

## **ABDALAJIS EAST RAILWAY TUNNEL (SPAIN)- DOUBLE SHIELD UNIVERSAL TBMS COPE WITH EXTREMELY POOR AND SQUEEZING FORMATIONS**

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For over than 30 years Double Shield TBMs were successfully utilised all around the world in a variety of geological formations. However in some circumstances Double Shield TBMs required the execution of by-pass tunnels and other special hand mining works to face special extremely poor conditions, and mainly: important and rapid squeezing phenomena, very unstable tunnel faces (flowing ground) and combinations of the two. To overcome these limitations the new Double Shield Universal (DSU) TBM type was designed and successfully tested in a first experimental application in the 18 km long Val Viola tunnel in north of Italy.

Following this first experimental application a DSU TBM has been specifically designed and manufactured for the 10m diameter high speed railway tunnel of Abdalajis (Spain). This DSU TBM is characterized by extended facilities to treat the ground ahead of the face.

In the first 2,5 km of tunnel the encountered argillite formation was very unstable with rapid convergence of the tunnel walls and frequent face collapses. Large gas inflows with pressures up to 11 bars were measured in this section. In particular for about 600 m at the contact with the adjacent limestone formation the argillite rock was completely altered by the tectonic action and transformed in to a kind of flowing gravel with very low friction and small cohesion.

To advance the TBM under these conditions it was necessary to make large use of expanding foams to fill large voids in front and over the cutterhead. In addition several patterns of chemically grouted micro-piles were executed from inside the TBM shield to improve the ground characteristics and stability ahead of the machine.

Despite these extreme conditions and the restrictions to the tunnelling operations given by the gas presence the TBM was able to advance without requiring any bypass or hand mining excavation and without the shield to get trapped.

The article describe with details the technologies and methods adopted to overcome these special geological conditions as well the possible improvements to DSU technology that have been derived from the Abdalajis experience.

### **1. TBM DESIGN DEVELOPMENT**

In the last 10 years, while from one side the TBM tunnelling market has grown substantially the development of new TBM design has been poor.

In the recent 5-7 years however in Europe the market demand for long railway large diameter tunnels in variable ground conditions required to develop new TBM design in order to face these particular tunnelling conditions .

The application of the standard TBM types in these particular type of tunnels is in fact very risky.

In particular:

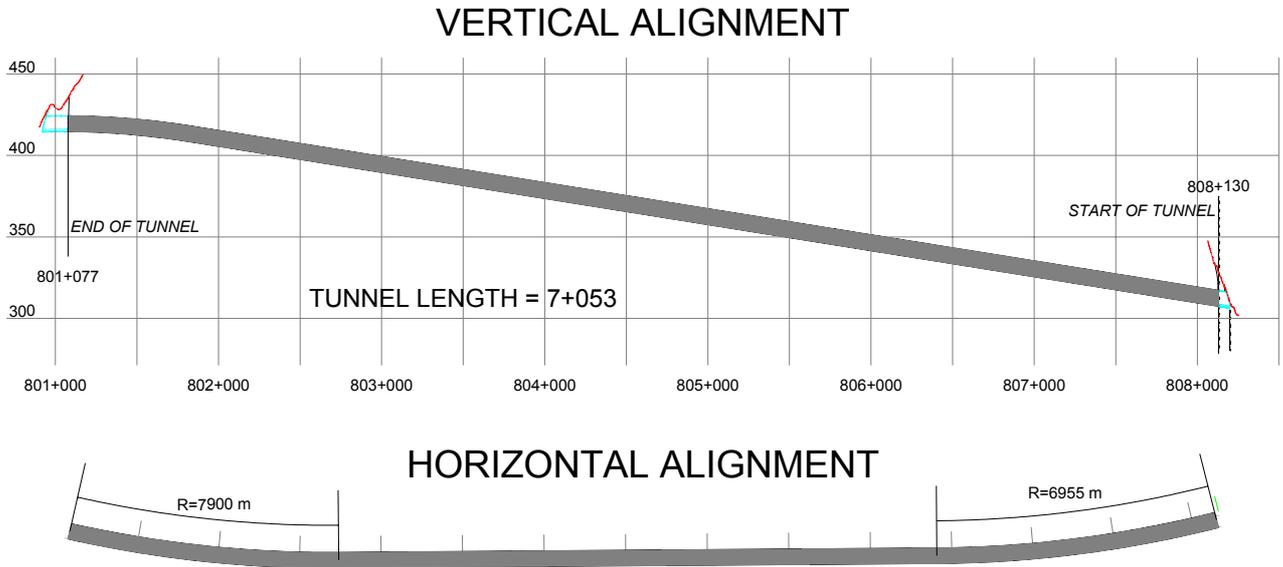
- Open gripper type TBMs are too sensitive to poor rock conditions especially in these large diameter range.
- Single shield TBM can not reach high performances in hard rock and are sensitive to squeezing ground and face instabilities
- Double shield TBM while in good to fair rock can achieve very good performance are still sensitive to squeezing ground and to face instabilities

