorado River. Orange Line has four underground stations in downtown Austin. The project also includes two emergency egress buildings, one storage track facility, and the two approach structures. Precast tunnel segments are to be made of fiber-reinforced concrete (FRC). FRC segments are superior for crack control and more cost effective overall and are therefore the preferred solution for this project. This paper presents the details of the design of tunnel, stations, and other underground structures of this major project.

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Tunnel linings made of precast concrete segmental rings - from design choice to installation and performance

D. Marini & G. Venditti
BBT SE, Bolzano, Italy

ABSTRACT: The life cycle of a precast concrete segmental ‘ring’ must be based on a series of considerations: first of all, the logistics involved in moving the segments to the final installation point while complying with safety requirements relevant to all steps of the lining process. Once installed and during operations, regular maintenance should be carried out with the aim of guaranteeing ring performance over the entire life of the infrastructure. The mechanized excavation of more than 45 km of the Brenner Base Tunnel, with overburdens up to 1,700 m, has provided significant experience of the particular characteristics of employing segmental ring linings.

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TBM excavation underneath a road viaduct and railway lines for Warsaw M2 metro line: 3D modelling and monitoring results

M. Minno, L. Ciocchetti, F. Capata & V. Capata
SGS - Studio Geotecnico Strutturale

ABSTRACT: The 2nd stage of West extension works for M2 metro line in Warsaw included the TBM excavation underneath an existing road viaduct which overpassed an operating railway line. Specific modelling works were carried out at executive design stage to verify the ground movements produced by the TBM excavation and hence the impact on such assets. Empirical methods and 2D PLAXIS and 3D MIDAS GTS NX numerical analyses were executed and the acceptable results justified the removal of the soil improvements initially foreseen at feasibility stage. Particular effort was given to correctly model the TBM excavation sequence in order to achieve the target volume loss and 3D modelling allowed to capture viaduct differential movements in longitudinal and transverse direction during tunnelling.

A set of monitoring instrumentation was installed on site including ground pins and levelling pins for manual measurements and mini-prisms and tilt-meters for automatic readings. TBM excavation was completed by November 2020, no damage was induced and monitoring results showed a very good agreement with predicted results. The study of such case history provides a good insight into 2D and 3D modelling of TBM works with particular reference to ground movement and damage assessment.

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From calamity to full compliance – The Rijnlandroute bored tunnel project

H. Mortier
DEME Infra/Comol5, Zwijndrecht, Belgium

M. Brugman, Y. Liem, B. van de Water & J. Vervoort
Arthe C&S, Utrecht, The Netherlands

O. Gastebled & S. Giuliani
Vinci Construction Grand Projets, Rueil-Malmaison, France

ABSTRACT: In the Rijnlandroute twin bored tunnel project, the break-out procedure was based on an arrival into an inundated shaft. Although an identical procedure was adopted for both tunnel drives, at the second drive the temporary watertight seal failed shortly after dewatering the shaft. The leakage generated soil transport from around the tunnel lining into the shaft, and by this a significant disturbance of the soil support finally leading to huge deformations and structural damage of the tunnel rings close to the arrival shaft. An exhaustive investigation campaign was implemented to define the residual support stiffness of the disturbed soil. Subsequently, a soil improvement was executed whereby the efficiency was checked by using the Multichannel Analysis of Surface Waves (MASW) technique in combination with common cone penetration tests. After checking the available space and the required clearance profile, the most appropriate secondary lining was developed in order to make this part of the tunnel fully compliant again. This meant that all criteria regarding structural strength, water tightness, fire resistance and durability needed to be met. The article will describe the investigations made, the design options considered, and the execution process implemented.

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Fundamental TBM selection criteria in urban environment based on engineering geological and geotechnical conditions

D. Papouli
MSc Geologist, Thessaloniki, Greece

V. Marinos
School of Civil Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT: This paper presents an adopted methodology for Tunnel Boring Machine (TBM) selection, based on the results of engineering geological - geotechnical feasibility assessment of tunnels. The selection of the appropriate TBM is analysed and presented step by step, addressing all issues that cover most engineering geological and geotechnical critical aspects of the selection process. The applicability of each type of TBM is discussed using a significant number of sampling boreholes and in situ - laboratory testing, obtained from an extensive ground investigation campaign, in urban environment. This information was elaborated in order to obtain a better engineering geological understanding and ground zonation with respect to mechanised tunnelling. Besides the expected geomaterial behaviour, the TBM selection is also based on the percentage of fines at the tunnel profile, the permeability and hydraulic head, while abrasiveness, sticky behaviour, clogging risk and mixed ground conditions are also taken into account. Finally, an example of the application of TBM type selection methodology in urban tunnel is given.

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Development of waterjet drilling system with dual nozzles for granite

Jun-Sik Park & Hyun-Jong Cha
Pusan National University, Republic of Korea

Eun-Soo Hong
HBC INC, Republic of Korea

Tae-Min Oh*
Pusan National University, Republic of Korea

ABSTRACT: Rock excavation is essential for the development of underground space. In general, rock excavation is performed by a mechanical method such as a jumbo drill or blasting using explosives. These conventional methods cause various complaints owing to factors such as dust, noise, vibration when excavating hard rocks such as granite. These complaints cause significant economic loss during the construction process. Waterjet drilling is a method for excavating rocks using only water and abrasives. Waterjets for drilling rocks can overcome problems associated with conventional rock excavation methods. The waterjet rock drilling system minimizes dust and vibration generated during the hard rock drilling process. In this study, a waterjet drilling system equipped with a double nozzle was developed. In addition, granite drilling performance was analyzed using the developed waterjet drilling system. This new drilling method reduces the construction time and cost by resolving complaints.

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Numerical investigation of segmental lining with compressible layers in deep soft rock

J. Park, J.B. An, J. Kim & G.C. Cho
Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Republic of Korea

ABSTRACT: With tunnel boring machine (TBM) technology development, tunnels are being constructed even in challenging environments. Nevertheless, there is still a problem in that excessive stress is induced in the segmental lining during shield TBM tunnelling in overstressed rock. Structural solution based on the resistance principle causes overdesign of segmental lining and increases direct construction cost. Therefore, studies on various deformable supports that allow some tunnel wall displacement after excavation to reduce the support pressure have been conducted based on the yielding principle. In TBM tunnelling, the prefabricated composite segments with a compressible layer combined at their extrados can be considered, but this design is not well established. In this study, a numerical analysis based on the finite element method was performed to investigate the effect of the compressible layer on the segmental lining and the surrounding ground in the deep soft rock.

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A study on the wear and replacement characteristics of the large diameter EPB Shield TBM disc cutter through field data analysis

J.S. Park
Hoban E&C., Seoul, The Republic of Korea

K.I. Song
Inha University, Incheon, The Republic of Korea

T.Y. Ko
Kangwon national University, Kangwon, The Republic of Korea

ABSTRACT: The disc cutter and cutter bit, which are the most important factors to increase the excavation efficiency of a TBM, are key factors in the design and construction of the cutter head. The suitability of arrangement, spacing, number, size and material of disc cutters for given ground conditions determine the success or failure of TBM construction. The disc cutter, which is a representative consumable part in TBM construction, can cause enormous disruption to the construction cost as well as the construction cost, unless accurate prediction of wear and replacement cycle is accompanied. In this study, based on the field disc cutter replacement data of the earth pressure type shield TBM (EPB Shield TBM), which is a type of shield TBM that is typically applied in Korea, the ground conditions, field conditions, and excavation data with the wear prediction model various correlations were analyzed through comparison.

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Estimation of face pressure based on empirical and numerical methods in mechanized tunnelling

A.S. Peker & B. Zengin
TEKFEN Engineering, Istanbul, Turkey

ABSTRACT: The most important issue to be considered during the tunnel construction is to be ensure the excavation stability. In EPB TBM method, the face support pressure is one of the effective way to provide excavation stability. The aim of this study is to calculate the face support pressure of TBM excavation carried out in soft ground conditions as part of a metro line passing through an urban area in Istanbul, Turkey, by using different empirical and numerical methods. The results obtained from these different approaches were compared and discussed. Results show that empirical methods may give different values based on the assumptions made. However, almost all empirical approaches are in good agreement with the numerical method. Moreover, it has been shown that when the face support pressure, whose purpose is to reduce the deformations caused by excavation, is applied less or excessively as a result of calculation error, it causes the deformations to increase.

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Successful usage of steel fibres in the Parisian metro network expansion

B. Rossi & P. Decobecq
ArcelorMittal Fibres, Bissen, Luxembourg

A. Cornille
GIE Alliance, France

F. Delort & A. Bertrand
Stradal, a CRH Company, France

ABSTRACT: In this article we will develop and detail all the technical challenges that have been taken up on this major project and the technical solutions that have been engineered for the use of ultra-high strength steel fibres in these tunnel lining segments. The Grand Paris Express is made of four new subway lines in Paris, numbered 15, 16, 17, 18, connected with the existing network, extending the lines 11 and 14, totaling of 200 km, 90% of which are underground. Sixty-eight new stations are built to accommodate more than two million passengers per day. The whole project will cost around 36 billion euros and will be completed in 2030. At the highest activity level, twenty TBMs will contemporarily dig the Parisian underground. With the aim to highlight new technologies and seeking sources of embedded carbon reduction and an increase in durability, the Société du Grand Paris has adopted the usage of the Steel Fibre-Reinforced Concrete for the Tunnel Lining Segments. After many investigations and tests, to date, four lots of these extensions have allowed for the usage of steel fibres, combining a total length of tracks around 48 km. This proves that this technology, which has been used for a long time in many countries, is now also validated in France. To achieve the specified mechanical requirements of the lines 16-2, 16-3 and 18-1, the precast concrete segments are exclusively reinforced with the ultra-high tensile strength ArcelorMittal Fibre Type: HE++ 90/60. ArcelorMittal, which has been manufacturing and producing steel wire fibers for more than 30 years, has supported the customers with its experience and know-how already acquired on other major projects abroad like: Doha Metro in Qatar, CrossRail, Thames Tideway Tunnel and Long Itchington Wood HS2 in UK, Ejpovice Railway tunnel in Czech Republic, Świnoujście Road Tunnel in Poland.

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Increasing safety in small-diameter tunnelling: The role of automation and microtunnelling

P. Schmäh, M. Lübbers & F. Seng
Herrenknecht AG, Schwanau-Allmannsweier, Germany

ABSTRACT: Safety is a major concern of clients and contractors in the tunnelling industry, especially in small-diameter tunnelling for water and sewage, cable ducts or pipelines. Tightened safety regulations in terms of accessibility and escape routes increasingly limit the options in the planning and construction of small segment lining tunnels in the diameter range below ID 4000 mm. Technological solutions are being developed in order to increase the degree of automation in segment lining, and to expand the application range of microtunnelling to even longer and larger drives. The aim is to provide the tunnel construction industry with safe and efficient technologies and with highest flexibility for successful implementation of demanding projects. Even combined concepts of lining methods and/or machine types can be considered for specific project conditions. This paper will discuss the latest developments in automation, related opportunities and limitations, and future trends in microtunnelling.

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Determination of the flow behaviour of excavated soils – Correlation between consistency and the penetration resistance

M. Schröer & M. Thewes
Ruhr University Bochum – Institute for Tunnelling and Construction Management, Bochum, Germany

ABSTRACT: The consistency of a cohesive soil is an important parameter when driving with Earth Pressure Balance shields (EPB shields). It determines the flow behaviour of the excavated material or the support medium in the excavation chamber and the screw conveyor. Furthermore, depending on the consistency and other parameters of cohesive soils, e.g. the plasticity index, clogging can occur in front of the cutting wheel, which can cause high impacts on productivity and costs due to reduced excavation speed and downtime due to cleaning measures. A quick experimental identification of the consistency of the excavated material during the excavation process and an appropriately adjusted conditioning of the soil can help to make EPB excavations safer, more cost-efficient and easier to plan in the future. For this purpose, a new displacement-controlled penetration test for measuring the flow behaviour was developed for both cohesionless and cohesive soils. Initial test series show that there is a clear correlation between consistency and the corresponding penetration resistance of the new penetration test. Further, the penetration resistance also depends on the plasticity index of the soil. Numerous test series with the new penetration test show a high rate of reproducibility of 95 %. Thus, a quick determination of the consistency of the excavated muck will be possible in the future. The consistency can be checked and, if necessary, conditioning measures can be adapted. The risk of adhesion and clogging can thus be reduced and the support pressure transmission improved. Furthermore, tests with foam-conditioned cohesionless sands have shown that the resolution of the relevant measuring range is sufficiently large to quantitatively differentiate the foam injection rate (FIR). The developed test device is therefore a precise and more versatile alternative to the frequently used slump test, which is not suitable for cohesive muck.

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Expanding the application range of EPB shields using SolidFoam

Marius Schröe, Nils Gramlich & Markus Thewes
Ruhr University Bochum – Institute for Tunnelling and Construction Management, Bochum, Germany

Lars Langmaack
MC-Bauchemie Müller GmbH & Company KG, Bottrop, Germany

ABSTRACT: When driving EPB shields, cohesive clayey and silty soils are suited best to support the tunnel face, provided having a sufficiently deformable consistency. In contrast, cohesionless, coarse-grained or very permeable soils without additional, often complex and expensive conditioning measures cannot be used as support medium. In highly permeable soils with ground water pressure, EPB shields may even reach their limit of applicability.

MC-Bauchemie in cooperation with Ruhr University Bochum have newly developed a highly flexible and cost-efficient system for conditioning very coarse ground. This new conditioning solution combines two existing approaches, 1) conditioning with foam and 2) addition of a High-Density Slurry containing a large amount of fines. This results in a new and flexible method, where a foam is produced from a High-Density Slurry. This High-Density Foam (SolidFoam™) could temporarily be used during the operation of an EPB-TBM, when driving through highly permeable soils or transition zones.

To introduce this new method of conditioning into tunneling practice, a series of laboratory tests regarding the reliable and practical production of SolidFoam™ were performed. The results include conditioning tests with coarse soil and SolidFoam™ to study the effects on the workability of the conditioned muck and on the reduction of its permeability to prevent undesired ground water penetration into the excavation chamber.

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Correlation study between indentation indices and physical-mechanical properties of rocks

A. Shaterpour-Mamaghani, H. Copur, C. Balci & D. Tumac
Department of Mining Engineering, Istanbul Technical University, Istanbul, Turkey

T. Erdogan
Sargin Construction and Machinery Industry Trade Incorporated, Ankara, Turkey

E. Dogan
Senior Mining Engineering, Istanbul, Turkey

O. Sirin
Eti Bakir A.S., Kastamonu, Turkey

ABSTRACT: Indentation test is one of the laboratory approaches that is used to predict the performance of Raise Boring Machines (RBMs) and Tunnel Boring Machines (TBMs). This test is a nonstandard laboratory experiment that was originally developed to provide a method to predict the normal force acting on the cutters used on mechanical miners. However, in some cases due to difficulties in obtaining rock samples as well as insufficient laboratory equipment it is not possible to perform indentation test. In this study, based on the indentation tests on different rock samples obtained from raise-boring projects in Turkey, three indentation indices (brittleness indices and force index) are obtained; then, the multi-variable correlations between these indices and physical-mechanical properties of rocks are investigated. The study indicates that all three indentation indices can be estimated by using the velocity of P-wave, static elasticity modulus, Cerchar abrasivity index, and Schmidt hammer hardness of rocks.

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Validity of stickiness and consistency index in assessment of cutterhead clogging potential of cohesive soils

R. Shetty, A. Eisenman, S. Lopez & M.A. Mooney
Colorado School of Mines, Golden, USA

ABSTRACT: Cohesive soils are reported to have the highest cutterhead clogging potential in the consistency index (I_c) range of 0.50–0.75. The stickiness index (λ) determined from laboratory mixing tests on a soil sample has been used as an indicator of clogging potential. However, the values of λ that define the range of a clogging potential category are yet to be validated using the data from mixing tests conducted on a wide variety of soil types from different projects whose cutterhead clogging behavior is documented. In the present study, mixing tests were performed on six different clayey soils covering the I_c range between 0 to 1 to study the influence of soil type and specimen volume on the variation of λ with I_c. From the test results, it is observed that magnitude of λ_{max} (maximum stickiness index) varies for different soil types, whereas the critical I_c corresponding to λ_{max} (I_{ccl}) falls within a unique range (0.8–1.0) for all the soil types tested. The results from mixing tests conducted in the study are compared with the data from the literature that corroborated with the findings of the present study. The dependency of λ_{max} on soil type suggests that the clogging potential criterion solely based on λ value may not provide a complete picture of soil's clogging potential. A two-fold criteria in which soil in its critical I_c range is tested for λ, and the clogging potential is then determined by comparing the laboratory λ with the values of λ obtained from tests on in-situ soils whose clogging potential behavior is known, provides a promising approach to determine soil's clogging potential from laboratory tests.

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New technology of readily biodegradable soil conditioning foaming agents

Mike A. Sposetti
Global Technical Manager TBM, Underground Construction, Master Builders Solution, UAE

ABSTRACT: Time today represents a new factor that must be taken in consideration when conditioning the soil during TBM mining. The longer the foam remains stable, the higher the quality of soil conditioning, the less the consumption. A new technology of readily biodegradable foaming agents represents a new way to manage the rheology of soil, ensure safety and proper extraction; these new foaming agents boast a more durable surface tension on the bubbles that ensures longer stability over time. In this way, not only the foam shall work longer but overall consumption shall be reduced when compared to conventional foams. Indeed, it is now possible to work with higher FER and lower FIR without reducing the quality of the foam and, at the same time, increase its stability over time. With this new technology, the TBM excavation cycle is optimized, contributing to the overall schedule to complete a tunnel.

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The washing-out resistance of the two-component grout: A laboratory test campaign

C. Todaro, A. Carigi, D. Martinelli & D. Peila
Politecnico di Torino

ABSTRACT: The two-component grout is the backfilling technology more frequently used in tunnelling construction where shielded machines are adopted. Despite its intensive use, different aspects of the technology have not been deepened sufficiently, particularly concerning the role of the two-component grout in the waterproofing of the tunnel. In fact, despite in scientific literature the engagement of the two-component grout in the protection of assembled linings against the water inflows is often mentioned, no proofs of this ability are available. Furthermore, in case of presence of water, the freshly injected two-component grout may be washed out reducing its thickness and, consequently, its waterproofing capacity but also this aspect have never been investigated. In this work, the impact of water on the fresh two-component grout is studied in laboratory by using an innovative apparatus, expressly designed and realised for the purpose. A test procedure is introduced and preliminary obtained outcomes highlight the aptitude of the grout to exhibit the washing-out resistance.

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Development of a tension-resistant single pass segmental lining in high pressure tunnels. The experience of Snowy 2.0 (Australia)

N. Valiante & H. Elgarhi
Webuild S.p.A., Design Services, Rozzano (MI), Italy

F. Lazzarin
Future Generation JV, Sydney New South Wales, Australia

R. Crapp & R. Stucchi
Lombardi SA, Giubiasco Ticino, Switzerland

ABSTRACT: Snowy 2.0 is a 2000 MW pumped hydro-electric expansion of the existing Snowy Scheme in Australia. A special part of the project is the Inclined Pressure Tunnel (IPS), with an internal diameter of about 10 m, which will experience extraordinary hydraulic conditions, where internal pressure variations reach up to 70±25 bars during transients. The lining solution, currently under study, is a single pass segmental lining where special steel couplers, named as FACS (Force-Activated Coupling System), are placed in the longitudinal joints between the segments to provide tensile resistance. The innovative joint connection comprises pin-socket steel couplers with cup springs that deforms during assembly of tunnel segments, providing hence pre-compression of the joints. The connections create a continuous heterogeneous ring, reducing the risk of joint misalignment and dislocation and preventing joint openings during operation. This paper provides an overview of the solution FACS, discussing design aspects and construction and testing of prototypes.

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Refurbishment of a 15,2 M TBM (S19 Rzeszów Południe – Babica project) 17 years after its first use (M-30 Madrid project)

F. Vara
Global BD Director Tunnels & Railways, ACCIONA Construction, Spain

M. Calero
Self-Performance Office Tunnel Manager, ACCIONA Construction, Spain

ABSTRACT: Refurbishment of TBMs is an activity that has become a more common task in the last years due to various factor: improvement of cost and schedule in the overall procurement and manufacturing process, alignment with the Sustainability Development Goals (SDG), and reduction of CO2 emissions, etc. In addition, it is a fact that a refurbished TBM is normally performing better than a brand new one, as a refurbished one has not only been tested before but improved for the new performance. ACCIONA executed the M30 project (Madrid, SPAIN) with a 15,2 m OD EPB TBM that was the biggest of the world at the time (2005). After finishing the project, the TBM was dismantled and has been maintained during years in a yard in Villarubia de Santiago (Spain). In 2020 ACCIONA got awarded the project S19 Rzeszów Południe – Babica, where the TBM proposed was the same as the used in the M30 project in Madrid. The paper will describe how ACCIONA´s Self Performance Office (SPO) office has refurbished the TBM, updating all the main components and adapting the TBM to the new challenging project requirements (pressures up to 6.5 bars), describing the complex operations of cleaning, rebuilding and adapting the new and more modern components to the previous TBM, including the precast factory molds.

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The assessment of intact rock strength for penetration

H. Wannenmacher
RWTH Aachen, Germany
Implenia Austria GmbH., Salzburg, Austria

P. Hamdi & F. Amann
RWTH Aachen, Germany

T. Marcher & T. Frühwirt
Technical University of Graz

ABSTRACT: The term "rock mass" involves a complex interplay of two components: the intact rock and spatially distributed rock joints of various orientations and persistence. Besides the degree of rock mass fracturing, the intact uniaxial compressive strength (UCSi) is a crucial parameter for estimating feasible penetration rates for tunnel boring machines (TBMs). Therefore, typical penetration and excavation rate prediction models rely significantly on properly quantifying the (UCSi). However, the failure process of rock specimens subjected to uniaxial compression can be complex due to internal flaws or heterogeneities on the microscopic scale (i.e., not visible before testing by the naked eye), causing premature failure before reaching the true intact rock strength. Internal flaws can substantially contribute to the fracture initiation and propagation processes of the rock, and their impact on strength must be considered when defining intact rock strength properties for penetration prediction. Improper quantification (e.g. an underestimation due to flaws or insufficient specimen preparation) can substantially impact the predicted versus the achieved penetration rates, with a significant impact on cost and time. This paper proposes an engineering approach including a rigorous filtering process of laboratory results obtained according to international standards and regulations. The method allows for a comprehensible determination of the unconfined compressive strength (UCS) for penetration prediction.

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Semi-analytical approach to estimate slurry penetration in highly permeable soils

A. Wiendl*, J. Fillibeck & R. Cudmani
Zentrum Geotechnik, Chair of Soil Mechanics and Foundation Engineering, Rock Mechanics and Tunneling, Technical University of Munich, Germany

ABSTRACT: Bentonite slurries are commonly used for tunnel face stabilization during slurry shield tunneling. In highly permeable soils uncontrolled slurry flow into the adjacent soil can cause loss of support and ultimately lead to a collapse of the tunnel face. In this contribution, innovative slurry flow tests were carried out to investigate slurry penetration in coarse soils, considering the influence of the slurry, the soil and the applied fluid pressure. Experimentally, a clear correlation between the slurry penetration, fluid pressure, rheological properties of the slurry and permeability of the soil was observed. Based on the 1D-Navier-Stokes equation, a semi-analytical model to estimate the slurry penetration in coarse soil as a function of the characteristic shear resistance of the slurry determined with a rheometer, the soil permeability and the fluid pressure was derived. The experimental results indicate that using appropriate bentonite-filler mixtures slurry shields become feasible, even in very highly permeable soils.

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Computational modelling of artificial ground freezing in mechanized tunnelling

R.J. Williams, M.A. Alsahly & G. Meschke
Institute for Structural Mechanics, Ruhr University Bochum, Germany

ABSTRACT: An advanced processes-oriented computational model for mechanized tunnelling has been extended to consider ground improvement by employing artificial ground freezing during the tunnel construction and excavation process. A numerical study is presented, in which the numerical simulation of the tunnel drive through a frozen ground is performed. The model considers the thermo-hydro-mechanical behaviour of the frozen ground and is capable of simulating tunnel advancement with mutual interactions between all relevant components, In this paper, the influence of the heat source induced by the TBM on the frozen ground during tunnel construction and the TBM advancement process is investigated numerically.

Keywords: mechanized tunnelling, artificial ground freezing, finite element method

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Development of environment-friendly tail grease for shield tunnelling method

Kenji Yamashita & Masataka Hayashi
Obayashi Corporation General Manager-in-Charge

Kenta Matsubara
Obayashi Corporation General Manager

Soichiro Arai
Obayashi Corporation Manager-in-Charge

Takashi Arai
ENEOS Corporation Expert Grease R&D Group Lubricants R&D Department Lubricants Company

Kazuyuki Takakuwa
ENEOS Corporation Grease R&D Group Lubricants R&D Department Lubricants Company

ABSTRACT: The shield tunnelling is a tunnel construction method that can prevent the generation of noise and dust on the ground surface, and it has been often used in areas where reduction of impact on the surrounding environment is particularly required. To further reduce the environmental burden of the shield tunnelling method, an environment-friendly tail grease namely "SEALNOC BD" was developed by replacing the conventional material of tail grease used for a water tightness mechanism of a Tunnel Boring Machine (TBM) with a biodegradable and low-toxic material. Through the performance test and the application to actual construction works of this developed product, it was confirmed that the basic performance was equivalent to or more than the conventional product. Furthermore, this product has acquired the first "Eco Mark" certification as a tail grease, under the only Type I environmental label in Japan in accordance with the ISO 14024.

Keywords: Shield tunnelling, Tail grease, Biodegradation, Environmental burden reduction

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Finite element analysis of surface settlement above TBM tunnels for Jakarta MRT project

N. Yingyongrattanakul & S. Nagano
Oriental Consultants Global Co., Ltd., Tokyo, Japan

W. Maulina
PT MRT Jakarta, Jakarta, Indonesia

T. Boonyatee
Chulalongkorn University, Bangkok, Thailand

ABSTRACT: To estimate the ground settlement caused by TBM excavations for the Jakarta MRT Phase 2A, three sections of 2D-FE analyses were carried out. The estimated maximum ground settlements for the ground loss ratio of 1.0% are between 16.58 – 20.31 mm. The estimated settlements and maximum differential settlements of the nearby heritage buildings, located 5.8 – 8.6 m from the TBM alignment, are in the ranges of 9.23 – 12.15 mm and 1/1197 – 1/835, respectively. The impacts to heritage buildings shall be reduced by carefully designing TBMs and controlling the TBM's face and tail void pressures, e.g. by causing the ground loss ratio less than 1.0%. It can be concluded that the building settlements will be less than the allowable values when the ground loss ratio is not greater than 0.75%.

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Innovation and application of triple-mode shield machine/TBM

C.P. Zhong
Guangzhou Metro Group Co., Ltd., Guangzhou Guangdong, China

W.B. Zhu
Chinese Society for Rock Mechanics & Engineering, Beijing, China

ABSTRACT: This paper reviews the background of the invention of the triple-mode shield machine/TBM, defines and classifies the triple-mode shield machine/TBM, explains the working principle of the triple-mode shield machine/TBM, and clarified the applicable geology formation and environment of the triple-mode shield machine/TBM. The application achievement of the triple-mode shield machine/TBM is summarized, and the improvement measures are proposed. It has an important reference for the construction of tunnel boring machine under similar strata and environmental conditions.

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Monastiraki Station main tunnel temporary lining design, using microtunnels

E. Zygouri & D. Bairaktaris
D. Bairaktaris and Associates Structural Design Office Ltd, Athens, Greece

ABSTRACT: Monastiraki Station is a complex Athens Metro Station, at the historical centre of Athens, near the Acropolis ancient monument. At this point there is a cross section of two different metro lines, the oldest one line 1 that exists since 1895 and the new line 3. The new tunnel line 3 passes below the oldest one and there is no connection between two tunnel lines. The connection between two lines is implemented trough an intermediate building that lies near the main station structure. The station includes a main tunnel wherethe temporary structure was constructed under an umbrella of microtunnels because of difficult construction conditions and weak soil. The need to use microtunnels came from the very soft surrounding rockmass causing large surface settlements, about 90mm, during the excavation of the cross- over access tunnel of the station. Purpose of the design was the surface settlements reduction and the safety of temporary supporting lining, in the Main Tunnel underground excavation construction stages. The most important scope of the design, was to restrict surface settlements, at the very densely populated area of Monastiraki. For the design of the tunnel temporary lining with microtunnels, a 2-D finite element model is used, containing the cross section of the temporary lining and the surrounding soil up to the ground surface. A non-linear elastoplastic analysis is applied by the introduction of a Mohr – Coulomb failure criterion for the soil plane Finite elements. The whole application was successful and the limiting of settlements, under serviceability conditions, was achieved. During the construction, the provisions of the study were verified to a very large extent, with a deviation that does not exceed 5%.

Conventional tunnelling, drill-and-blast applications

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Investigation of microfine cement both rheological properties and permeation in soils

K. Boschi
DICA, Politecnico di Milano, Milan, Italy
DISAT, Bicocca University, Milan, Italy

R.P. Castellanza
DISAT, Bicocca University, Milan, Italy

C.G. di Prisco
DICA, Politecnico di Milano, Milan, Italy

D. Grassi
Master Builders Solutions, Treviso, Italy
DISAT, Bicocca University, Milan, Italy

ABSTRACT: Permeation grouting, i.e. injections at low pressure, of microfine cements is frequently adopted in tunnelling and underground structures to either increase the mechanical properties or reduce the hydraulic conductivity of soils. From an applicative point of view, the time dependent permeation process, crucial to assess the spatial contour of the final content of the injected microfine cement, is highly affected not only by operational parameters, geometry of injection sources and particulate phase nature of the grout under exam, but also by its time-dependent rheological properties. This latter aspect is not deeply investigated in literature, especially in the ranges of shear rates, times and water-cement ratios commonly adopted during permeation grouting treatments. To this aim, in this paper, a comprehensive investigation has been performed, combining laboratory experiments with theoretical approaches. The time-dependent rheological properties of microfine cements characterized by different water-cement ratios have been first quantified by means of rheometric tests and described with a Bingham's law. The microfine cement permeation in granular media has then been experimentally investigated and so the employment of a Darcy's law modified to incorporate the temporal evolution of Binghamian grout rheologies has been validated for microfine cement flows.

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Origin of the vibrations induced by tunnels' excavation

M. Cardu
DIATI Politecnico di Torino, Italy

C. Todaro
IGG-CNR, Torino, Italy

ABSTRACT: In rock excavation (especially with explosives, but also in mechanical excavation), the vibrations of the medium where the excavation develops (rock mass) and those of the surrounding air (sound) are of great importance. After a synthetic description of the most common expressions of the "site laws" (charge - distance - vibration intensity correlations), attention is paid to the different types of technical problems where such correlations can be employed, on the basis of experimental cases and of literature data. Examples are presented consisting of suitable modifications of the excavation procedure to reduce the problem of vibrations. These modifications may concern, even jointly, the reduction of the pull, the increase of the drilling density (with corresponding reduction of the charges of the single holes), the increase of the delay numbers, the modification of the excavation system or, also, the isolation of the volume to be excavated with mechanical pre-cuts. The conclusions provide a straightforward approach to the assessment of charge per delay limits and recommendations are provided.

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Correlation between the Round Panel test and the Barcelona test for the control of shotcrete reinforced with fibers in tunnels

S. Carmona
Department of Civil Engineering, Universidad Técnica Federico Santa María, Chile

C. Molins
Department of Civil and Environmental Engineering, UPC - Barcelona Tech, Spain

C. Parada
Barchip Chile S.A.

ABSTRACT: The use of fiber-reinforced shotcrete (FRS) is widely used for the construction of tunnel linings in highway, mining and hydroelectric projects in Latin America, which are designed using their flexural toughness determined by testing round panels. However, these tests are complex to perform and require large specimens. Alternatively, the Barcelona test, which consists of subjecting a cylinder to double punching, is quite simple and requires a relatively small specimen, it has been proposed to simplify the systematic control of the FRS on site. For this, it has been necessary to establish a correlation between the flexural toughness and the energy dissipated by the cylinder subjected to the Barcelona test. This paper presents the results of a preliminary research carried out using the results of the control tests of three mines in Mexico, where tunnel linings have been built using shotcrete reinforced with low amounts of synthetic fibers. The differences obtained between the estimated and experimental values lower than 10%.

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3D numerical investigation of the axial forces acting on tunnel junctions constructed in fractured/weathered to very blocky rockmass

F. Chortis
Archirodon NV, Athens, Attica, Greece

M. Kavvadas
National Technical University of Athens, Athens, Attica, Greece

ABSTRACT: This paper investigates the effect of constructing a new circular (cross-passage) junction tunnel, perpendicularly intersecting existing deep circular (twin) main tunnels, in rockmass, excavated with full-face conventional method and supported with shotcrete lining, via parametric 3D numerical analyses, by varying the diameter of the main and junction tunnels, the overburden height, the strength and deformability of the surrounding rockmass. The analyses focus on the distribution of the circumferential and longitudinal axial forces developing at the primary support of the intersection areas and quantify the interaction effects by comparing the axial forces at the primary support of the main tunnels before, during and after the construction of the junction tunnel. The results of the analyses are used to produce normalized graphs accompanied by analytical equations for the axial forces acting on the intersection zones between the main and the junction tunnels, applicable for preliminary estimations of primary support requirements at tunnel junctions.

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3D numerical investigation of the bending moments acting on tunnel junctions constructed in fractured/weathered to very blocky rockmass

F. Chortis
Archirodon NV, Athens, Attica, Greece

M. Kavvadas
National Technical University of Athens, Athens, Attica, Greece

ABSTRACT: This paper investigates the effect of constructing a new circular (cross-passage) junction tunnel, perpendicularly intersecting existing deep circular (twin) main tunnels, in rockmass, excavated with full-face conventional method and supported with shotcrete lining, via parametric 3D numerical analyses, by varying the diameter of the main and junction tunnels, the overburden height, the strength and deformability of the surrounding rockmass. The analyses focus on the distribution of the circumferential and longitudinal bending moments developing at the primary support of the intersection areas and quantify the interaction effects by comparing the bending moments at the primary support of the main tunnels before, during and after the construction of the junction tunnel. The results of the analyses are used to produce normalized graphs accompanied by analytical equations for the bending moments acting on the intersection zones between the main and the junction tunnels, applicable for preliminary estimations of primary support requirements at tunnel junctions.

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Challenges faced during conventional tunneling in urban environment – Mumbai Metro Line 3

A. Singh
AECOM India Private Limited, Mumbai, India

G. Raju
AECOM India Private Limited, Delhi, India

S. Gupta
Mumbai Metro Rail Corporation Limited, Mumbai, India

ABSTRACT: Mumbai Metro Line 3 (Line 3) is one of the unique and most challenging ongoing underground metro works in India. The project covers the approximately 33.5km long underground metro rail system running from Cuffe Parade Station in the south of Mumbai to the Seepz station at the northern end with 26 underground stations and associated tunnels. The construction of Line 3 is divided in 7 contract packages. The fully underground MML3 project comprises mixed ground condition of various weathering grade of rock throughout the tunneling stretch. Out of 26 underground stations 7 stations are constructed with combination of cut & cover boxes and conventional tunneling. In this project there are 3 crossovers, stabling tunnels at two stations and 88 cross passages connecting the bored tunnels which are constructed conventionally. In this paper, few very crucial challenges faced during design and construction of conventional tunneling are discussed. At present, 90-95% of conventional tunneling is successfully completed and remaining to be accomplished soon.

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Design and planning of excavation sequence and blasting techniques for large UG caverns

Rakesh Khali & Naveen Bahuguna
G R Infraprojects Ltd., Delhi, India

ABSTRACT: The cavern construction technology governs many important aspects of design and design processes continue to the end of construction phase. The choice of reasonable excavation sequence and control blasting is one of the key techniques for construction of large underground powerhouse. 26.2m wide,57.3m high and 202.9m long cavern of 1000MW Tehri pumped storage project is under construction with top heading & benching method to accommodate 04 reversible turbines of 250MW each. Geology encountered was Fair to poor and lot of large openings where there, so excavation of cavern was very challenging, and special excavation techniques were used. Due to vicinity of underground cavern close to under operation cavern of 1000 MW Tehri HPP, control blasting techniques adopted to maintained design PPV and minimize over excavation of cavern with heading & benching. This paper presents selection of excavation sequence, control blasting techniques with heading & benching of powerhouse cavern for different ground condition, and continuous monitoring blasting performance and optimize blasting design to maintain designed PPV and retain designed Geometry of cavern.