The extremely difficult geological conditions of the Abdalajis twin railway tunnels (east drive tunnel and west drive tunnel) were more than a good reason to booster the TBM design research and develop new type of TBM and new associated technologies.

The Double Shield Universal TBM in the Face Support configuration that was developed for these tunnels is part of a new family of TBMs that, as will result more clear in the following chapters of the present paper, starting from a main general design concept can be configurated into different specialised versions to suit the particular project requirements and geology.

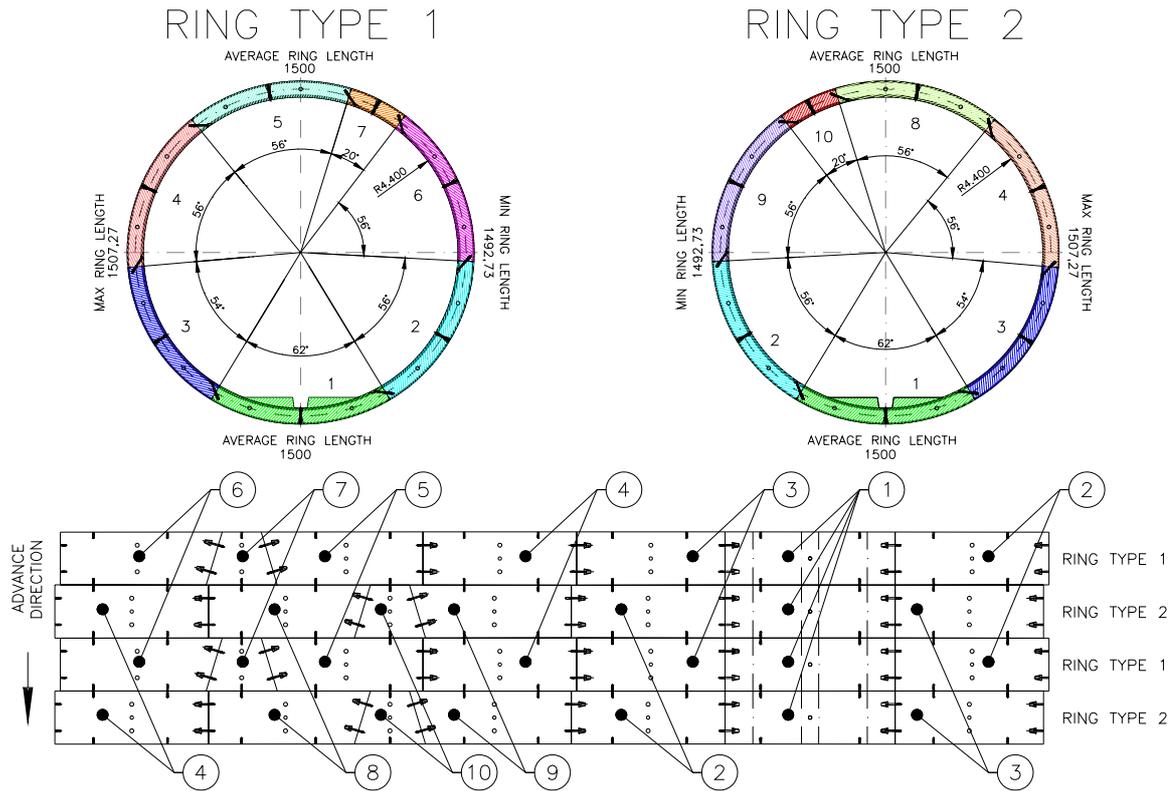
## 2 – THE ABDALAJIS PROJECT

The Abdalajis Tunnel East is one of the two 7,1 km long railways tunnels part of the new high speed railway line from Cordoba to Malaga and its alignment is shown in Figure 1.