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A 3-dimensional numerical analysis of the intersection of tunnels and shafts

A. Khetwal
WSP USA

S. Khetwal
Dr Sauer and Partners, USA

K.G. Sharma
Indian Institute of Technology Delhi, New Delhi, India

A. Panciera
Lombardi Engineering Limited, Minusio, Switzerland

ABSTRACT: The technological innovation in underground structures instigates complex, economical, and efficient structures like powerhouse caverns, stations, tunnels, subways, metros, and many more. The complexity in these structures increases with the addition of intersections. These intersections can be horizontal, vertical, or inclined, subjected to stress concentrations, requiring special design considerations. The requirement of an extra support system is dependent on the rock mass properties, cavities dimensions, intersection angles, overburden, and in-situ stress conditions. The present study aims at assessing the effect of variable depth and in-situ stresses on various angles of tunnel intersections under similar rock mass conditions. Thirty-nine cases are analyzed to evaluate the variation in stress and deformation due to changes in the three input parameters: depth, in-situ stress, and intersection angles. FLAC3D, a finite-difference method-based numerical software, is used for the analysis. Thirty-six cases were evaluated by varying the in-situ stress ratio from 0.5 to 3, overburden from 100 m to 1500 m at intersection angles of 90°, 60°, and 30°. The results show that the 30° intersection is most critical. An increase in the in-situ stress and overburden results in a considerable increase in deformation. The values of the strength-stress ratio show the potential squeezing condition primarily for 30° intersection and high overburden.An analysis of vertical intersection to account for stress conditions at shaft intersections was performed. The results show that edges of vertical and horizontal junctions demand longer inclined bolts and support. The addition of vertical intersection with the multiple in-plane intersections proves to be most critical. The effect of parallel tunnels and their intersection showed a minimum of 2.5 times the diameter between the tunnels as a clear distance is required to avoid overlapping the plastic zone. The application of three-dimensional numerical analysis is assessed for two intersections of cross passage and adit for the T-48 tunnel project in the Himalayas. The results showed the intersections to be stable with extra support. However, the comparison of results with monitoring data did not provide sufficient information due to errors in the positioning of instruments. Still, overall the analysis showed that the rock mass parameters considered are conservative for the tunnel design. However, the necessity for a 3-D analysis for stability assessment and an extra support system at intersections is required.

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Face stability of tunnels under the groundwater level: Comparison of existing theories and introduction of a new analytical method calibrated on 3D FEM calculations

D. L'Amante & G. Fantauzzi
Systra, France

ABSTRACT: The stability of the excavation face is one of the main aspects to be studied during the design of tunnels. The excavation at tunnel face causes a change in the existing stresses of the ground, that tent to find a new equilibrium state, transferring the forces to the surrounding ground through a 3D arching effect. The collapse of the tunnel face can occur if the strength of the ground is not compatible with the new stress state, creating risks for workers and equipment in the tunnels and for people and structures above the ground (in the case of shallow tunnels). The failure mechanisms acting at the tunnel face are not yet fully understood as published analytical formulations give sometimes diverging conclusions. The present paper tries to shed light on the problem of the face stability. After a review of some widely used existing analytical methods, the results of parametric studies using 3D finite element method calculations are presented from which a new analytical approach applicable for tunnel under the groundwater level is derived. The case of conventionally excavated tunnels (without the application of face pressure or reinforcements at the face) is considered in the present paper.

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High temperature ground improvement

J. Malone & C. Paraskevopoulou
School of Earth and Environment, University of Leeds, UK

B. Jones
Inbye Engineering, UK

G. Doulkas
STRABAG UK Ltd., UK

ABSTRACT: High-temperature ground improvement is becoming more widely used for various geotechnical applications. However, examples of the application of ground heating to tunnelling are limited. This study aims to assess the applicability of high-temperature ground improvement to tunnelling by reporting the variation in Unconfined Compressive Strength (UCS) and other geotechnical properties of clay and sand after heating to high temperatures. Laboratory experiments were conducted to assess the engineering properties of clay and sand specimens heated in a furnace at temperatures ranging from room temperature (~25°C) to 1200°C. The results show that a high temperature of 1200°C considerably affects the UCS and point load strength index of the clay and sand specimens, mainly mixed clay and sand specimens with ratios of 3:1 and 1:1 sand to clay. A higher clay content results in increased depth and frequency of surface fracturing within the specimens resulting in reduced material strength. The highest value of UCS obtained from the experiments is 1.9 MPa by heating a 25% clay 75% sand specimen to 1200°C until it becomes vitrified. Generally, high temperatures (~1200°C) result in an increase in the UCS strength index of soft clayey, sandy soils.

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Modernization of a century old Mont-Royal Tunnel

M. Motallebi & B. Esmaeilkhanian
AECOM, Montreal, Canada

V. Nasri
AECOM, New York City, USA

ABSTRACT: Réseau Express Métropolitain (REM) is the new light rail transit network of Montreal, Canada. This electric and fully automated LRT network will facilitate mobility across the Greater Montreal Region by providing 67 km of twin tracks and 26 stations. This new LRT network uses existing Mont-Royal Tunnel (MRT) to connects Downtown Montreal to the north side of the Island of Montreal by passing through Mount Royal mountain. In addition, two of the project stations will be built inside this tunnel by enlarging it from a double-track tunnel to side-platform station at the location of these stations. The Mont-Royal Tunnel (MRT) is a century-old railway double track horseshoe tunnel. The tunnel is approximately 5 km long, 8.8 m wide and 5.5 m high, with a constant 0.6% grade. In order to use MRT in a modern transit system, the tunnel needed to be inspected, rehabilitated and be compliant to the recent safety standards. This paper presents a summary of history and characteristics of the existing tunnel plus the implemented steps to upgrade the tunnel. It includes the details of the structural inspection and rehabilitation methods of the tunnel. Further, this paper summarizes the procedures for the space proofing, construction of the separation wall, and the tunnel enlargement. It also describes parts of complications encountered during the constructions and solutions implemented to tackle these issues.

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Montreal metro blue line extension tunnels and caverns

V. Nasri & M. Bakhshi
AECOM, New York, USA

G. Maurel & R. Saghaee
AECOM, Montreal, Canada

ABSTRACT: The development of the Montreal metro Line 5 also known as Blue Line Extension toward the northeast are located between the existing Saint-Michel station and Anjou. It consists of 6-km long double track tunnel, five new stations and seven auxiliary structures. Most of tunnel length (5.5 km) will be excavated by a 9.6 m diameter shielded rock TBM and supported by a precast segmental tunnel lining system. Based on the project master schedule, the five stations will be built first and then the TBM will skid through the already built stations. For the inter-station tunnels, the shielded rock TBM excavation method with segmental liner installation was selected based on the existing geotechnical challenges, evaluation of the project construction cost, schedule and risk, noise, and vibration. TBM will be fitted for probing and pre-excavation grouting to control water inflow into the tunnel during the excavation in fractured limestone and shale formation under the downtown of Montreal where lower rock quality and high water infiltration rates are anticipated. The latest development in segmental liner technology and the latest segmental liner design code ACI 533.5-20 were used for the design of the tunnel segmental liner of this project. The stations and auxiliary structures will be built using the controlled drill and blast method or roadheader. Two thin layers of shotcrete separated by a layer of spray-on membrane will be used as the initial and final liner of the underground stations and auxiliary structures resulting in significant construction cost and time savings. This paper presents major design aspects of the TBM tunnel and mined station caverns of this major project in Montreal, Canada.

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Design and construction of the deepest underground station in Canada

V. Nasri & T. Vovou
AECOM, New York, NY, USA

ABSTRACT: The Réseau Express Métropolitain (REM) is an electric and fully automated, light-rail transit network designed to facilitate mobility across the Greater Montreal Region (Canada). This new transit network will be linking downtown Montreal, South Shore, West Island, North Shore and the Airport. Spanning over 67 kilometers once completed, the REM will be one of the largest automated transportation systems in the world after Singapore, Dubai and Vancouver. The REM system will connect to existing bus networks, commuter trains and three lines of the Montréal metro (subway). To deliver this major design-build project, several underground works are undertaken. One of the major and challenging underground works of this project is the Édouard-Montpetit Station. The Édouard-Montpetit Station is an interchange station that will connect the deeply sitting REM tracks laid within the century-old existing Mont-Royal tunnel to the existing metro station of the same name located closer to the surface. The tracks being located at approximately 70m below surface, the Édouard-Montpetit station will be the deepest in Canada. This paper will present various components of the design and construction of this deep underground station and the numerous challenges and solutions put forth for its successful completion. It discusses a case of a very deep transit station located in a dense urban area and excavated in hard rock on top of an existing 100-year-old tunnel. The details of design and construction as well as their specific challenges are explained, and the solutions selected to overcome these difficulties are described. Two thin layers of shotcrete combined with permanent rock bolts and a layer of spray-on waterproofing membrane are used for both initial and final liner of the station shafts, tunnels, and caverns resulting in an optimized design and construction process.

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Application of radar measurement for energy efficient blast calculation by the tunneling

J. Ortuta & M. Bakoš
Amberg Engineering Slovakia, s.r.o., Bratislava, Slovakia

V. Greif
Department of Engineering Geology, Comenius University Bratislava, Bratislava, Slovakia

ABSTRACT: Reflectivity is the amount of transmitted power returned to the radar receiver. The reflectivity is proportional to the number and the size of the stones in a volume unit. This means that stone size is linearly with radar reflectivity. This paper discusses the application of Doppler radar as the possibility of fragmentation material measurements during the blasting and the direct possibility of its further use in building other construction such as road embankments where grain size plays a decisive role. With this refinement, it is possible to omit additional crushing of the material, which is associated with financial costs. Effective use of residual material, as well as mitigation of environmental impact by associated technologies, would be achieved.

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A framework to assess the expected utility of the observational method

T.P. Roper
The University of Queensland, Brisbane, Australia
Acciona Construction, Sydney, Australia

J. Karlovšek
The University of Queensland, Brisbane, Australia

ABSTRACT: When faced with design problems that have significant uncertainty attached, geotechnical and tunnelling professionals use the instrument of the Observational Method. The decision to apply the observation method, or not, to a given tunnelling design problem can be complex. This leads to debate amongst practitioners, who approach the choice from various angles, due to the absence of any agreed-upon decision criterion. To solve this, a framework is proposed using principles of economics, probability and decision theory. The framework uses the theory of Expected Utility, allowing for both tangible and intangible construction costs to be accounted for. The framework is tested using case study data from a recent Sydney tunnelling project. Following a survey of practising tunnel Project Managers, a new factor is introduced termed the Cost of Uncertainty. The proposed method is a sound starting point when choosing between implementing the observation method or not.

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Development and application of remote monitoring systems for tunneling works in conventional tunnel construction

K. Sakai, K. Mitani, T. Tani & S. Miyamoto
Taisei Corporation, Tokyo, Japan

ABSTRACT: The authors developed two remote monitoring systems and applied them to a mountain tunnel construction site: "T-iMonitor Tunnel" for excavation and "T-iMonitor Tunnel Concrete" for lining works. The former can monitor and record remotely the operational status of heavy machinery and temporarily installed facilities together with working environments. All the data are transmitted to a cloud server via internet connection, with which a developed Web application visualizes them on smart devices. Combining operating facilities and machinery hours, the system can automatically analyze the cycle-time for a round of excavation. The latter uses proximity, temperature and pressure sensors equipped on a traveling steel formwork for the secondary lining, and visualizes the occupancy and condition of fresh concrete cast in the formwork. The system could eliminate cumbersome works on sites such as checking the concrete casting process from narrow windows and documentation.

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French hill road tunnels: A pragmatic rock support approach

P. Salak & O. Nathan
Dr. Sauer & Partners Ltd., Tel Aviv, Israel

O. Koc & A. Pamsl
Dr. Sauer & Partner GmbH, Salzburg, Austria

ABSTRACT: The French Hill project involved the design and excavation of 3.5km of tunnels in an urban environment, including intersections and passages between the tunnels. The geology encountered in the tunnel face ranged from fill material to chalk and carbonate rock with karstic voids of variable size and shape. The tender design, which followed the empirical guidelines of the Q-System, was optimized for the construction phase. The final design, described in this paper adopted a more pragmatic approach, adopting either systematic bolting or shotcrete shell support classes, depending on the expected rock mass quality. The applicability of the various support options was evaluated using both continuum and discontinuum computer models. The utilization of the rock mass capacity using this optimized design led to a successful excavation of the tunnels. In order to meet the tight construction schedule, up to 12 excavation faces were mined simultaneously.

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Development of projection mapping technique for the tunnel face

T. Tani & Y. Koga
Taisei Advanced Center of Technology, Taisei Corporation, Tokyo, Japan

S. Miyamoto
Civil Engineering Division, Taisei Corporation, Tokyo, Japan

ABSTRACT: A technology is developed that can project ground information such as images of the tunnel face and rock hardness/softness data directly on a shotcreted tunnel face. The system is simply operated using push buttons installed on the driver's platform of the drill jumbo (the hydraulic rock drilling machine). There is no need for the installation of projectors, surveying work, or interaction with a PC, which are problematic in the severe tunnel environment, because the technology has been designed for safety and ease of use by field workers and other staff in charge at the tunnel face. It is confirmed that appropriate quantities of explosives can be determined according to rock mass strength, greatly reducing the need for extra shotcreting near the face due to over-blasting. Further, damage to construction equipment due to flying rocks is prevented. All of these improvements contribute to improved construction efficiency and on-site safety.

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Blasting and vibration control for hard rock shafts in urban centers

I.J.F. Teixeira, C.V. Chanquini, F. Abreu, P. Messa & L.B. Partelli
Acciona Construccion, Brazil

ABSTRACT: Large diameter shafts have been used in Brazil since the 1980s, usually in mass transport projects such as metro stations, ventilation shafts, emergency exits and auxiliary structures. When in soil, the advance is done in partial excavations with the application of deformable shotcrete lining as the excavation proceeds, but for rock shafts, the excavation and mucking of the material must be preceded by rock desegregation techniques, which may be done by blasting or by mechanical methods, if there are restrictions on the use of explosives. This paper describes the methodology and processes involved in the successful excavation of a large deep shaft in granite with approximately 40.0 m diameter and 40.0 m deep in a high dense urban area. Special focus is given to the detailed blasting plans and vibration output as well as the measures applied to avoid flyrock debris including a newly developed solution.

Tunnelling in challenging conditions,

case histories and lessons learned

Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Tunneling with low rock cover within tight geometric constraints

M. Abrahamsen & R. Alves
Rambøll, Copenhegen, Denmark

C. Cátedra
Cowi, Copenhagen Denamrk (Former Rambøll during current project)

ABSTRACT: The case studied in this article covers a mined twin track railway tunnel within Scandinavia. Where due to weakness zones and uncertainty on the rock levels, the usually drill and blast solution had to be replaced by soft ground tunneling.

A local lowering in the top of rock was identified in the existing geological information, resulting in very low rock cover (or potentially no rock cover). The soil above the rock consists of high permeable ground with more than 10m of water pressure.

The lowering is located below existing pile founded buildings and under a public road with a range of utilities. This high congestion of both the surface and underground space made it impossible to perform ground investigations prior to construction, to confirm the rock level above the tunnel.

This led to a temporary solution comprising of ground freezing, pipe umbrellas, heavy support frames and a redesigned underpinning of the building immediately above the tunnel.

The current paper summarizes the design process and the chosen design, and the considerations for dealing with uncertain geological conditions within a congested areas with high water pressure.

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Ground settlements induced by tunneling in soft and variable rock formations. Observed performance of SEM tunnelling for a section of Athens Metro - Line 3

Argyris Alexandris*
Archirodon NV, Athens, Greece

ABSTRACT: Appraisal of ground settlements induced by urban tunneling, provide valuable input for quantifying risks associated with settlement induced damage to buildings and surface facilities. Methods to evaluate such hazards are empirical in nature, and buildup of the empirical database with local data is the best way to gain confidence on such predictions. The motivation of this study is to present and compile tunnel induced ground settlements along a section of Athens metro located in the western suburbs of Athens and associate them with the encountered geology, tunnelling sequence and applied support measures. The study focuses on parameters of settlement trough developed in soft rock formations characterized by great variability and heterogeneity, like the local Athens schist and as well as marly Neogene deposits encountered in the Athens basin. In the studied section max settlement values s_{max} have been controlled well along most of the tunneling length, but specific incidents associated with tunnel face instabilities, resulted to high settlements values, just above tunnel axis. Volume loss V_L has been confined in the range V_L =0.5%–1.0% while values of settlement trough width parameter i were found in the range of i values reported in the literature for stiff clays/soft rocks.

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Structural design of Piraeus port metro station

D. Alifragkis, E. Gavrielatou & A. Gkavogiannis
Attiko Metro S.A., Athens, Greece

ABSTRACT: This case study refers to the construction method and the structural design of a new Metro Station at Piraeus Port within the Athens Metro Line 3 Extension. The Station is fully underground and located near the sea docks, under the main traffic artery, close to a landmark building housing Metro Company offices and an existing modern footbridge. Strict requirements such as the Station's large dimensions, preservation of groundwater level and maintenance of the port traffic as well as the difficult hydrogeological conditions led originally to adopting the top-down method with permanent diaphragm walls. Due to technical reasons, it was later decided to change the method to a classic cut & cover structure with temporary retaining diaphragm walls and prestressed steel struts. Various design issues had to be resolved by the Owner ATTIKO METRO SA and the Contractor/designer. The decision to change the construction method to cut & cover instead of top down offered better solutions, nevertheless disclosed controversies in the design and the construction phases. As large ground and water pressures acted on the walls, the 30m long steel struts, which also suffered temperature axial loads, had to be huge square sections of welded thick plates specially fabricated. The structural design of the Station permanent lining had to consider the consecutive construction stages of rising up the concrete building frame while removing struts plus installing the waterproofing membrane. Another major design issue was the large uplift forces on the Station structure from high groundwater. The Station entrances were also constructed as cut & cover using retaining secant piles or short diaphragms with steel struts. A sensitive monitoring system was installed to record deformations and stresses of the retaining structure itself, as well as of the adjacent structures. Finally, proximity to seawater brought about a carefully chosen waterproofing system that covered the whole of the Station and entrances. Construction is now completed and the Station is fully operational.

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Construction of the largest road tunnel in Brazil - Tamoios Highway, Caraguatatuba, Sao Paulo

P.P. Anjos & L.D. Valva
Engetec Construçoes e Montagens, Rio de Janeiro/RJ, Brazil

ABSTRACT: This article aims to contribute with a brief presentation of the main actions and results acquired, both in the development of the project and in the execution methods during the underground excavations for the execution of the structure. The dimensioning of the drainage systems, ventilation and emergency exits in the construction and operation phases, together with the specificities and geological and geotechnical aspects of the Serra do Mar region, were crucial for the development of the final project. Allied to this, the best engineering techniques for structural reinforcement and quality reconditioning of the adjacent massif were applied.

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The Icelandic glacier tunneling system

H.Ö. Arngrímsson
VERKÍS Consulting Engineers, Reykjavík, Iceland

R. Sævarsson
EFLA Consulting Engineers, Reykjavík, Iceland

ABSTRACT: In the year 2010, two pioneers in Iceland came up with the idea to create the first man-made glacial tunnel as an all year around tourist attraction. After three years of planning the excavation started in 2014. The project goal was to make glaciers in Iceland safe and accessible to all and let people experience the "blue ice" found at approximately 30 meters depth, crevasses and all which a glacier has to offer. The excavation was 5.500 m^3 of ice and took 12 months to complete. The tunneling system consists of a 6 ton excavator with a drum cutter attachment and two telehandler payloaders. The maximum length excavated during one shift was 20 m/day. This article will describe the history of making the largest man-made ice cap glacier tunnel in the world, location of the tunnel, the tunneling system used, problems encountered, safety measures, investigations done on the glacier and the experience gained for future projects like this around the world.

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Condition assessment survey and repair work of the headrace tunnel for the Warangoi HPP

B. Ashcroft & B. Børresen
Multiconsult Norge AS, Oslo, Norway

F. Mamia & L. Labe
PNG Power Ltd, Port Moresby, Papua New Guinea

ABSTRACT: The Warangoi hydropower project, commissioned in 1983, is located in East New Britain Province, Papua New Guinea. Water is conveyed through a 6.85 km long headrace tunnel comprised of precast concrete segments. Due to wear and tear, including significant sediment erosion, it was decided that the project's existing infrastructure should be refurbished and modernized. The plant was stopped in June 2019 and the tunnel dewatered. A detailed condition survey of the tunnel was subsequently carried out. This paper presents a detailed analysis of the different types of tunnel lining defect recorded during the survey. These defects are compared against various factors, including chainage and which tunnelling team was undertaking excavation at the time. This paper covers the severity of the various defects, ranging from the relatively inconsequential, to those critical for stability. A brief summary of the repairs undertaken is given, as well as conclusions drawn from the survey.

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Triple layered tunnel supports system against extremely high squeezing ground condition

D. Awaji, R. Hase, K. Matsuo & S. Okubo
Shimizu Corporation Co., Ltd., Tokyo, Japan

J. Nakamura
Hokkaido Regional Development Bureau, MLIT, Hokkaido, Japan

ABSTRACT: Otonaka Tunnel (L=4,686m) is one of the most difficult tunnelling projects under squeezing ground condition in Japan. Some supports were heavily deformed and tunnel section was completely closed or obstructed by ground heaving. To overcome this condition, it is necessary to design the triple layered perfect circle support structure. During excavating, it is necessary to constrain initial displacement by short distance ring closure which is around 5m behind tunnel face. As a result, these construction methods have ensured the stability of tunnel support structure under extremely high squeezing ground conditions.

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The performance of an EPB-TBM in a complex geology with frequently encountered dykes and in transition zones

M. Aymir, İ. Yağcıoğlu & B. Türker
Gülermak-Nurol-Makyol JV, İstanbul, Turkey

N. Bilgin
Istanbul Technical University, Istanbul, Turkey

ABSTRACT: The performance of an EPB-TBM was studied in the Silurian-Lower Devonian aged Pelitli Formation consisting of siltstone and sandy limestone which was a part of the current Metro Project in Istanbul. The geology is complex and often cut by andesite dykes. These magmatic intrusions are high-strength rocks. However, contact zones or transition zones with the main rock are highly fractured and weathered. These zones are critical in mechanized tunneling which is liable to tunnel face instability, face collapses, or jamming of the cutterhead. TBM thrust force, torque, penetration, EPB face pressure, and specific energy values are carefully analyzed and compared when cutting the main rock, andesite dykes, and transition zones. The mean EPB face pressure being 0.9 bar was increased up to 2.5 bar in the weathered part of the dyke, which played a mitigation factor in eliminating the unfavorable characteristics of transition zones.

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Comprehensive loess soil adhesion properties assessment: Insights from laboratory tests and atomic scale analyses

X.D. Bai, B. Wu & W.C. Cheng
School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, China
Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering (XAUAT), Xi'an, China

ABSTRACT: During tunnel excavation, 'clogging', induced by sticky material, often occurs at the cutting face through to separation and transport for disposal, causing unplanned downtimes and additional project costs. However, past studies have mainly focused on the clayey soils' clogging properties, and there is a pressing need of studying the clogging potential of mixtures containing the majority of silt soil while tunnelling in North-West China. In this study, the effect of the proportion of particles in different sizes on the adhesion, fluidity, and consistency of the additive-silt mixtures was investigated. The effect of sand and clay addition on the adhesion force and fluidity was explored. Sand has a good viscosity reduction effect on low plastic silt, and adding sand will significantly reduce adhesion and increase fluidity. The addition of clayey clays (kaolinite and bentonite) to silt has a certain adherence reduction effect. The former reduces the risk of clogging due to the more content of non-expansion of kaolinite, while the latter is due to the fact that a large fraction of bentonite increases the liquid-plastic limit of the soil mixture and increases the water film thickness, resulting in the reduction of adhesion ratio. The variation of the soil consistency against the additive fraction was opposite to the variation of the maximum adhesion ratio. The findings highlight the role of additives in reducing the adhesion forces and the importance of cutting off the provision of additional water in preventing the sticky material transformation.

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TBM technology taking up the challenges of steep gradients

K. Bäppler
Herrenknecht AG, Schwanau, Germany

ABSTRACT: The market dynamics in tunnelling are driven by the globalized world and increasing urbanization. Pressing issues these days include climate change, CO_2footprint, sustainable development and a spirit of corporate social responsibility. Hydropower for example can deliver a range of benefits to society and the environment. Power-related benefits include clean and flexible generation and storage, in addition to reduced dependence on fossil fuels and avoiding pollution. The focus of this publication is on the TBM tunnelling technology in use for Australia's largest-ever hydroelectric project, Snowy 2.0 with challenges such as steep gradients, long tunnel drives and hazardous conditions.

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North-West road bypass of Merano - South Tyrol - Italy

G. Barovero
P.A.C. S.p.A, Capo di Ponte, Brescia, Italy

M. Moja, E.M. Pizzarotti & F. Prati
Pro Iter S.r.l., Milan, Italy

J. Strimmer
Autonomous Province of Bolzano, South Tyrol, Italy

ABSTRACT: The project consists of a 2.200 m long-tunnel, composed of a section in loose ground for about half of its total length and a section in metamorphic rock for the other half. The peculiarity of the portion in loose ground, on which this paper is focused, is that it crosses the town with shallow overburdens, about 10 m at most, running along or under numerous buildings. The rocky part, characterized by higher overburden, up to 100 m approximately, presents an underground roundabout with an overall diameter of 42 m, consisting of a toroidal tunnel with a central rock pillar of 8 m of diameter, for the connection with the future underground parking of Monte San Benedetto.

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Class A predictions of damage level in an historical fortress induced by twin tunnelling

D. Boldini & C. Spaggiari
Sapienza University of Rome, Rome, Italy

J.K. Abul
WSP-Golder, London, UK

S. Fuoco
Infrarail, Florence, Italy

E. Lusini
University of Bologna, Bologna, Italy

ABSTRACT: Tunnelling below historical city centres requires the accurate analysis of the impact of construction works on cultural heritage monuments, which need to be preserved from any possible damage. In this paper, the undercrossing of an historical masonry structure in the city of Florence (Italy), the *Fortezza da Basso*, by two tunnels of the new high-speed railway underground line is analysed. The interaction problem is studied by a 3D class-A finite element numerical model. Advanced constitutive laws are adopted to describe the key features of the mechanical behaviour of both soil layers and masonry structures. The results of the analyses show that the excavation process is likely to induce a negligible to slight damage in the historical fortress when a typical surface volume loss of 0.5% is considered in greenfield conditions.

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The successful crossing of an extended fault zone in carboniferous squeezing rocks: A practical case from TELT's SMP4 construction site

M. Calorio
Tunnel Euralpin Lyon-Turin (TELT), Turin, Italy

F. Franchetti
Alpina S.p.a, Milan, Italy

L. Rew, A. Counilh & A. Saitta
Egis Tunnel, Pringy, France

B. Serrano & C. Salot
Tunnel Euralpin Lyon-Turin (TELT), Le Bourget du Lac, France

ABSTRACT: The Saint Martin La Porte « SMP4 construction site » is the last exploratory gallery of the 57,5 km long TELT project. In 2017 the excavation works of Part 3b commenced using the conventional method. Part 3b is a 1,5 km long section of the south tube that crossed the Houiller Front, a Carboniferous formation characterised by squeezing ground behaviour with high overburden. This Paper describes the successful crossing of the largest fault zone encountered at Ch 10+600 during the excavation of the exploratory tunnel. This fault has an extension of about 80 m with high squeezing rocks composed mainly of fault gouge, coal and tectonized shale. This geological accident demonstrated the successful application of the most recent innovations in yield-control support systems applied to conventional tunnelling as a result of more than 15 years of research work on "squeezing rock" at the Saint Martin La Porte site.

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Grand Paris Express line 16-1: Difficulties of mining under a rail junction into a steel bell

L. Carlos, F. Grisel & G. Pini
Eiffage Genie Civil, Paris, France

ABSTRACT: The Line 16 Section 1 is the biggest section of the Grand Paris Express project. It involves the construction of 19 km of news tunnels and five stations over a period of 6 years. The most complicated and important station to be built, named Saint Denis Pleyel, will serve the line 14, 15, 16, 17, 18 and RER D. It is locate next to the busiest rail junction point in Europe, which is composed, of 43 tracks used for high-speed trains, regional trains, overground metro, commercial trains and parking. The TBM-2B, focus of this study, mined under this rail junction at a depth of 22.5 meters without any interruption allowed and limited settlement. A 16 meters long steel structure was installed inside the station in front of the diaphragm wall to allow the TBM to enter the station without any water infiltration.

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Challenges in the construction of a tunnel under crossing a channel in Singapore

Z. Chen, T.Y.S. Chew, C.W. Wan & D. Loh
Water Supply (Network) Department, PUB, Singapore

ABSTRACT: To increase the conveyance capacity to Western Singapore and to meet long-term water needs in a more cost-effective manner, four new transmission pipelines consisting of 2 numbers of 2200 mm diameter and 2 numbers of 1200mm diameter water pipes will be needed by 2024 to convey water from a Water Reclamation Plant to existing networks in the western region of Singapore. Out of the several possible routes studied, the most cost-effective and technically feasible route was selected by laying the proposed 1.6km-long pipelines that under crosses a channel via a 6m diameter subsea tunnel. This paper outlines the challenges the team faced throughout the project thus far. It also examines the difficulties such as the construction of a 56m-deep launching shaft near a highly sensitive 700mm diameter Gas Transmission Pipeline (GTP) and at a location with high groundwater; and manpower and supply disruptions caused by the COVID-19 pandemic situation

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TBM performance in a complex geology when driving a water conveyance tunnel in Istanbul

M. Cinar & F. Kara
Kalyon Construction Company, Turkey

N. Bilgin
Istanbul Technical University, Turkey

ABSTRACT: Two EPB-TBMs are working on this project in complex geology. A certain amount of this tunnel in length is subjected to a detailed study of TBM performance. A water ingress of 60 m^3/h was experienced in a transition zone from clay to an interbedded siltstone-claystone formation, and 115 m^3 of double component polyurethane was applied to create a curtain to stop the water ingress into the tunnel. It is emphasized that EPB face pressure is a mitigation factor in overcoming face collapses and TBM jamming in transition zones. A face pressure of 2.1 bar was a key factor in passing a major transition zone. Normalized thrust force, normalized torque, penetration and specific energy values were compared with those of other 8 projects in Turkey in different formations in order to understand better the effect of the operational parameters and geotechnical properties on TBM performance of EPB-TBM.

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The second trunk line project - Construction of a deep railway station in the heart of Munich

J. Classen
Implenia Construction GmbH, Munich, Germany

R. Listl
DB Netz AG, Munich, Germany

ABSTRACT: The second trunk line project in Munich is a key factor to relieve commuter traffic in Bavaria's capital. The existing trunk line collects incoming trains from all directions in one tunnel that runs from east to west through the center of the city. The new tunnel will double the capacity to avoid congestions. Three new stations will be built, the deepest of which is the Marienhof station, situated directly behind Munich's city hall. At a depth of 40m, it will be the deepest regional train station in Germany. Via access tunnels, which will be excavated under compressed air, it will connect to the existing subway network. The large platform tunnels extending the east and west of the central access will also be driven under compressed air. With a section of 430m² it will be one of the most challenging underground operations ever executed in Munich. Further challenging tasks are the extensive lowering of water table by installing more than 100 wells in the city center, and the compensation grouting to reduce settlements of the neighboring historic buildings and the nearby subway tunnels. The paper focuses on the experiences so far and the future challenges of the project.

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Problems derived from designing tunnels in loose soils with rock mass methodologies

N. Della Valle & P. García de Haro
Tunnelconsult Engineering, Barcelona, Spain

B. Koçak
TMD, Tünel Mühendisliği ve Danişmanlik, Istanbul, Turkey

ABSTRACT: The use of typical rock tunnelling construction methodologies to excavate tunnels in soil is a practice that continues to be found today in some large projects. The erroneous adoption of the NATM philosophy as if it were a sequential excavation (SEM) is the most common case. The excavation by conventional means of tunnels in soils, in which their length does not justify the use of a TBM, is not usually exempt from difficulties. This article presents the case of a tunnel to be excavated in loose fine sand, with an excavation area of about 180 m^2, and a few meters of overburden, whose conception in the early stages of design does not fit properly to the existing ground and has subsequently required considerable design changes during construction.

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Repurposing of reception shaft, Mumbai Coastal Road Project – Case study

A. Di Fabio & A. Panciera
Lombardi Engineering Limited, Giubiasco, Switzerland

M. Varma, S. Kumar & P. Kachhy
Lombardi Engineering India Private Limited, New Delhi, India

S. Singh & S. Pajni
Larsen & Toubro Limited, Mumbai, India

ABSTRACT: As part of Mumbai Coastal Road Project - the connection between Nariman Point and Bandra Worli, a total length of 10.58 km - Package IV (MCRP4) includes submarine twin tube tunnels. Current Package's total length is 4,480 m, of which 2,008 m are excavated by means of one slurry shield and supported/lined by precast segments. Each tube will accommodate a three-lane carriageway, for an internal diameter of 11 m and an excavation diameter 12.19 m. To enable the launching and receiving of the TBM, two shafts were constructed at North end and South end of the package. The reception shaft is 42m long and 30m wide with a depth of 26m below the ground formation level at +3.0 msl. The intention was to disassemble the TBM after the first drive to reassemble and relaunch it from the original shaft – the "launching shaft". However, due to logistical constraints, given the project location in a dense urban setting, and due to time delays, because of stoppage of works during Covid lockdown, the Contractor of the project decided to relaunch the TBM from the reception shaft itself by rotating the TBM and save approx. 60-75 days. Due to this dynamic need of the project, reception shaft was repurposed for relaunching with additional ancillary structures (like Heavy weight modular gantry crane foundations, TBM reaction frame, Slurry treatment plant on surface etc.,) in and around the shaft which weren't foreseen during the excavation of shaft. This paper discusses design aspects with special focus on challenges which were needed for this repurposing of shaft.

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On transfer technology of drilling-blasting construction method and shield construction method at the interface of a subsea tunnel and its application

B. Du, C. Song & W. He
China Railway Liuyuan Group Co.,Ltd, Tianjin, China

K. Li
China Railway First Group Co.,Ltd, Xi'an, China

ABSTRACT: As for the running tunnel section between Wuyuanwan satation-Liuwudian station of Xiamen metro line 3, the construction method of "dismantling shield in the subsea first, and continually excavating the rest of section by the drilling-blasting method" is adopted. It is required to overcome such technical difficulties as shield dismantling in a confined space, long-distance single-line transportation, long-distance blind ventilation, protection of formed segments, waterproofing of joint structures, etc. The paper systematically expounds the transfer technology of various construction methods in Wuyuanwan station-Liuwudian station section and mainly introduces the solutions to the above construction difficulties. It has been proved in practice that this technology can greatly improve the construction progress under the premise of guaranteeing construction safety and structural function completeness, having reference significance for the subsea tunnel constructed by multiple combined method.

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Yielding elements made of high-strength expanded polystyrene (HS-EPS)

M. Entfellner & H. Wannenmacher
Implenia Austria GmbH, Salzburg, Austria

W. Schubert
Graz University of Technology, Graz, Austria

ABSTRACT: Yielding elements as a part of the shotcrete lining represent the state-of-the-art for tunnelling in overstressed weak ground conditions. They avoid an overstressing of the shotcrete lining during the early curing process. A novel yielding element is introduced, which overcomes existing systems' drawbacks. The innovative system is lightweight and allows for rapid installation. Furthermore, the modular setup of the element permits on-site adaption to react to actual deformation patterns and changing ground conditions. Recent experiences from an application in an alpine base tunnel in overstressed weak ground conditions are presented.

Keywords: Tunnelling, Yielding Principle, Ductile Lining, Overstressed Weak Ground, Squeezing Ground, Fault Zone, Yielding Elements, HS-EPS

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Algiers metro – Extension E. Beaulieu Station, a case study

R. Espírito Santo & M. Conceição
TPF Consultores de Engenharia e Arquitetura, Lisbon, Portugal

A. Mohamed & I. Mahieddine
Cosider Travaux Publics, Algiers, Algeria

M. Haouchine
Entreprise Metro d'Alger, Algiers, Algeria

ABSTRACT: Since its opening, in 2011, Algiers Metro has been the object of several expansion works, presenting nowadays an approximate length of 13.50km and fourteen stations. Extension E, connecting El Harrach Centre to the new terminal of Houari Boumedienne International Airport, is currently under construction and involves the execution of a 9.50km double-track TBM tunnel, as well as nine underground stations and ten ventilations shafts. Located below a busy crossroads of the Algerian capital, the Beaulieu Station, despite initially conceived as a typical cut-and-cover station, was deeply reshaped and is now characterized by a very intricate layout comprised of four open-air excavated bodies (with excavation's spans and maximal depths of around 25m and 32m, respectively) and two large-diameter (19m) underground galleries. Its geological context, essentially composed of heterogenic quaternary sandy and clayey deposits (water table placed at a 20m depth), the urban environment of the area and the resulting need of an efficient deformation control, in addition to the impossibility of employing prestressed ground anchors, led to the adoption of a solution consisting of pile walls and several levels of robust steel strutting systems, combined, on what concerns the station's central shaft and due to the need of quickly restoring surface occupation, with a top-down executed roof slab. In turn, the little overburden heights (OH) of the underground galleries excavated by means of the conventional tunneling method (of roughly 10m) and their proximity to nearby vulnerable buildings led to the adoption of an important soil treatment around the galleries, stiff pre-supports and primary linings, as well as of very restrictive excavation procedures, besides other additional measures. A complex ramp system was developed as a way of, apart from providing horizontal access to all excavation fronts in safer conditions, overcoming the imposed schedule constraints. This paper describes the geological and geotechnical site features, as well as the overall conception and executive procedure of such Station.

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Benchmarking tunnelling production rates: Challenging case histories of mechanized and conventional tunnelling in different geological conditions

M. Falanesca & D. Merlini
Pini Group Ltd, Lugano, Switzerland

R. Schürch
Pini Group Ltd, Zurich, Switzerland

R. Marclay
Pini Group Ltd, Sion, Switzerland

M. Neuenschwander
Neuenschwander Consulting Engineers, Bellinzona, Switzerland

ABSTRACT: Starting from the early stages of the project, the correct estimate of the tunnelling production rate, is necessary to meet the Client's requirements and make the working time reliable for the Contractor. This paper aims to provide a benchmarking tunnelling production rates on the basis of several challenging case histories for both mechanised and conventional tunnelling. A number of variables, including ground conditions, tunnelling method, length, diameter, tunnel layouts, maintenance requirements will be critically analysed in order to compare the theoretical and real average advancing rate. The case histories include mainly the major Alpine railway base tunnels built or under construction excavated with Hard-Rock Gripper TBM, Single and Double Shield TBMs and conventional tunnelling with full-face or partial excavations.

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An integrated design approach for the renovation of masonry railway tunnels of central Italy with ARCHITA and MIRET

F. Foria, S. Gazzola & M. Calicchio
ETS Srl, Rome, Italy

ABSTRACT: In the last decades and certainly in the near future, survey, analysis and maintenance of existing structures will be one of the major fields of interest for civil engineering and infrastructure management. Existing structures have been realized in the past with different design conditions from their actual capacity, like foreseen life-span, loads and geometries. For this reason, civil works could be inadequate to fulfil modern requirements and guarantee the conservation state of structural elements. The paper focuses on the case study of Sipicciano 1 and 2, masonry tunnels in Italy, near Viterbo (Lazio), on the Attigliano-Viterbo railway line. The tunnels are located in a complex area interested by different superficial mechanisms that compromise the structural state of the lining and the global stability of the tunnels. ETS has been in charge of the survey, inspection, investigation campaigns and detailed design for the renewal of the tunnels. The entire design process has been carried out with the MIRET approach (Management and Identification of the Risk for Existing Tunnels). The tunnels are digitalized and structurally assessed with a Scan-to-BIM workflow thanks to ARCHITA, a multi-dimensional mobile mapping system developed by ETS equipped with laser scanner, thermal cameras, linear cameras and Ground Penetrating Radars. The geometrization and informatization of the models, from the inspection to the design, are here concretely applied to the design process of Sipicciano 1 and 2 tunnels renewal, making also comparisons with direct inspections and results of preliminary consolidation operations.

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Low cover tunnelling under North America's busiest highway

A. Gakis
Dr. Sauer & Partner, Salzburg, Austria

C. Karner
Dr. Sauer & Partners, Washington DC, USA

T. Schwind
Dr. Sauer & Partner, Salzburg, Austria

ABSTRACT: Two new rail tunnels were excavated under the 401/409 Highway in Toronto to increase the capacity of the existing Kitchener rail corridor. The alignment of the new tunnels passes next to the existing Highway 401/409 tunnel and directly under the busiest Highway in North America, which remained operational throughout construction. The sequential excavation method was utilized, combined with 80cm pre-support steel tubes installed from the two portals and an intermediate temporary shaft. The two tunnels, about 10m high and 8.5m wide, were excavated in the fill of the existing highway embankment and the underlying glacial till, with a narrow soil pillar in between. The biggest challenge in this project was assessing and minimizing the impact on the operational highway and existing rail tunnel. The design and construction were successfully completed by the Toronto Tunnel Partners in 2021.

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Jet grouting treatment for excavating a large tunnel in saturated soil in Norway

F. Gallego & W. Summerer
ILF Consulting Engineers, Innsbruck, Austria

ABSTRACT: Norway has a long tradition of rock tunneling, however the design of the Drammen Soil Tunnel had to overcome a combination of unique challenges unprecedented in the country. This is a large cross section (156 m^2) high-speed railway tunnel excavated in saturated glaciofluvial sediments with little to no cohesion. Dewatering to lower the groundwater table was not permitted, moreover, the tunnel runs beneath Drammen's streets and buildings with an overburden as low as 8 m, for this reason there were very strict requirements in terms of allowed ground movements. The design solution consists essentially of a 2 to 2.5 m thick jet grout ring around the tunnel excavation profile built from the surface, for this purpose, a total of 2100 jet grout columns, up to 2.5 m in diameter, were installed. The result was a safe tunnel excavation in very stable and dry ground, with minimal deformations and notably low ground movements.

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Construction of the First Street Connector Tunnel as part of the Northeast Boundary Tunnel Project in Washington D.C.

B. Giurgola
The Lane Construction Corporation, Seattle, WA, USA

F. Azzarà & F. Bonaiuti
The Lane Construction Corporation, Washington DC, USA

Norbert Fuegenschuh
BeMo, Vienna VA, USA

ABSTRACT: In 2015, the Tunnel Boring Machine (TBM) used for the First Street Tunnel Project (FST) was abandoned in place after completion of the 822 m long (2700 ft) tunnel drive. Later in 2022, as part of the Northeast Boundary Tunnel (NEBT) project, the connection between FST and NEBT was completed, including a challenging removal of the FST TBM from inside the NEBT. This paper describes the design and construction efforts necessary to perform the final connection at the intersection of FST and NEBT, including ground improvement, SEM excavation works, TBM dismantling and installation of permanent lining.

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Discrete fracture network combined with discontinuum based design for deep shafts – quantifiable risk assessment and design method

I.S. Haryono, P.W. Booth & A. Purwodihardjo
WSP-Golder, Brisbane, Australia

B. Vorster
Glencore Coal Assets Australia

ABSTRACT: Deep shafts provide critical support services for underground mines and therefore robust engineering assessment and design processes are vital for their successful, cost-effective construction and reliable operation. With the trend towards increasingly challenging and complex shaft projects in terms of diameter, depth, ground conditions and demands for optimisation, there is an ever-increasing need for improvements to the engineering processes. Conventionally, geotechnical assessments for shafts have widely employed empirical methods such as the Raise Bore Rock Quality (Q_R) system proposed by McCracken & Stacey (1989). While these methods have provided a useful tool to aid design, they have typically been based on a limited database of project experience and so their results need to be interpreted in the context of local experience and engineering judgement. To advance the engineering process and achieve optimised designs, a more quantified approach that considers the site-specific conditions is required. This paper describes an approach based on Discrete Fracture Network (DFN) modelling integrated with discontinuum-based numerical modelling. In this approach, features observed in drill core and televiewer logs are used to derive a stochastically representative 'synthetic rock mass' model, which then can be exploited to assess potential rock mass behavior. The DFN model developed was incorporated into a full-fledged 3D discontinuum model to assess the rock mass instability, joint-controlled wedges and stress-induced spalling potential. This combined approach allows us to quantify the likelihood of instability in different rock strata, potential rock wedge sizes, factor of safety of different wedges, potential rock mass deformation and potential major failure mechanisms which are a combination of major instability factors. Ultimately, this approach allows engineers to optimise possible solutions for shaft excavation and support design.

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Lessons learned during excavation of the incredibly challenging Yin Han Ji Wei water diversion tunnel

L. Home
Robbins, USA

H. He
Robbins, China

ABSTRACT: The 2022 breakthrough of an 8 m diameter Main Beam TBM at China's Yin Han Ji Wei project was a triumph of technology and perseverance – crews at the 17.5 km long tunnel encountered over 14,000 rock bursts, some with energy as high as 4,080 kJ. The rock, consisting of mainly quartzite and granite, was estimated to have a rock hardness of between 107 and 309 MPa UCS, with high abrasivity and a maximum quartz content of 92.6%. The incredibly challenging tunnel also experienced at times severe water inflows, with one particular event exceeding 20,000 m3 of water in one day from a single point. In-tunnel ambient temperatures peaked at 40 degrees Celsius and 90% humidity. Throughout the challenges, the crew and support teams found ways to persevere – whether through unique ground support, or increased monitoring and analysis. In this paper, we will examine the successes and lessons learned in the incredibly challenging ground conditions, determining what worked best to confront each condition as it came up. Recommendations will be made towards what could be used successfully on future projects that encounter these geological features.

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Stilling basin built in the form of ultra-large cross-sectional tunnel

S. Igarashi, A. Fujimi, S. Murakami & K. Akiyoshi
Obayashi Corporation, Tokyo, Japan

ABSTRACT: In a discharge tunnel of the Amagase dam redevelopment project, a stilling basin section is an ultra-large cross-sectional tailrace tunnel. This tunnel passes through a weak fracture zone intervening in sandstone and mudstone with small overburden. Therefore, it is excavated through multiple bench cut with advancing side and center drifts, and observational construction is adopted during excavation. This section is under very difficult conditions and has only few similar design examples, so safety was prioritized. Safety, workability, profitability, and inner smoothness of tunnel lining has been secured by prior corner casting and upper/lower-divided-type travelling form in a 40% steep slope section. Tunnel behavior was controlled as estimated; an ultra-large cross-section tailrace tunnel was constructed reasonably.

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Failure of tunnels across the world: Case study

Waqas Imteyaz & Swapnil Mishra
Indian Institute of Technology (ISM), Dhanbad, Jharkhand, India

ABSTRACT: Today, tunneling across the globe has become a one-stop solution to speed up mobility and connectivity between locations, and also interestingly this can be achieved without damaging our environment by maintaining the proper green cover. But, making a tunnel is not easy as it seems to be because rock is a material that is unknown to us, unlike concrete. The failure of the tunnel may arise because of the squeezing rock condition, rock bursting condition, and also because of the insufficient support system provided. So, in this paper, detailed case studies of several tunnels have been done and the reasons for their failure have been in detail analyzed. Finally, a guideline regarding the support and the necessary investigation, and the tunnel profile have been made that would be helpful in the construction of the tunnels.

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Tunneling through a graphite bearing fracture zone during the expansion of the Stockholm metro to Nacka

H. Ittner, M. Roslin & L. Martinsson
THETA Engineering AB, Stockholm, Sweden
On behalf of Region Stockholm - Administration for Extended Metro, Stockholm, Sweden

C. Iskender
Nitro Consult AB, Stockholm, Sweden
On behalf of Region Stockholm - Administration for Extended Metro, Stockholm, Sweden

R. Swindell & P. Sunesson
Sweco AB, Stockholm, Sweden

ABSTRACT: This paper presents a case study of tunneling through a graphite bearing geological structure during the excavation of an access tunnel for the expansion of the blue metro line to Nacka. A straight section of the access tunnel and the graphite bearing zone had almost the same orientation and geographical location which made the excavation works particularly challenging. The graphite formation had not been identified during the pre-investigation and it followed the tunnel heading during the excavation of over 170 m. Parts of the fracture system was connected to an overlying aquifer resulting in ground water inflow in those sections. The rock conditions were handled through a combination of spiling bolts and reduced round lengths. Sections with higher water inflows were challenging due to reduced adhesion of shotcrete, leaking bolts and bolt holes. A close cooperation between the designer, site geologist, client's supervisor and contractor enabled a successful passage of the zone area.

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Semi-analytical prediction of ground surface settlements due to EPB tunnelling in Kolkata

H. Jain & Th. G. Sitharam
Department of Civil Engineering, Indian Institute of Science Bangalore, Bengaluru, India

ABSTRACT: A novel Gaussian distribution function is used to model the ground volume loss around the tunnel periphery based on which an attempt has been made to predict the ground settlements by using linear elastic analytical solutions. A set of around 6 m diameter twin-tunnels spaced 6 m apart are being constructed in Kolkata using Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) at a cover depth of around 20 m. The ground strata is predominantly silty clay, clayey silt with concentration of sand around the tunnel region. A ground volume loss of around 1-2% has been observed at different transverse sections on the tunnel alignment. Field monitoring reported after the tunnelling appears to conform with the analytical solutions. The disparity in the analytical and the field observations can be attributed to non-linear, anisotropic and non-homogenous soil behaviour around the tunnel opening. The simplicity of the solution allows it to be used by the engineers without having to go for complicated analytical and numerical solutions.

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Geotechnical challenges of conventional tunnelling underneath sensitive structures

Haluvally Jayarama
Larsen & Toubro Construction, Heavy Civil IC, Mumbai, India

Subodh Kumar Gupta & Charuhas Jadhav
Mumbai Metro Rail Corporation, Mumbai, India

ABSTRACT: Marol station, a part of 33.5 km underground metro line from Seepz-Colaba in Mumbai, is situated at a road junction and surrounded by hotels, commercial establishment, and a Fire Station. It passes underneath an operating elevated metro pier at a shallow depth of 26 m between its two successive spans of 28.63 m. While the vertical circulation of passengers and services in the underground station are accommodated in two box structures constructed by Cut and Cover method on either side of the elevated metro piers on two different roads, its platforms have been constructed by first driving both UP and Down alignment tunnels by TBMs and then widening them by conventional tunneling method. Both the platforms are connected to the vertical circulation of the station by 16 cross-passages. This paper discusses in detail the various challenges faced during construction of widening Tunnel without restricting any operation of existing metro piers.

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A case study on design and construction of mined tunnel in challenging ground conditions in Singapore

Y. Jinrong & M. Claudia
COWI Singapore Pte Ltd, Singapore

K. Sharique
COWI India Ltd, Gurugram, India

G. Venkatesh
Leighton Contractors (Asia) Limited (Singapore Branch), Singapore

ABSTRACT: This paper presents a case study on design and construction of mined tunnel for DTSS2 in Singapore. The geological condition comprises excavation in soft soil, hard rock as well as unexpected fault zone with high water permeability. The analysis methods for mined tunnel in rock used included the Q-system, analytical closed-form calculations, kinematic analysis using the Unwedge software, while the analysis method for mined tunnel in soil was carried out using finite element method with ground stress relaxation assessment. Mechanical excavation with hydraulic breakers and excavators were adopted for construction of the mined tunnel. Probe drilling and grouting were carried out to form a water-tight zone surrounding the tunnel profile. Convergence points were installed and monitored to ensure the movement of the mined tunnel is within design limit. The excavation of the mined tunnel has completed in March 2022, the maximum convergence of mined tunnel recorded was well within the design work suspension level.

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Control of water leakages during TBM excavation – An example from the Follo Line tunnel project

A.K. Kalager
Bane NOR, Oslo, Norway

ABSTRACT: Experiences from the execution of the two 20 long Follo Line tunnels may pave the way for the importance of a good understanding of how the geological and hydrogeological conditions may affect the achievement of a watertight tunnel. Different mitigations implemented, both during and after excavation by double shield TBMs, have defined a lesson learned for the performance of future TBM tunnels in order to control water leakages.

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Watertight rail tunnel excavation and environmental conservation of wetlands registered under the Ramsar Convention

A. Kameyama
Tsuruga Construction Site Office, Japan Railway Construction, Transport and Technology Agency (JRTT), Fukui, Japan

R. Kashiwagi
5th Construction Div. Hokuriku Shinkansen Construction Office, Japan Railway Construction, Transport and Technology Agency (JRTT), Fukui, Japan

T. Ishida
Construction Site Office of Miyama Tunnel, Sumitomo Mitsui Construction Co., Ltd, Fukui, Japan

ABSTRACT: The Miyama Tunnel is a 768m double-track tunnel located on the Hokuriku Shinkansen Line (between Kanazawa and Tsuruga) and in the city of Tsuruga in Fukui Prefecture. The site has many active faults which could lead to sudden groundwater seepage. The tunnel is also near the Nakaikemi Wetlands, which are registered under the Ramsar Convention. This made the prevention of any lowering of the groundwater level a concern. Five measures were taken, to reduce any negative effects on the wetlands due to excavation. First, the route was realigned, based on the suggestion by experts. Second, watertight lining was applied to keep the groundwater level stable. Third, various measures were taken to shorten the time of construction. Fourth, extensive and continuous survey were conducted. Lastly, a water level recovery plan was created. No major effects on the wetlands have been observed but monitoring surveys are conducted to help maintain the wetlands.

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Construction of headrace tunnel of Vishnugad-Pipalkoti HE Project (444MW) in extreme geological conditions: Issues and challenges - A case study

R.K. Khali
G R Infraprojects Limited, Gurugram, India

S. Potnis
MITWPU, Pune, India

ABSTRACT: Vishnugad-Pipalkoti HE Project(444MW) is under construction on Alaknanda River in Distt Chamoli, in the state of Uttarakhand. This Project will generate 444 MW Power by installing four turbines of 111MW each. The central feature of this project is its 13.5Km long headrace tunnel with an 8.8 m finished diameter. Out of its 13.5 km length,12.3 km is to be bored by using a double-shield TBM of 9.86 m diameter and the remaining 1.2 km to be bored with the help of DBM. The present authors want to highlight the issues and challenges faced during transportation and installation of the TBM and the universal geological surprises faced by the working team after starting the boring and the remedial measures adopted, therefore. The paper also discusses the analysis and design of the large-sized adit bored in the extremely poor rock conditions and the innovative measures undertaken for its construction.

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Design criteria for caverns under high stress rock conditions for Snowy 2.0 Power Station Complex

S. Khodr, P.L. Tonioni & P. Lignier
Tractebel, Paris, France

A. Lambrughi
Webuild, Cooma, Australia

M. Diederichs
Queens University, Ontario, Canada

I. Ching
Snowy Hydro Limited, Cooma, Australia

F. Lazzarin
Webuild, Cooma, Australia

ABSTRACT: Snowy 2.0 is a major hydro power project currently under construction in Australia. This new development aims to increase the capacity of the existing Snowy Mountains hydro power scheme by 2000 MW, making it the largest source of renewable energy in Australia and one of the largest pumped-storage projects in the world. The exceptional size of the Power Station Complex, situated at about 720m depth under significant in-situ stresses, in sedimentary rocks of fair to good resistance represented a major design challenge. This article presents the main features of the Snowy 2.0 Power Station Complex (PSC) project, in particular the geological context and the general layout of the PSC. It focuses on the methodology adopted for the definition of the design criteria, with the absence of relevant code or standard for the design of large deep underground caverns under high stress conditions. These criteria concern mainly (i) the stability analysis of the rockmass surrounding the excavation, including the stability of the rock pillars at the centre of the Power Station Complex; and (ii) the design of the rock support composed of fully grouted rockbolts, shotcrete and wiremesh.

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Collapse of a pressurized subsea tunnel in cohesive marine deposits

S.H. Kim, K.H. Kim & D.H. Kim
Department of Civil Engineering, Konkuk University, Republic of Korea

S.H. Kim
Department of Civil Engineering, Hoseo University, Republic of Korea

J.H. Shin
Department of Civil Engineering, Konkuk University, Republic of Korea

ABSTRACT: It is common to install pressurized water mains or heat supply pipes in tunnels. Highly pressurized pipes often leak through cracks or joints and may cause the tunnel to be pressurized. In this study a very special case of subsea tunnel collapse relating to internal pressure was investigated. It was found that the internal pressure of the tunnel was sufficiently high to cause the tensile failure of the segment lining joints, and probably caused the hydraulic fracturing at the surrounding soils. In this study the tunnel failure mechanism and hydraulic fracturing of surrounding ground was investigated. To identify the tunnel joint failure mechanism, back calculation using numerical structural analysis was carried out. The possibility of hydraulic fracturing was evaluated using theoretical method and small-scale model tests. It was found that the joints of the segment lining and the surrounding soils were relatively weak to resist internal pressure.

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Experiences and challenges during implementation of the Blominmäki sewage tunnels, Espoo, Finland

I. Konstantas, C. af Hällström & J. Salmelainen
Kalliosuunnittelu Oy Rockplan Ltd, Helsinki, Finland

J. Paajanen
SRV Oy, Kerava, Finland

J. Yli-Kuivila
Helsinki Region Environmental Services, Helsinki, Finland

ABSTRACT: The sewage tunnels of the Blominmäki Wastewater Treatment Plant (WWTP) consist of approximately 20 kilometers of inlet and discharge tunnels, access tunnels and shafts. The most challenging and technically critical parts of the Finnoo II contract were: The connection of the operating offshore tunnel of the old treatment plant with the Blominmäki discharge route, through a vertical shaft. Lack of information regarding the exact location, the shape and the geological conditions of the existing tunnel called for an accurate excavation design to avoid a potential tunnel collapse and rock blocking or massive waterflow during breakthrough. The precise implementation of the connection between acceleration and pumping underground caverns. The connection, in addition to the demanding excavation of complex geometry caverns, also included the implementation of six openings of square cross-section, slightly inclined, to install pipes for the flow of the treated wastewater.

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Experiences on the use of GBR in tunnel and cavern projects

C.S. Lau
Department for Infrastructure and Transport, SA, Australia; Formerly Salini Australia Pty Ltd, NSW, Australia

A. Dematteis
Lombardi Engineering Ltd, Giubiasco, Switzerland

R. Ovena
Lombardi Ingegneria, Milan, Italy

A. Di Fabio
Lombardi Engineering Ltd, Giubiasco, Switzerland

ABSTRACT: The use of Geotechnical Baseline Report (GBR) as a risk allocation tool for tunnel and cavern projects is being adopted around the world. Whilst the overall benefits of using a GBR have been well publicised, there are various implementation issues related to the geological model, the details of physical and behavioural baselines, including their selection, definition, measurement and verification, and competency of the project team. In addition, whether a differing ground condition is foreseeable and how the entitlement for relief is determined need to be compatible with the contents of the GBR and the form of contract to realise the intended benefits. This paper provides a critical analysis of the issues related to GBR in the context of large scale, Design and Build, tunnel and cavern projects. Examples of physical and behavioural baselines and geohazards will be discussed based on the project experiences of the authors in Australia and overseas. The approaches of the FIDIC Emerald Book and the ASCE Gold Book, and their implications on the contracting parties will also be described. The impacts of these GBR related issues on design and construction are very significant, to the extent of dictating the project schedule and cost, which in turn influencing the success of the project. The final part of the paper attempts to summarise lessons learned from the discussions and some recommended practices.

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Experimental investigation of long-term degradation of mudstone

Jialu Liu, Hiroyuki Tanbara & Ying Cui
Yokohama National University, Yokohama, Japan

ABSTRACT: This research investigated the long-term degradation potential of the soft rock sampled from a real tunnel site through X-ray diffraction analysis (XRD), accelerated slaking test, and creep test. The minerals contained in the samples were analyzed by XRD, and expansive minerals and wearable minerals have been found. Further, an accelerated slaking test was conducted to discuss the possible slaking. Moreover, the creep test using triaxial test apparatus was conducted to check the strength reduction due to slaking. The experimental result indicates that some minerals have the property of degradation and sedimentation and are one of the factors that cause rocks to slake. Based on the acceleration slaking test, the sample can be separated to level 2, so the rock is not easy to slake. Creep property and significant strength loss of the rock were obtained for this rock trough creep tests.

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Ground freezing for cross-passages in Milan Metro Line 4

G. Lunardi, G. Cassani & M. Gatti
Rocksoil S.p.A., Milan, Italy

A. Pettinaroli & P. Caffaro
Studio Ing. Andrea Pettinaroli, Milan, Italy

G. Pirro
MetroBlu S.p.A., Milan, Italy

A. Celot
Webuild S.p.A., Milan, Italy

ABSTRACT: The paper presents the application of the ground freezing for the construction of the cross-passages in the downtown stretch of the Milan Metro Line 4. The design requirements of the ground freezing, as well as the materials and equipment used will be described in detail; the design criteria will be focused by means of analytical and FEM analyses, concerning the thermal and static behavior of the frozen ground during excavation. The monitoring system to follow up and calibrate the freezing process will be illustrated too. Finally, some aspects and detailing deriving from the jobsites and construction process will be described, which represent a lesson learned very useful for future applications.

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Tunnel volume loss study on various geological conditions in Singapore

C.B. Ma, Thiri Su, J. Kumarasamy & K.H. Goh
Land Transport Authority, Singapore

ABSTRACT: In a land-scarce country like Singapore, it is inevitable that demands for new space has led to the creation of complex underground networks. As our underground network becomes increasingly built up, the relationship between underground infrastructures in the urban areas also becomes progressively intricate, which presents multifaceted challenges in underground tunnel construction where potential occurrence of ground settlement is the main drawback. With the volume loss induced by tunnel excavation as the main determinant of ground settlement, this paper presents the studies on the volume loss caused by bored tunnelling in different geological conditions in Singapore with a variation of tunnel boring machines (TBM) used in some of the recent Metro line projects such as Downtown Line (DTL), Thomson-East Coast Line (TEL) and Circle Line 6 (CCL6). Back analysis on trough width parameter from the available data is also discussed. The main findings of this study also provide references for impact assessment of bored tunnelling in future projects.

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New high speed railway Lyon-Turin site: A successful experimental crossing in the zone Houiller Briançonnais

E. Mathieu
EIFFAGE-BIEP, France

F. Martin
SPIE BATIGNOLLES GENIE CIVIL, France

S. Festa
COGEIS, Italy

S. Pelizza
Emeritus Professor Politecnico di Torino, Past President of the ITA, Italy

ABSTRACT: The construction of the Saint-Martin-La-Porte 4 works has been completed since October 3, 2022. This is the first worksite for the excavation of the Lyon-Turin rail base tunnel: 10.4 km were excavated in the final section on the south pipe axis of the project. This work was carried out in advance of the overall project, with the aim of verifying its feasibility. Located under a large overburden, the crews excavate in the geological unit of the Houiller Briançonnais consisting of arenaceous and black shales with coal levels, the most challenging geotechnical environment of the project, and characterized by strong convergence. 7 years of work were necessary to excavate 9 km of tunnel with TBM and more than 3 km in conventional method. The last two years have been particularly dedicated to the excavation in conventional method of 1.4 km in the geological zone of the Houiller Briançonnais; an experimental crossing in heterogeneous geology, with squeezing rock (convergence > 1 m in diameter), and at significant depth (overburden between 600 and 650 m in part 3b). These difficulties have allowed the Contractors group to reinvent itself by developing innovative methods for excavation and support. This article proposes to carry out the synthesis of this atypical context, of the forecasts, excavations, surveys, monitoring of deformations, back-analysis and model adjustment, evolution of methods and finally a planning synthesis.

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Geotechnical assessment of ground surface settlements induced by microtunneling construction. Case study: Pikrodafneza stream

P. Matsouliadis
Dipl. Civil Engineer, M.Sc., Intrakat Constructions S.A, Greece

C. Stratakos & A. Ntountoulakis
Dipl. Civil Engineer, M.Sc., Athens, Greece

ABSTRACT: The present paper is focused on the assessment of ground surface settlements induced by a Microtunneling construction located in Pikrodafneza stream, part of Eshatia stream settlement project. In order to conduct the study, both semi-empirical and numerical method have been employed followed by measurements in-situ. Semi-empirical method has been settled as a preliminary analysis followed by FE models examining two soil conditions, whilst systematic measurements' acquisition was employed during construction. The results are deduced in terms of ground surface settlements and evaluation of the geotechnical conditions.

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Brenner Base Tunnel, Lots Mules 2-3 (Italy): The construction experience of the emergency stop in Trens

D. Merlini & M. Falanesca
Pini Group Ltd, Lugano, Switzerland

A. Voza & A. Spaziani
BBT-SE, Bolzano, Italy

G. Bella
Pini Group Ltd, Lugano, Switzerland

ABSTRACT: The Brenner Base Tunnel (BBT) incorporates the latest safety standards in tunnelling. The project consists of two main tunnels, an exploratory tunnel and four adits. The operational safety plan of the BBT includes the construction of cross-passages and 3 emergency stops. The emergency stops connect to the external adits allowing the intervention of emergency vehicles and the extraction of smokes in case of fire. The present paper focuses on the construction experience related to the construction of the Italian emergency stop in Trens. This underground work consists in a central tunnel connected through cross-passages to the main tunnels. The main design and construction challenges are represented by the interaction between underground structures in combination with the high overburden and medium-low strength rock mass. The excavation is currently successfully completed. A comparison between the forecast geology and the cross-check will be analyzed also considering the data from the in-depth monitoring system.

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Design challenges and construction experience of the main tunnels of Brescia-Verona high-speed railway

D. Merlini
Pini Group SA, Lugano, Switzerland

M. Tanzini
Pini Group srl, Como, Italy

F. Avesani
Consultant for Pini Group srl, Como, Italy

M. Falanesca
Pini Group SA, Lugano, Switzerland

R. Rutigliano, A. Anania & M. Laffranchi
Cepav Due, Brescia, Italy

ABSTRACT: This paper describes the main underground works of the Brescia - Verona high-speed/high capacity railway which is part of the new Milan-Venezia railway link. An overview of the design challenges and construction experience of single-bore double-track and twin bored single-track tunnels, bored in urbanized area by traditional excavation technique and by a tunnel boring machine will be shown. For the mechanized excavation of the Lonato tunnel, an EPB TBM with a diameter of 10.03 m are used. In particular, the construction experiences for the first tube completed in September 2022 are discussed. The geotechnical and design challenges are related to the sub-crossings of the A4 motorway with extremely reduced ground overburden, ranging between 7 and 12 m, and large extension up to 425 m. The excavations are carried out in highly heterogeneous geological formations consisting of glacial, fluvioglacial and glacio-lacustrine deposits with very variable permeability values.

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Non-open-cut tunnel construction technology and monitoring system for railway underpass

A. Miwa, Y. Ohara, T. Ushida, T. Shimizu & T. Nakayama
Railway technical research institute, Kokubunji, Japan

ABSTRACT: In this paper, authors describe the history of underpass construction in Japan and suggest a stability evaluation method using seismic prospecting. Ground destabilization around excavation face causes track settlement. It is required to develop a real time stability evaluation method during excavation. First, we executed trapdoor tests and validated the change of elastic wave velocity ratio when the area around excavation face became unstable. Second, we executed excavating test in embankment buried a steel pipe used in real underpass construction and confirmed the same tendency. As a result, we clarified that destabilization of around excavation face caused by excavation is detected by focusing on the elastic wave velocity ratio.

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Design considerations for deep caverns in Opalinus Clay

D. Morosoli & G. Anagnostou
ETH Zurich, Zurich, Switzerland

L. Cantieni
National Cooperative for the Disposal of Radioactive Waste (Nagra), Wettingen, Switzerland

ABSTRACT: The planned radioactive waste repository in Switzerland will be located within a *ca.* 900 m deep and 100 m thick layer of Opalinus Clay. Low- and intermediate-level waste will be emplaced in caverns with a diameter of 14 m. The great depth of cover and the rather low strength of Opalinus Clay (uniaxial compressive strength in the order of 3-5 MPa) are expected to result in squeezing conditions, which will be demanding to handle on account of the large dimensions of the cavern cross-sections. The paper investigates alterative concepts for the tunnel support, considering the uncertainties and peculiarities of the Opalinus Clay's response to tunnelling – *inter alia* its very pronounced time-dependency. The development of relevant deformations will not cease even after several decades, while in the presence of a stiff lining the rock pressure would reach very high values within the service life of the caverns (in the order of about 3-4 MPa within a period of 20-30 years after excavation).

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Anti-soil ingress for immersion joints

H. Mortier
DEME Infra, Zwijndrecht, Belgium

P. Menge & P.-J. Verdonck
DEME, Zwijndrecht, Belgium

ABSTRACT: In the existing metro tunnel in Rotterdam, failures of the immersion were encountered. The omega joint's fixation was broken out of the concrete. After elaborate studies it was concluded that the Gina was pushed inwards due to the highly compacted soil column at the outer side of the Gina gasket and in between the end faces of both adjacent tunnel elements, whereby cyclic seasonal movements made the soil volume increase every winter and gradually push the Gina gasket inwards every following summer. This experience resulted in the contract requirement to foresee an anti-soil ingress measure in two simultaneously designed tunnels. The paper will enlighten how the mechanism was modelled and which mitigating measures were implemented in the execution of both tunnels. Numerical comparisons were made in between the two new tunnels and the existing Rotterdam metro tunnel to validate the design approach. Sensitivity analyses were made to assess the influence of soil cover, joint geometry, and the different behavior between the joint in the roof slab and the joint in the outer walls.

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Hybrid SCL and handmined shaft - A case study from the bank station upgrade project

Ali Nasekhian & Zhen Ng
Dr Sauer and Partners Ltd. London, UK

Garry Savage & Stuart Macknight
Dragados SA. London, UK

ABSTRACT: The Bank-Monument station, located in the heart of London, is a key interchange served by five lines and is one of the most congested complexes within the London Underground (LU) network. The Bank Station Capacity Upgrade (BSCU) project aims to increase station capacity by 40%, including provision of step-free access from street level to Northern line level at ~30mBGL and Docklands Light Railway line level at ~40mBGL via a new shaft. The lower section of this shaft is squeezed between two existing segmental concrete lined tunnels that are 3.5m apart at the springline level. The shaft was designed using a hybrid method of sprayed concrete lining (SCL) and traditional hand-mining, maximising the benefits of both tunnelling construction methodologies commonly utilised in London Clay. This paper addresses challenges in the design and construction of the shaft, including numerical modelling predictions against monitoring data recorded during construction.

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Tunnelling in challenging topography and geological conditions for a railway doubling project in Eastern Ghats, India

S.S. Nirmal, L. Kumar, A. Shaz & R. Gupta
RITES Limited, Gurgaon, India

ABSTRACT: East Coast Railway is constructing a new railway line parallel to an existing one in Koraput- Singapur Road section. This 164 km long railway line has 36 existing tunnels and 24 tunnels for proposed second line. The existing line was constructed in 1982 through a dense forest and varying geology. This paper focuses on a smaller section of 45 km length between Tikri and Bhalumaska with 19 proposed tunnels.

The existing railway line passes through steep gradient with sharp curves. This region has low population and has dense forests. Proposed line is planned to increase capacity of section. Planning optimised alignment was a challenge with range of factors affecting the decision.

The project encountered geological challenges during design of proposed Tunnel 23. Various failures were recorded while existing Tunnel 23 was constructed. The challenges faced during execution of project and how decisions were made while following sustainable practices are discussed.

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Study into the TBM jamming hazard in Opalinus clay

A.N. Nordas, M. Natale & G. Anagnostou
ETH Zurich, Zurich, Switzerland

L. Cantieni
National Cooperative for the Disposal of Radioactive Waste (Nagra), Wettingen, Switzerland

ABSTRACT: The National Cooperative for the Disposal of Radioactive Waste (Nagra) in Switzerland has designated Opalinus clay as a host rock for a deep geological repository. The drifts for high-level waste storage (∅ 3.5 m) are to be constructed with a shielded tunnel boring machine (TBM) at depths where squeezing conditions may occur and the ground is fully saturated. This paper studies the TBM shield jamming hazard during excavation or long TBM standstills by means of 3D, transient, coupled hydraulic-mechanical Finite Element computations. An anisotropic linearly elastic and perfectly plastic constitutive model with a Mohr Coulomb yield condition is adopted for the Opalinus clay. Of practical interest is the influence of anisotropy and ground desaturation on the time-dependent ground deformations after excavation. The study concludes that shield jamming is not critical. The results offer practical guidance for the identification of critical design aspects for underground systems in pronouncedly anisotropic ground.

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Investigation of the effect of ground freezing on shield tunnel restoration

S. Park, C. Hwang, S. Yang & H. Choi
Korea University, Seoul, Republic of Korea

T.Y. Ko
Kangwon National University, Chuncheon-si, Gangwon-do, Korea

Y. Son
SK ecoplant, Seoul, Republic of Korea

ABSTRACT: While a cross passage of shield tunnels was excavated near the Nakdong River in South Korea, the tunnels were suddenly destroyed by inappropriate grouting reinforcement due to high gas content unexpectedly existing in the alluvial soil deposit. To restore the collapsed tunnels, broad and deep excavation was performed along with diaphragm walls to replace the damaged tunnels with box structures. In addition, ground freezing was applied to connect the box structures inside the diaphragm walls to the intact tunnel sections. The excavation and two stages of ground freezing were conducted simultaneously, according to the construction plan. In this study, temperature changes in the ground and the horizontal displacements of the diaphragm wall were monitored and analyzed. Soil type, water content, and distance from the freezing pipes influenced the ground temperature distribution. The deformation of the diaphragm walls was induced by the combined effect of the deep excavation and frost expansion of the frozen soil.

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TBM Cutter head management sub-sea in the Arabian Gulf

G. Peach
Mott MacDonald, Doha, Qatar

H. Vigil
PORR, Doha, Qatar

ABSTRACT: The Musaimeer pump station and outfall project located in Doha (Qatar) was required to construct a long outfall tunnel using an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) with a segmental lining. This tunnel had only one access point located at the launch shaft and was driven directly out from the shoreline, and connecting to a diffuser bed located 10.2 km offshore. The TBM cutter head was designed and equipped with both soft ground scrappers and hard ground cutter discs (Single, Twin and Double). The performance of any TBM can be influenced by many individual factors or combination of factors; perhaps the most significant of these factors is the performance of the cutting tools on the cutterhead. This paper will detail the two different specifications of hard ground cutters used and their individual performance and the impact of tribocorrosion on each type of cutter. The project had to carry out cutterhead interventions at full hydrostatic pressure (3.5 Bar) due to the extensive fractures in the seabed strata. The experience gained will be explained and the result was the changing of only 105 hard ground cutters during two years of tunnelling.

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Zhinvali HPP tailrace tunnel maintenance: Investigations, design and works implementation under challenging constraints

B.M. Quigley, A. Arigoni & S. Liccardo
Gruner Stucky SA, Switzerland

G. Matcharadze
Gruner Stucky Caucasus Ltd, Georgia

ABSTRACT: Zhinvali HPP is one of the most important water supply schemes for Tbilisi city. It was commissioned in 1985 and after almost 30 years some rehabilitation works for its 8.8 km long tailrace were considered necessary to ensure its service continuity.

The visual inspection along the tunnel showed a relevant widespread damaging state of the lining, with risk of structural instability in some stretches.

A sustainable decision-making process was implemented to address a short and a long-term rehabilitation plan. The main constraint for the planning, design and works was the limited tunnel outage for maintenance in order not to interrupt the activities of the plant for more than one month per year.

A multistage investigation program was developed to acquire knowledge of tunnel layout and of concrete lining features and to analyse the reasons of the tunnel damaging state. In the short-term planning, damages have been scanned and a priority actions list was drawn up, to ensure the tunnel functioning after outage period in the most damaged zones.