*Figure 1 – TUNNEL ALIGNMENT*

The excavation diameter is 10 meter and the lining is the tapered ring type made of 45 cm thick precast segments (Figure 2) with a final internal diameter of 8,80 m. The adjacent segments are connected with bolts and the adjacent rings with plastic connectors. An EPDM profile is used to seal the joints between segments. The gap between the segments and the rock surface is filled with pea-gravel and in a second stage the pea-gravel is grouted with a cement based mixture.



*Figure 2 – TUNNEL TYPICAL SECTION*

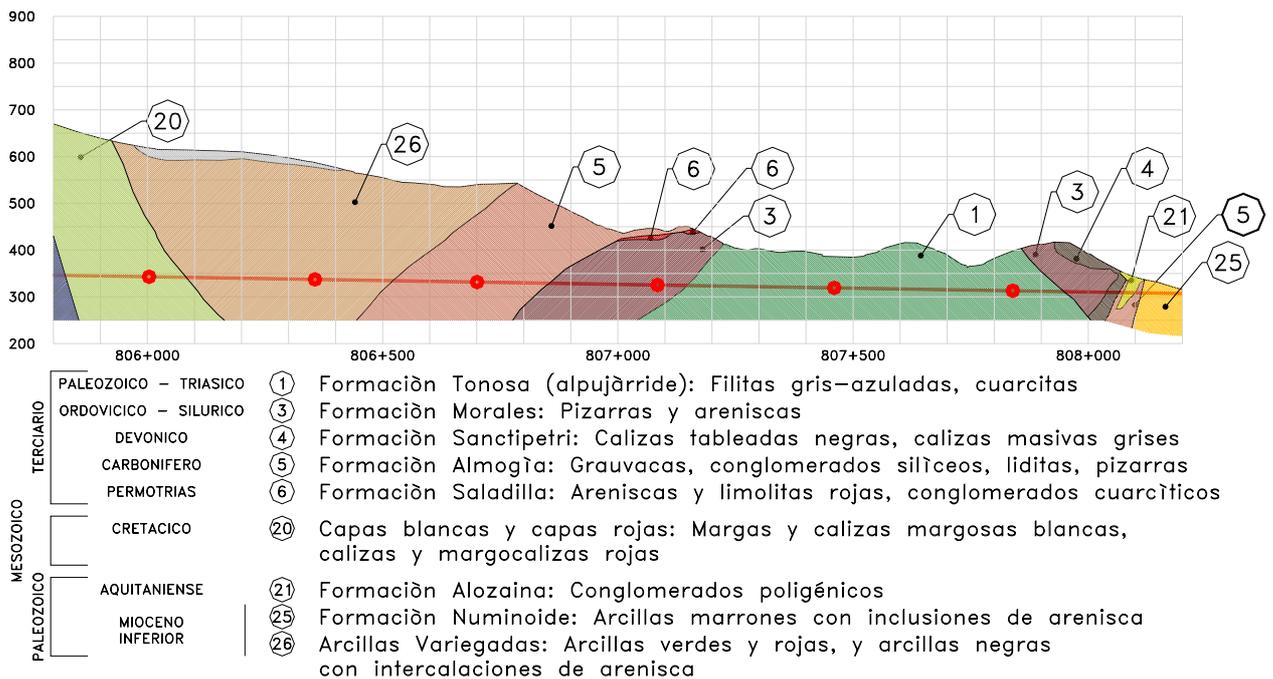
### 3 - THE GEOLOGY OF THE TUNNEL

The Abdalajis tunnel geology can be divided in two sections:

- the first section (Figure 3) in weak and very weak formations having a total length of about 2 km
- the second section in more competent sedimentary rocks under high overburden

The present article deals mainly with the excavation of the first section, characterised by the following formations:

- phillade and quartzite - Formacion Tonosa
- slate and sandstone –Formacion Morales
- conglomerate –Formacion Almogia
- argillite - Arcillas Variegadas



*Figure 3 – FIRST SECTION OF TUNNEL - GEOLOGY*

The rock formations in this section of the tunnel were expected to be of very low geo-mechanical characteristics, and were considered by many technicians an impossible task for a TBM, due to the high and rapid convergence and the potential face instability phenomena.

At the same time high pressure water flows were expected in the fractured limestone formations to be encountered after the argillite formations.