Since 2014 up to 2020 a rehabilitation plan was implemented yearly. Despite of all the constraints imposed for the execution of inspections, investigations and works, the operations successful restored the damaged zones of the tunnel, although new damages have been detected during the latest inspection.

All the data collected over time contributed to have a considerable background on tunnel conditions and to identify their sources. Considering that a short-term approach could only restore the tunnel functionality without eliminating the source of damaging, a long-term concept was then proposed. It consisted in a large-scale rehabilitation works to improve the hydraulic performance of the tunnel, reaching the original design capacity and steady operation conditions.

This paper will address and detail all the inspection and design activities carried out for this project.

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Design aspects of swelling of shales for tunnelling projects in Southern Ontario, Canada

M. Rahjoo
AECOM, Burnaby, British Columbia, Canada

V. Nasri, M. Sepehrmanesh & M. Soudkhah
AECOM, New York, USA

ABSTRACT: Swelling may result in excessive pressure and deformation of support system of tunnels if it is not properly investigated by testing and not accounted for in construction and support design. The Georgian Bay and Queenston Shales in Southern Ontario have been reported to have potential for swelling behavior. Swelling is driven by osmosis and diffusion processes that are originated from an outward salt concentration gradient from the rock pore fluid to the ambient fluid. It is known that even when the outward salinity difference exists and water is accessible, swelling does not occur unless the confining stresses applied to a volume of shale is below the suppression stress threshold. It is also known that swelling rate decreases over time, and therefore the maximum swelling is expected to occur in the early days and months after swelling initiation rather than in years, but still swelling strain can increase to several times of the 1-year swelling strain over the lifetime of tunnelling projects. Various constitutive models have been proposed and used in numerical codes to capture time- and confinement- dependency of swelling. In this paper, these models are briefly reviewed and different aspects of design of tunnelling projects in Southern Ontario shale formations are discussed with a few examples of recent and old projects.

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Case study in the construction of tunnels on the Durango - Mazatlán highway (Mexico)

A. Ramírez-Piedrabuena
Director of Studies, Grupo Triada, Mexico

L. Cañete-Enríquez
Tunnel Manager, Grupo Triada, Mexico

W. Araújo-Quimbaya
Coordinator/ Senior Designer, Grupo Triada, Mexico

ABSTRACT: The objective of this article is to present some case studies of the construction of tunnels on the Durango – Mazatlan highway, which during the period between 2006 and 2013 was built in the north of Mexico. This road is made up of 61 tunnels in a stretch of approximately 80 km in length and crosses the Sierra Madre Occidental, which is why this number of tunnels were considered and it was sought to comply with three important points: first, minimize the environmental impact of the area, second, avoid high-altitude cuts (greater than 30 m) and third, comply with the geometric specifications established in Mexico for 2 and 4 lane roads. It is also important to mention and analyze that the Secretariat of Infrastructure, Communications and Transport (former SCT), used the experience of design and construction of road tunnels nationwide obtained over 26 years (1980 to 2003) and thus initially projected sixty-three tunnels on said highway, specifically in the El Salto – Concordia section (km 115 to km 195). Another point to develop in this case study is that during the construction period of some of these tunnels there were various situations (failures), which forced changes and/or modifications in the geotechnical considerations assumed and, in the construction, procedures originally proposed during the project development stage. Finally, it is important to consider that this type of experience has contributed to the development of recommendations for the design and construction of tunnels; such is the case of the Manual published by the SCT in 2016, without forgetting that it is still the responsibility of designers, supervisors, builders and government authorities to continue in the advancement and innovation of this issue to face new challenges, which contribute to improving the country's infrastructure.

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Construction of Kalbadevi underground metro station of Mumbai metro line 3 by dealing with numerous social and technical challenges in the congested old city – financial capital of India

A. Rawat
Hindustan Construction Company Limited

S.K. Gupta, S. Dalvi & R.R. Kumar
Mumbai Metro Rail Corporation Limited

ABSTRACT: Construction of Kalbadevi Underground Metro Station of Mumbai Metro line 3 is an engineering challenge on one hand and a potboiler mix of social complications on the other. The under-construction station is in the midst of dilapidated buildings on congested lanes. The construction site was home of residential and commercial buildings, a fish market and an old bazar. 12 structures were demolished for a later in-situ rehabilitation. All the Project Affected Persons would be resettled in the area back to preserve their livelihood and social connect under a unique scheme. The project faced challenges of land acquisition, rehabilitation of PAP's and litigations in superior courts for likely construction induced impacts on the structural integrity of a 160-year old heritage structure of high religious importance of a minority community. On engineering front, the station has two rectangular portions being constructed by cut & cover method to accommodate vertical circulation. Two platforms on UP & DN line tracks and a central horizontal circulation is created in caverns done by Conventional Excavation. Because of the topographical and logistical limitations, the alignment tunnels between adjoining stations for both UP & DN tracks were done by TBM's and subsequently the lined tunnel widened by Conventional Excavation to create caverns to house the platforms and services. There were 131 structures in the Zone of Influence of the station box. Innovations were done in Blasting Design, to limit blast induced ground vibrations from propagating to the surrounding structures. Critical structures were supported and repaired. Real-time monitoring was put in place. The station is now 61% complete. The paper would discuss in detail as to how these issues of both social and technical nature were successfully dealt to execute this station in a complicated urban setting.

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Tunnel construction under dense urban agglomeration - The Dwarka Najafgarh metro corridor

A. Sahu
Manager, Delhi Metro Rail Corporation, Delhi, India

A. Kumar
Project Manager, Delhi Metro Rail Corporation, Delhi, India

ABSTRACT: Underground constructions underneath roads in busy areas of urban city can bring out many unexpected challenges. One such challenge was faced by Delhi Metro Rail Corporation Ltd (DMRC) during construction of underground RCC box tunnel at Najafgarh area of Delhi urban city, where the adjacent buildings were as near as 1.5 m from the soldier piles line. During rains soil piping was observed in the thin area between building lines and soldier piles lines which caused excessive settlement in the ground resulting in formation of sink hole, partial collapse of the building, cracking and tilting in the buildings, damage of roads and utilities. An immediate technical solution was required. This paper highlights the case study of challenges and complications encountered during construction of underground RCC box tunnel on busy carriageway road with simultaneous instrumentation monitoring of adjacent building while maintaining smooth plying of traffic.

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Numerical analysis of the Melbourne metro town hall station cavern

D.P. Sainsbury
Geotechnica Pty Ltd, Melbourne, Australia

B. Coombes
Noma Consulting Pty Ltd, Melbourne, Australia

R. Storry
Bouygues Construction Australia, Melbourne, Australia

A. Amon
Noma Consulting Pty Ltd, Melbourne, Australia

ABSTRACT: The Melbourne Metro Tunnel Project is delivering twin nine-kilometre rail tunnels in Melbourne, Australia. In addition to the tunnels, five new underground stations are being constructed. Two of the new stations – State Library and Town Hall – are complex cavern and adit excavations located in Melbourne's City Centre. The State Library Station, located predominantly underneath Swanston Street and a busy tram route, is surrounded by a mixture of modern, educational and heritage developments requiring the excavation sequence and primary support to be designed to ensure minimal surface impacts. To simulate the anisotropic rock mass response to the excavation of the State Library Station, FLAC3D numerical analysis was undertaken. The analysis adopted the ubiquitous joint constitutive model approach and was used to assess the performance of the primary lining design and to determine the impacts the predicted ground displacements may have on the surrounding structures. Calibration and validation of the ubiquitous joint modelling parameters for the Melbourne Formation has been completed against the measured and observed responses throughout excavation.

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Displacement characteristics and unilateral deformation of tunnel supports in excavation of tunnel with high overburden

Takeshi Sato
Central Japan Railway Company, Aichi, Japan

Kazuo Sakai, Takeyuki Ichida & Tomoyuki Nishitani
Taisei Corporation, Tokyo, Japan

Kiyoshi Kishida
Graduate School of Engineering, Department of Urban Management, Kyoto University, Kyoto, Japan

ABSTRACT: Displacement monitoring allows us to evaluate the adequacy of applied tunnel support as well as to select and install suitable support proactively during excavation. The monitoring also helps us to examine the ground conditions adjacent to an advancing tunnel face. A 4.2-km-long tunnel, Hirogawara adit, with a maximum depth of 860 meters, was excavated in the Akaishi Mountains of central Japan. Correlation between the initial and final displacement was confirmed as monitoring data were accumulated concurrently with ongoing excavation. Then, the final displacement was predicted from the initial displacement readings, which led to the proactive application of optimum rock supports. Meanwhile, the monitored displacement showed characteristically anisotropic or asymmetric patterns of tunnel deformation: the larger horizontal strain than the vertical one, the larger displacement of the right sidewall than the left one. The monitored displacements as well as observed unilateral deformations indicated the possible presence of anisotropic ground conditions.

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Frankfurt U5 metro extension – the challenging high pressure inner city project

T. Schade & R. Iffländer
PORR GmbH & Co. KGaA, Düsseldorf, Germany

L. Langmaack & D. Uhlmann
MC-Bauchemie GmbH & C. KG, Bottrop, Germany

ABSTRACT: Frankfurt, one of the most densely populated capitals in Germany, needed an extension of its Metro Line U5 from the main railway station towards the newly created district 'Europaviertel' which is part of an urban rehabilitation plan affecting over 30.000 people.

For the first time in Frankfurt, TBMs were used for metro construction. Driving in full EPB mode at up to 3,2 bar in clay and sand/clay mixed face geology with sensitive surface construction as well as the connection to the existing tunnel system from the 1970s makes this project unique.

Apart from the 2k annulus grout – first time implemented in Germany for a city tunnel project, EPB startup with a prefilled working chamber has been used very successfully together with highly ecologic tail sealants and soil conditioning system with minimum impact on the excavated soil.

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TBM excavation under high water pressure

R. Schuerch, P. Perazzelli & M. Piemontese
Pini Group Ltd, Zurich, Switzerland

M. Scialpi
Pini Group USA Inc., Washington D.C., USA

ABSTRACT: The main challenges related to TBM excavation under high water pressure are investigated on the example of the JWPCP Effluent Outfall Tunnel Project. The tunnel will transport secondary treated effluent from the Joint Water Pollution Control Plant in Carson, California. With a total length of approximatively 7 miles, a finished internal diameter of 18 feet, it will be excavated by using a TBM designed to cope with high water pressure up to 10 bar. The unicity of the project is due to the variety of subsurface conditions: over the first half of the alignment the tunnel runs in urban area at low overburden, while the second half of the alignment is characterized by higher overburden and water table along with extremely weak rock mass.

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Classification of fault zones in mechanized tunneling projects

F. Shayan & A. Uromeie
Tarbiat Modares University, Tehran, Iran

J. Hassanpour
University of Tehran, Tehran, Iran

ABSTRACT: The crossing of fault zones by underground works is often coupled with serious technical problems for tunnel boring machines. Fault zones may sometimes act as highly conductive groundwater channels or natural flow barriers. Such barriers can develop very-high water pressure behind or inside them. Crossing through them, especially with deep galleries, there is a considerable risk of meeting a sudden flow of water and crushed rock material under high pressure. Squeezing problem and collapse of tunnel surrounding rocks may also cause long delays in tunnel advance due to jamming of shield or cutterhead. So, to avoid difficulties in tunneling projects, it is very important to identify the main characteristics of fault zones and predict material behavior in such complex zones before crossing them by TBM. Knowledge gained from the application of TBM in different types of fault zones in various geological conditions can be utilized as a tool for predicting tunneling conditions in a given geological situation. In this paper, based on the experiences gained from mechanized tunneling in Iran and considering the most important influencing factors, a preliminary proposal for the classification of rock mass behavior and geological hazards in fault zones has been presented.

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Construction of platform tunnel by conventional tunneling below heritage buildings

P. Singh
L&T STEC JV Mumbai, India

R. Mittal & S.K. Gupta
Mumbai Metro Rail Corporation, India

A.H. Khan
L&T Construction, India

ABSTRACT: Urban Metro Tunneling in Mumbai has recently witnessed a positive breakthrough in last few years and Mumbai Metro Line-3 is one such project planned fully underground from Colaba to Seepz and in construction stage. Tunnel construction in the financial capital of India has its own unique set of challenges including presence of shallow groundwater table, sound bed rock, presence of heritage buildings, some of them are severely dilapidated, with heavy traffic movements on roads. This study is based on the case of Hutatma Chowk station of the Mumbai Metro Line-3 project, where it was proposed to construct a part of the station below the road and one platform tunnel of 253 m long, 9.7 m height, 11.78 m wide below heritage buildings by conventional tunneling due to topographical constraints. A rock pillar of only 3 m was available between the east side wall of the station box and the platform tunnel. Legal and regulatory circumstances led to a situation where the TBM would have been on hold for about 26 months having cascading effects on linear activities. This study analyses the challenges faced leading to an innovative and unorthodox solution and sequence of works resulting in minimum impacts on construction schedule.

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Design and construction challenges of deep shafts in chalk

R. Sivakumar, A. Maheetharan, M. Bevan & I. Thomas
Tunnelling and Ground Engineering, Jacobs

ABSTRACT: Five deep shafts are under construction as part of the Central 1 (C1) section of High Speed (HS2) Phase One, a new high-speed railway linking London to the Midlands, UK. These shafts form an integral part of the 16km long twin bore Chiltern tunnel providing ventilation and access for emergency interventions. The depth of these shafts varies from 35m to 67m depending on the vertical alignment of the tunnel and topography. Four of the shafts provide intervention and ventilation facilities, have an internal diameter of 17.8m, are formed using diaphragm wall construction. The fifth shaft, required only for intervention, has an internal diameter of 10.8m and is formed using cast in-situ caisson sinking method. The ground conditions at the shaft sites consist of a weathered chalk sequence which are complicated by the presence of infilled dissolution features.

Along the C1 alignment the twin running tunnels are positioned at 25m centre to centre spacing. In the case of first four shafts the TBMs directly intersect the shaft walls forming the ventilation openings and service access routes into the tunnel. The fifth shaft has been located between the two running tunnels and service access to the tunnels is made via sprayed concrete lined adits. This paper describes some of the key design and construction challenges associated with these shafts.

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Groundwater control measures implemented in Singapore's deep tunnel sewerage system phase 2 (DTSS2) project

Aung Ko Ko Soe, Woo Lai Lynn, Benedict Chionh & Kyi Khin
Public Utilities Board, DTSS2 Department, Singapore

ABSTRACT: Groundwater control measures are very important and desirable to implement in urban deep excavation and tunnelling processes to prevent excessive drawdown and subsequent settlement. They form an integral part of the project to protect the various stakeholders' interests such as deterioration of construction performance and significant impact to existing utility services and building structures. In Singapore's Deep Tunnel Sewerage System Phase 2 (DTSS2) Project, a major used-water infrastructure project, criteria and guidelines for ground water control scheme are outlined in the contract specifications for implementation at all of its deep tunnel shaft excavation sites. In this requirement framework, there is no restriction to the approach, method and procedure used on groundwater control based on prevailing ground condition and construction schedule. Following the guidelines, detail plans and designs for groundwater control scheme such as permeation grouting, pumping test, monitoring & groundwater recharging, are developed for implementation at each tunnel shaft location. However, there are certain sites in the project where implementation of such a pre-groundwater control scheme is subject to own assessment. This paper briefly explains the concept, principle, and procedure implemented, and also reviews the effectiveness and the benefits of groundwater control in construction risk mitigation.

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Ground freezing for deep shaft excavation shaft 17B-1 New York City Water Tunnel No. 3 New York, New York

J. Sopko
Keller, USA

ABSTRACT: Construction of Shaft 17B-1, a part of the New York City water supply's system Tunnel No. 3 required the excavation of approximately 38m (123ft) of water bearing overburden soil and 160m (527ft) of gneiss bedrock to make a connection to Water Tunnel No. 3. Ground freezing was specified as the method to provide temporary earth support and ground water control for the overburden material. The specifications required the placement of a temporary liner as the frozen earth was excavated. This paper describes the various approaches that were evaluated to determine a technically feasible, cost-effective lining approach. It further describes a comprehensive method of evaluating the frozen soil that ultimately led to the elimination of the temporary liner facilitating efficient and safe excavation of the shaft. Design, construction, and excavation methods are discussed.

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Extending immersion technology for the first immersed tunnel in the Alps

M.Ø. Sørensen & S. Sterkenburgh
Ramboll, Copenhagen, Denmark

J. Bubel
Ramboll, Hamburg, Germany

ABSTRACT: The Dreilindentunnel project is part of a larger development project which establishes a through-going train station in Lucerne. The project includes a 375 m long inner-city water crossing under the shallow water area of the Vierwaldstättersee. This paper addresses the comparison of the different tunnel types considered for the water crossing with their main challenges leading to the Immersed Tunnel as the preferred solution. The purpose of this paper is to disseminate knowledge of the Immersed Tunnel Technology and its benefits aiming to inspire owners to assess thoroughly the different tunnel types for each water crossing.

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Tunneling construction challenges on Mumbai coastal road project

V. Surana, J.D. Celentano & G.V.R. Raju
AECOM, India

M.M. Swami
BMC, India

ABSTRACT: This paper presents the challenges encountered in the construction of the twin 2.0Km, 12.2m diameter undersea Coast Road Tunnel. Construction of the Coast Road tunnel was unique in many respects as it extended the barriers previously undertaken in India's Tunneling industry. The TBM, "Mavala", named after a Maratha warrior, is currently India's largest and the Coast Road tunnel therefore India's largest TBM constructed tunnel. Additionally, the tunnel is India's first undersea tunnel and when commissioned its design will embrace all current International Highway Design and Operational Standards which include many unique Fire and Life Safety systems including what is believed to be the world's first Bi-directional Saccardo Ventilation system. The paper presents some of the many challenges in achieving these unique Indian firsts.

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Taxaquara fault – A complete solution for a complex problem

I.J.F. Teixeira, C.V. Chanquini, G. Aguiar & M. Vassalo
Acciona Construccion, Brazil

C.A. Campanhã, P. França, M. Gurgueira, D.D. Carlo & E. Fechio
CJC Engenharia, Brazil

ABSTRACT: São Paulo Line 6 is currently one of the most challenging projects worldwide. A design and build megaproject integrating the simultaneous construction of more than 15 km of TBM tunnel, 15 stations, 17 shafts and around 2km of non-mechanized tunnels. The main tunnel is divided in two streches, to be bored by two EPB-TBMs (10.61m OD) starting from the same shaft – VSE Tiete. The north run starts right in the transition between sedimentary soil and hard granite, with a 40m long parallel fault to the tunnel drive – Taxaquara Fault. A complete risk analysis of the construction methodoloy was performed, consubstantiated in a special geotechnical and hydrogeological survey, which concluded that the best solution would be the combination of twin shafts with a series of sprayed concrete lining (SCL) tunnels with external and internal dewatering. This paper describes the risk assessment, design, and construction phase necessary to successfully complete this challenge.

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Evaluation of over-excavation for Earth Pressure Balance (EPB) shields through data analytics

C. Teo, Y.L. Paterson, J. Kumarasamy & Y.H. Zhang
Department of Geotechnical and Tunnels, Land Transport Authority (LTA), Singapore

ABSTRACT: The utilization of EPB shields has advanced tunnel construction but there are still certain tunnelling risks such as settlements, sinkholes and movement/ vibrations to neighboring existing infrastructures (Shirlaw & Boone. 2005). In order to minimize and prevent such risks, derivation of over-excavation ratio by volume and weight of excavated material is required. Along with that, Building and Construction Authority (BCA. 2017) also enforced a regulation that over or under – excavation ratios (OERs) excavation should not exceed ±15% (over 115% or below 85%). However, in the local industry, the over-excavation ratios (OERs) reported by tunnelling contractors are based on rough estimation since factors such as spillages during the muck skips transportation, error from the crane measurement were unaccounted for. This paper reviews data retrieved from past tunnelling works, establishes a framework for back analyzing excavation data and proposes correction and bulking factors to better estimate the OERs.

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Numerical analysis of mechanical responses during the construction of multi-arch tunnel with central drift excavation method in shallow soft ground

Y. Tong, J.W. Chen, S.F. Wang, Z.H. Li & S.W. Chen
Broadvision Engineering Consultants, Kunming, China

Y. Yue*
Yunnan Communications Vocational and Technical College, Kunming, China

Z.K. Huang*
Tongji University, Shanghai, China

ABSTRACT: The multi-arch tunnel has been a vital component of mountainous expressway construction. In this work, a multi-arch tunnel with central drift excavation method in soft ground under shallow topography as well as shallow-unsymmetrical topography is simulated in conjunction with field application. Mechanical responses such as vault settlements and horizontal convergence deformations at the shoulder are analyzed for parallel sub-tunnels. Lastly, the crucial construction step as well as with the construction interference is revealed. The vault settlement is primarily triggered by the excavation of the upper bench area itself. The horizontal convergence deformation at the shoulder mainly increases during the excavation of the upper bench area itself as well as the middle bench area. Excavation of the central drift causes the initial disturbance. The subsequent sub-tunnel indeed adversely affects the stability of the antecedent one. The unsymmetrical topography aggravates negative mechanical responses and construction interference.

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Conventional excavation for widening of TBM bored tunnel by mechanical means for Shitladevi station, Mahim

Sunilkumar Vishwakarma
Tata Projects Limited, Mumbai

Arbind Kumar Rai
ITD Cementation Limited, Mumbai

Ravi Ranjan Kumar & Datta Binnar
Mumbai Metro Rail Corporation, Mumbai

Akash Devendra Shinde
CEC-ITD-TPL JV, Mumbai

ABSTRACT: This paper covers the widening of tunnel boring machine (TBM) bored tunnel on the downline to accommodate the platform for Shitladevi metro station which was carried out by conventional excavation by adopting only mechanical means due to presence of dilapidated buildings above the TBM bored tunnel.

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The use of fiber optics for ground and tunnel support monitoring – Two decades of lessons learned

N. Vlachopoulos
GeoEngineering Centre Queen's University – Royal Military College, Kingston, Canada

ABSTRACT: Two decades ago, the author along with his research group and industrial sponsor began to develop a novel Rayleigh-based distributed optical strain sensing technology capable of monitoring strain along a temporary support scheme at sub-centimeter spatial resolution. This line of research has been extended to monitor Fully Grouted Rock Bolts (FGRB) and rock mass deformation with an increased resolution of sub-millimeter spacing (0.65 mm). This non-trivial optical technique has been tested in the laboratory and has since been implemented at multiple active tunnelling and mining sites around the world. Within this context, this paper summarizes selected lessons learned over the past two decades regarding the use of fiber optics for monitoring the ground conditions and support elements utilized in underground excavations while also highlighting the evolution of the research, development, implementation and impact of this sensing technique with a view to optimizing and improving tunnel support design.

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Impacts and challenges faced during deep excavation 1125.3m, rock encountered its effects on support and solution: A case study review from Suki Kinari Hydro Power Project 870 MW Pakistan

H. Waheed
Tunneling Institute of Pakistan (TIP), Islamabad, Pakistan

A. Riaz
Frontier Works Organization (FWO), Rawalpindi, Pakistan
Tunneling Institute of Pakistan (TIP), Islamabad, Pakistan

A. Hussain & A.Q. Khan
Tunneling Institute of Pakistan (TIP), Islamabad, Pakistan

ABSTRACT: Tunneling through conventional excavation-based drill and blast method offers variety of challenges, especially when it comes to excavation in Himalayan region. Though every drill and blast tunneling project experiences few project specific issues, however, tunneling in mountains with higher overburden typically poses risks of rock squeezing, which may result in rock support deformation. Suki Kinari Hydropower Project (SKHPP) is one of the largest hydropower projects constructed in the northern part of Pakistan. The project includes over 40 KM of tunneling component, being constructed in high altitude mountains with overburden upto 1125.3m. During construction of Head Race Tunnel (HRT), the tunnel went through rock squeezing conditions. This study intends to apprise the event of rock squeezing in HRT, its impacts on provided rock support systems and mitigation measures taken by construction team at project site.

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Water inrush and countermeasures at a tunnel in South-Link Highway, Taiwan

T.T. Wang
National Taiwan University, Taipei, Taiwan

C.J. Kuo
Futsu Construction Co., Taipei, Taiwan

C.L. Tseng
CECI Engineering Consultants, Inc., Taipei, Taiwan

K.F. Lo
Directorate General of Highways, Taipei, Taiwan

F.Y. Hsiao
Sinotech Engineering Consultants, Inc., Taipei, Taiwan

ABSTRACT: During construction of the cased tunnel groundwater gushed out with a maximum discharge exceeding 27 ton/min, endangering the stability of the excavated face and seriously hindered the construction progress of the tunnel. The groundwater inflow with a discharge of exceeding 20 ton/min lasted more than 30 days. Emergency drainage and reinforcement measures were immediately applied to avoid groundwater inrush-induced catastrophic collapse from the excavating face. Supplementary geological exploration was carried out before long to investigate possible causes. After the geological conceptual model has been figured out and possible influencing factors that account for the water inrush event has been understood, groundwater drainage and grouting improvement measures were used to overcome the groundwater inrush event. This manuscript introduces the background of the tunnel project and the process of water inrush, summarizes the results of supplementary geological exploration, and finally puts forward suggestions on the construction of tunnels in the argillite-like formation.

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Numerical simulation of circular tunnel intersections in anisotropic rock mass

A. Zafeiropoulos & P. Nomikos
School of Mining and Metallurgical Engineering, National Technical University of Athens, Zografou Campus, Athens, Greece

ABSTRACT: Jointed and fractured rock masses are often encountered during underground excavations. Their anisotropic behaviour is crucial for stability assessments of engineering structures; such as tunnel intersections. This paper investigates the effect of rock mass anisotropy on the intersection of circular tunnels using 3D Finite Difference Method (3D-FDM). The results of the study show that the discontinuities in the anisotropic rock mass differentiate the stress field around the tunnel section, as the values of the principle stresses are oriented according to the joints' direction. Maximum displacement is developed in the areas where the discontinuities are tangential to the tunnel section, indicating the significant effect of the anisotropy's orientation. In addition, the plastic zone becomes asymmetric around the tunnel intersection, with a greater expanse in the areas where the rock mass discontinuities are tangential to the excavation.

Innovation, robotics and automation

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LiDAR navigation in underground openings

Z. Agioutantis, V. Androulakis, S. Schafrik & J. Sottile
University of Kentucky, Lexington, KY, USA

ABSTRACT: In recent decades, the technological advances in the fields of artificial intelligence, data analytics, computer architecture, and wireless communication enable the ever-increasing integration of autonomous solutions into the mining industry infrastructure. Smart mines are anticipated to increase the mine workers safety and health, as well as increase the performance of the smart mine sites. One of the ways to fulfill that goal is to integrate autonomous vehicles into the mining cycle. Autonomous navigation in underground, hence GPS-denied, environments is a complex and challenging task. Nevertheless, structured underground environments, such as room-and-pillar mines or underground tunnel networks, allow for lightweight solutions. The current research demonstrates the framework for autonomous navigation inside a room-and-pillar panel. An efficient navigation system that incorporates data management, LiDAR mapping, path planning, and control in real-time has been developed for a lab-scale prototype equipped only with 2D LiDAR scanners. A multiple Random Sample Consensus (RANSAC) algorithm extracts salient features from the 2D LiDAR maps, which are input to a Stanley controller to define the vehicle's motion. Simulations in a mock mine section have shown the reliability of the prototype to navigate around underground pillars. The same concepts can be applied to any system of underground openings with linear segments

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Utilising remote sensing to digitally map discontinuities in tunnelling

A. Allen, C. Paraskevopoulou & J. Smith
School of Earth and Environment, University of Leeds, UK

A. Bedi & M. Invernici
Bedi Consulting Ltd., London, UK

ABSTRACT: Extracting rock discontinuity parameters from a rock mass using remote sensing equipment, which is increasingly being mounted on remotely operated vehicles, is essential to improve safety, data processing efficiency and data quality. Over the last decade, research has focused on extracting rock discontinuity parameters from point cloud data collected from above-ground environments such as quarries, rock slopes, road cutting, etc. However, the extraction of rock discontinuity parameters from point cloud data via manual digital mapping and, more recently, using semi-automatic algorithms is steadily becoming the new normal. This research focuses on extracting rock discontinuity sets dip and dip direction from point cloud data collected from a drill and blast tunnel section. The approach has identified the limitation of using DSE in hard rock drill and blast tunnels and set the framework for additional research using the DSE and other semi-automatic algorithms in hard rock tunnels to extract rock discontinuity parameters from point clouds.

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A new approach to measure the stress level in tunnel linings of the Italian highway networks

G. Ascari, A. Dalle Fratte & A. Terraneo
AKRON S.R.L., Bovisio Masciago, Italy

C. Alessio & L. Baccolini
TECNE Gruppo Autostrade per l'Italia S.p.A., Rome, Italy

ABSTRACT: In the framework of ongoing design activities focused on the rehabilitation works of almost 600 highway tunnels of Autostrade per l'Italia's network, a smart analysis method which mixes historical calculation techniques with innovative standards has been developed. The key point of the method is the reliability of measurements regarding the actual stress level acting in existing linings, since it directly involves tunnels stability during the construction stages as well as tunnels' strength and resilience in the long term. The experimental measurement of the stress level in the tunnel linings typically leads to a set of uncertainties and issues: the need to define standardized survey procedures which can be carried out under objective conditions, significance level/surrounding conditions/validity of measurements and, finally, how to use measurements for design purposes. Following the statistical analysis related to a large database consisting of over 1,500 results of standard flat-jack tests, an experimental stage ranging from the depth of lining cutting and to the collection of strain measurements in the surrounding lining intrados by means of highly dynamic and sensitive sensors has been developed. This experimental stage has provided the main elements to assess the reliability of flat-jack test results and, in particular, to assess whether its actual representativeness is limited to the stress level acting on the lining intrados side or - and, in case, how - it can be extended to the whole lining thickness.

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Automated tunnel design with Dynamo and SAP2000

B.A. Boye & M.J. Wilcock
Jacobs

ABSTRACT: Tunnel lining designs are complex, requiring the combination of both geotechnical and specialist structural skills, often demanding thousands of hours of design effort for a single detailed design. The design is computationally demanding, and much of the design process needs to be performed consistently across different projects. As such, the initial development costs of an automation tool for tunnel lining design is justified to realise long-term benefits of improved design quality and time savings.

TunLIN is one such automation software that has been developed by the author and in-house team at Jacobs. At the core of TunLIN, the essential tasks which are required for all (or almost all) tunnel lining designs are performed from the fewest number of user inputs, and importantly, inputs are only ever defined once and in a format that is easily auditable. The calculations that TunLIN performs are processed in coded modules, using multiple programming languages. The source coding is fully auditable, protected and secure, with past revisions backed up. The user interaction with TunLIN is managed through AutoDesk Dynamo, specifically through the Civil 3D platform. Here, the project topographical and geospacial information can be pulled into TunLIN directly from the Civil3D alignment, or, alternatively, this information can be input by the user through tables within an Excel user input file. This single source of truth also contains material and action factors, load combinations, soil model, joint model amongst others. TunLIN can perform tunnel design using closed-form methods, or it can autonomously generate Finite Element models in SAP2000 or Plaxis; including extracting results and performing post processing.

This paper presents an overview of how TunLIN could be used to design a section of in-situ concrete tunnel lining for a new build nuclear power project using SAP2000, in particular how TunLIN could be a benefit on such a project where designs must undergo the greatest rigour and due-process.

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A collaborative inspection system composed of quadruped and flying robot for crack segmentation in tunnel environment

H.H. Chu & R. Cao
College of Civil Engineering, Hunan University, Changsha, China

L. Deng
Key Laboratory of Damage Diagnosis for Engineering Structures of Hunan Province, Hunan University, Changsha, China

ABSTRACT: Advanced robotic systems involving unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) have shown advantages in detecting damaged infrastructures, such as bridges, buildings, and nuclear power plants. Due to their ability to leverage varied vantage points, a robot team of heterogeneous UAVs and UGVs could collect full space information of the structure with wider coverages and higher robustness compared with that from each robotic platform alone. However, critical issues still exist when applying the UAV-UGV inspection system in the tunnel environment. One major problem is that the lack of light and GPS signals may lead to a higher probability of UAV collisions. Another problem is that the road surface in the tunnel is generally uneven with many obstacles and puddles, which could hinder the travel of traditional wheeled or tracked UGVs. To address the above issues, a novel collaborative robotic system was proposed that consists of a quadruped robot with strong obstacle-striding abilities and a collision-resilient UAV. In the proposed inspection framework, the quadruped robot follows a pre-planned path and scans the tunnel lining with the vision sensor. Based on the scanning results, the UAV equipped with a protective cage would be launched from the helipad of the quadruped robot to perform a closer inspection. To correct its flight trajectory and protect the UAV, a GPS-free self-localization algorithm is constructed based on the data from the onboard computer, camera, and inertial measurement unit (IMU). Finally, to ensure that the tiny defects can be detected efficiently, a multi-scale feature fusion segmentation network with the attention mechanism was applied to images taken by the UAV. The performance of the system is validated against a field test, which demonstrates the feasibility of developing and deploying a collaborative inspection system using quadruped and flying robots for tunnel inspection.

Keywords: Tunnel Inspection, UAV UGV Collaboration, Deep Learning, Quadruped Robot, Defect Segmentation

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Integration of robotics in underground mining construction works

C. Crespo
Acciona Tecnología y Servicios, Madrid, Spain

F. Rodríguez
Acciona Infraestructuras, Santiago de Chile, Chile

ABSTRACT: Since November 2021, Acciona has been testing the SPOT quadruped robot (Boston Dynamics' Spot) in the underground mining site in Chile, with the main goal of reducing risks for human personnel while increasing process control and productivity. The following tasks are currently being performed by the robot: high precision scanning for section control, high precision scanning after applying shotcrete to perform quality control by measuring the thickness, thermal monitoring of the shotcrete to estimate setting level and early mechanical resistance, image acquisition of the tunnel face that allows generating a geologic report and robotic exploration of the tunnel after blasting, to identify misfired explosives.

Acciona's Robotics & Automation team has implemented several sensors over the robotic platform Spot: Leica's RTC360 scanner, Leica's BLK360 scanner and Teledyna's GXM320 thermal camera. Thanks to this integration, the robot can execute scans and taking thermal images. Together with the environment sensing, obstacle detection and autonomous capabilities of the robot, Spot can navigate autonomously through the mine, collecting data and generating automatic reports.

The Robot has demonstrated the ability to move through the aggressive environment of a mine with unstable rocks, water and mud, without many problems. Areas with low illumination have been no issue thanks to the LiDAR system incorporated on the robot. Also, the navigation and autonomy systems have been able to work in these circumstances, performing well despite the differences in the environment for each location.

This paper covers the design of the activities to be performed by the autonomous system, the system and the integration of its payloads and the results of the integration of this platform into a mining construction site.

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New development of sprayed concrete with improved waterproofing, durability and sustainability performance

K.G. Holter
Norwegian Geotechnical Institute, Oslo, Norway

T.A.M. Hammer
SINTEF, Trondheim, Norway

N.H. Trussell
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: Sprayed concrete in combination with rock bolts is successfully being used for permanent rock support in tunnels. The main shortcoming is that sprayed concrete alone is unable to function as the permanent waterproofing with strict requirements on a dry interior tunnel surface. Final linings with precast or cast-in-place concrete with sheet membrane waterproofing represent an excessive structural design in hard rock conditions. The SUPERCON research project (Sprayed sUstainable PErmanent Robotized CONcrete) is currently aiming to improve the sprayed concrete technology to enable a permanent waterproof tunnel lining, based entirely on sprayed concrete.

Laboratory and full scale spray application testing include innovative mix designs with significantly reduced cement content. The effects of the use of fly ash and limestone powder binder replacement, hydration accelerators and high-performance shrinkage reducing agents as well as adding of polymer modification to the concrete mix and special steel fibres for the distribution of cracks in the hardened concrete were studied. A significant reduction of the autogenous shrinkage potential, and a reduction in the water transport (capillary suction and permeation) through cracks in the concrete using polymeric modification of the concrete was achieved. The use of shrinkage reducing measures in the mix, combined with anti-dryout measures on the sprayed concrete surface significantly reduce cracking risk. The research results so far indicate the feasibility of a waterproof sprayed concrete without a waterproofing membrane.

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Mobile mapping systems and algorithms for Italian tunnel assessment

F. Iacobini & A. Pranno
Rete Ferroviaria Italiana – Technical Department, Rome, Italy

ABSTRACT: Over the last few years, mobile mapping systems for monitoring civil railway works have found widespread use because they offer several advantages to Infrastructure Managers. Since 2013, RFI, the Italian Infrastructure Manager, has started a project for surveying the railway tunnels with mobile mapping systems. This system is based on the integration of different sensors on a railway vehicle. The system collects a large set of data about the geometry and the defects of tunnel lining. By means of a specific algorithm there is the possibility to define a priority in the planning of maintenance interventions and a comparison of different tunnels. The use of mobile mapping systems clearly represents a powerful tool for Infrastructure Managers. The paper shows up the main features of the technology, his advantages and the results obtained.

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Automation of tunnel lining construction with self-compacting concrete: Full-scale experiment and numerical simulation

K. Kato, H. Koyama, T. Hiromitsu, S. Fujiwara, C. Kuroda, N. Utagawa, T. Ono & Y. Uno
SATO KOGYO CO., LTD., Japan

ABSTRACT: There are increasing demands to construct tunnels without skilled laborers as facing a decrease in the number of laborers in the tunnel industry in Japan. The construction automation of tunnel linings with Self-Compacting Concrete (SCC) has been developed to be constructed without skilled laborers. Concerning placing the SCC, managing the placement and predicting the flow of the SCC is critical for verifying the construction automation.

The full-scale experiment was carried out with the construction automation. The full-scale lining formwork was prepared to construct the lining that is 9.22 m wide, 6.61 m high, 10.50 m long, and 0.40 m thick. The SCC was alternately placed through the steel pipe installed on the lower center of the right and left side of the formwork using a concrete pump until the formwork was filled with it. The placement of the SCC and the pressure acting on the formwork were monitored in real-time. During the experiment, the volume of approximately 80 m^3 of the SCC was placed.

The lining concrete was placed in approximately 3 hours with 3 skilled laborers. Also, the post-investigation showed that the lining concrete could be placed with quality using the concrete pump only. The proposed construction automation of the tunnel lining can contribute to reducing the number of skilled laborers, and improving quality and safety.

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Vision-based measurement method with segmentation for concrete tunnel crack inspection

J. Kim, J. Park & G.C. Cho
Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Republic of Korea

S. Shim
Department of Geotechnical Engineering Research, Korea Institute of Civil Engineering and Building Technology (KICT), Goyang, Republic of Korea

ABSTRACT: Many underground infrastructures have been built as technology has advanced, and today, after 30 years or more, they are in a state of deterioration, necessitating safety management. As the necessity is emphasized, many studies using computer vision are being conducted to overcome problems such as the high cost and lack of objectivity of the conventional method that relies on manpower. Many studies are focused on deep learning-based crack detection, and research on crack quantification essential for inspection is still insufficient. In this study, a method to obtain the crack width of a concrete surface based on computer vision was proposed through a lab-scale experiment and compared with the previously studied method. Methods to increase applicability by overcoming the limitations of RGB-D cameras were additionally presented and analyzed. The results of this study are expected to play a significant role in the future development of automated systems for concrete tunnel cracks.

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Underground replacement of a 100 year old tunnel using the sequential demolition method

G.J.E. Kramer, P. Eng. & J. Habimana, ing
Hatch, Canada

ABSTRACT: The Réseau Express Métropolitain (REM) by la Caisse de dépôt et placement du Québec (CDPQ) is a major transit project in Montréal, Canada. The automated LRT system will include 26 stations connected by 67 km of track. A section of the REM goes through the 5 km long existing Mount Royal Tunnel which was completed in 1917. The southernmost 540 m of the tunnel was constructed using a clever double arch consisting of plain concrete precast segments. A 92 m length of which was not in an acceptable condition after 100 years of deterioration and required replacement. This paper describes the implementation of an innovative sequential demolition and replacement method that was performed completely underground and coined "The Sequential Demolition Method". The design was developed by Hatch with the Joint Venture CIMA + HATCH (CCH) retained by REM to oversee implementation by the NouvLR on a cost reimbursable approach.

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Automation in segmental lining production, use of robots, hydraulically systems and artificial intelligence

Stefan Medel
Herrenknecht AG, Division Formwork, Schwanau, Germany

ABSTRACT: Worldwide construction companies are suffering from the lack of getting skilled and experienced workers for the production of lining segments for TBM-driven tunnels. For many years the focus was on how to reduce manufacturing costs, but now its solely about getting required staff. As this was getting more and more important, Herrenknecht decided to invest in automation systems for the segment production. Such systems are now in place and proving that a significant reduction of labour is possible without reducing output and quality requirements.

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New products for rapid refurbishment of existing tunnels

D. Michelis
MAPEI S.p.A, UTT – Underground Technical Team

E. Dal Negro
MAPEI S.p.A, UTT – Underground Technical Team, Business line Director

ABSTRACT: Underground infrastructures are becoming more and more of utmost importance for designer, construction companies and suppliers as it is necessary to adopt new approaches to build durable infrastructures and to refurbish the existing ones with rapid and efficient methods.

It is important that the construction products are engineered to satisfy the main urgent and long-term objectives, such as mechanical properties and durability under the specific condition of use, and to match the required timing necessary to fulfill the goals under safety conditions. Under these conditions, the producers of construction chemicals must provide certified cutting-edge technologies, including pre-bagged mortars for bolting, light weighted products with fast development of mechanical properties, waterproofing systems able to contrast and manage water inflows, in combination with solutions to refurbish concrete even with heavy thicknesses.

It is clear that a strict relationship between designer – construction company – chemical producer is mandatory to fine-tune innovative solutions that can benefit the development and finalization of all phases of a complex system.

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The use of an innovative fiber optic methodology to capture the axial response of rib spacing and grout annulus effects on grouted rock bolts

K.S. Moore & N. Vlachopoulos
Royal Military College, Kingston, ON, Canada

ABSTRACT: The fully grouted rock bolt is used extensively as a ground support element within various underground projects. The physical testing of available research is largely focused on small embedment length samples as historic monitoring techniques and technologies have noted limitations as it pertains to capturing the mechanical behaviour of longer samples. To address this gap, the authors have developed a monitoring technique using fiber optics. This methodology captures the axial response by producing a continuous strain profile along the length of the rebar as well as the representative confining medium across a wide range of loading. This paper summarizes the results of a robust laboratory investigation to determine the impact of rib spacing arrangements as well as the size of grout annulus on bolt performance as it relates to rock bolt behaviour. The efforts of such results will be used to improve rock bolt support lengths for ground design purposes.

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Innovative steering of tunnel boring machines

Emil Nathanson, Stefan Mauerberger & Gerhard Wehrmeyer
Herrenknecht AG, Schwanau, Germany

ABSTRACT: Directional steering of tunnel boring machines is a process of minimizing horizontal and vertical deviations with respect to a designed tunnel alignment. Until today, shield machine operators perform steering manually for example by adjusting thrust cylinder pressures. At the same time, they need to monitor the entire tunnelling process and interact with the tunnelling team. How well this is executed depends to a large extent on the professional experience of the operators. Construction companies are having increasing difficulties finding qualified personnel for tunnelling. One reason for this are the high complexity of tunnel boring machines and their operation. In addition, the training of operators is time-consuming and usually takes place during tunnelling. To enable operators to cope with tunnel boring machines efficiently and safely, the steering system is being developed further step by step towards a fully automatized system. An important milestone is the development of semi-automatic control of active steering actuators. In this article, an innovative thrust cylinder control system and the respective intuitive human-machine interface are presented.

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Innovative methodology for advanced structural condition assessment of tunnels

A. Parasyris
University of StrathClyde
D. Bairaktaris & Associates Ltd.

D. Bairaktaris
D. Bairaktaris & Associates Ltd.

ABSTRACT: A methodology for holistic structural condition assessment of tunnels through high technological monitoring tools is proposed in this article. The methodology is divided into structural evaluation in real time through pre-installed equipment at the construction phase, and to post event structural evaluation through robotic inspection. The first part focuses on the static evaluation of the permanent tunnel lining after a strong earthquake in real time through fiber optic measurements. For this purpose, an improved type of fiber optic sensors is used, installed on inner and outer transversal reinforcing bars at eight points along the perimeter, allowing the recording of the time history of the elongation developed during the seismic action. A reformulation of the Parc-Ang criterion has been developed, allowing accurate automatic estimation of the degree of damage in each critical section according to the Moment-curvature diagram and the overall degree of indeterminacy of the structure. In the second part, the innovative model for crack analysis is described extensively, through which it is possible to calculate internal forces at the position of the structure where the crack is occurred, but also to estimate the possible locations of invisible cracks in the back face, based on the measurement of cracks' geometrical characteristics (widths, depths, angles and spacings) with sensors placed in robotic tools. Soil pressures and the internal forces N, V, M along the perimeter of the tunnel cross-section are calculated based on convergence measurements along 5 cords. The appropriateness of the methodology has been validated through the European Research Programs Tunneling, Monico, Robospect and Resist while the numerical results presented in this paper are obtained by application of robotic measurements in autonomous software packages implemented in JAVA programming language.

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3D printing of tunnels

D.P. Phillips & T.M.A. Delport
hyperTunnel Ltd., UK

ABSTRACT: Construction of underground tunnels via tunnel boring machine (TBM) is regarded as costly – particularly in terms of human labour, machine construction and material requirements, and significant time duration of projects. Several recent examples of this construction method demonstrate the large cost and time associated with manufacturing TBMs prior to the actual tunnelling process beginning, as well as the requirement of the TBMs to be supported by hundreds of personnel. When deployed to construct kilometres of tunnel, advancement rates result in projects typically taking years to complete. hyperTunnel proposes an alternative construction method which "3D prints" tunnels using swarm robotics – *hyperSwarm*. hyperSwarm consists of thousands of small individual tunnelling robots working concurrently in an effort that is envisaged to substantially reduce environmental impact, reduce project lead-time to months rather than years, and reduce costs by orders of magnitude. Advanced integration and management of the robotic swarm means only a small team of engineers would be required to remotely operate the swarm, presenting further benefits in labour costs, as well as health and safety. An overview of the 3D printing construction method deployed by hyperSwarm, as well as its development, is provided. Various stages of the development are detailed, including robotic functions and the way construction materials are controllably placed to form underground structures ahead of the tunnel excavation.

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Long-term structural behavior of inner-city segmental tunnel linings investigated by an innovative structural monitoring

F. Rauch & O. Fischer
Chair of Concrete and Masonry Structures, Technical University of Munich, Munich, Germany

ABSTRACT: In the prognosis of internal forces in segmental tunnel linings engineers face major uncertainties. This is due to e.g. the complex load-bearing behavior and simplified assumptions in calculations. It leads to an unclear reliability of segmental linings, which is unfavorable especially in challenging loading conditions e.g. due to high-rise buildings in the vicinity of inner-city tunnels. Hence, a better insight into the real structural behavior and the actual internal forces is desirable. So far no standardized or well-established structural monitoring system exists for segmental linings. This is why a new innovative structural monitoring system for long-term measurements has been developed. The monitoring system is applied to the segmental linings of a newly build inner-city tunnel. The development process, the instrumentation and the functionality of the system are presented as well as measurement results. Finally, insights into the real structural behavior gained by the measurements are given and findings are discussed.

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Automating fault identification along the HS2 Chilterns tunnel alignment from aerial LiDAR scanning

G. Sercombe & C. Paraskevopoulou
School of Earth and Environment, University of Leeds, UK

A. Bedi
Bedi Consulting Ltd., London, UK

I. Vazaios
Ove Arup & Partners Ltd, London, UK

ABSTRACT: Faulting along the HS2 Chilterns tunnel alignment is underreported, so remote sensing data is used to identify the location of faults. The growing accessibility of remote sensing data means it is increasingly being harnessed for site investigation. However, this data is often large and time intensive to interrogate manually. As such, computer vision techniques can be employed to automate the identification of faults and tectonic lineaments along linear infrastructure in LiDAR-generated digital terrain models (DTM). This work aims to investigate how the surface expression of a fault can be seen in a region's geomorphology using LiDAR data and to generate a DTM creating a script that automates fault identification using computer vision and evaluates the performance of the workflow against manually identified faulting. The algorithm is susceptible to man-made features and performs better at larger scales. Most manually identified faults had corresponding tectonic lineaments; however, not every detected line segment corresponded to faulting. The results suggest that automated lineament extraction can be an effective tool for preliminary site investigation but should not be used without subsequent ground investigation to confirm any conclusions drawn.

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Underwater car keeps current flowing

M. Short
Kelley Engineered Equipment, LLC (KEE), Seattle, Washington, USA

S. Drobny
Ballard Marine Construction, Washougal, Washington, USA

ABSTRACT: In 2018 the Great Lakes Water Authority contracted a design-build repair project of the raw water tunnels that supply fresh water to the city of Detroit Michigan. The contract purpose is to fix extensive cracking and degradation of the tunnels observed in earlier investigations. Typically, new tunnels would be constructed to replace the old failing tunnels. This requires long lead time TBM's and the associated costs of tunneling as well as service interruptions when the new tunnels are connected. Ballard and Kelley have worked together to create a new method wherein a team of divers partnered with a Kelley designed pipe transporter to install stainless steel liner plates in the existing tunnel in-situ with its use, thereby extending the life of the water utility without interruptions to service.

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Some hydro-mechanical properties of treated sand with colloidal silica

G. Spagnoli
DMT GmbH & Company KG, Essen, Germany

G. Tintelnot
TPH Bausysteme GmbH, Norderstedt, Germany

ABSTRACT: The following paper shows some hydro-mechanical tests performed on a sand grouted with varying colloidal silica mixtures. By diluting the original product, i.e. part A which is the Geogrout seal with 40% solid content, and additionally changing the amount of accelerator, part B, the soil mechanical improvement was investigated. Unconfined compressive strength tests, permeability and direct shear tests were performed on the non-treated and treated sand. Some statistical considerations have been also performed. Results clearly point out the increase in strength and decrease in permeability, therefore indicating the colloidal silica as a valuable solution for ground improvement by grouting.

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The benefits of InSAR monitoring during the construction of the Ceneri Base Tunnel

D. Stocker, D. Merlini & M. Falanesca
Pini Group Ltd, Lugano, Switzerland

A. Del Col
AlpTransit Gotthard, Luzern, Switzerland

C. Gervasi & I. Iannicella
TRE Altamira s.r.l., Milano, Italy

ABSTRACT: This paper introduces the InSAR method as an advanced tool to measure and monitor ground displacements during all phases of a tunnelling project. The monitoring was focused on the southern sector of the tunnel which was the most densely urbanized area and with a low overburden. The extensive monitoring system included both standard activities (measurements of vibration phenomena, topographical measurements from the surface, monitoring of groundwater levels, assessments of the condition of the buildings before, during and after the works) and the innovative satellite monitoring system InSAR. The area subject to satellite monitoring has a length of approx. 5.5 km and a width of 1 km, 500 m on both sides of the tunnel axis. SqueeSAR® information is summarized for specific areas following the progression of tunnelling. Finally, the results from the design predictive analyses, the in-situ deformations recorded during the excavation and the satellite monitoring data are discussed.

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Storytelling as collaboration support for 3D tunnel monitoring

C. Traxler
VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, Vienna, Austria

K. Chmelina
GEODATA Ziviltechnikergesellschaft mbH, Vienna, Austria

ABSTRACT: In this paper we present a prototype system for collaborative visual analysis of tunnel monitoring data. Remotely located analysts (e.g., geotechnical experts) explore a dynamic 3D scene either with conventional desktop setups or fully immersive with virtual reality headsets. They can inform peers about results and insights by creating a presentation with integrated storytelling mechanisms. The experience is based on a 3D scene of a construction site, featuring digital twins of tunnels as key elements, which are enhanced by geospatially anchored sensors. Animated visualizations show the progress of the construction and its effect on sensor values. A story is defined by choosing stations and timepoints in the 3D scene and adding narrations and additional media. Storytelling is a powerful method for asynchronous collaboration because it makes an analysis session more comprehensible and reproducible, thereby increases trust. Furthermore, it is also very effective for the training of apprentices.

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Continuous advance – developments for a new Herrenknecht TBM

J. Tröndle, G. Wehrmeyer & F. Steiner
Herrenknecht AG, Schwanau, Germany

ABSTRACT: Conventional mechanized tunnelling is separated into two consecutive process steps, the advance and ring building. In the past it was not possible to run both processes in parallel. During ring building the machine is stopped, so ring building is associated with a loss of time for the advance. To increase the efficiency of the tunnel excavation process, the machine is equipped with a system for continuous mining. The two process steps can be carried out at the same time, which improves overall performance and reduces project runtime and thereby the cost of the project. The continuous advance increases the total daily advance rate by a factor of up to 1.6 compared to the discontinuous state-of-the-art advance, resulting in a significant reduction in construction time especially for longer tunnels. In addition, higher system performance and utilization increases energy and resource efficiency, so the environmental impact is significantly reduced.

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Characteristics of laser ablation-excited vibrations in concrete

N. Yasuda
Kyoto University, Kyoto, Japan

T. Asakura
Research group for tunnel engineering, Chiyoda-ku, Tokyo, Japan

ABSTRACT: This paper reveals the characteristics of laser ablation-excited vibrations in concrete through laboratory experiments by comparing the frequency response function obtained from hammer-induced vibration. The results show that the characteristics of laser-excited vibration are not flat, and high-frequency vibration is more strongly excited. This is because the excitation source of the laser ablation-excited vibration is not the reaction force of material removal from the concrete surface but the sound pressure excited by laser ablation. Therefore, it is necessary to consider these vibration characteristics and the vibration excitation source when the laser ablation is used as a substitute for a hammer.

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Detection system of inner lining cracks for the Athens Metro

P. Yiouta-Mitra
National Technical University of Athens

L. Lecornu
IMT Atlantique

Z. Mouroutis
Attiko Metro S.A

ABSTRACT: A significant aspect of a subway tunnel condition assessment is the systematic inspection of the inner concrete lining state. Fractures and cracks are one of the most common problems of the tunnels in service. It is therefore necessary to detect and classify them according to their characteristics and danger level. Underground infrastructure such as metro tunnels comprise many kilometres in length. Innovative technology is vital for the efficient maintenance through detection of possible failures due to fracturing. We will present a new semi-automatic system of detection of crack presence under development for the Athens metro. The system is composed of an acquisition system (camera) geolocated, a module of cracks detection and an analysis module. In this paper, we will focus on the system core, i.e. segmentation and extraction of the fractures. The segmentation module is based on a class of artificial neural network deemed more suitable for the analysis of visual images, i.e. an efficient convolutional neural network (CNN). So the first step of this study is to find the most suitable CNN and its optimized parameters in terms of precision. Several CNN will be compared. The extraction module will first extract the segmented cracks and then define a set of parameters such as length, width, area and form. This extraction takes into account that the camera has limitations and a crack could be present on several images. Future applications of this system include the automatic surveillance of the fracture evolution in time and the application of adapted prevention measures.

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Compressible linings solutions: A multi-scale mechanical and technical demonstration up to a full 6m diameter surface loading “accelerator” device

J. Zghondi & G. Armand
ANDRA, Meuse/Haute-Marne Underground Research Laboratory, Bure, France

L. Kerner & B. Terrade
University Gustave Eiffel, MAST/EMGCU, Champs-sur-Marne, France

N. Dias & J.M. Bosgiraud
ANDRA, Châtenay-Malabry Cedex, France

ABSTRACT: Compressible linings can be the solution for deep underground tunnels with differed mechanical behaviour. That is the case for the geomechanical response to excavation prevailing in the mid-level of the Callovo-Oxfordian (COx) claystone formation where Cigéo (the French Deep Geological Repository) will be implemented. In order to optimize the lining thickness, Andra studies different compressible solutions. An ongoing qualification process was set out, starting from the qualification at the product properties level until reaching the implementation phase in an experimental tunnel. The article presents the ongoing program, where qualification is twofold: scientific and technological. The solution concept has to prove that elasto-plastic behaviour remains uncompromised in a lining at full scale ~~at~~ while answering technological requirements at the different conception stages. A higher level of robustness was proposed by Andra and its partner University Gustave Eiffel (France), using a surface “accelerator” ring loading test system. This unique experimental device allows different loading simulations of long-term Cigéo interface behaviour, on different compressible full rings solutions (6m diameter). These loading tests confirm the long-term compressible behaviour of the rings and provide data to consolidate specific behavioural law modelling. The positive outcomes of this technical process will provide “elements of proof” of the robustness of the compressible lining designs forecast for Cigéo.

BIM, big data and machine learning applications in tunnelling

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BBT, Lot Mules 2–3. Application of machine learning on TBM parameters for risk prediction tools

F. Amadini & A. Flor
Systra - Sws, Trento, Italy

M. Secondulfo
Ghella, Rome, Italy

D. Baliani
Webuild, Rome, Italy

F. Cernera, M. La Morgia, A. Mei & F. Sassi
Department of Computer Science, Sapienza University of Rome, Italy

ABSTRACT: The risk of TBM jamming because of squeezing rock mass or excessive caving (instability of the cavity) conditions is always a focal point while boring long and deep tunnels with shielded TBMs. Mechanized excavation provides a large amount of real-time data, for each machine's parameters. Several analyses have been executed to assess the correlations between different sets of TBM parameters for the exploratory tunnel. Instead of analysing the full dataset, a different approach is proposed, with data processed sequentially to simulate the real excavation situation. The probability distributions are recalculated together with their statistical parameters while advancing. This approach is extended also to the training of a Machine Learning model able to foresee the behavior at future rings based on past rings (using a Recurrent Neural Network). The predictions show a promising first step toward creating practical tools that can assist contractors and designers to correlate and predict TBM excavation data. These tools will assist to predict and quantify high risk situations that could arise during excavation.

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Multi-camera-based tunnel segment detection and inspection using Artificial Intelligence

A. Boerzel & F. Werres
VMT GmbH, Bruchsal, Germany

L. Steinmann, J. Fehrenbach & D. Fehrenbach
preML GmbH, Lahr/Schwarzwald, Germany

ABSTRACT: Tunnel segments for large traffic tunnels are subject to the highest quality standards in the concrete precast industry. Given their large dimensions, it is inevitable that various defects occur during production or transportation. This paper presents a novel approach to the quality control of the segments at the latest possible location inside the tunnel boring machine (TBM) before the final ring erection. An artificial intelligence (AI) based computer vision (CV) software was developed to check images of the segments, with the images being collected by four cameras inside the TBM. The system “segment check” is able to detect missing dowels and misplaced seals, as well as cracks and spallings. By adopting various AI-based image processing modules, this work is on the forefront of applying AI in the tunnelling world. Results show high accuracy for a 3D pose estimation network of the segment, as well as for the segmentation and classification networks which are used to perform the quality inspection.

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BIM modelling of underground structures in the design and operation phases. What can we expect?

S. Charlemagne, F. Robert, M. Macary, J. Doreau-Malioche & C. Banos
CETU (Centre for Tunnel Studies), Bron, France

ABSTRACT: The use of BIM (Building Information Modelling) is growing rapidly in the field of infrastructures. The CETU carried out an experiment consisting in modelling two underground structures as fully as possible in order to check whether the expectations stemming from business uses can be correctly dealt with. The first tunnel, at the design stage, made it possible to question the benefits of BIM in terms of project management, to process the civil engineering and equipment interfaces, the clearance and the representation of the geology, hydrogeology and geotechnics. The second tunnel, in the operation phase, dealt with issues relating to asset management, retro engineering based on points cloud and the reporting of inspections and defects on civil engineering and equipment.

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Tunnel-Crack-DatasetGAN: A multi-scene deep domain adaptive crack generator for tunnel-lining crack segmentation

H.H. Chu
College of Civil Engineering, Hunan University, Changsha, China

E. Agapaki
M.E., Sr. Rinker School of Construction Management, University of Florida, Gainesville, USA

L. Deng
Key Laboratory of Damage Diagnosis for Engineering Structures of Hunan Province, Hunan University, Changsha, China

ABSTRACT: Lining cracks are the most common structural damage and are critical for the service life of tunnels. Their early identification is important to monitor damage while ensuring tunnel safety. The use of deep learning (DL)-based methods to detect cracks on the surface of tunnel linings has attracted increased attention in recent years. However, DL-based tunnel crack segmentation methods have two major limitations: one is the lack of sufficient tunnel crack images, and the other is the lack of refined image labels, each of which is time-consuming and labor-intensive to capture in the tunnel environment. To solve these problems, a multi-scene deep domain adaptive crack generator called Tunnel-Crack-DatasetGAN (TCDGAN) is proposed inspired by a novel generative adversarial architecture—DatasetGAN. TCDGAN can be used to automatically generate synthetic tunnel crack images, hence overcoming the aforementioned restrictions. With the consideration of the characteristics of tunnel cracks, three improvements are proposed based on the original DatasetGAN architecture. Firstly, the constant learned input in the original style-based generator is replaced by Fourier features, which improves the equivariance of the generated refined crack branches adjacent to the main crack. Secondly, a novel strategy called adaptive pseudo augmentation (APA) is introduced to alleviate the overfitting problem that may occur due to insufficient source-crack images for initial training. Thirdly, a path length-based regularization operation is introduced to ensure that the model can converge to the optimal gradient during the training process. By these means, the proposed TCDGAN can be utilized to generate massive tunnel crack images with high-quality pixel-wise masks requiring a handful of source-crack images and minimal human effort. The quality of the synthesized tunnel crack image-mask pairs was visually evaluated, and the good performance of some representative segmentation models trained by the synthetic dataset demonstrates the feasibility of the proposed method.

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Quantitative estimation of TBM disc cutter wear from in-situ parameters by optimization algorithm improved back-propagation neural network: A case study of a metro tunnel in Guangzhou, China

X. Ding
School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China
South China Institute of Geotechnical Engineering, South China University of Technology, Guangzhou, China

A.Y. Xie
Department of Civil and Environmental Engineering, Western University, London, Canada

H. Xue
School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China

ABSTRACT: Unplanned worn disc cutters maintenance can cause casualty and financial loss. Good knowledge of cutter wear will facilitate the design of the excavation plan and elongate cutter life. Cutter wear is subject to multiple influential factors, which can be regarded as a nonlinear multivariate question. Back propagation neural network (BPNN), a robust machine learning method in this field, can shed light on it. A shield tunneling section from Metro Line 18 in Guangzhou, China, only encounters hard rock strata. There are 49 manually measured cutter wear. The tunnel boring machine records over 250 types of parameters per second with a real-time logging system. According to 28 types of influential parameters from previous studies, 14 input parameters are selected to reflect the effect of machine, geology, and operation on the output, cutter wear, which is quantified as the average radial reduction of cutter ring. By extrapolation and interpolation, a dataset with 1434 samples is established from the Pan-nan section. Cutter wear is distributed to each ring within the inspection section with a published model. To overcome the inherent weakness of BPNN, we apply SMBO (Sequential Model-based Optimization) and GA (Genetic Algorithm) and compare their effectiveness. SMBO and GA returns model with R2 of 0.968 and 0.971. Error tracing reveals GA model tends to overestimate records with slight wear.

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Tunnel 4.0: Managed digital twin for tunnel operations

N.S. Diren & S. Althen
Yunex GmbH, Munich, Germany

ABSTRACT: Many processes can be replaced by digital twins to increase efficiency by performing actions that would be difficult to perform in the real world. This concept attracts increasing attention, especially for tunnel projects where real-world testing requires tunnel closing during operation. Scenarios can be tested in a digital environment in full compliance to health and safety guidelines and without extra cost using a Digital Twin. It integrates various data repositories, processes, and applications such as BIM, Asset Management, Traffic Management & Control, and Traffic Simulation to test and validate potential interactions around the asset - not only for scenario testing, but also for functionalities such as maintenance and operator training, design verification, and operation optimization. Furthermore, each of these activities and processes have their own toolchain and dataset, and use-cases are limited to the individual application. To employ the connectivity of this integration, it is necessary to create a single digital representation of the entire asset in which all project participants fulfill their responsibilities throughout the project life cycle. This paper explains the proposed "Managed digital twin" for tunnel operations with a case study of an existing tunnel project in Germany.

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Tunnel euralpin lyon turin CO8– Design of temporary support profile of base tunnels and cross-passages

A. Ettaouil
Pini Group, Paris, France

G. Ragazzo
Systra-SWS, Torino, Italy

J. Pepiot
JV Implenia/NGE-GC/Itinera/Rizzani De Eccher

B. Bitetti
Pini Group, Paris, France

L. Peano
Systra-SWS, Paris, France

F. Rich
Pini Group, Paris, France

ABSTRACT: The new Lyon-Turin railway project involves the construction of a 57 km twin-tube tunnel between France and Italy. Pini France and Systra-SWS are the designers of the construction site 8 (CO8). This part of the project includes the construction of the tunnel portal on the Villard-Clément platform, two 2.8 km long tubes of the base tunnel in the direction of Saint Martin la Porte, the cross-passages between tubes and the niches.

This paper presents the general approach followed to design each temporary support for the base tunnel, cross-passages and technical rooms. The design of the primary lining profiles deals with the variability of the ground and water conditions, the excavation attended behaviour, the construction planning and the identified geological hazards that could be encountered along the alignment.

Particular attention is paid to the intersections between the tunnels both in terms of numerical modelling and construction methods and phases. Two types of intersections are present in the project: the one between the cross-passages and the base tunnel and the one between the cross-passages and the technical rooms. 3D models have been developed for the tunnel intersections.

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Digital strategies and technologies in the management of existing railway tunnels

F. Foria, E. Moschetti & M. Calicchio
ETS Srl, Rome, Italy

V.M. Grigoras & B. Boyaci
Bentley Systems, Incorporated, Exton, PA, USA

ABSTRACT: The knowledge, the preservation and the maintenance of existing infrastructures are some of the most challenging matters facing modern civilization. It is fundamental to carry out digital strategies and technologies to know and predict the conditions of existing structures. The paper focuses on Italian railway tunnels. Italy is one of the countries with the highest and oldest number of tunnels in the world. ETS introduced a new method for the diagnostic of existing tunnels through an innovative multi-dimensional survey system (ARCHITA) and a new approach for the Management and Identification of the Risk for Existing Tunnels (MIRET). The approach is very fast and minimally invasive. The integrated instrumentation within ARCHITA allows to have almost all the information necessary for the geometrization and diagnostics of a structure with non-destructive tests, preserving the integrity of the structures in the preliminary assessment phase. A new tunnel modelling and design solution, OpenTunnel, is used to model and analyze the existing tunnels, aiming to create digital twins of the real structures. The defects results and analysis are digitalized and manipulated in a specific IT environment by ETS. Different case studies are presented throughout the paper.

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Development of a ground forecasting system based on the geological and groundwater conditions in mountain tunneling

T. Fukuda
Shimizu Corporation, Tokyo, Japan

S. Yoshikawa
Shimizu Corporation, Institute of Technology, Tokyo, Japan

K. Hosono & S. Iwanaga
Geoscience Research Laboratory, Kanagawa, Japan

ABSTRACT: In recent years, with the development of IoT and ICT technologies, an environment has been created in which digital data related to construction can be easily obtained. In this paper, we have developed a system based on the concept of digital twin, which integrates digital data and numerical simulation technology. First, the system reproduces in a virtual space the "water inflow rate at the face" and "results of the geological survey at the time of construction," which are acquired during tunnel excavation. Next, the system updates this information on time. Finally, the system uses numerical simulations to constantly predict signs (water inflow and geological changes) that will occur in the near future. The information predicted by this system can be disseminated on time in a form that can be easily understood by anyone. Therefore, this system is a technology that can contribute to safe and secure construction

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A novel holistic approach to rehabilitation of underground structures

V. Gall, T. Martin & L. Boyd
Gall Zeidler Consultants, Ashburn, Virginia, USA

ABSTRACT: Water infiltration into subgrade infrastructure can cause major impacts on their performance. In addition to damaging the structure, water intrusion leads to deterioration of installations including electrical and mechanical components and in patron discomfort. To remedy these impacts, leak remediation is often carried out to halt water infiltration. Remediation methods include coatings, drainage, injection/stitch grouting, curtain (backside) grouting, and/or internal umbrella systems. Selection of the rehabilitation method depends on the structure's use, owners' priorities, its installations, structural conditions, surrounding ground, and hydrogeologic conditions. Since many factors influence the rehabilitation method chosen, a novel holistic approach is undertaken to understand leakage causes and consequences to develop the most appropriate, efficient, and reliable solution to extend the structure's life. A reconnaissance phase combines geologic, hydrogeologic, and as-built information with detailed digital scans and visual observations to develop a database of existing conditions. This database, called a tunnelband, is used to develop the rehabilitation solution and made part of the contract documents, allowing for an informed bid by specialty contractors. Tunnelband and the preferred rehabilitation system are portrayed in contract documents, which are procured in various contract types depending on the owner's preference and project characteristics. The pool of contractors are required to submit their understanding of this holistic approach by developing and supplying the owner with a detailed workplan. The completed rehabilitation is portrayed in detailed as-built drawings which also provide the owner with an operation and maintenance manual outlining for periodic observation of the structure and checking of its performance. Ultimately, this information is implemented into a "BIM Digital Twin" that is used by the operations and maintenance staff for long-term observations. This proposed novel framework for leak rehabilitation is currently being used successfully in a number of projects throughout the United States.

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Establishing the digital engineering approach for the UK's Geological Disposal Facility: Aligning a major capital programme in the nuclear sector to adopt ISO 19650, enabling BIM

D. Garbutt, CEng MICE FGS A. McCabe & A. Nawell
Nuclear Decommissioning Authority, UK

A. Gigante Barrera Phd & D. Ruikar
Arup, Solihull, UK

ABSTRACT: The United Kingdom's (UK) Geological Disposal Facility (GDF) comprise a series of underground spaces such as disposal areas, service areas, and accessways to a surface site. Nuclear Waste Services (NWS), part of the Nuclear Decommissioning Authority (NDA) a government entity, has been tasked with delivery of the GDF.

The digital GDF initial actions project (DGIA) created the foundation upon which continued development and understanding of the digital engineering requirements of the GDF are being progressed. The project high-lighted the need to develop a common data environment (CDE) approach to working across the GDF. The project pointed towards outlining the required steps needed to develop the Building Information Management/Modelling (BIM). The GDF is a system of a systems, the project also developed the GIS procedures needed for a major programme and set the requirement to bring both GIS and BIM systems into alignment to facilitate the interoperable ecosystem of the GDF.

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Data science in TBM tunneling: Use cases, benefits and challenges

Katharina Glueck & Kathrin Glab
Herrenknecht AG, Schwanau, Germany

ABSTRACT: The tunneling industry is exploding with data gathered from various sources, like sensors installed at TBMs, site equipment and periphery, but also from secondary sources like tunnel information models (TIM) and third-party project data. Sensor data is structured data in digital form, used for documentation, analysis and reports, diagnosis of failure and design of future projects. Secondary data is often stored in unstructured form and hence unfit for data science while still highly relevant for predictive analysis. Manual analysis of these vast amounts of data is time intensive and calls for automated data analysis. Data science methods are useful tools to analyze the data and make predictions to increase operational efficiency, improve maintenance, safety aspects and prevent downtimes during the tunneling operation in an automated approach. However, it is also crucial to understand the underlying behavior of the data under different conditions, like changing ground conditions or fault zones, as well as the influence of the human factor. Ensuring high quality and consistency of different data sources becomes a challenging task e.g. for the performance of machine learning models. This paper summarizes the lessons learned on a data science project in TBM tunneling and it describes the benefits and challenges as well as a roadmap for data science in the tunneling industry. It will be crucial to combine the knowledge of different domains, like mechanical engineering, civil engineering, information technology, data engineering and data science for new applications and use cases in TBM tunneling. Further challenges in human resources like an aging technical work force, limited availability of personnel with the necessary skillsets and limited awareness of the required cultural changes, are hampering the progress in the field of data science in TBM tunneling.

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Safety level assessment of segmental linings in rock

N. Gottardi
Ruhr University Bochum, Bochum, Germany

S. Freitag
Karlsruhe Institute of Technology, Karlsruhe, Germany

G. Meschke
Ruhr University Bochum, Bochum, Germany

ABSTRACT: The expansion of the underground tunnel network is calling for new methods to allow for their monitoring in an efficient way. A new approach to assess the safety level of segmental lining of tunnels excavated in rock based on discrete monitoring points is developed. Artificial Neural Networks (ANNs) are deployed for the prediction of quantities of interest, chosen for the assessment of the utilization level of the lining, based on input strains. A finite element (FE) model of the lining is created to generate the data required for the training of the ANNs. Eventually, two benchmark scenarios are defined in order to test the approach, by creating FE models representing the excavation process and the lining installation. The predictive model is fed with the input quantities of the testing scenarios and a comparison among predictions and reference quantities is drawn.

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Generating a digital twin for tunneling projects during the construction phase

F. Hegemann, J. Stascheit & U. Maidl
Maidl Tunnelconsultants GmbH & Co.KG, Duisburg, Germany

R. Gangrade & P. Kottke
Arup US Incorporated, San Francisco, USA

ABSTRACT: During a tunneling project, multiple data sources generate large amounts of data that must be analyzed for an efficient and safe tunneling operation. This is especially true during the construction phase, where a massive amount of data is generated by the tunnel boring machine (TBM) at a resolution as small as 5 seconds. Efficient tunnel construction requires integrating TBM data with the ground data and instrumentation and monitoring. Thus, a holistic, integrated platform is required, which can handle all types of data representing the single source of truth and provide an opportunity to analyze TBM-ground interaction. The model stored and managed by this platform represents the digital twin of the tunnel. In this paper, an integrated approach is presented employing the web-based process controlling software PROCON – that handles TBM data, shift records, cutter tool consumption records, ring damage information and other relevant construction data, thus connected to multiple applications for evaluating options during tunnel construction. The data is fed into and extracted from PROCON using the underlying API. The approach allows to feed and extract data from PROCON using API, thus integrating live TBM data into a 3D (or nD) BIM model environment leading to Digital Twin development. The as-built tunnel with TBM and ground data is imported into a Virtual Reality (VR) software using PROCON as an intermediate storage platform. The comprehensive dataset provides an opportunity to apply machine learning based predictive modeling to calibrate the designs and support upcoming tunneling.