#### **4- THE DOUBLE SHIELD UNIVERSALE TBM CONCEPT AND THE ABDALAJIS TBM DESIGN**

The DSU design concepts and characteristics have been described in detail in the article “NEW DESIGN FOR A 10 M UNIVERSAL DOUBLE SHIELD TBM FOR LONG RAILWAY TUNNELS IN CRITICAL AND VARYING ROCK CONDITIONS” published in the RETC 2003 Proceedings by Wolfgang Gutter and Paolo Romualdi.

This new type of TBM was developed and tested the first time by modifying in the tunnel an existing 3,7 m diameter Wirth DS TBM that was stuck by the squeezing ground in a fault area under high cover in the Val Viola tunnel project, in the Italian Alps.

Basically the existing TBM was modified by :

- a. Increasing the diameter of excavation to increase the overcutting in respect of the rear shield and of the segmental lining
- b. Increase the diameter of the front shield to eliminate the step-back joint between the front and the rear shield,

These rather simply modifications allowed the TBM to restart the excavation and to achieve over 25m/day of production in the same ground that was trapping the TBM before.

This initial success encouraged SELI engineers to further develop the design of this new type of TBM with the attempt to realise a machine able to cope with the almost impossible tunnelling conditions expected in the Abdalajis tunnel.

The typical technical characteristics of a DSU TBM are:

- Total shields length in the range of 10 m, i.e. equal to the length of a single shield TBM of similar diameter
- Rear shield diameter much smaller than front shield; to allow the TBM advance also in squeezing ground
- New telescopic articulation design to eliminate the problem of packing the joint in loose ground
- Over-cutting facilities to increase the rock to segments clearances in squeezing ground
- High main and auxiliary thrust to move the shields even in very rapid squeezing ground
- Capability to advance in double shield mode even in the poor and instable ground conditions. Since in large diameter tunnels the instability phenomena occur more easily this feature allow the DSU TBM to advance with maximum productivity in a wider range of ground conditions

Depending the characteristic of the tunnel to be bored the DSU TBM can be configured into different design arrangements and in particular:

- a) DSU CP (Compact) Figure 4- In this configuration, that is combined with a special design of the back-up and of the rest of the tunnelling system, the DSU TBM is designed and manufactured for easy and fast erection/operation and disassembly. This to be utilised in very short tunnels were the cost and time of assembly and disassembly a normal “full size” system would preclude the convenience of utilizing the mechanical excavation.
- b) DSU RS (Rock Support) Figure 5- were the TBM is equipped with facilities to install rock bolts and shotcrete to locally substitute segmental lining . This configuration is recommended were most of the tunnel is in very good rock and no lining is foreseen if not locally rock-bolts and shotcrete while only short sections requires the installations of a full precast lining
- c) DSU GT (Ground Treatment) Figure 6- were the TBM is equipped with extra facilities to treat the ground in front of the machine (through the shields and through the cutterhead). This configuration is indicated when the tunnel cross disturbed rock formations under high cover
- d) DSU EPB (Earth Pressure Balance) Figure 7- were the TBM is capable to maintain an EPB pressure at the face. This configuration is indicated for tunnel having a section to be excavated in soil and/or very weak rock under shallow cover

For the Abdalajis tunnel, were disturbed rock formations under high cover and high water pressure inflows were expected, the selection of n.2 DSU GT type of TBMs was there the more logic selection.

The TBMs specifications and shield detail design was developed by SELI in cooperation with Mitsubishi of Japan and the Robbins Company of USA.

The TBM specifications and general assembly drawings are indicated in figures 8 and 9 below

The most special characteristics and design features of these TBMs are:

- The extremely high power and torque for a 10 m diameter rock TBM; .....kW and .....kNm
- The high main and auxiliary thrust, respectively .....kN and .....kN
- The 30 cm standard clearance between the excavation and the segmental lining outer diameter
- The possibility of additional overcutting of 20 cm on diameter
- The possibility to displace vertically the cutterhead in respect of the shield
- The .....total through the shield probe/pipe positions in the upper 180° of the section

## 5- TBM BEHAVIOUR IN SQUEEZING GROUND

Tunnel convergence was one of the biggest concerns in the project design phase since the large tunnel diameter and the presence of argillite rock formations under high cover.

The DSU TBM proved however to be able to cope with the rapid convergences of the tunnel walls without any problem and without having to use the full overboring capability of the machine, thanks to the particular shield design of this new type of TBM.