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Comparison between machine learning algorithms for TBM advance rate prediction

Shengfeng Huang, Pooya Dastpak, Misagh Esmaeilpour, Kaijian Liu & Rita L. Sousa
Department of Civil Environmental, and Ocean Engineering, Stevens Institute of Technology, Hoboken, USA

ABSTRACT: Prediction of tunneling performance is intimately connected to the prediction of Advance Rate (AR), which is crucial to optimize tunnelling operation and steering tunnelling processes. However, the forecasting AR is accuracy remains a challenge due to its dependency on several factors. Several methods have been introduced to predict the performance of tunnel driving, which are often of two types: closed-form equations or regression analysis. In the study, we developed regression models to predict AR from tunnel boring machine (TBM) based on machine learning (ML) algorithms. Five different popular ML algorithms, including k-nearest neighbor (KNN), support vector regression (SVR) model, artificial neural networks (ANN), random forest regression (RF), and classification and regression tree (DT), were applied to develop TBM AR prediction models using data monitored during construction. More than 600 dataset examples were collected from a TBM project between the Salgueiros and Sao Bento stations of the Porto light metro project in Portugal. 7 useful features were selected based on empiricism. 80% of the dataset were assigned for training and 20% for testing the models. The performance of developed models was evaluated and compared in terms of coefficient of determination (R^2) and root mean square error (RMSE). The results show that SVR is the best AR predictor among the five algorithms tested.

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Optimization of shield tunneling parameters under controlled surface settlements

P. Jongpradist, S. Wainiphithapong & C. Phutthananon
Construction Innovations and Future Infrastructures Research Center, Department of Civil Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

ABSTRACT: The construction of the tunnel usually leads to settlement which normally depends on the tunnel geometries, geological condition and tunnel construction parameters. The tunnel construction rate commonly decrease with more strict value of controlled surface settlement, resulting in an increase of time and budget of tunnel construction. This study develops an approach to determine the optimal tunneling parameters using genetic algorithm (GA) with varying allowable surface settlements incorporated with the artificial neural network (ANN). The ANN is used to construct prediction models of surface settlement and tunnel construction rate. In this study, the MRTA Blue Line data are used to train the ANN and used as case study for determining optimal tunnel construction parameters. The results demonstrates that the approach of combination of ANN and GA can be an efficient tool for application in tunnel construction. With the data of MRTA blue line, to obtain the maximum construction rate, the penetration rate and grouting pressure have to change significantly with the variation of allowable settlement.

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Investigating the effectiveness of transfer learning in rock strength prediction

A.L.J. Khoury & C. Paraskevopoulou
University of Leeds, Leeds, UK

A. Benardos
National Technical University of Athens, Athens, Greece

ABSTRACT: Uniaxial Compressive Strength (UCS) is an essential and critical mechanical parameter for design and stability assessment in rock engineering. In practice, accurate measurement of the UCS of rocks is obtained through laboratory-based direct testing, however, these are expensive, time consuming, and destructive. To overcome these shortcomings, numerous researchers have employed indirect methods to generate UCS-predictive models using soft and hard computing methods. Although, these indirect models remain limited due to insufficient availability of data restricting their applicability to different sites and lithologies. Therefore, alternative methods to overcome this shortage of data are necessary and of a high interest. In this study, an Artificial Neural Network (ANN), a Decision Tree (DT), and Multi Linear Regression (MLR) model are used to develop UCS predictive models. To this end, an experimental dataset of nineteen UCS, point load tests and bulk density measurements on sandstone was built and three statistical metrics were used to evaluate each model performance. Subsequently, Transfer Learning (TL), a technique which allows smaller datasets to be used, is applied to ANN to test its effectiveness. The results showed that TL achieved superior predictive performance on unseen data compared to the ANN, DT and MLR models and can be effectively applied to enhance the performance of a model built with a small dataset.

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Soft ground tunnel lithology classification using resampling and supervised learning

K. Kilic, H. Ikeda & T. Adachi
Department of Geosciences, Geotechnology and Materials Engineering for Resources, Graduate School of International Resource Sciences, Akita University, Japan

Y. Kawamura
Division of Sustainable Resources Engineering, Faculty of Engineering, Hokkaido University, Japan

ABSTRACT: Lithology identification is crucial in tunnelling with a tunnel boring machine (TBM) for mitigating the instability risks and for optimizing the time-consuming excavation. However, in most cases, the lithology classes are not adequate due to the low number of drilling holes, anisotropy, and heterogeneity of the rock layers. In this paper, the proposed method is to classify the lithology of the tunnel surrounding layers using automatic machine learning. An earth pressure balance (EPB) machine recorded 18 operational parameters in real time along with the three main lithologies. Python Pycaret was applied to create 14 different classifiers for comparison automatically. According to the Pycaret results, Light Gradient Boosting Machine (LightGBM) model was selected as the best classifier. Due to the imbalanced distribution of tunnel layers, LightGBM performed with five different resampling models to obtain the resampling model for the imbalanced distribution of the classes.

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Stage-updated TBM operational parameter prediction model using random forest algorithm

D. Kim
Department of Geotechnical Engineering Research, Korea Institute of Civil Engineering and Building Technology (KICT), Korea

K.-H. Lee & N.Y. Kim
Safety Innovation & Disaster Prevention Research Division, Korea Expressway Corporation Research Institute, Korea

K. Kwon & H. Choi
School of Civil, Environmental, and Architectural Engineering, Korea University, Republic of Korea

ABSTRACT: The shield tunnel boring machine (TBM) excavation progress in an urban area was evaluated by monitoring surface settlements near the tunneling face. This study implemented a stage-updated machine learning modeling method to predict the TBM operational parameters and corresponding the maximum surface settlements around the tunnel alignment before being excavated yet. Five TBM machine control parameters, i.e., advance speed, backfill grout injection volume, face pressure, thrust force, and cutter torque, were predicted by learning the preceding excavation records. Subsequently, the predicted machine parameters were utilized to predict the surface settlements in upcoming excavation zones. The settlement database was collected from a subway tunnel project in Hong Kong to establish and verify the developed model. The maximum surface settlement predicting model was validated at 5 locations, demonstrating a root mean squared error of 2.488 mm.

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Estimation of uniaxial compressive strength at tunnel face using TBM operation data

T.Y. Ko
Kangwon National University, Chuncheon, Republic of Korea

T.H. Kim
SK Ecoplant, Seoul, Republic of Korea

ABSTRACT: One of the most crucial factors influencing the excavation speed of TBM tunnels is rock strength. Laboratory tests in geotechnical investigations can determine rock strength, but determining the UCS for the entire TBM excavation section is impossible. To apply the appropriate operation parameters during TBM excavation, determining the rock strength that affects the excavation speed is essential. Therefore, the objective of this study is to estimate rock strength using machine data obtained during TBM excavation. The slurry shield TBM excavation of the rock strata provided the TBM machine data and the UCS required for the analysis. The data were split in a ratio of 7:3 for training and testing, pre-processed with scaling, and outlier removal. According to the findings, the Adaboost model is inferred to be the most accurate at predicting UCS from TBM excavation data, with root-mean-square error and determination coefficient values of 5.14 and 0.96, respectively.

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3D numerical simulation of TBM excavation for predicting surface settlements - state of the art

B. Kratz
Université Paris-Saclay, CentraleSupélec, ENS Paris-Saclay, CNRS, LMPS - Laboratoire de Mécanique Paris-Saclay, Gif-sur-Yvette, France
Université Paris-Saclay, CNRS, CentraleSupélec, Laboratoire des signaux et systèmes, Gif-sur-Yvette, France
Socotec Monitoring France, Palaiseau, France

P. Jehel
Université Paris-Saclay, CentraleSupélec, ENS Paris-Saclay, CNRS, LMPS - Laboratoire de Mécanique Paris-Saclay, Gif-sur-Yvette, France

M. Tatin
Socotec Monitoring France, Palaiseau, France

ABSTRACT: Tunnels offer efficient transportation infrastructure in urban areas such as the Grand Paris Express in France. In urban areas, a densely built environment is exposed to the surface settlements caused by tunneling, and consequently, vulnerable buildings and infrastructure can be damaged. To mitigate this risk, the tunneling process is designed such that the surface settlements remain below a given threshold. Many numerical methods have been developed and are commonly used to simulate the surface settlements induced by a tunnel boring machine (TBM). In this paper, the first objective is to present the state of the art of TBM excavation 3D finite element (FE) modeling. From this literature review, each modeling approach is compared with respect to defining the geometry, meshing, setting the boundary conditions, and implementing TBM excavation parameters. Also, many simulations must be run to validate the modeling assumptions, calibrate the model using sensor data, and account for uncertainties in the boundary conditions, soil properties, and tunneling process. The second objective of this review of the literature thus is to identify the driving instruction parameters that impact settlements and methods to implement them in a 3D finite element model.

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Interface impact assessment using BIM and Leapfrog on Sydney Metro West

D. Lai & M.P. Crisp
Mott MacDonald, Sydney, Australia

J. Jiang
Mott MacDonald, Auckland, New Zealand

R. Wong
Mott MacDonald, Hong Kong

S. Thorin
Sydney Metro, Sydney, Australia

ABSTRACT: Building Information Modelling (BIM) was implemented at the early concept design stage of the Sydney Metro West project to identify and analyse critical interfaces and develop a robust design. Automation and scripting tools were used on the federated BIM platform to save time and improve output accuracy, facilitate cross-discipline coordination and eliminate repetitive tasks. In combination, Leapfrog was used to interpret and visualise the distribution of the geotechnical units. The combination of BIM and Leapfrog models resulted in a powerful tool for interface impact assessment on Sydney Metro West – Eastern Tunnelling Package. This enabled the concept design team to visualise constraints associated with ground conditions and the dense built environment, and reduce the likelihood of impacts. This also facilitated ground movement impact assessment through parameter calibration.

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Deep learning methods for underground deformation time-series prediction

E. Ma
School of Highway, Chang'an University, Xi'an Shaanxi province, China

M. Janiszewski & M. Torkan
Department of Civil Engineering, School of Engineering, Aalto University, Espoo Helsinki, Finland

ABSTRACT: Prediction is a vague concept that is why we need to conceptualize it specifically for underground deformation time-series data. For this impending issue, this paper employs an advanced deep learning model Bi-LSTM-AM to address it. The results show its applicability for practical engineering. The proposed model is compared with other basic deep learning models including long short-term memory (LSTM), Bi-LSTM, gated recurrent units (GRU), and temporal convolutional networks (TCN). These models cover the most common three forms of deep learning for time-series prediction: recurrent neural networks (RNN) and convolutional neural networks (CNN). This research is supposed to benefit the underground deformation time-series prediction.

Keywords: underground engineering, time-series, deep learning, deformation prediction, machine learning

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Development of virtual TBM construction simulation teaching system based on Unity3D

X.B. Meng
CREG, Zhengzhou, China

A.C. Jiang
Yellow River Engineering Consulting Co., Ltd., Zhengzhou, China

B. Gao, Q. Ma, G.Z. Wang & Y. Yan
CREG, Zhengzhou, China

ABSTRACT: In order to solve the problem of difficult and risky on-site training of TBM operation, lack of training methods and teaching aids in school, Simulation TBM teaching system contains the basic functions including Thurst & Guide, CutterHead & Rotate, Segment Hoist & Erect, Inject, Foam/Bentonite/Water etc fluid system and most of the action operation of TBM construction. In order to further adapt to the working conditions of the construction site, the coordination of virtual geological characteristic parameters, propulsion history replay and trouble setting & shooting with examination has been developed. It is a shield construction simulation teaching system based on the combination of real piano platform and unity3D virtual technology. The system facilitates the combination of theory and practice in the teaching process of colleges and universities, and students have a more intuitive understanding of on-site construction.

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Development of penetration rate prediction models for hard rock TBM in construction phase by deep learning and block model techniques: A case study in Mae Tang-Mae Ngad Tunnel, Northern Thailand

Nantapol Monthanopparat & Tawatchai Tanchaisawat
Chiang Mai University, Chiang Mai, Thailand

Chawalit Tanomtin
Right Tunnelling Pub Co., Ltd., Samut Prakarn, Thailand

ABSTRACT: The prediction models are proposed to utilize through multi stages in a project such as, preliminary and feasibility state, design, tender, and construction. As a result, its low accuracy exceeds the expected accuracy range (The association for the advancement of cost engineering, -10% to +15%). For example, when entering the input data from Mae Tang – Mae Ngad Project through existing models, the values of root mean square error that are evaluated by comparing between the actual and the predicted rates of penetration have its results between 0.356 and 0.893. The errors show that efficiency of prediction model remains as same level as the penetration rates of standard deviations of actual rate of penetration which equal to 0.323 and 1.238 m/h. This research aims to create a model for predicting tunnel boring machine performance through deep learning in construction phase by Deep Feed Forward and Long-Short Term Memory and applied block models with mining technique. The prediction model is created and validated using data gathered from Mae Tang – Mae Ngad project over 300 datasets from ring number 2350 to 2649. Input parameters for the model are selected through the correlation examination. Parameters that correlated with 5 rate of penetration variables are Thrust, Torque, Cutterhead Speed, Rock Mass Type, and Uniaxial Compressive Strength. UCS value is determined by Indirect test from Schmidt hammer at Tail Shield and Invert Distance technique filling missing value. Rate of penetration in validation set resulted its root mean square errors as 0.162 and 0.216 from Deep Feed Forward and Long-Short Term Memory techniques respectively. Deep Feed Forword is more accurate whereas Long-Short Term Memory is more adaptive to fluctuate geological conditions and nonassessable input parameters in advance as it is recurrent neural network of deep learning, which also usable to predict previous datasets. Results from the prediction model development can lead to further Rate of penetration prediction framework development for other situation of tunnel excavation in the future.

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Methods for local big data integration to reduce geotechnical uncertainty and risk on subsurface infrastructure projects

M.A. Mooney
Center for Underground, Colorado School of Mines, Golden, Colorado, USA

J.G. Grasmick
Emprise Concepts LLC, Evergreen, Colorado, USA

R. Gangrade
Arup, San Francisco, California, USA

ABSTRACT: Sensing and information technologies, adopted now routinely on underground urban infrastructure projects, have enabled the production of massive streams of spatial-temporal data. Yet, geotechnical risk remains uncomfortably high and more often than not drives the schedule, cost and overall risk of such projects. In short, geotechnical risk is not decreasing in proportion to the uptake in big data. The reasons for this include a lack of methods to translate the increased spatial-temporal data into a commensurate reduction in geotechnical risk. This paper presents research-driven methods to reduce geotechnical risk using the increased data now available. A typical urban TBM project environment is presented and data from multiple actual tunnel projects is used to demonstrate method efficacy. The paper first addresses the quantification of baseline spatial geotechnical parameters and their uncertainty, and the consequential risks that exist during tunnel construction, e.g., ground and building deformation, stuck TBM, clogging, groundwater inflow, etc. Because these risks are quantified based on apriori site investigation data, optimization of geotechnical site investigation to best decrease risk uncertainty is addressed and demonstrated. Geotechnical monitoring data and TBM data collected during tunnel construction is used with back-analysis techniques to improve estimation, including decreasing uncertainty, of geotechnical parameters. This is demonstrated using 3D computational modeling of ground deformation and machine learning/empirical model-based estimation of clogging and TBM cutterhead wear risk. The paper also presents the reduction in geotechnical risk uncertainty by implementing a machine-learning approach to characterize the ground through which the TBM advances. A Bayesian approach to updating estimate magnitude and uncertainty of tunneling-induced ground deformation is presented by using the monitoring data and back-analysis.

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Are we ready for TBM tunneling automation? Two strategies to improve model performance

Saadeldin Mostafa & Rita L. Sousa
Department of Civil, Environmental and Ocean Engineering, Stevens Institute of Technology, Hoboken, NJ, USA

Beatriz Klink & Herbert Einstein
Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

ABSTRACT: The single most significant challenge facing the field of tunneling is not being able to know with a fair degree of certainty what lies underneath the surface. Despite the availability continuous machine performance data recorded by TBMs, and despite much previous research, real time forecasting models for ground conditions still do not exist. Without models that predict geology and the related uncertainties, automation of tunneling construction is nearly impossible, since these models are needed for real time optimization of tunneling operation. In this paper we briefly review the existing research and available predictive Machine Learning models that have been developed to forecast ground during TBM construction, and we list their main limitations. Suggestions for future research, are provided to develop more robust and generalizable geological forecasting models. Insights from a case study are used to illustrate two potential solutions to improve ML model prediction performance.

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Study on the digitalization of tunnel inspection using deep learning

Y. Ohara, T. Nakayama, A. Miwa & T. Shimizu
Railway Technical Research Institute, Kokubunji, Japan

ABSTRACT: Approximately 70% of Japan's railroad tunnels are over 60 years old. To ensure safety, regular inspections once every two years are obligated by law and soundness judgement is conducted by skilled inspectors. However, the soundness judgment is partly based on qualitative criteria of each inspector, and this could increase variability of judgements. In addition, it is expected to be more difficult to secure skilled inspectors in the future due to the declining birthrate. Therefore, we used deep learning to automatically judge the soundness of cut and cover tunnels for the purpose of improving efficiency of the inspections. In this study, the accuracy of automatic judgement verified by using the actual soundness judgement in the inspection and the accuracy was confirmed to be approximately 60% if the safe side judgement was treated as correct.

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Computer vision and machine learning for cost-effective fully automated visual inspection of tunnels: A case study

F. Panella, J. Lucy, E. Fisk, S.T. Huang & Y. Loo
Ove Arup & Partners Ltd., London, UK

ABSTRACT: Effective asset management of underground infrastructure requires timely and detailed visual inspections for condition monitoring. To date, the common approach for visual inspections is heavily manual and can be slow, expensive, and subjective to the engineer's experience. The present paper describes the end-to-end development of an automated visual inspection workflow. The proposed two-stage pipeline applies the state-of-the-art Deep Learning (DL) algorithms for object detection and tracking to identify structural defects in tunnels. Then, via a novel computer vision approach, it detects and tracks natural features for a precise sensor-less in-tunnel defect mapping. The output is a DL-powered digital twin of the inspected infrastructure. It drastically reduces manual input for repetitive tasks and focuses on the employment of highly trained engineers for validation purposes only. This means that engineering knowledge is more effectively spent. These results will impact the construction industry's approach to visual inspections shifting it towards automated strategies.

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Near surface full waveform inversion via deep learning for subsurface imaging

A. Parasyris
University Of Strathclyde
D. Bairaktaris & Associates Ltd.

L. Stankovic, S. Pytharouli & V. Stankovic
University Of Strathclyde

ABSTRACT: In order to meet increasing safety standards and technological requirements for underground construction, the estimation of Earth models is needed to characterize the subsurface. This can be achieved via near-surface or standard Full-Waveform Inversion (FWI) velocity model building, which reconstructs the Earth model parameters (compressional and shear wave velocities, density) via recordings obtained on the field. The wave function characterizing the Earth model parameters is inherently non-linear, rendering this optimization problem complex. With advances in computational power, including graphics processing units (GPUs) computing, data driven approaches to solve FWI via Deep Neural Networks (DNN) are increasing in popularity due to its ability to solve the FWI problem accurately. In this paper, we leverage on DNN-based FWI applied to field data, to demonstrate that instead of depending on observed data collected from multiple boreholes across a large distance, it is possible to obtain accurate Earth model parameters for areas with varied geotechnical characteristics by using geotechnical data as prior knowledge and constraining the training models according to a single borehole to map the large geological earth cross section. Also we propose a methodology to simulate acoustic recordings indirectly from laboratory tests on soil samples obtained from boreholes, which were analysed for compressive strength of intact rock and Geological Strength Index. Layers'geometry and properties for a section of total 3.0 km are used for simulating 15 2D elastic spaces of 200 m width and 50m depth assuming receivers and Ricker-wavelet sources. We adopt a Fully Convolutional Neural Network for Velocity Model Building, previously shown to work well with synthetic data, to generate the 2D predicted Earth model. The results of this study show that the velocity model can be accurately predicted via DNN through the appropriate training with minimum demands for borehole data. The performance is evaluated through both metrics focused on image quality and on velocity values giving a multifaceted understanding of the model's true ability to predict the subsurface.

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Reduction of risks and operation improvement in TBM tunneling through advanced techniques of data management, processing and analysis

E. París & S. Arrate
SENER Ingeniería y sistemas S.A., Barcelona, Spain

ABSTRACT: Tunnel Boring Machines have proven, during the last decades, high levels of efficiency as a preferred system in tunnel construction, especially in urban areas where the improvement of transport structures is currently expanding. This efficiency doesn't necessary mitigate risks, especially for third parties, notwithstanding the own risks towards the machinery that can cause long-term and costly reparation stops. Operation parameters, connected by advanced analysis to settlement information, TBM georeferencing, and estimated ground deformations among others, play a major role when talk about keeping excavation risks under control and out of danger ranges. Therefore, the management, processing and analysis of operation data are key elements for accurately determining the existence of a risk, its possible consequences and the best way of mitigating it. Nowadays, the connection and processing of data, combined with the digitization in tunneling works, allows us to achieve a very efficient use of information, thus allowing a very clear improvement in the management of operational risks, not only during the excavation phase but also during the operation and maintenance phases. These techniques significantly support the tunnel's life cycle. This paper will present the readers with real cases of application in tunneling works, introducing these techniques of processing and analysis aimed at producing a more comprehensive vision of the operation and enhancing the decision-making process, making it more agile, precise and effective when handling potential risks.

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Automated semantic segmentation of 3D point clouds of railway tunnel using deep learning

Jeongjun Park, Byung-Kyu Kim, Jun S. Lee, Mintaek Yoo & Il-Wha Lee
Korea Railway Research Institute, Euiwang-si, Gyeonggi-do, Republic of Korea

Young-Moo Ryu
Korea Expressway Corporation Research Institute, Hwaseong-si, Gyeonggi-do, Republic of Korea

ABSTRACT: Scan-to-BIM is precise method for BIM (Building Information Modeling) by measuring existing structures with LiDAR (Light Detection And Ranging), but has a limitation in that it consumes a lot of manpower, time, and cost. In order to overcome this limitation, studies on automating the semantic segmentation of 3D pc (point cloud) using deep learning are being conducted, but they have been actively applied to the architecture field. Research in the railway field is about applying deep learning to simple bridge data, and there are very few studies on railway tunnels in which various objects. In this study, using deep learning, semantic segmentation of the actual measurement 3D pc data of the railway tunnel was performed and its applicability was reviewed. By applying representative deep learning algorithms, we examined which algorithms are suitable for tunnel pc segmentation. Also, the effect of changing the hyperparameters of the training data on accuracy and IoU (Intersection over Union) was reviewed.

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Settlements in conventional tunneling with deep neural networks

M. Parra, F. Ochoa-Cornejo, F. Hernandez & G. Corral
University of Chile, Santiago, Chile

ABSTRACT: The construction of a tunnel can induce subsidence in the ground at surface level, which can affect and cause damage to existing structures, especially in areas with high building density. This paper presents a deep neural network model (DNN) to estimate the maximum surface settlement "S_{max}" in a tunnel excavated with using conventional tunnelling. The structuring of the deep learning algorithm was performed using the TensorFlow library in Python 3.0. The DNN model was trained, tested, and validated using a synthetic database composed of several numerical models automated with Python in the finite element program PLAXIS2D. Variables associated with soil properties, support characteristics, surface overburden in the context of the conventional tunnelling process were considered for the modelling. To verify the estimation capacity of the DNN model, performance tests and statistical analyses were carried out, with the results showing good predictive capacity of the model for the three variables analysed.

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Tunnel Digitalization Center – Beyond BIM in underground construction

V. Petschen
SCAUT Association

R. Brandt
HBI Haerter

O. Celebi
Siemens Digital Industries

R. Wyss
Amberg Engineering

N. Elkuch
Elkuch Group

ABSTRACT: Digitalization opens the possibility of avoiding the waste of three very important assets. We can minimize the unnecessary loss of materials, time, and information by optimizing our use, presentation, and exchange of data. The more complex a construction is, the higher the number of participants in a project are, the bigger the infrastructure network of which a tunnel is part of, the better the digitalization shows its advantages. Digital continuity is the key for cross-phase and cross-divisional system solutions. With the help of 7 industry partners, under the coordination of the Swiss Center of Applied Technologies (SCAUT) the aim of the Tunnel Digitalization Center (TDC) is to showcase and develop new use-cases among very different stakeholders to innovate and demonstrate thirds the complex digital processes in a real environment. With this project, SCAUT aims to make an important contribution to the digitalization of the whole tunnelling industry. From BIM and electromechanical equipment to operation and digital services in maintenance, several possible applications of the digital twin: at the TDC solutions across the entire value chain and life cycle are demonstrated. It allows demonstration and simulation in a realistic environment. Innovative uses cases, like cloud solutions, BIM and IoT for tunnelling are part of it. In this paper the concept of the TDC is going to be presented, and the use cases shown there focusing on simulations, commissioning, operation, and maintenance.

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Tunnel Euralpin Lyon-Turin CO08 – BIM implementation in conventional tunneling

F. Rich
Pini France Engineers, Paris, France

C. Giai Via
Systra, Rome, Italy

B. Bitetti
Pini France Engineers, Paris, France

G. Ragazzo
Systra-SWS, Torino, Italy

J. Pepiot
Implenia France, Le Bourget du Lac, France

S. Lione
TELT, Torino, Italy

ABSTRACT: In conventional tunnelling, geology and excavation behaviour allow to define the most appropriate excavation method and support sections needed during the construction phases. Because of the uncertainties on the real on-site geological conditions and soil behaviour, the design and project execution stages demand flexible organization and tools. The rapid rise of Building Information Modelling (BIM) represents a major opportunity for tunnel engineering, construction industry and public organizations to improve quality and efficiency of all services. Given the size of the project, its heterogeneity, strategic role, and sustainability, TELT puts forward the fully BIM approach to ensure the efficiency of the design, organization of information flows.

This paper focuses on the BIM application on the construction site 8 (CO08) of the Tunnel Euralpin Lyon Turin (TELT) project. The project is implemented by the Contractors' JV IMPLENIA FRANCE/NGE GC/ITINERA/RIZZANI De ECCHER and the design JV PINI France and Systra-SWS. The DAUB recommendation for BIM in tunnelling is applied. A database is created for all the structures and part of the structures of the project (supporting structures of the tunnel portal, conventional tunnel primary support, pre-support and final lining). All the components are fully modelled in BIM, according to the TELT technical specifications and requirements. A 3D geological model has also been implemented in order to have a dynamic comprehension of the geological sequence in all part of the tunnel alignment, to characterize the geological/geotechnical conditions and uncertainties at the tunnel face during construction, and to allow the Contractor to adapt its methods and support section.

Dynamic 4D and 5D models are developed. This will permit the Contractors to efficiently follow and adapt the construction works and methods on site.

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The digitalization of the Tunnel Schöneich - Using a digital twin to improve operation and maintenance workflows of an existing road tunnel

R. Sanfilippo, P. Canini, E. Carrera & M. Neidhart
Lombardi Engineering Limited, Switzerland

R. Eberle
Swiss Federal Roads Office FEDRO, Switzerland

M. Wieland
Aegerter & Bosshardt AG, Switzerland

ABSTRACT: The refurbishment of the existing Tunnel Schöneich at the entrance of the city of Zurich is part of the big project of the Swiss Federal Roads Office (FEDRO) called "Covering Schwamendingen". After the complete renovation of this existing tunnel, a digital twin for the operation and maintenance of the entire tunnel and all technical equipment's has been developed.

Starting from the survey of the internal geometry of the tunnel with laser-scanning technology and from the documentation coming from the design and the construction phase, passing through a recognition of the information needed for its operation and maintenance the goal was to provide a Digital Twin for the life cycle management of this tunnel, using the Building Information Modelling method. By adopting an openBIM approach and a structured data management system, it has been possible to test how to manage all the information and classification needed for the operation and maintenance of this asset in any kind of digital platform with any downside of data lock-in.

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Forecasting long term tunnel longitudinal settlement and horizontal convergence using machine learning techniques

S. Sarna & M. Gutierrez
Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO, USA

M. Zhu
Department of Geotechnical Engineering, Tongji University, Shanghai, China

ABSTRACT: Long-term longitudinal settlement and horizontal convergence of metro tunnels are critical problems. To be able to forecast tunnel settlement and convergence for a distant future is crucial to pursue remedial measures in a timely manner. Existing research mostly focused on forecasting overall tunnel health condition combining multiple tunnel responses besides settlement and convergence, rather than forecasting them directly. Moreover, the forecasts are based on immediate earlier measurements of these responses and are unable to predict them into the future. This research aims to develop methods that are capable of forecasting tunnel settlement and convergence for future tunnelling operation based on early measurements. Machine Learning (ML) algorithms are trained to develop predictive models. The use and validity of the ML algorithms are demonstrated using data collected from the Metro Line 1 in Shanghai during its operational years. It is shown that the developed models could successfully predict tunnel longitudinal settlements and horizontal convergences as far as 14 years apart.

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Early implementation of BIM in large infrastructure projects to manage complex interfaces in a dense urban environment

A. Shivasami, D. Lai, S. Dowdell & N. Gklotsos
Mott Macdonald, Sydney, Australia

G. Clifton
SMEC, Sydney, Australia

S. Thorin
Sydney Metro, Sydney, Australia

ABSTRACT: Early adoption of Building Information Modelling (BIM) helps steer large infrastructure projects in the right direction from the outset. This is demonstrated on the 24-kilometre long Sydney Metro West project, and specifically on the Eastern Tunnelling Package (ETP) which forms part of the wider project. The ETP portion of the project extends from The Bays to the Sydney CBD and involves 3.5 kilometres of tunnelling and large-span cavern excavation beneath Sydney's heavily urbanised environment. Consequently, the alignment is adjacent to numerous assets such as high-rise building basements, key utilities, heritage buildings, and other critical infrastructure. A mature Building Information Model (BIM) was rapidly developed throughout the Concept Design phase and delivered at the commencement of the 'Request for Tender' process. This paper presents the substantial benefits of early BIM implementation while also providing detailed insight into the numerous challenges that impede early BIM adoption in dynamic and dense urban environments.

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Analysing and predicting surface settlements from metro construction using machine learning methods

K.N. Sioutas, A. Vlachogiorgos & A. Benardos
School of Mining and Metallurgical Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT: Tunnel Boring Machines (TBM) are the predominantly used for the excavation of metro tunnels in urban areas, as at the same time they can achieve almost zero disturbance to the surrounding rock mass and can attain high advance rates. Nevertheless, the complexity of the geological and geotechnical conditions along with the vulnerability of surface structures can give rise to surface settlements and potential problems. Although there is a number of methods of both empirical and computational nature to make predictions of the anticipated settlements, the introduction of modern machine learning applications can further assist in a more accurate perdition and assessment of risk prone circumstances. In the paper the analysis of the surface settlements is made with machine learning methods utilizing data coming from the construction of Athens metro Line 2, namely an interval part of the Hellinikon extension project. The data taken into account consist of both the geological and geotechnical conditions encountered and the EPB-TBM operating data. Several Artificial Neural Networks (ANNs) were developed utilizing a different set of input parameters and were evaluated against their prediction performance capabilities as compared with real measurements. Four ANNs showed the most promising results having an average prediction accuracy of more than 79% and a consistent behavior across almost the entire range of the test dataset used, closely following the trend and behavior of the measured settlements.

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Deep learning for masonry lined tunnel condition assessment

J. Smith & C. Paraskevopoulou
University of Leeds, Leeds, UK

A. Bedi & M. Invernici
Bedi Consulting Ltd., London, UK

ABSTRACT: The condition assessment of masonry lined railway tunnels typically involves manually identifying lining defects from photographic and lidar surveys taken of the tunnel intrados. This process is time-consuming and subjective to the assessor's judgement. However, recent developments in machine learning achieve the quality metrics required to automate the detection of defects from noisy and irregular tunnel data, offering the potential to reduce tunnel assessment and maintenance costs. This paper proposes a deep learning workflow for defect segmentation. The method is evaluated on the task of masonry block segmentation from lidar data. Acceptable performance is achieved on a sample tunnel section, suggesting that similar methods are applicable to other masonry lined tunnel defect segmentation tasks.

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Development of simple floating dust sensor during tunnel construction using video image sequences – algorithm of automatic particle recognition

K. Tanaka, S. Nakashima, H. Hayashi & M. Shinji
Yamaguchi University, Ube, Japan

K. Ide
Obayashi Corporation, Tokyo, Japan

N. Kishida
Dobocreate Corporation, Ube, Japan

ABSTRACT: In tunnel construction work, dust is generated at almost all activities from rock blasting, rock drilling, rock bolting, transport operations and spraying wet concrete on tunnel walls. Each of these activities had the potential to expose workers to airborne contaminants that, if not adequately controlled, can lead to significant harm, such as lung dysfunction. Therefore, it is essential to monitor dust concentration in the air during tunnel construction work to minimize health damage caused by dust. The Digital Dust Indicator and the Low Volume Sampler are famous devices for the dust concentration monitoring in tunnel construction. However, their common weak point is that they lack instantly because they require post-measurement work to know dust concentration readings. “Low cost”, “portable” and “real-time” are the keywords for sophistication of air dust monitoring devices for tunnel construction.

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Capabilities and challenges of big data application in tunneling: Recent advances and future trends

K. Tolouei, E. Moosavi & M. Gholinejad
Department of Petroleum and Mining Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
Research Center for Modeling and Optimization in Science and Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

ABSTRACT: The rapid development of information technology in recent decades means that the digitalization world has experienced an explosion in the magnitude of data being captured and recorded in various industry fields. The most fundamental challenge for Big Data (BD) applications is to explore large volumes of data and extract useful information and develop techniques that automatically discover new, hidden, or unsuspected data from the large text collection. Although the advances in computer systems and internet technologies have witnessed the development of computing hardware following Moore's law for several decades, the problems of handling large-scale data still exist when we are entering the age of BD. In addition, some existing and emerging concepts like cloud computing, data mining, machine learning, the internet of things, smart grids, and automation will continue to drive and even accelerate the growth of data. Storing, managing, and analyzing such a huge amount of data can't be simply done by using traditional databases and techniques. Instead, it requires a new class of advanced technologies. Under such a circumstance, BD management has recently emerged to address this deficiency. The traditional tunneling industry is also experiencing an increase in data generation and storage. BD will change the way of gathering geological data, methods of rock classification, application of design analyses in the field of tunneling as well as tunnel construction and maintenance processes. BD, data mining had to be introduced with the most relevant techniques to analyze data related to tunneling operations. The concept of machine-generated data was also necessary for the further parts, as log files and reports from tunneling equipment are used in the data analyses. The paper briefly described the current situation of the tunneling industry, focusing on its challenges, and also mentioning some of its other unique attributes.

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BIM Implementation in a major tunnel rehabilitation

T. Vovou, H. Bosques-Mendez & V. Nasri
AECOM, New York, NY, USA

ABSTRACT: The purpose of this paper is to present the application of the Building Information Modeling (BIM) methodology in the rehabilitation of a 100-year-old tunnel for the Réseau Express Métropolitain (REM) project in Montréal, Canada. Rehabilitation consisted of repairing the interior structure, adding a fire-rated wall to comply with modern standards, optimizing the track alignment, and redesigning the drainage, ventilation and electrical systems. Niches were excavated in the side walls of the tunnel for telecommunication needs and local enlargement of the roof was required for the installation of jet fans. Due to the complexity of the design, developing an accurate representation of the structure was very important. 3D laser scanning played an important role in providing measurements of the interior structure and current condition. Grasshopper and Rhino scripts were also incorporated to the workflow to accurately model the repetitive structural elements along the tunnel to match with survey points, elevations and required clearances. Extensive clash detection analysis was performed in Navisworks to identify clashes between the new train envelopes and the existing tunnel wall, as well as between the train envelopes and new center wall walkway. The intent of this exercise was to accurately identify clash zones and identify areas along the tunnel where additional excavation in the existing side walls would be optimized so that both the train can safely pass through the tunnel and the excavation is cost-efficient. The paper also describes the challenges and limitations that were identified, mostly related to the interoperability, exporting processes, processing times due to the large size of the files, and software glitches. Overall, the creation of a dynamic model was significantly beneficial, especially during the construction phase, as it was updated to reflect the actual conditions, thus giving the opportunity to the designers to further optimize the design as needed.

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TunAID - Interactive simulation-based tunnel track design tool for mechanized tunneling in urban areas

Y. Zendaki, B.T. Cao & A. Alsahly
Ruhr University Bochum, Bochum, Germany

S. Freitag
Karlsruhe Institute of Technology, Karlsruhe, Germany

G. Meschke
Ruhr University Bochum, Bochum, Germany

ABSTRACT: Alignment design in urban tunneling aims at selecting an optimal tunnel track satisfying various design specifications and safety constraints as well as considering the environmental and socio-economic impact. In this work, an interactive tunnel track design tool is proposed, which enables finding optimized tunnel alignments by considering the impact of the tunnel advancement on existing infrastructure as a design criterion. An advanced numerical simulation model based on the Finite Cell Method (FCM) is utilized to predict the damage to existing buildings, during the tunneling process. To enable interactive applications in real-time, the FCM simulation model is substituted by a model reduction technique based on Proper Orthogonal Decomposition and Radial Basis Functions (POD-RBF). The fitness function to be minimized in the optimization problem is the maximum principal strains in all existing buildings. The Particle Swarm Optimization (PSO) algorithm is used to solve the minimization task. Finally, the alignment optimization is demonstrated in a real-time manner within a software environment. In each optimization step, the current optimum tunnel alignment and the associated risks of damage to all existing buildings are visualized in the developed software package. The proposed and developed strategy can be used to improve the tunnel alignment decision-making as well as can be extended by incorporating multi-objective functions for the optimization of tunnel alignment design.