This achievement represent a very important step in the tunnelling technology since it will allow the utilization of mechanized excavation in many critical tunnels to be bored under high cover in weak rock formations were before only the conventional method was adopted, with the consequent high costs and long construction times.

## 6- TREATMENT AND STABILISATION OF THE TUNNEL FACE AND AHEAD OF THE FACE RAVELLING GROUND SECTIONS

A long section of the tunnel in the argillite (Arcillas Variegadas formation) was characterised by large instabilities of the tunnel face.

In the most critical sections the ground was behaving like a non cohesive ravelling ground.

Under these conditions, without taking special measures, the over-excavations and face collapses would have buried the TBM in the tunnel.

For this reasons the following measures were implemented in several critical sections:

- **Face stabilization treatments** - (Figure 10) - when the over-excavation at the face was increasing above a couple of meters in front and above the cutterhead, the TBM advance was stopped, the voids filled with resin foams and the collapsed material in front of the face consolidated with chemical grout mix. Than the TBM was advanced for few strokes until the treatment had to be repeated.

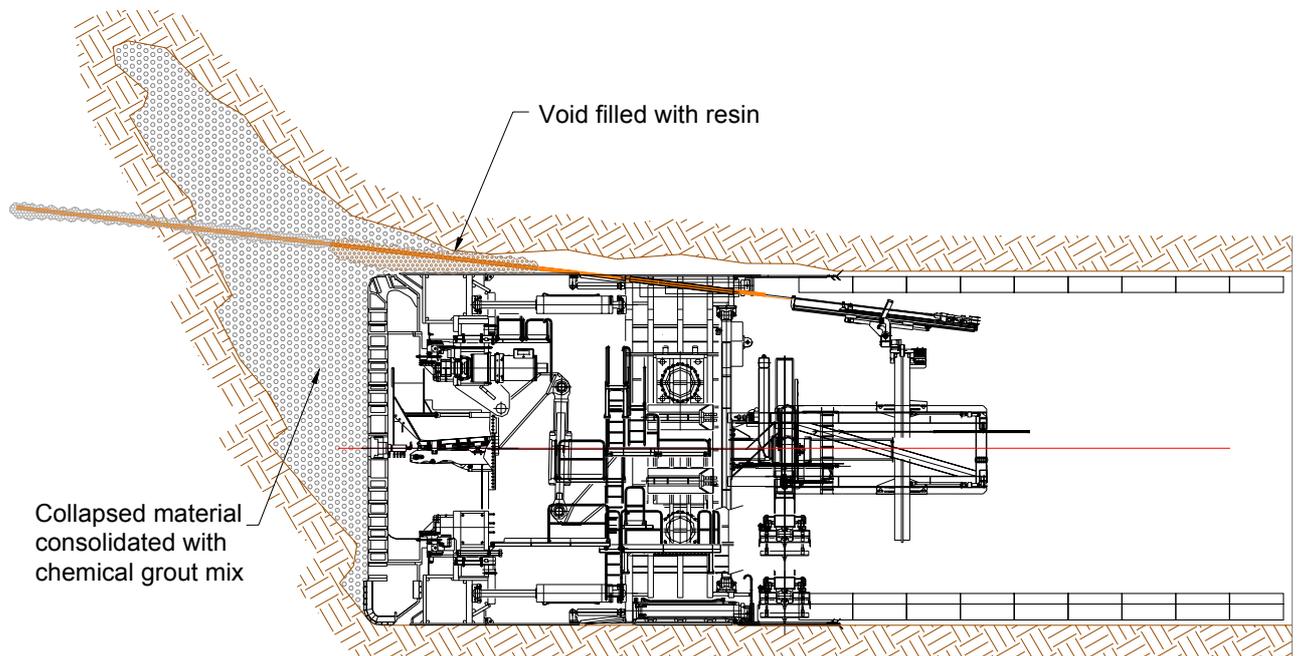


Figure 10 – FACE STABILIZATION TREATMENT

- **Pre-treatment of the ground ahead of the face** - (Figure 11) - in the most critical sections the weak argillite was behaving like a flowing gravel and even the above described face stabilization

treatments were not sufficient to control the face collapses and the ground itself had to be treated in front of the TBM.

A pattern of fiberglass pipes were executed through specific holes in the rear shield of the TBM in order to stabilise the crown of the tunnel. These pipes were then grouted with chemical grouting mix (GEOFOAM or MEYCO), very successful in penetrating in the argillite formations and increase the cohesion of the ground enough to avoid face collapses.