Safety, risk and operation of underground infrastructure

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Analytical study of anomalies in tunnel lining thickness: Critical temperature variations

S. Aiello, V. De Biagi & B. Chiaia
Politecnico di Torino, DISEG, Dipartimento di Ingegneria Strutturale, Edile e Geotecnica, Turin, Italy

C. Alessio & L. Baccolini
TECNE Gruppo Autostrade per l'Italia S.p.A, Rome, Italy

R. Fantuz
ASPI Autostrade per l'Italia S.p.A, DT9 Udine Branch, Italy

ABSTRACT: In recent years, the scientific community has developed increasingly innovative, automated, and non-invasive techniques to indirectly assess structural conditions. One of the main reasons is the challenge related to ageing infrastructures approaching the end of their service life. Several monitoring campaigns carried out with the use of non-destructive surveys such as Ground Penetrating Radar (GPR) have revealed the presence of anomalies in the lining thickness of many Italian tunnels. This study proposes an analysis of the state of stress of the concrete lining of tunnel sections with thickness anomalies which are subject to significant temperature fluctuations.

The research related critical anomaly thickness values as a function of thermal fluctuations and loads on these areas of the lining.

This can enable parametric management of tunnel management companies' databases so that hazardous situations can be identified using artificial intelligence algorithms, making this type of method competitive in terms of time and cost.

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Seismic performance of a major twin tunnel with unreinforced concrete lining: Expert witness study for the needs of arbitration

I. Anastasopoulos
ETH Zurich, Switzerland

G. Gazetas
National Technical University of Athens, Greece

ABSTRACT: The paper studies the seismic performance of a major twin tunnel, with unreinforced concrete (UC) lining. The work is part of an expert witness study for an arbitration. For confidentiality reasons, the key conclusions are presented, without revealing sensitive information. Situated in Greece, the tunnel is part of a major motorway, under construction at the time of the dispute. With a total length of almost 6 km, and overburden ranging from 30 to 300 m, the tunnel was constructed by conventional means of drill and blast. After its completion, the seismic safety of the UC lining was disputed by the owner. An expert witness of the owner assessed the adequacy of the UC lining through pseudo-static "pushover" analysis. Assuming elastic response, the earthquake-induced tensile stresses were found to exceed the tensile strength of concrete, concluding that the UC lining is insufficient. We were subsequently appointed by the contactor to conduct a more sophisticated expert witness study. The problem was analyzed with the finite element method, employing a nonlinear model for the rock mass, and the concrete damaged plasticity (CDP) model for the UC lining. An initial elastic pushover analysis, using the parameters as the owner's expert witness, gave compatible results. Then, nonlinear pushover analysis was conducted, with and without the surrounding rock mass. Without the beneficial compression offered by the rock mass, the UC lining fails at drift $\delta = 1.7$ mm. Confined by the surrounding rock mass, it is capable of sustaining much larger deformation without collapsing. Finally, nonlinear dynamic time history analyses revealed that tunnel damage is a function of shaking intensity and initial loading. Even with conservative assumptions, no collapse mechanism would develop and the residual drift is negligible.

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Decision support tool for resilience assessment of road tunnels

K. Anastassiadou & U. Bergerhausen
Federal Highway Research Institute, Bergisch Gladbach, Germany

F. Lindström & C. Zulauf
EBP Schweiz AG, Zurich, Switzerland

ABSTRACT: A web-based decision support tool for resilience assessment of road tunnels was developed in order to assist infrastructure managers and owners to strengthen the resilience of their road system on a long-term basis. With this research, an important milestone for the integration of resilience assessment as a component of transport infrastructure management has been achieved and the foundation was laid for transferring theoretical concepts from research to practice. This way decisions in infrastructure management to maintain the functionality of roads can be better prepared and measures or investments better justified in the future.

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Risk management process for underground works

G. Armetti & A. Panciera
Lombardi Engineering Ltd., Bellinzona-Giubiasco, Switzerland

ABSTRACT: The effective organization of the whole risk management process, based on the early coordination between all the stakeholders, plays a fundamental role in underground works. To define the risk management process during the construction and for the durability of the Pakal Dul Hydroelectric Project structures, two main references have been considered: the "Joint Code of Practice for Risk Management of Tunnel Works in the UK" (BTS), and the "Recommendation on the characterization of geological, hydrogeological and geotechnical uncertainties and risks" (AFTES). This process has been organized in four levels, that are: Risk Management System, Risk Management Plan, Risk Assessment, and Mitigation Measures Management. The effective communication and the early coordination between the parties, as well as the prompt and precise definition of a coding system, are fundamental to limit all shortcomings in the risk management process. To this purpose, a Risk Management Committee supporting the construction process should be established.

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Self-rescue in traffic tunnels - Applications

M. Bettelini
Amberg Engineering Limited, Regensdorf-Watt, Switzerland

ABSTRACT: Self-rescue represents the most important and critical safety element in case of fire in underground traffic infrastructures. State-of-the-art simulation tools allow for a comprehensive simulation of fire scenarios in traffic infrastructures. This paper focuses on sample applications of the combined simulation of fire scenarios, traffic management, smoke propagation and self-rescue in underground traffic infrastructure. Selected key issues, such as the interaction between emergency exits and tunnel ventilation, are reviewed based on real-life examples for road and rail tunnels.

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Self-rescue in traffic tunnels - Simulation method

M. Bettelini
Amberg Engineering Limited, Regensdorf-Watt, Switzerland

ABSTRACT: Self-rescue represents the most important and critical safety element in case of fire in underground traffic infrastructures. Ideally, all persons should vacate the underground space immediately after fire onset without leaving their vehicles. In case of self-recue on foot, through the tunnel portals or through emergency exits, they will move in a hostile environment and will be exposed to several risks. The primary requirements for successful self-rescue are the availability of emergency exits, an appropriate smoke-management system and specific, rapid information. These elements must be properly accounted for at design stage. Advanced simulation techniques provide excellent tools for analysis and design. This paper focuses on the combined simulation of fire scenarios, traffic management, smoke propagation and self-rescue in underground traffic infrastructure.

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Monitoring daily and seasonal movement of an immersed tunnel

Wout Broere & Xuehui Zhang
GeoEngineering Section, Department of Geoscience & Engineering, Delft University of Technology, Delft, The Netherlands

ABSTRACT: Daily and seasonal deformation behavior of immersed tunnels potentially impacts the structural integrity. In this study, distributed optical fiber sensors (DOFS) are used to instrument both dilation and immersion joints of the Heinenoordtunnel, an immersed tunnel in the Netherlands. This DOFS system proves capable of measuring joint opening and uneven settlement at half-hour intervals. The field monitoring shows the Heinenoordtunnel behaves more like a rigid body and exhibits a cyclic vertical movement under daily tide impacts over a period of 12 hours. Moreover, the joints show a cyclic seasonal opening which is negatively correlation with temperature variations, i.e. the tunnel joints are compressed when the outside temperature rises and vice versa. These monitoring results provide new insights into the daily and seasonal deformation of immersed tunnel structures.

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Correlation of ROV observations with actual damage in the Tala headrace tunnel

D. Brox
Dean Brox Consulting, Vancouver, Canada

S. Wangdi & L. Namgyal
Druk Green Power Corporation, Thimphu, Bhutan

ABSTRACT: The Tala headrace tunnel comprises a 100% concrete lined, 22 km, 6.8 m internal diameter component of the 1020 MW run-of-river hydroelectric scheme located along the Wangchu River in Bhutan that was totally commissioned in early 2007. Construction of the headrace tunnel experienced some very adverse geotechnical conditions that required design modifications including a reduction of the internal diameter along two areas and a re-alignment of a -1200 m portion of the tunnel. The headrace tunnel operated without any issues until late 2018 when fragments of concrete started to enter into the powerhouse units. An unwatered inspection of the headrace tunnel was performed in early 2021 using a remote operated vehicle (ROV) that provided a survey of the entire tunnel and an indication of the structural conditions and integrity of the tunnel. Based on an independent technical evaluation of the findings of the ROV inspection and the perceived associated risks for continued operations, a decision was made to dewater the tunnel and perform a manual inspection. The findings of the manual inspection were found to be in good agreement with the interpretation of the observations from the ROV inspection that comprised damage in the form of major cracking and exposure of reinforcement at multiple areas of the concrete lining consistent with the locations of reduced internal diameter. Advances in sonar technology and ROVs have now allowed reasonably accurate identification and interpretation of structural damages in operating hydroelectric tunnels.

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Seepage mitigation in karst with customised grouting techniques; The rehabilitation case of Enguri pressure tunnel, Georgia

Eirinaios Christakis
Tractebel Engineering GmbH, Frankfurt, Germany

ABSTRACT: Aging hydropower facilities require engineered interventions to assure resilience and enable optimal energy production. Defective pressure tunnels result in water losses, and in the long term, can raise stability concerns. An integral part of seepage mitigation consists of an extensive, tailor-made grouting strategy, where surrounding rock-mass should be integrated to the lining system. Pressure grouting improves rock mass properties, i.e. increase of intact strength, consolidation of fractured zones, backfill of karstic voids, and reduction of permeability (primary waterproofing). Furthermore, proper grouting backfills voids at the rock/concrete interface, and seals cracks and fissures within the lining segments. Enguri Hydropower Scheme has produced energy since 1980 with its circular-shaped concrete lined 15km-long pressure tunnel been completed in 1978. The tunnel was excavated through a narrow ridge of Cretaceous karstic limestones, and Lower Tertiary marl-sandstones. During a three-months plant outage, a super-intensive drilling and grouting programme was conducted through the concrete segments. Customised grout mixes (cement-based, chemical, as well as hybrid) were injected in various tunnel stretches of water-loss potential. The injection of 2.8 million m^3 grouts, resulted in the substantial reduction of water-loss which in turn, proportionally increased power generation.

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Experimental study on macro synthetic fibre reinforced concretes subjected to tunnel fires

T. Clarke
Group Engineering Manager, BarChip Australia Pty Ltd, Woolloongabba, Australia
PhD Candidate, Institute of Sustainable Industries & Livable Cities, Victoria University, Werribee, Australia

S. Fragomeni
Professor in Structural Engineering, College of Sciences and Engineering, Victoria University, Footscray, Australia

M. Guerrieri
Associate Professor, Institute of Sustainable Industries & Livable Cities, Victoria University, Werribee, Australia

ABSTRACT: This paper presents an experimental study of macro synthetic fibre reinforced concretes (MSFRCs) exposed to the RABT-ZTV (train) fire curve. Large scale panels were utilised in this investigation and the procedures suggested in the EFNARC “Guidelines for testing of passive fire protection for concrete tunnel linings” were followed. Modifications were made to the suggested curing regimes to match more closely those experienced within a tunnel environment and adopted for current project fire testing requirements in Australia. A comprehensive investigation was undertaken to determine the effect of micro-PP fibre dose rate on the spalling behaviour of MSFRCs, and the subsequent effect that this had on the temperature development within the concrete section due to fire exposure. Furthermore, cores were extracted from the panels post-fire to determine its impact on the compressive and tensile strength properties of MSFRC subject to elevated temperatures. This paper provides detailed experimental results that can prove useful for the application of macro synthetic fibres within fire critical tunnel infrastructure.

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Tunnels revamping a compulsory necessity for the assessment of tunnels safety and duration

M. Coli
Department Earth Sc., Florence University, Italy

M. Tanzini
Pini Group S.r.l., Milan, Italy

ABSTRACT: Most of railway and motorway tunnels were built more than 50 years ago and consequently are approaching or have already reached their design working lifetime. The lining of these tunnels have been subjected to ageing and degradation with impact on their functionality and user's safety. For these tunnels, it is necessary not only to provide the periodical inspection and ordinary maintenance of the tunnel lining, as local repair and rehabilitation, but also to carry out a complete check-up of the whole tunnel structure to evaluate how to extend the service state of tunnel structure. The experience pointed out the main faults for these tunnels stay in the concrete used for the definite lining, regarding both the quality and durability and the modes of put-on place. The main faults registered by in situ inspections (cores and GPR) are poor quality of the concrete with very low UCS, unbundling of ready mixed concrete, minor thickness in respect to the designed one and presence of voids behind the lining. The geological/geotechnical conditions of the surroundings soil/rock mass and the stress and strain conditions around the periphery and into the tunnel lining rarely play significant role. In order to achieve maintenance full revamping, it is essential to acquire all the information through direct inspection, geophysical investigation and in situ monitoring and to set up an evaluation method of tunnel health by back analyses of static condition, and, if relevant damages rise up, to identify the actual causes of the problem for defining the repair works. An integrated approach for the assessment of the tunnel structure conditions based on the RES (Rock Engineering Systems) interaction matrix is useful taking into consideration geological, hydrogeological and geotechnical conditions along the tunnel, structural performance, tunnel surveillance and inspection results, service condition and guideline for the maintenance, repair and rehabilitation works.

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Interactions between safety, maintenance and repair in long, deep-lying, high-speed railway tunnels, using the example of the Koralm Tunnel

F. Diernhofer
ILF Consulting Engineers Austria GmbH, Austria

H. Steiner
ÖBB Austrian Federal Railways, Austria

ABSTRACT: Extraordinarily long, deep-lying high-speed railway tunnels are complex systems that require a large amount and variety of installed equipment to ensure safe, and ideally, uninterrupted rail operations. Each individual installation inside a tunnel (in the tunnel tubes, cross passages or rescue stations) requires regular maintenance as well as servicing and renewal.

New transalpine railway tunnels, such as the Lötschberg, Gotthard and Ceneri tunnels, consist of two separate single-track tubes connected at regular intervals by cross passages, which serve as escape routes into the safe tunnel tube and accommodate the necessary railroad equipment.

The 33-km-long Koralm Tunnel (KAT) in Austria, in which railway equipment is currently being installed, also falls into this category. Using the KAT as an example, the interactions between maintenance, safety and repair in tunnels are discussed, and a methodical approach to dealing with failure of and disruptions to safety-relevant systems, whilst only restricting rail operating conditions for a limited period of time, is given.

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Tunnel inspections with the aid of high-performance image acquisition tools: An insight on key parameters for a successful detection of structural defects

J. Doreau-Malioche & F. Paillette
Center for Tunnel Studies (CETU), Bron, France

M. Puglia & P. Spohn
Amberg Infra 7D, Regensdorf, Swiss

S. Frachon & B. Poli
Setec-Diadès, Lyon, France

ABSTRACT: New tunnel inspection tools using state-of-the-art technologies for high-performance image acquisition are developed to better address the operational constraints faced by tunnel managers in organizing inspections. To date, there is no regulation or technical guideline setting a framework of practices for the use of these tools. CETU, in partnership with tunnel managers and three operators developing innovative inspection tools, has conducted field tests to compare the results obtained with the one of traditional inspection as defined by the French regulation ITSEOA. The present paper focuses on the key parameters that ensure a good quality acquisition for identifying structural defects on two-dimensional images. It also aims at providing tunnel managers with a first insight of how to define their specifications and organize the intervention on site.

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The strength of concrete in existing Italian tunnels

A.P. Fantilli & B. Chiaia
Politecnico di Torino - DISEG, Torino, Italy

M. Giordano
Autostrade per l'Italia, Roma, Italy

ABSTRACT: To assess the performances of existing Reinforced Concrete (RC) tunnel linings, the current structural analyses need the definition of material properties, especially of concrete strength. Such parameter is usually measured by means of destructive tests on concrete cores drilled from the lining, or by means of indirect non-destructive analyses, such as the acoustic emission techniques or the rebound hammer test. Nevertheless, in several cases, a rough estimation of the compressive strength of concrete is sufficient, without performing any test on the structures. This is the case of more than 500 highway tunnels built in northern Italy, which date back to the Sixties of last century and are currently in service. Accordingly, the *strength-for-age* curves, introduced to calculate the average strength (and the percentiles) of a concrete cast in a specific year, can be used for concrete linings. They are based on the results of about 500,000 tests performed on concrete cubes since 1897 and stored in a database available at the Politecnico di Torino (Italy). As a result, through the strength-for-year curves, a rapid assessment can be performed and the priorities of retrofitting, necessary to mitigate the risks associated with the service of RC tunnels, can be better identified.

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Role of variable speed drives in safe, reliable and sustainable tunnel ventilation

M. Fedorovicheva
ABB, Finland

ABSTRACT: The urbanization is expanding. By the end of the century, 50% of the world's population will be urban. Cities and their infrastructure grow rapidly. This also applies to tunnels and metros. The important aspect in such projects is ventilation. Ventilation ensures well-being of tunnel users in normal situations and provides safety in case of emergencies.

Active ventilation is based on air movement via a fan wheel run by an electrical motor. To control the air flowrate, direction and pressure, variable speed drives are used. They are a vital part of ventilation as they help ensure process efficiency, reliability and tunnel safety.

Ventilation typically consumes a lot of energy used by a tunnel, so drives are often employed to increase tunnel energy efficiency and decrease operating expenses. Drives adjust the fan motor speed based on the vehicle fumes concentration, therefore saving energy.

In case of a fire, drives make smoke control flexible. They regulate fan speed and rotation direction to ensure smoke stratification and combat backlayering for safe evacuation. Fire in a tunnel implies fast response from ventilation and smoke extraction systems. Drives provide prompt fan start, stop, rotation direction change which are the key requirements in tunnel ventilation.

Active front end drives go beyond fan speed control. They ensure power quality eliminating disturbances in the network, for reliable ventilation. It is important for long tunnels with weak power supply and long cabling. This type of drives also contributes to the tunnel sustainability, as power quality affects power network equipment sizing. The drives allow to decrease e.g. electrical generator size by 50% or transformer size by 20% – a huge input to the carbon footprint reduction.

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Capturing soil transition location uncertainty in TBM tunnelling

R. Gangrade
Arup US Inc., San Francisco, CA, USA

J. Grasmick
Emprise Concepts LLC, Evergreen, CO, USA

M.A. Mooney
Colorado School of Mines, Golden, CO, USA

ABSTRACT: Transitions between geological/geotechnical soil units have a critical impact on the operation and performance of a tunnel boring machine (TBM). In the current industry practice, deterministic profiles are relied on, and the possible locations of transitions are not quantified. This paper investigates into the efficacy of geostatistics to quantify the uncertainty in soil transitions. The results presented herein validates that information entropy, a metric to quantify uncertainty in categorical units (soil/rock units), is insufficient and misleading in quantifying the uncertainty of critical features, such as soil transitions. A geostatistics-based probabilistic modeling approach is presented to quantify the uncertainty in soil transition locations. The approach is applied on a soft ground tunnel project in North America and results are validated using actual TBM data. The assessment enhances the confidence in using geostatistics to improve ground awareness for efficient tunnel construction, minimizing different site condition (DSC) claims, and improving decision-making on tunnel projects.

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Numerical analysis about the influence on soil displacement from the construction of the tunnel in limited space

J. Guo
Department of Geotechnical Engineering, Tongji university, Shanghai, China
Shanghai Construction NO.1 (Group) Co., LTD., Shanghai, China

G.B. Liu
Department of Geotechnical Engineering, Tongji university, Shanghai, China

L. Xu
Shanghai Construction NO.1 (Group) Co., LTD., Shanghai, China

ABSTRACT: Nowadays, with the rapid development of the economy, the constructions of the tunnels in congested urban area are increasing. Therefore, many new tunnels will be excavated near the existing underground structures. Based on a project in Shanghai, this study conducted the 3D numerical analysis to investigate the soil displacement induced by the construction of the tunnel in limited space which was formed by the existing underground infrastructures. To enhance the understanding of close-proximity tunneling, the integrated numerical models of the construction of shield tunnel in limited space and the construction of shield tunnel in half-infinite space were established, respectively. The results revealed that the soil in the limited space was disturbed significantly. The maximum ground subsidence and the range of ground settlement induced by the construction of tunnel in limited space were 60% and 50%, respectively, smaller than those induced by construction of tunnel in half-infinite space. The ground settlement patterns under these two circumstances were almost the same. Moreover, a soil settlement trough appeared below the bottom slab of the underground structure. The findings can provide a better understanding of the soil displacement induced by tunnel excavation in limited space in soft clay stratum and can offer the guidance for the similar projects.

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Tunnels and underground stations ventilation system

A. Haghighat & N. Shahcheraghi
AECOM, Oakland, USA

V. Nasri
AECOM, New York City, USA

ABSTRACT: In modern transit systems, maintaining air quality, environmental control, and Fire Life Safety within the underground portion of the system is an important component of the overall design and its compliance with the established life safety and comfort guidelines and standards. Typical, Heating, Ventilation, and Air Conditioning (HVAC) systems do not have sufficient capacity to control the heat and smoke from a large train fire at the station platform. Therefore, emergency ventilation and smoke control of the tunnels is combined with that in the underground stations. These emergency ventilation systems (EVS's) require a large space and are often housed inside the stations that serve the underground portion of the transit system. Since underground portions of transit systems are often in dense urban areas, real estate and construction costs present a challenge to the system designers and minimizing the space requirements of the EVS becomes of paramount importance. An introduction to the principles of tunnel ventilation is presented and application of these principles in the underground portion of the Réseau Express Métropolitain (REM) in the new Montreal Airport Tunnel is discussed. The presentation includes the theoretical background, design criteria, regulatory requirements, analysis methods, and advanced numerical techniques used in developing the design of the tunnel ventilation system (TVS) and their specific application in the underground portion of the REM project. The proposed TVS design is presented, and results of the analysis are discussed.

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Verification of effectiveness of tunnel face monitoring supportive system using VR on evacuation behavior of workers

Ryohei Hase, Yasuji Mihara & Dohta Awaji
Shimizu corporation, Tokyo, Japan

Rieko Hojo
Nagaoka University of Technology, Niigata, Japan

Shoken Shimizu
National Institute of Occupational Safety and Health, Japan, Tokyo, Japan

ABSTRACT: At tunnel construction sites, disasters caused by tunnel face collapses are often serious once they occur. To avoid this situation, it is necessary to detect crack on tunnel face as soon as possible before the occurrence of bed rock cave-in, and secure time for evacuate from there. We are now developing a "tunnel face monitoring supportive system" that helps crack identification on tunnel surface using a camera with AI. This system enables to identify cracks accurately and quickly while avoiding work near dangerous points and ensuring safety. An objective and quantitative comparison of monitoring functions, such as crack identification by the camera-mounted AI, with human visual inspection confirmed that the average travel distance to detect cracks can be reduced by approximately 28% with the introduction of this system. It was found that this system reduced the time required to evacuate the tunnel and assisted in efficient crack monitoring.

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Well-being at work for tunnel construction workers in Japan - Quantitative evaluation using behavior-based safety

Rieko Hojo
Nagaoka University of Technology, Niigata, Japan
National Institute of Occupational Safety and Health (JNIOSH), Japan
Safety and ANSHIN Technical Research Center (SATEC), GOP Company, Ltd

Ryohei Hase, Dohta Awaji & Yasuji Mihara
Shimizu corporation, Tokyo, Japan

Shoken Shimizu
Safety and ANSHIN Technical Research Center (SATEC), GOP Company, Ltd, National Institute of Occupational Safety and Health (JNIOSH), Japan

ABSTRACT: Well-being described as a further goal after SDGs, is gradually spread out the many worksites. Parallelly advanced technologies has been started to be introduced into tunnel construction sites. Although it is expected that productivity and safety of tunnel workers are supported by such technologies, whether tunnel workers feel well-being by introduction of technologies has never been examined. In Psychology there are two kinds of well-being, Subjective Well-Being (SWB) and Psychological Well-Being (PWB). SWB is an overarching ideology that encompasses such things as "high levels of pleasant emotions and moods, low levels of negative emotions and moods, and high life-satisfaction." SWB is one definition of happiness. We assumed that SWB involves the feeling of safety and ANSHIN of workers at work. On the other hand, the idea of PWB, Carol Ryff established in the same year consists of six factors, which are positive relationships with others, personal mastery, autonomy, a feeling of purpose and meaning in life, and personal growth and development, which consists of happiness of people. Psychological well-being is attained by achieving a state of balance affected by both challenging and rewarding life events. It is hypothesized that PWB expresses worthwhile of worker at work. Usually both WBs are used to ask general people with questionnaires for happiness with long-span. It has been said that WB is hardly changed for short time. There is no questionnaire or examinations to measure WB at work for workers. Our final goal is establishment of methodology to measure WB of workers at work including tunnel workers. As the first step, we compared the results of well-being between tunnel worker of a major construction company and tunnel miners using existing questionnaires. We examined and checked if WB of workers changed with short span. We found that well-being was quite different between two kinds of tunnel workers.

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Influence of grouting on recovery of longitudinal differential settlement of shield tunnel lining

Y.S. Hua, H.W. Huang, D.M. Zhang* & P.D. Li
Tongji University, Shanghai, China

ABSTRACT: Shield tunnel is a typical linear structure with extreme dimension scale in longitudinal direction and assembled by several segments, which is prone to differential settlement due to the disturbance of adjacent construction, which will endanger the safety of tunnel operation. At present, soil grouting is mainly used for settlement control in practice. However, grouting parameters always rely on engineer experiences. It is necessary to analyze the influence of grouting parameters on the effect of grouting lifting. In this study, a finite difference numerical simulation method is employed for analyzing the grouting impact at the shield tunnel. The influence of typical grouting parameters including the grouting volume and grouting range on tunnel settlement control was analyzed in more detail. Simulation results demonstrate that grouting can effectively recover the differential settlement of tunnel lining, and the selected grouting parameters have significant effects.

Keywords: Shield tunnel, Longitudinal differential settlement, Numerical simulation, Grouting parameters

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A probabilistic approach to evaluate the seismic loss of metro tunnels in Shanghai City

Z.K. Huang, D.M. Zhang* & W.D. Zhou
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai, China

K. Pitilakis
Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

G. Tsinidis
Department of Civil Engineering, University of Thessaly, Volos, Greece

S. Argyroudis
Department of Civil and Environmental Engineering, Brunel University London, London, UK

ABSTRACT: Tunnels are crucial lifeline components in the mega cities. This work studies the direct seismic cost of metro tunnels subjected to earthquake events. The degree of tunnel damage and the corresponding direct seismic loss is derived considering various tunnel burial depths. The developed framework is then applied in the metro tunnels located in Shanghai city, China. Specifically, the direct seismic loss of one tunnel ring and the whole Metro Line 10 under different hazard scenario is estimated. Results highlight the significant function of tunnel buried depths towards more efficient seismic loss assessment. The findings of this study constitute useful elements in seismic loss management in terms of lifeline resilience.

Keywords: circular tunnels, seismic vulnerability, cost, infrastructure

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Estimation of permanent lining stress of road tunnel by ultrasonic velocity

T. Ishimura & A. Kusaka
Public Works Research Institute, Tsukuba, Japan

N. Isago
Tokyo Metropolitan University, Hachioji, Japan

ABSTRACT: For deformed tunnels, it is necessary to carry out appropriate repair work and reinforcement work according to the state of defects and deformation, in order to ensure the structural stability of the tunnel and the safety of users. For that purpose, advanced technical judgment is required to accurately and reliably grasp the mechanism and factors of the defects. In this paper, we focused on the ultrasonic velocity on the lining surface as one of the methods for supporting to grasp the condition of the tunnel lining. The relationship between the strain and the ultrasonic velocity of the lining surface was examined by the full-scale lining loading experiment, and the ultrasonic velocity in the actual tunnel was measured. The possibility of estimating the stress state of the lining was also examined based on the results.

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Modelling underground mine ventilation characteristics using artificial neural networks

Maria Karagianni & Andreas Benardos
School of Mining & Metallurgical Engineering, NTUA, Athens, Greece

ABSTRACT: Underground bauxite mining exploitations is a challenging environment for ventilation. A controlled underground ventilation system can significantly improve the environmental and working conditions at the mines. In this paper, the modelling of a section of an existing complex underground ventilation network assisted by machine learning (ML) techniques and more particularly by the use of Artificial Neural Network (ANN). The developed ANN is focusing in the prediction of NOx concentration at a selected mine site in order to model its operating characteristics so that they can be automatically adjusted to the existing conditions, ensuring better working conditions and creating a safer and controlled underground environment. The above model can make prediction that are accurate and respond to actual conditions and can be the basis for a further improvement of the Ventilation on Demand (VoD) technology.

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A 3D numerical study of sprayed concrete lined junctions

A. Keneti
SMEC, Melbourne, Australia

A. Thomas
All2plan Consulting ApS, Copenhagen, Denmark

B. Sainsbury
Deakin University, Melbourne, Australia

ABSTRACT: At a junction, tunnels leave from a 'parent' tunnel/shaft and typically the connection is perpendicular. Sprayed concrete linings offer many advantages for support of such complex tunnel junction geometries. While the stress distribution in the main tunnel or shaft is reasonably well understood – at least conceptually – very few studies have considered the loads in the 'child'/adit tunnel. These loads are critical for determining an optimum excavation sequence and lining thickness based on the effective stresses in the adit tunnel. Of critical importance is the longitudinal behavior of these tunnels which is often neglected in the design process. While some simplified analytical calculation methods can be used to assess the impact of the complex stresses in the junction on the 'parent' tunnel, there is no equivalent design tool for the adit. In this study, advanced three-dimensional numerical simulations investigate the structural-ground interaction during the sequential excavation of an adit off a vertical shaft. Real case study data from the Heathrow Airport Terminal 5 project is used to validate the results of the numerical analysis. The results highlight the key influences at an underground junction and thereby can provide a design basis to improve the efficiency of design at junctions and associated tunnels.

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Increasing the capacity in long railway tunnels through combination of railway operation control and tunnel control

Sebastian Klabes & Markus Pichler
Siemens Mobility AG, Switzerland

ABSTRACT: Ambitious tunnel projects are currently being carried out all over the world to increase capacities, shorten travelling times and strengthen railway transport in its competition. Especially, in long railway tunnels, critical events, which might quickly turn into a disaster, shall be avoided at any time. A crucial factor is effective supervision and fast response of the railway operator (dispatcher). The optimized interaction of the tunnel control system and the railway control system support the railway operator (dispatcher). Siemens Mobility delivered both systems for the 57 km long Gotthard base tunnel, which started commercial operation in 2016. Considering experiences during the project execution and the current operational experience we will show how the overall capacity can be increased by combining railway operation control and tunnel control. We will illustrate this exemplarily by discussing an operational risk of railway operation in long tunnels. We show, how the fast and effective reaction of the railway operator (dispatcher) enables to manage the operational risk effectively.

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Evaluation of mechanical behavior of hanging and anchorage system supporting jet fan for safety of road tunnels

Y. Koizumi & A. Kusaka
Public Works Research Institute, Tsukuba, Ibaraki, Japan

Y. Tatsumi
Public Works Research Institute, Tsukuba, Ibaraki, Japan
(Presently), Toda Corporation, Chuo, Tokyo, Japan

ABSTRACT: In road tunnels, hanging and anchorage system is used to support electrical and mechanical equipment, including a jet fan. In this paper, we report measurement results of tensile forces of six turnbuckles hanging a jet fan in an actual road tunnel. We also report pull-out tests of post-installed anchors to evaluate the effect of cracks and fiber sheeting on the pull-out strength. From the results of the measurement and the experiments, we summarized the points of attention of hanging and anchorage system to ensure the safety of road tunnels.

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Earth, Fire, Water, Wind: Addressing insurance expectations by pro-actively taming the four elements

T. Konstantis
Risk Engineering Consultant, Marsh Specialty, London, UK

ABSTRACT: All underground works are exposed to diversified risks, with the overall "risk profile" depending upon several factors, such as complexity, configuration, layout, major interfaces, etc. Each structure, including both temporary and permanent works, can be adversely affected, necessitating a bespoke and dedicated approach. This paper elaborates in depth on the four major hazard sources (namely earth, fire, water, wind), describes their salient characteristics and properties and delineates the various ways that the project can be affected, with any adverse outcome impacting the critical project areas such as cost, time, quality, health & safety, etc.

Nevertheless, these adversities can be proactively moderated by experienced risk engineers with the use of comprehensive and well-recognized guidelines, the timely provision of beneficial feedback and articulation of targeted loss control recommendations. The final achievable outcome is the reduction of the total cost of risk with tangible benefits to all project stakeholders.

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Seismic experiment of tunnel-group metro station in rock site

Ruozhou Li*
College of Civil Engineering, Tongji University, Shanghai, China

Yong Yuan
State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

ABSTRACT: Metro station constructed in rock strata is composed of a group of tunnels, mining at the levels both station hall and platform connected via horizontal passages, vertical shaft, and escalator corridors between them. There is sudden change in structural stiffness at a junction of various tunnel cross-sections. The joint of the junction may be sensitive to earthquake excitation. In this experimental investigation, shaking table test of a stratum-station model with geometric similarity ratio of 1:30 was carried out. The model materials of the stratum and the tunnel structure were selected following similitude law. The acceleration responses of the model and the strain of the structure were observed at key locations, when the seismic motion is input in the direction along the cross section of the station. The lateral input of synthetic seismic waves has a significant amplification effect on the ground model in the region of 15~30Hz. The spectrum characteristics of measurements show that the acceleration magnification of the stratum increases in the vertical direction till ground. At the junction between the station tunnel and the vertical passage the amplification effects of acceleration are more obvious than that at another portion. At the spandrel of the lower section of the vertical passage the maximum strain response is the largest.

Keywords: Metro station, Tunnel-group, Seismic performance, Shaking table test, Rock engineering

Shaking table test of fault site effect on seismic response of fault-crossing tunnels

R.H. Li
Department of Geotechnical Engineering, Tongji University, Shanghai, China

Y. Yuan
State Key Laboratory of Disaster Reduction in Civil Engineering , Tongji University, Shanghai, China

X. Zhao
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

ABSTRACT: Tunnels crossing inactive faults may suffer from severe damage during earthquakes. Fault sites have a significant hanging wall effect during earthquakes, but this effect on the tunnel seismic response has not been specifically quantified. In this study, shaking table tests were conducted to investigate the fault site effect and seismic response of fault-crossing tunnels. The hanging wall effect is the results of the geometric effect due to the asymmetric distribution of inclined fault. This geometric effect will lead to the reflection of seismic waves between the ground surface and fault interface and exacerbating the acceleration of the hanging wall. The acceleration of the tunnel located in the hanging wall is significantly greater than that located in the footwall, which is not only attributed to the dynamic characteristic of the site, but also the interaction between the dynamic characteristics of different areas of the site. For the tunnel sections located in the hanging wall, the influence range of the fault is approximately twice the tunnel diameter, for those located in the footwall, the fault has limited effect.

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A probabilistic approach to evaluate the risk due to a fire in unidirectional road tunnels ventilated by jet fans

D. Martinelli & P. Oreste
Department of Environment, Land and Infrastructures Engineering, Politecnico di Torino, Italy

ABSTRACT: The risk produced by a fire is one of the most important aspects to be analysed for the safety of a road tunnel. In one-way ventilated tunnels with jet-fans it may happen that during a fire the fumes move in the opposite direction to that of the fresh air entering the tunnel. This phenomenon (back-layering) can involve people fleeing towards the mouth of the mountain with dramatic consequences. Since many parameters that characterize the phenomenon are known only with a certain approximation, it is necessary to adopt a probabilistic approach. In this work this approach is illustrated, applying it to a road tunnel in Northern Italy. The probability that the fumes of the fire can reach people fleeing has been plotted as a function of the total number of jet-fans in the tunnel, so that the definition of the ventilation system can be carried out in the design phase in relation to safety during the emergency phase.

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Tunneling in urban areas exacerbates unplanned risks

N.A. Munfah
Gall Zeidler Consultants, New York, USA

ABSTRACT: Tunneling in urban areas imposes high construction risks, if unaddressed during the planning and design phases, will result in severe consequences. The overbuilt conditions, the low ground cover, the presence of unchartered utilities and foundations, connections to existing operating systems, etc. exacerbate tunneling risks in urban areas and increase the severity of their consequences. There are unique geotechnical and environmental risks associated with tunneling in urban areas such the potential of mixed ground conditions, presence of boulders and gravel, the presence of old abandoned foundations, the potential of presence of contaminated grounds and ground water, etc. In addition, there are also risks related to public safety, the present of active and abandoned utilities, maintaining surface traffic, maintaining pedestrian movement, impact on businesses and the daily lives of the people. There are also risks associated with construction logistics, material delivery, and equipment, the risk of impact on existing landmarks and historic buildings as well as the potential presence of artifacts and relics. In addition, of the major risks are dealing with project stakeholders, approvals and permitting process, affected communities, and the geopolitical and funding risks.

This paper addresses tunneling risks in urban areas using examples from projects from around the world and mitigation measures.

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Performance and monitoring results of repair work to prevent chloride attack in operating subway tunnels

Y. Mutou
Metro Rail Facilities Co., Ltd., Tokyo, Japan

S. Nakamura
Tokyo Metro Co., Ltd., Tokyo, Japan

N. Ogura
CORE Institute of Technology Corporation, Tokyo, Japan

ABSTRACT: In the case of Tokyo metropolitan subway tunnels located near tidal rivers and coastal areas, the deterioration of reinforced concrete due to chloride attacks by leakage water include chloride ions is progressing at a rapid rate. In order to prevent the deterioration of chloride attack in subway tunnels, we have standardized judgement method for repair areas by spraying silver nitrate solution and repair method for using sacrificial anode material and surface impregnation material. In addition, we applied a surface impregnation material that inhibit chloride ion penetration to concrete when chloride attack is detected even if no concrete deformation can be confirmed as preventive maintenance. Tokyo metro conducted chloride attack countermeasure repairing in operating subways since 2014, and have already carried out it over 6,551m. In some of the repaired sections, monitoring has been continuously carried out by visual inspection, chipping survey and measurements of protective current discharge rate and depolarization. As a result, we confirmed these repair works are effective by checking the entire repaired section after more than seven years had passed since repair, with no problematic deformations occurring.

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Road tunnel fire risk analysis: Is 1-D analysis inferior to 3-D?