In the worst tunnel sections this treatments have been repeated each 3-5 m.

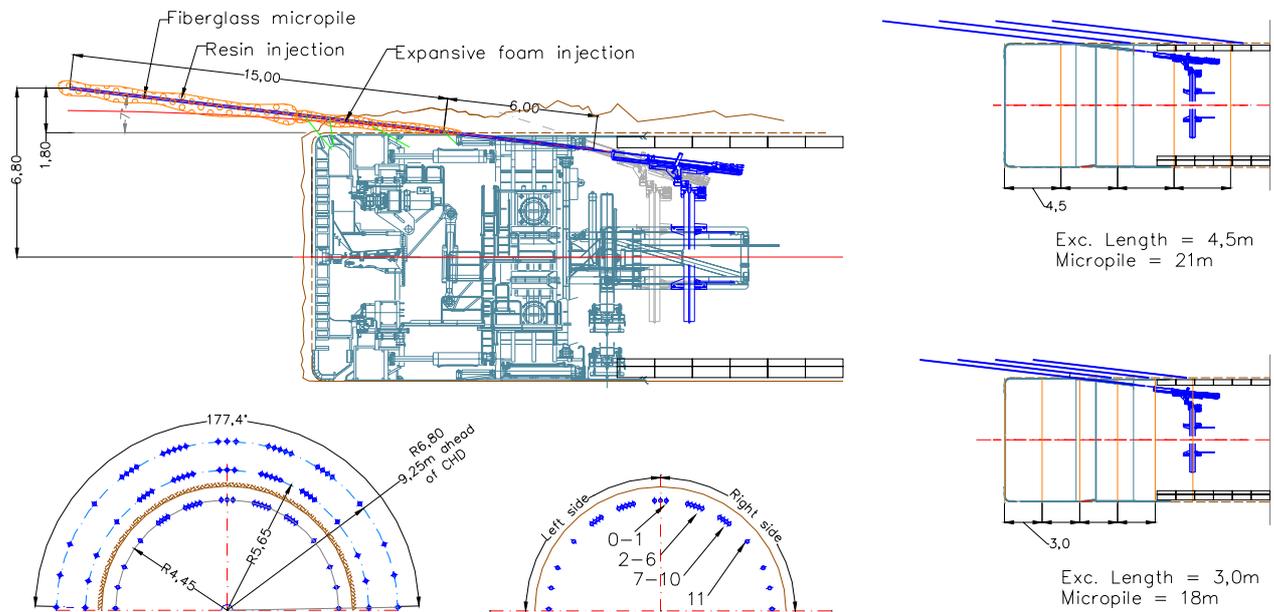


Figure 11 – PRETREATMENT OF THE GROUND AHEAD OF THE FACE

## 7- THE INFLUENCE OF GAS INFLOWS ON THE TUNNELING OPERATIONS

The geological reports and investigations made before the project execution did not foreseen the presence of gas. Therefore the TBM was equipped with a standard gas monitoring system. Every time the concentration of gas overpasses a given percentage of the lower explosion limit, the system causes the automatic shut down of the electric supply to the TBM and Backup except for:

- the back-up ventilation booster fans
- the dust scrubber and related fans
- the gas monitoring system
- the communication system
- the emergency lighting system

The ventilation system installed on the TBM backup is designed for 37,5 m<sup>3</sup>/s of air from the backup rear end to the TBM area. This amount of air maintains an air speed all along the backup of 0,61 m/s.

Despite the forecast, few minor gas inflows occurred already at chainage 1600 and important gas inflows occurred almost continuously between chainage 1850 and chainage 2050 in the argillite formation.

The gas was measured in a probe hole at a maximum pressure of 11 bar.

The exceptional volumes and the extraordinary pressure of the gas inflows, as well as the continuity of the inflows for long tunnel sections, caused big delays and disruption to the TBM advance and required additional installations to increase the air speed in some critical area in the TBM shield area.

To avoid the formations of gas pockets in the TBM shields several compressed air agitators were installed in critical locations (Figure 12) and at the same time several additional gas sensors were installed.

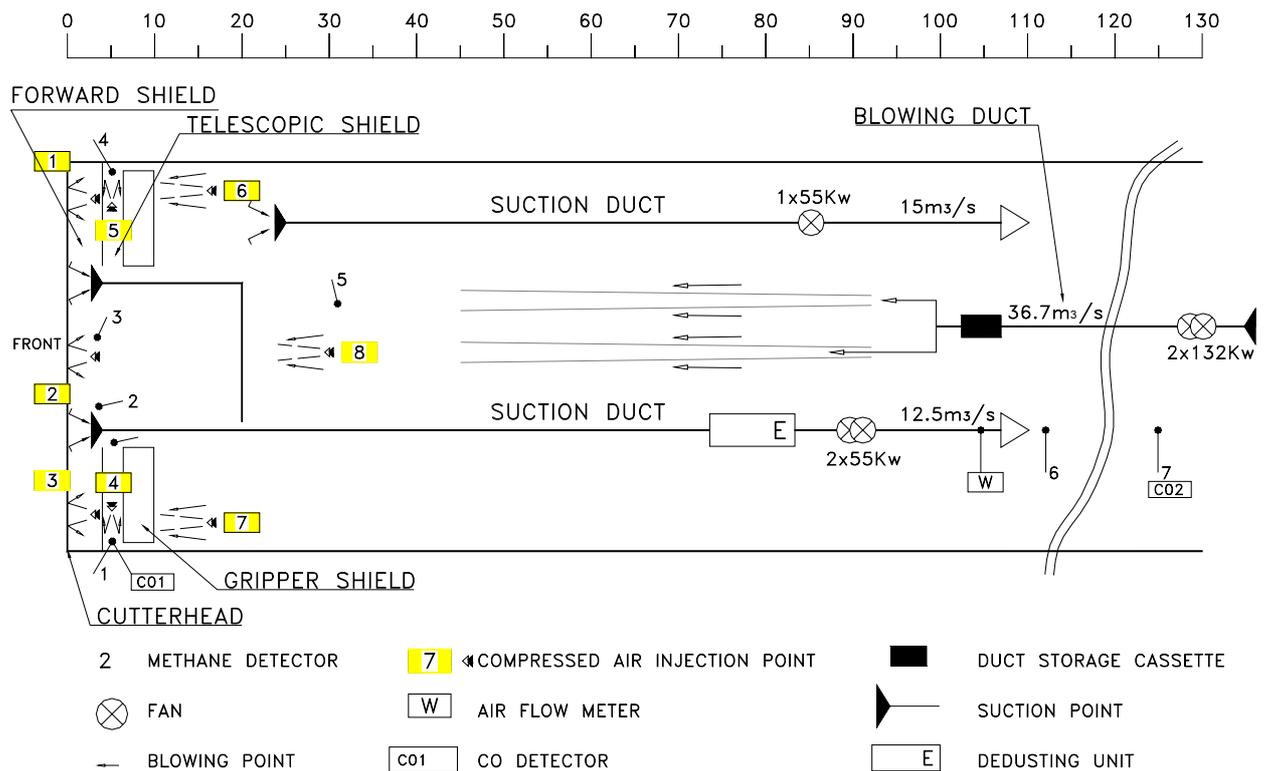


Figure 12 – MODIFIED VENTILATION SCHEME

Moreover, the upper limits of admitted gas concentration, initially set up at 20% of the lower explosion limit, was reduced to 10% in the attempt of increasing the level of safety in the tunnel. These measures increased substantially the efficiency of the gas control and monitoring system. However, despite the improvements, the power shut downs due to high gas concentrations were frequent and in some sections of the tunnel they were occurring every few revolutions of the cutterhead. The stand by time of each shut down varied depending the volume and pressure of the gas inflow and was ranging from few minutes up to several weeks. In total about 2000 hours of stand by have been caused by gas inflows; this despite the particular additional measures implemented on the TBM to increase the air flow in the critical area. The presence of gas negatively influenced the TBM advance much more than the simple stand by time, this because:

- the TBM could not advance in the critical geological section with the required speed and continuity and the stand by time imposed by the gas presence caused the ground to develop the instabilities
- the frequent stops and restart of the cutterhead caused the ground at the face to be disturbed much more than under normal operating conditions
- the presence of gas delayed or even prevent the implementation of the special treatments at the face and of the ground ahead of the face
- the frequent stops and restarts of the tunnelling operations did not allow the tunnel shifts to reach the proper efficiency and every time such a complex industrial plant had to be put again in operation some problems occurred

## 8- TBM OPERATION UNDER HIGH PRESSURE AND HIGH VOLUME WATER INFLOWS

Soon after the TBM has passed the argillite formation and entered the limestone formation, the tunnel crossed an heavy fractured and faulted area with with high pressure water inflows up to 600 lt/sec (36.000

lt/min) mixed with rock debris that, transported by the water, actually submerged the TBM and Back\_Up system.