P. Ntzeremes, D. Pikiokos, D. Kolaitis & K. Kirytopoulos
School of Mechanical Engineering, National Technical University of Athens

ABSTRACT: Road tunnels are one of the most critical infrastructure elements of modern road networks. Fire, probably the most dangerous accident in a tunnel, is rare but if they occur, they can have disastrous consequences. As far as the management of fire events is concerned, the common practice is based on risk analysis studies being conducted following the specific requirements each country has adopted. The country-based normative standards dictate whether a one-dimensional or a three-dimensional analysis shall be performed. Both kinds of analysis aim to provide a forecast of the evolution of the fire and, as such, to give a reliable indication of the threat that a fire event would pose to the successful evacuation of the users being trapped inside the tunnel. However, the 1-D and 3-D analyses do not always provide identical results and cautiousness should be shown not to introduce unnecessary, additional, resource-consuming safety measures or the opposite. This study provides an illustrative comparison of the one-dimensional and three-dimensional analysis to showcase the fallacies that may occur. The analysis is applied on a typical Greek tunnel fulfilling the minimum requirements of Directive 54/2004/EC. The results illustrate that differences in the obtained results may indeed occur. For instance, the gas temperature estimated from an 1-D analysis is higher than the 3-D analysis at low heights, close to the fire source (up to 50 m), while the radiant heat flux levels are much lower than the corresponding 3-D predictions. However, these differences are alleviated further upstream of fire location. By uncovering potential fallacies and challenges included in risk analysis studies towards fire events, this study aims to support tunnel operators and risk analysts in proposing realistic safety measures, when and if necessary.

Keywords: Fire, risk analysis, road tunnel, safety measures, simulation

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Development near underground rail corridors – Engineering assessment with case studies

J. Pan, A. Kuras & N. Loganathan
WSP Australia Pty Ltd, Sydney Australia

ABSTRACT: Building development near underground rail corridors can have the potential to cause adverse impacts to the structural integrity and durability of existing underground rail infrastructure or impact the feasibility of future planned rail lines. Therefore, it is important that developers can demonstrate that their planned construction will not compromise existing rail infrastructure and their operation or the feasibility of building new rail infrastructure. Deep excavations and building foundation, if poorly designed and implemented, can potentially cause significant ground deformation, alter loading profiles on underground structures and other engineered features. It can become imperative that detailed engineering and risk assessment is undertaken by developers to give confidence to the relevant rail authority that their construction will not be cause for concern. Through this process the impacted authorities are better placed to give their concurrence, as part of the local development application process.

This paper presents general discussion on the methodologies and approaches that have been applied in Sydney, Australia, to assess the impacts of new development on existing or planned rail corridors, in accordance with the relevant guidelines and standards. Some typical case studies are discussed to illustrate the processes that have been implemented and the type of assessments that have been undertaken to ensure that building development and rail assets can co-exist without adversely impacting each other.

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Engineering correlations for critical velocity estimation in road tunnel fires: A comparative assessment using CFD tools

G. Papadima & D.I. Kolaitis
School of Mechanical Engineering, National Technical University of Athens, Greece

ABSTRACT: One of the most frequent fire protection strategies used in conventional road tunnels is to employ jet fans to achieve longitudinal ventilation, aiming to eliminate the hazards associated with smoke back-layering. In this context, it is necessary to determine the "critical ventilation velocity" that prevents the development of toxic smoke flow upstream of the fire. Towards this end, a range of empirical correlations, aimed at estimating the critical ventilation velocity, has been proposed. This study aims to comparatively assess several such empirical correlations, using Computational Fluid Dynamics (CFD) simulations as a benchmark. Initially, the Fire Dynamics Simulator (FDS) CFD code was validated against experimental measurements obtained in a mechanically ventilated, 854 m long tunnel. Subsequently, the FDS code was used to estimate the same tunnel's critical velocity in a series of parametric simulations, by varying the exhaust volume flow rates delivered by the jet fans, as well as the maximum Heat Release Rate (HRR) of the fire. It was found that the critical ventilation velocity generally increases with increasing fire size, until a certain HRR value, after which it becomes independent of the fire power. Predictions of nine different engineering correlations used to determine the critical ventilation velocity were then compared against the obtained CFD numerical results; the obtained discrepancies varied significantly, ranging from 1% to 47%, thus suggesting that the investigated correlations exhibit notably different levels of prediction quality.

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ASET Estimation through fire dynamics simulation for various cases of fire incidents in rail tunnels

D. Papakonstantinou, A. Kallianiotis & A. Benardos
National Technical University of Athens, Athens, Greece

ABSTRACT: Although the frequency of fire accidents in tunnels or metro stations is low, in worst cases they may lead to severe fatalities and damages. During a fire incident an underground space, smoke is the main source of danger for the occupants. In order to have a more accurate prediction of fire impacts, most safety standards enforced worldwide suggest the development of special risk analyses. However, there is no specific guidance regarding the selection of fire size, fire duration or burning materials. These parameters affect the thermal and smoke propagation within the underground space and therefore the available safe egress time. In this paper several rail-fire cases are selected, based mainly on information gained through real-scale experiments and a fire dynamic analysis is conducted for different geometries of metro tunnels. The available safe egress time for every case is determined through the fractional effective dose (FED) that occupants might receive in a period of time, which is a measure of incapacitation because of toxicity. Based on the above, detailed data on the environment created for each fire case in a given tunnel geometry are presented. These data can provide an indication for the risk that each case may produce for the occupants and they could be used as a first guidance for an engineer, before the conduction of the risk analysis. Furthermore, conclusions about the influence of the key parameter's evolution on the tenability conditions inside the tunnel can be drawn.

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Statistical interpretation of tunnel project characteristics and their influence on technical risks – current and future challenges

C. Paraskevopoulou
School of Earth and Environment, University of Leeds, UK

P. Spyridis
Faculty of Architecture and Civil Engineering, TU University of Dortmund, Germany

D. Proske
School of Architecture, Wood and Civil Engineering, Berner Fachhochschule, Bern, Switzerland

G. Doulkas
STRABAG UK Ltd., UK

ABSTRACT: Tunnels are an increasingly significant part of our built infrastructure. Simultaneously, they are subject to a diversity of inherent uncertainties associated with the geotechnical, hydro-geological, and physical environment surrounding them. The associated risks can materialize on many occasions, leading to disasters with substantially high reinstatement costs, incurred delays, and damage to adjacent third-party assets and the environment. Such disasters can occur due to extreme natural events and unforeseen and unforeseeable ground conditions or accidents. but also, human-driven issues, such as substandard design, poor project management, aggressive project timelines leading to safety shortcuts, compressed budgets and application of innovative techniques not yet fully tested and validated, are some factors contributing to an increased probability of risk materialization and disastrous events. This paper aims to provide a statistical interpretation of tunnel project characteristics and their influence on technical risks based on a database with approximately 400 tunnel failure cases. A further goal of the study is to support decision-makers in the risk management process, such as owners, engineers, and insurers by improving their understanding of project sensitivities. The results indicate the significance of technical characteristics (such as tunnel dimensions, construction type, and ground formations). Still, they also reveal some dependence between lower project risks and the application of current project and risk management practices.

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Design of stress level for accelerated life test of HLW repository sensor

Changhee Park, Hyun-Joong Hwang & Gye-Chun Cho
Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea

Chang-Ho Hong
Disposal Performance Demonstration Research Division, Korea Atomic Energy Research Institute (KAERI), Daejeon, Korea

ABSTRACT: The high-level nuclear waste (HLW) repository is exposed to a number of stresses, including high temperatures, high humidity, and radiation. These stresses cause the structure to deteriorate and create cracks. Therefore, structural health monitoring with monitoring sensors is required for safety. However, sensors could also fail due to the stresses. Given that the sensors are installed in the bentonite buffer and the backfill tunnel, it is impossible to replace them if they fail. That's why it is necessary to assess the sensors' durability under the repository's environmental conditions before installing them. And an accelerated life test can be used for this purpose. In this regard, an accelerated life test can be used. Before conducting the test, the proper stress level must be designed first to get reliable data in a short time. In this study, a methodology for designing stress levels is described.

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The effect of explosions in road tunnels on critical structural elements

V. Peterson
KTH Royal Institute of Technology, Div. of Concrete Structures, Stockholm, Sweden

F. Lozano
Chalmers University of Technology, Div. of Structural Engineering, Gothenburg, Sweden

M. Johansson
Chalmers University of Technology, Div. of Structural Engineering/Norconsult AB, Gothenburg, Sweden

M. Hallgren
KTH Royal Institute of Technology, Div. of Concrete Structures/Tyréns AB, Stockholm, Sweden

A. Ansell
KTH Royal Institute of Technology, Div. of Concrete Structures, Stockholm, Sweden

J. Magnusson
The Swedish Fortifications Agency, Eskilstuna, Sweden

ABSTRACT: In the present paper, the walls of a concrete frame used for over-decking in a road tunnel were first designed using the relevant design provisions. The response of the wall was then analysed using non-linear finite element analysis, and the results of the finite element analysis were compared to what was predicted using the design guidelines. Additionally, simulations of the blast load resulting from gas leakage during transportation were conducted as a separate study. The results from two vapour clouds containing gases of hydrogen and propane were compared.

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Impact of evacuees' "psychological profile" in road tunnel fire evacuation simulations

D. Pikiokos, D.I. Kolaitis & K. Kirytopoulos
School of Mechanical Engineering, National Technical University of Athens, Greece

ABSTRACT: This study aims to assess the effect of the evacuees' assumed "psychological profile" in a typical road tunnel fire evacuation simulation. A combined CFD and evacuation simulation software (FDS + Evac) was used to model the fire evacuation process in a typical road tunnel. The tunnel is at the order of 500 m long and has no mechanical ventilation installed; a time-varying fire source, with a peak heat release rate equal to 100 MW, was employed. Six vehicles were assumed to be located within the tunnel; overall, the evacuation of 70 passengers, i.e. 55 adults and 15 children, was simulated. The agents were grouped according to their "psychological profile during evacuation", using three distinct "evacuation types", namely the "conservative", "active" and "follower" type. The obtained results suggest that the psychological profile of the agents may have a significant impact on the selection of a specific evacuation exit and on the overall duration of the evacuation.

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The impact of battery electric bus fire on road tunnel

H. Raza & S. Li
WSP USA, USA

ABSTRACT: An increasing number of transit authorities are pursuing a transition of their entire bus fleets to zero-emissions technology, specifically battery electric buses, to decarbonize the transportation system. This continuous shift to battery powered buses is associated with new hazards, including fires containing lithium-ion batteries undergoing thermal runaway reactions. This study focuses on identifying any key fire-life safety issues associated with a battery electric bus fire in an underground infrastructure. A design fire heat release rate curve for a battery electric bus is developed and fire scenarios in a roadway tunnel are modeled with occupants egressing. The analysis accounts for the severity of the structural impact from the thermal exposure on the tunnel. Results are compared with a conventional internal combustion engine bus fire scenario which would provide insight into fundamental questions including whether battery electric bus fires cause conditions in a tunnel to be more harmful.

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Time-dependent impact of expansive soil location on tunnels

Ashraf Saqib & Liu Changjian
Graduate School of Urban Innovation, Yokohama National University, Japan

Cui Ying
Faculty of Urban Innovation, Yokohama National University, Japan

ABSTRACT: Expansive soils in the geological strata around tunnels can threaten their stability severely. The high shrink-swell ability of these soils significantly impacts the tunnel's long-term operation. The location of the expansive layer plays a crucial role in adjudicating the consequent response of the tunnel to additional swelling pressure. This study evaluates time-dependent response to stresses due to expansive soil's specific location around the tunnel through model tests. The lab-prepared expansive soil sample was placed at the crown, shoulder, wall, and invert sections of the reduced-scale tunnel model and saturated to evaluate the tunnel response to swelling pressure in the context of time. The results projected a significant rise in pressure at different tunnel sections with time, implying long-term stability problems associated with the location of expansive layers in geological repositories. The movement of the surrounding ground was further evaluated through particle image velocimetry (PIV). The results suggest a strong relationship between expansive soil location, tunnel stability, and alterations in surrounding ground movements. Furthermore, the tunnel's ground displacements decreased with the expansive soil's depth. Therefore, the location of expansive soil around the tunnel can seriously impact the sustainability of the tunnel by influencing a specific section of the tunnel in direct contact with expansive strata and can cause the surrounding ground to deteriorate simultaneously.

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Visualization of workers behavior at tunnel construction sites in Japan using behavior-based safety procedures

Shoken Shimizu
Safety and ANSHIN Technical Research Center (SATEC), GOP Co., Ltd., National Institute of Occupational Safety and Health, Japan (JNIOSH)

Yasuji Mihara, Dohta Awaji & Ryohei Hase
Shimizu corporation, Tokyo, Japan

Rieko Hojo
Nagaoka University of Technology, Niigata, Japan, National Institute of Occupational Safety and Health, Japan (JNIOSH), & Safety and ANSHIN Technical Research Center (SATEC), GOP Co., Ltd.

ABSTRACT: Nowadays, the number of tunnel accidents have been decreasing yeah by year and some advanced technologies such as AI and/or ICT devices are getting to be introduced into tunnel construction site. It might be true in near future that safety of tunnel worker is supported by such technology. In fact, we are now developing a “tunnel face monitoring supportive system” that helps crack identification on tunnel surface using a camera with AI. However, on the hand, safety at many tunnel worksites is still depending on workers attentiveness in the present circumstance. The work on the face of tunnels is carried out efficiently by a small number of sophisticated workers in Japan. In addition, it is no exaggeration to say that safety is also supported by their efforts. Behavior of workers at tunnel construction site are required multiple work at the same time, for example excavation of tunnel face, operate heavy machines, drill holes for blasting and monitor tunnel face for finding sediment collapse as soon as possible. Establishment of the effective “tunnel face monitoring supportive system” needs behavior analyses of tunnel workers and machines at tunnel face. Therefore, we analyzed and visualized their behavior using behavior-based safety procedure. As the results, we found that almost of all behaviors between workers and machines have not had time overlap. Based on these results, we are planning to continue developing the system that more effectively support the safety management of workers at the tunnel faces.

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Risk management in Outfall tunnelling, the MPSO tunnel, Doha, Qatar

J.B. Stypulkowski, A.M. Najder Olliver & Khalid Saif F S Al-Khayareen
Public Works Authority (ASHGHAL), Doha, Qatar

ABSTRACT: The Musaimeer Pumping Station and Outfall (MPSO) is a successfully completed 10km-long and 3.7m-ID outfall tunnel. MPSO is a part of a bigger system comprising a pumping station, an offshore riser shaft and an 84-port diffuser field. This system will drain storm and groundwater from southern Doha, Qatar, at a peak flow rate of 19.7m^3/s. The authors present how the geotechnical risks during tunnelling were identified, managed, and mitigated based on cross-correlation of the results from the client's extensive offshore geotechnical investigations in weak/soft rock mass, the contractor's Seismic Reflection (SR) survey and Electrical Resistivity Tomography (ERT) survey as well as the Bore-tunnelling Electrical Ahead Monitoring (BEAM) System used during tunnelling. Good and continuous correlation was observed between the different types of geotechnical investigations, which significantly reduced the risks during outfall tunnelling and allowed for consistent, safe, and uninterrupted operations along the whole alignment. The authors have also compared the laboratory test results obtained from the borings performed during the first ground investigation phase of MPSO with the ones collected for the upstream connecting tunnel completed in 2017 to expand a database for weak rocks common to the Doha area.

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Monitoring of compressed air workers during hyperbaric interventions in TBM

N. Subbotina
Oxicamaras SRL Medical Center, Buenos Aires, Argentina

J. Castro & L. Pellegrini
CCMI Consortium Ghella, Buenos Aires, Argentina

J. Frydman & L. Correa
Fisiocorp SA Medical Center, Buenos Aires Argentina

ABSTRACT: The medical monitoring of tunnel workers during hyperbaric interventions is part of medical surveillance and assessment of decompression procedures. 24 workers were selected and trained, 3 persons at a time worked under pressure, with a total of 186 records collected from 69 interventions. Working pressure ranged from 0.9 bar to 3.6 bar. The bottom time varied between 0:30 and 7:45 hours. Vital signs showed following changes after the surfacing: blood pressure was slightly reduced, heart rate increased, keeping all parameters within normal limits; psychologically the workers stayed positive. One case of bends was observed and successfully treated. Medical monitoring showed appropriate selection and training of personnel for the compressed air environment, the compression and decompression protocols were adequate.

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A holistic tunnel safety concept for a 20-year-old tunnel upgrade to an ADR "Category A" tunnel

K. Tsiamouras
Aegean Motorway S.A., Greece

ABSTRACT: Following the elaboration of a Tunnel Safety Documentation for the T4 tunnel, several deviations from the European and national Standards were identified. Moreover, due the tunnels' special characteristics and its ageing equipment, the rehabilitation plan had not only to upgrade the level of safety to "Category A" as per the ADR agreement, but also to perform heavy maintenance works and provide sustainable solutions for the tunnel operations and the local community. The construction methodology poses significant challenges in the operation and the construction. Therefore, special provisions, technical and operational, were required in order for the transport of heavy and dangerous goods vehicles to be allowed in the tunnel during construction. The Covid pandemic and the geopolitical conditions (Ukraine war), seem to negatively affect the projects' duration and financing. With a budget of more than €20M, it is the first tunnel upgrade project of this magnitude and complexity in Greece, that sets the basis as refence for future tunnel upgrades.

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Shaking table test of segmental linings with Ground-Penetrating Shield Tunnel (GPST) under transverse excitations

Qi Wang
Department of Geotechnical Engineering, Tongji University, Shanghai, China

Yong Yuan
Department of Geotechnical Engineering, Tongji University, Shanghai, China
State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

ABSTRACT: The dynamic responses of the ultra-shallow embedded tunnel, like GPST (ground penetrating shield tunnel), remain unclear compared to regular shield tunnels. In this paper, large-scale shaking table tests are performed to investigate the dynamic responses of the GPST. The physical model is designed to reproduce the system composed of tunnel launching and arrival at the ground level. The buried depth of the model tunnel ranges from -0.5D to +0.5D. The site-specific earthquake motion is adopted as seismic excitations along the transverse direction. The acceleration response, diameter deformation ratio, joint extension and dynamic earth pressure are investigated to reveal the dynamic characteristics of GPST. The results show a significant correlation between dynamic response and buried depth. In terms of acceleration response, the acceleration response increases with the decrease of the buried depth. Specifically, the acceleration of the tunnel at the shallowest buried depth reaches four times the input motion. Moreover, the structure has the 'whiplash effect'; the overground structure oscillates violently due to earthquakes. However, the diameter deformation and joint opening response are opposite, showing that the diameter deformation response gradually increases with burial depth.

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Numerical analysis of rehabilitating an existed tunnel by grouting with different grouting volumes considering soil spatial variability

Z.W. Ye, J.Z. Zhang & D.M. Zhang
Tongji University, Shanghai, China

H. Shao
Shanghai Rail Transit Maintenance Support Co., Ltd. Engineering Affairs Branch, Shanghai, China

ABSTRACT: The light-disturbance grouting technology has been widely used to rehabilitate the excessive deformation of tunnels caused by the unexpected surface surcharge. This study focuses on the effect of grouting with different grouting volumes on an over-deformed shield tunnel. Mean-while, the random finite difference method is adopted to consider the spatial variability of soil. The compression modulus of soil is highlighted and simulated with an anisotropic random field discretized by the Karhunen-Loeve expansion. After being verified by a typical case, Monte Carlo simulations are executed to quantitatively evaluate the influence of grouting on the mechanical response of tunnels under different grouting volumes considering the soil spatial variability. Results demonstrate that the soil spatial variability can affect the rehabilitation of the tunnel with the same grouting volume. Meanwhile, the distributions of the ratio of un-certainty results to its corresponding deterministic results under different grouting volumes are consistent.

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Experimental study on ultimate bearing capacity of shield tunnel segments under unloading conditions

K.P. Zhang, X.H. Zhang, Q. Zhang & Z.C. Pei
Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, China
Shanghai Key Laboratory of Rail Infrastructure Durability and System Safety, Tongji University, Shanghai, China

L.Z. Qi
Department of Civil &Mineral Engineering , University of Toronto , Toronto , Canada

ABSTRACT: Aiming at the 5.9 m inner diameter segment structure of a metro tunnel in a coastal city of China, the bearing performance and damage law of segments under extreme unloading conditions are experimentally studied based on the full-scale test loading platform of Tongji University. The test results show that in the design load stage, the horizontal and vertical convergence deformation and internal force of the segment increase linearly with the change of external load, and the increase is less than 18%. The maximum deformation and internal force of the segment mainly occur at the arch waist. After entering the unloading stage, the transverse and vertical convergence deformation of the segment increases obviously. The maximum transverse and longitudinal deformation of the structure in the final failure state is 185 mm and 189 mm respectively. Hence, it means that the tunnel enters the unloading condition when the lateral deformation rate of the tunnel is greater than 20% in the actual project. At this time, reinforcement measures should be taken as soon as possible to intervene against the impact of lateral unloading on the tunnel structure. The corresponding transverse convergence deformation of the first longitudinal seam bolt when yielding is 149 mm, and the corresponding transverse convergence deformation of the first circumferential seam bolt when yielding is 169 mm. In the final failure state, segment cracks mainly occur at the top, bottom and the arch waist of the tunnel structure. At the same time, the convergence deformation of segment structure at these locations is relatively larger. The experimental results can provide a scientific basis for optimizing segment structure design and carrying out structural safety evaluation.

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Experimental study on ultimate bearing capacity of the stagger-jointed shield tunnel reinforced by steel plate

Xiaohui Zhang, Zhengchuan Pei & Keping Zhang
Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, China
Shanghai Key Laboratory of Rail Infrastructure Durability and System Safety, Tongji University, Shanghai, China

ABSTRACT: To investigate the ultimate bearing capacity of the stagger-jointed shield tunnel structure reinforced by steel plate in soft soil areas, a full-scale experimental test is carried out on the three rings of the steel plate reinforced shield tunnel. The convergence deformation, structural internal force, and the peeling conditions of the tunnel and the steel plate is obtained. The conclusions are as follows: The peeling between the steel plate and the tunnel segment is the main form of the damage of the reinforced structure, which occurs mainly near the tunnel capping block. When the steel plates at four positions are peeled off, the reinforced tunnel structure enters the yield stage. The research results of this paper provide a reference for the reinforcement of the stagger-jointed shield tunnels in the soft soil areas in the future.

Keywords: Shield tunnel, Bearing capacity, Structure deformation, Steel plate reinforcement

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Time-dependent reliability assessment of shield tunnel considering corrosion of segment reinforcement and joint bolts

D.M. Zhang, Z.K. Huang*, W.D. Zhou & C.C. Chen
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai, China

Y. Tong
Broadvision Engineering Consultants, Kunming, China

ABSTRACT: Tunnels play a vital role in the modern city transportation system. This study investigated the reliability of the shield tunnels along with their service life, considering the influence of uncertainty corrosion on the segment reinforcement and the joint bolts. Firstly, the Gamma random process model was adopted to illustrate the material corrosion depth variation with time, according to the corrosion measurements from tunnel practice. Then, the framework for the reliability calculation process of the tunnel structure was proposed based on the secondary development method for Abaqus in Python. Finally, the tunnel structure's reliability and the corresponding failure probability curves under different corrosion conditions over time were evaluated. It was found that the failure probability of the joint section under the ultimate limit state may increase to 100% under 30% corrosion of the bolts. The results indicated that the corrosion of bolts and the steel reinforcement, which deteriorate the bearing capacity and stiffness of the segment, can lead to an increase in the failure probability of the tunnel along with its service life.

Contractual practices, insurance and project management

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Development of a Project Objective and Requirement System (PORS) for major infrastructure projects to align the interests of all the stakeholders

S.C. Becker & P. Sander
Department of Civil Engineering and Environmental Science, Institute for Construction Management, University of the Bundeswehr Munich, Neubiberg, Germany

ABSTRACT: Major infrastructure projects often exceed estimated costs and schedule. Therefore, they do not achieve the desired quality. The difference in objective interests of the project participants is a major problem. Based on the difficult contractual relationship and the late involvement of all contractors, there is a lack of information for all those involved. This gap of information can be described by the principal agency theory from the new institutional economics. One way to reduce this information deficit is to use other delivery models, contracts and methods. Delivery models like Integrated Project Delivery (IPD) with the contractual relationship and the early involvement of all the participants creates a sooner understanding of the project. This can reduce information losses. However, the current project execution models do not have a smart objective system which records the interests of the client from start to the end of the project. They are not documented with the start of the project, neither adapted iteratively. Also, these objectives don't get used to define the requirement and specify that. With the help of the recently created project objective requirement system (PORS), the objectives of all project stakeholders can be selected, checked and compared. Followed by the transfer to the requirement management. With the PORS an incentive contract can be created and thus an incentive mechanism implemented. In addition, the project delivery on time and within the budget is strongly supported.

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Contractual practices & project management: TELT time adjustment mechanism

M. Bertrand & A. Fontana
Pini Group, Lugano, Switzerland

C. Salot & C. Dumoulin
TELT, Le Bourget-du-Lac, France

M. Macary
CETU, Lyon, France

ABSTRACT: The fair management of Construction Time and deadlines is a key aspect of Contract Management for long and deep tunnelling Projects. Addressing geological and geotechnical uncertainties of such underground works is challenging and the need for a time adjustment mechanism has proved to be a « must-have » over the last decades, to prevent or reduce claims and disputes. While the Swiss practice is probably at the foundation of this approach, the FIDIC Emerald Book (2019) has set an internationally recognized and comprehensive approach to this mechanism. TELT, the bi-national organisation in charge of one of the World longest railways tunnels which is currently under construction and is now moving forward all along his 57km-length, has a long track-record in the implementation of time adjustment, for over 15 years. The present article reviews the implementation and progressive development of Time Adjustment in different Contracts of the TELT's project. The completed case of Adjustment of Time Mechanism is presented for the Saint-Martin-La-Porte Exploratory Works. Two major new contracts are now ongoing, one of which is CO6/7, awarded in 2021 and spanning until 2027. This contract is EUR 1.4 billion worth and includes the implementation of 3 TBMs for a bored length of 25km, and several other excavated structures. One of the key focus of interest for the present article is the articulation of the Schedules of Baseline and the planning tools.

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Conceptual framework of the Snowy 2.0 Pumped Storage Project (PSP) Geotechnical Baseline Report (GBR) for underground works

A.R.A. Gomes
Tunnels and Underground Works, SMEC Pty. Ltd., Sydney, NSW, Australia

B. Chapman
Tunnel Engineer and GBR Lead, Snowy Hydro Ltd., Cooma, NSW, Australia

M.S. Diederichs
Geological Engineering, Queen's University, Kingston, Ontario, Canada

I. Ching
Principal Engineer – Tunnels, SMEC Pty. Ltd., Sydney, NSW, Australia

ABSTRACT: The Snowy 2.0 pumped storage project in Australia is situated within a complex alpine geological and hydrogeological setting which entails significant geotechnical uncertainties for sub-surface construction. To address this condition, a Geotechnical Baseline Report (GBR) has been incorporated in the construction contract of underground works to stipulate the allocation of geotechnical risks between the Parties. This paper outlines the conceptual framework used in the preparation and development of this GBR and associated risk-sharing mechanisms.

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Lessons learned procuring a high availability tunnel asset for the A303 Stonehenge

D.R. Hull
COWI UK

ABSTRACT: The paper focuses on the experiences gained in developing the procurement strategy for the A303 Stonehenge. The removal of private finance led to a unique opportunity to utilise best practice from the private finance solutions and build them into the revised public procurement model. The use of availability moved the solution from a pure design and build to one embracing a maintenance period, where the contractors were accountable for testing and commissioning the assets to meet these requirements. Embedded in the approach was the use of outcome-based deliverables focused on targeting key areas that were important to the end customer and important for working in a World Heritage Site. The paper also highlights how high impact low probability tunnelling events were handled from a risk perspective and how the entitlement to a ground baseline report was removed. The resulting procurement provided an additional £200m of value delivered through the contract.

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Tunnelling design management – Particularities in design processes and setup of teams

D. Katsaris
Geotechnical Expert, Athens, Greece

C. Pline
Tunnel Expert, Annecy, France

M. Vincens
Technical Manager, Lyon, France

ABSTRACT: This paper elaborates on the elements that differentiate tunnelling design from other disciplines. Provides ways to distinguish judgement-based design processes to mass production. Give a thorough view to managers regarding the elements that affect significantly the performance of a team by analysing the social processes that affect cohesion and decision making quality. Explain the difficulties that managers face growing teams at specific magnitude and how this is substantiated by social science. Finally, an analysis is provided for the organisational and leadership model of a team required to perform under fast-track and unconventional design conditions with relevant example from similar practices.

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Tunnel and underground works: Managing insurance particulars in a well-structured and risk-averse environment

T. Konstantis
Risk Engineering Consultant, Construction and Infrastructure Practice, Marsh Specialty, London, UK

A. Towers
Assistant Vice President, Risk Management Group, Allied World Assurance Company Ltd, Singapore

ABSTRACT: Insurance policies which are fundamental for a tunnel project to commence and finalize are managed primarily by the Insurer and the Insurance Broker (acting on behalf of the Insured) and are premised upon specific conditions and requirements.

Because of the extremely technical nature of tunnel projects, the placement of the appropriate insurance policy presupposes the availability of specific information to establish bespoke policy wordings and clear terms & conditions. These can influence the level of the insurance premium and other critical elements (e.g. deductibles, sub limits, etc). A crucial role in this lengthy and (occasionally) attritional process is delegated to Risk Engineers, who can facilitate the entire process by delineating the project's overall "risk profile" through discernible services assisted by dedicated aids. These could create a healthy competition among Insurers, highlighting the Insurance Broker's invaluable role and finally satisfy the project's needs.

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Flood risks during construction of underground works – An insurance and risk management perspective

S. Konstantis & P. Spyridis
Partner, Ruler Consult, UK
Member of CIREG

P. Bravery
Global Head of Civil Construction, Liberty Specialty Markets

ABSTRACT: Flooding is becoming one of the world's most devastating natural hazards causing severe social, economic and environmental impacts. The number and severity of events are rising rapidly, driven by climate change. Flood risk can be minimized and managed by using a combination of early warning systems and response mechanisms, such as weather/flood management plans and physical barriers. Although the built environment is usually very resilient to such natural perils and largely responds well to natural catastrophes, assets and in particular underground works under construction are inherently far more exposed. The risk is compounded when flood risk during construction is not specifically addressed, the focus being on the completed asset only. This paper discusses potential flood hazards and vulnerabilities, proposes a flood risk assessment process and presents example cases and mitigation measures, with focus on construction of underground works. Reference is also made to a new best practice guideline being prepared by members of the Construction Insurance Risk Engineering Group (CIREG), which intends to introduce the concepts of Flood Risk Baseline Reports and Flood Risk Maps for managing and mitigating the associated risks.

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Tunnel assessment: The Italian case

G. Lunardi, G. Cassani, M. Gatti, A. Amadi, A. Marchiondelli, M. Malacalza, A. Vitiello, S. Verga & C. Nardone
Rocksoil S.p.A., Milan, Italy

A. Selleri
Autostrade per l'Italia S.p.A.

ABSTRACT: The age of the infrastructures and the ever-increasing levels of traffic make it necessary to deal with the problem of safety of the structures with the greatest rigor, by fully reviewing the methods of inspection, investigation and intervention adopted up to that moment. This article illustrates the experience gained by Rocksoil company on the tunnels of the Italian motorway network by proposing a new methodological approach that starts from an in-depth knowledge of the tunnel and its history and evaluates its state of consistency through a detailed inspection and a series of supportive diagnostic investigations. After complete defect identification and cataloging, the interventions aimed at re-establishing the safety conditions are planned and subsequent checks and monitoring are defined in order to verify their duration over time.

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Introducing the ATOM risk management methodology for managing risks in heavy subway projects – The middle section of the Tehran Metro L6 and Tehran-Eslamshahr subway phase 1

B. Mardani Givi
Sabir Intl. Co., Tehran, Iran

A. Akbarpour
Islamic Azad University (South Tehran Branch), Tehran, Iran

Z.S. Hashemi
Concrete Research and Education Center (Affiliated with ACI), Tehran, Iran

H.R. Abbassian Jahromi
K. N. Toosi University, Tehran, Iran

S. Mousazadeh
Iran Railways Development Consulting Engineers Co., Tehran, Iran

ABSTRACT: The concentration of population in big cities, traffic crisis and air pollution problems have urged authorities to lunch heavy subway projects to resolve transportation issues and bring more sustainability to the built environments. Considering factors such as complexity, size and challenges of metro line projects along with their budgets and schedules, that put them in the category of heavy construction projects, the way these projects interact with a whole urban society during the design, construction and operation phases, and the way they change the cities, the success of these projects is highly dependent on applying sound project management systems and at the very heart of that, a strong formulation and implementation of a dynamic risk management methodology. This is to scan the future of a project and plan for it ahead. The increasing number of researchers in the field of risk management and the high demand for risk analysts and managers by big companies around the world nowadays are good proofs of the vital role of effective risk management. In this research, while introducing the ATOM (Active Threat and Opportunity Management) risk management methodology, a brief review is given on how the risks of the EPCandF contract of the middle section (7.1 km) of the 32 km Tehran metro line 6 were identified and ranked based on this methodology with responses to its top risks (Hashemi et al., 2021). This laid the foundation for a comprehensive implementation and customization of the ATOM methodology in the ongoing 10 km Tehran-Eslamshahr subway project as supported by the client. The ATOM comprehensive risk management methodology is an eight-step process including 1. Initiating, 2. Identification, 3. Assessment, 4. Risk response planning, 5. Risk reports, 6. Implementation, 7. Major and minor reviews, and 8. Post-project reviews (Hillson & Simon, 2020).

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The roles of the financiers' certifier in urban transportation tunnels and as the financiers' advisor for hydropower tunnels

A.G. Noble
WSP Australia

ABSTRACT: This paper is in two parts. In the first part, it explores the role of the Financiers' Certifier (FC) in transportation tunnelling projects and explains some of the key risks and issues that may be encountered during the construction of urban transportation tunnelling projects from the perspective of the FC. It explains the key duties when acting as the financiers' *eyes and the ears* for technical aspects of such projects. The risks are discussed as to how the financiers perceive the risks and how they may be exposed if the risk eventuates. The paper explains the differences in the role from that of the Independent Certifier or Independent Verifier, and the interfaces between the borrower's (Owner's) obligations to the financier and to the contractor(s).

In the second part it again focuses on the perspective of an advisor to financiers and additionally covers the technical and risk management considerations in the planning, design, and construction of tunnels for remote hydropower projects. Many of the key risks and issues are similar for urban transportation tunnels and remote large scale hydropower tunnels, however the scale of these risks can differ and there are several very different and rather unique conditions in the remote hydropower project that financiers need to be aware of.

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Fair risk allocation in tunneling: A game modelling approach

L. Rosas Sánchez
SMEC, Australia

ABSTRACT: Tunneling involves risks that are unique. In order to manage risks, the tunneling industry has supported risk sharing approach. However, some private owners may prefer a single-point allocation of all risks to the contractor, particularly for encountered ground conditions. This attitude represents an adverse trend back way of thinking which induces adversarial relationships within the tunneling industry. In consequence, these owners need to be educated with the potential benefits of the ‘risk sharing approach’. In this paper, Game Modeling is used as an analysis tool of risk allocation in a tunnel construction contract. Game Theory is a branch of applied mathematics devoted to the logic of decision making in social interactions. The unfair allocation of risk is still affecting the reputation of the tunneling industry. These owners need to be educated with the potential benefits of the risk sharing approach. Game modeling can be used as an effective tool for this education campaign.

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Compilation of a Geotechnical Baseline Report (GBR) in complex ground conditions – The case of the new, under construction, line 4 of the Athens Metro

G. Stoumpos, K. Boronkay, E. Zampiras, G. Rovolis, M. Novack & N. Bousoulas
ATTIKO METRO S.A., Athens, Greece

ABSTRACT: Line 4 is a new, under construction, line of the Athens Metro. The bedrock of Athens is the Athens Schist, a slightly metamorphosed, intensely deformed, heterogeneous meta-sedimentary succession. The complexity of the ground conditions imposed significant challenges when these needed to be quantified for the realization of the Baseline Statements in the framework of the Geotechnical Baseline Report (GBR) that was prepared for the first time by ATTIKO METRO S.A. in 2018. No data in literature or case studies were found regarding such engineering geological conditions and GBR. Common tunnelling concepts such as mixed ground conditions had to be defined in a quantitative manner. An innovative approach was implemented that included (a) qualitative/semi-quantitative description of typical engineering geological behaviour with respect to TBM tunnelling, (b) quantification and definition of what constitutes mixed ground conditions and (c) dimensioning of karstic voids with respect to introduced sectors at the TBM excavation profile.

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Project Alliances: Do they work for tunneling projects?

M. Xanthouli
Contract Manager – International, Strabag Group, Vienna, Austria

C. Kerber
Head of Contract Management – International, Strabag Group, Vienna, Austria

N. Khokhar
Expert (Consultant), Strabag Group, London, UK

ABSTRACT: Project Alliance is a collaborative procurement approach developed and customised for the purposes of a single project and is recommended for projects where the actual works are challenging, the risks uncertain and the environments complex. If anything, tunnelling projects are known for carrying an inherent uncertainty most notably (but not exclusively) pertaining to ground conditions. Having said that, tunnelling projects are also infamous for cost overruns, significant delays and often suffer from numerous disputes that unavoidably result in damaged relationships between the contracting parties. This paper refers to the challenges that led up to the development of Project Alliance as procurement model, presents the structure, mechanisms and key features of a Project Alliance and critically discusses the suitability of Project Alliances for tunnelling projects.

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