In order to advance under these conditions a ...diameter pipe was installed from the TBM on the bottom of the tunnel to transport the water and the mud out of the back-up (Figure 13).

The boring strokes were alternated with long idling time for cleaning operation and for repair of electric and electronic components that were suffering for the very wet/submerged tunnelling conditions.

Despite this extreme conditions the TBM was able to advance and after ...meters entered again in a good and dry rock formation.

## 9- PERFORMANCE OF THE TBM IN NORMAL ROCK CONDITIONS

The traditional Double Shield TBMs are famous to outperform in a wide range of rock conditions.

The Double Shield Unversale GT type TBMs utilised in Abdaljis proved to have extra capabilities to overcome squeezing and ravelling ground, but how they did performed in the sections excavated under normal rock conditions?

The graphic of Figure 14 shows the Abdalajis TBM daily performances in the tunnel section in good-fair rock encountered after argillite and the water bearing fractured limestones.

Peak daily advances over 40 m and averages over 25 m/day have been achieved.

The rock formations in this section, even if not interested by very adverse critical conditions, were however changing meter by meter alternating very hard limestone rocks with weaker zones.

These performances demonstrate that DSU TBMs, while have extended the boring capability toward the worse and weaker rock formations, did not loose the “traditional” capability to outperform in good to fair rock.

## 10- POSSIBLE IMPROVEMENTS OF DSU TECHNOLOGY FOR FUTURE APPLICATIONS

The main improvements that can be implemented to DSU TBM design in order to further increase their capability to cope with extremely adverse ground conditions can be resumed as follow:

- install on the cutterhead a copy cutter system designed for rock application. (SELI has designed and tested in the Torino Metro Project a double copy cutter arrangement that proved to be able to work in soft rock). This system could improve the flexibility and rapidity to adapt the overcutting of the TBM in squeezing ground formations.
- Improve the connection between gripper shield and telescopic shield avoiding the possibility of vertical displacements between the two shields
- Improve the back-up system efficiency to cope with the higher peak and average advance rates that DSU TBMs are able to achieve
- Improve the efficiency and rapidity of execution of the patterns of grouted micro-piles executed from inside the TBM shields

The development of the different DSU configurations has further extended the flexibility of this TBM type to the different project and design requirements.

## 11- CONCLUSIONS

The Abdalajis twin tunnels were considered by many specialists behind the limits of today tunnelling technology

A special new type and new design of TBM was therefore selected for the execution of the project

The actual geological conditions in the tunnel were even worse than the expected,

Despite this the DSU TBMs in their GT configuration were able to overcome all the encountered critical conditions without requiring any handmining work or by pass tunnel

In the “normal” rock conditions the TBM was able to outperform

There is a large margin to improve this new technology both by improving some details of the DSU TBM design as well by developing the different design configurations of this new TBM family.

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### Career History

1984- Graduate as Doctor Mechanic Engineer at the Rome La Sapienza University  
1984-1987- SELI Spa -Design Engineer  
1987-1989- SELI- Spa Technical Director  
1989-2002- SELI Spa- Managing Director  
2002- 2005- SELI Spa- President  
2000- 2004- La Sapienza University- Contract Professor for Tunnel Mechanised Excavation

The Abdalajis Tunnel East is one of the two parallel 7,1 km long railways tunnels that are part of the new high speed railway line connecting Cordoba and Malaga.

Figure 1 shows the planimetric alignment and the location of the tunnel

The excavation diameter is 10 meter.

The tunnel is lined with a precast segmental lining (figure 2) having a thickness of 45 cm and a final internal diameter of 8,... m.

The segments are connected by bolts along longitudinal joints and by plastic connectors along radial joints.

An elastomeric seal is used to seal the joints between segments

The gap between the segments and the rock surface is filled with peagravel and in a second stage the pregravel is grouted with a cement based mixture.

#### 2- THE GEOLOGY OF THE TUNNEL

The Abdalajis tunnel geology can be divided into two major section:

A first section (figure 3) in weak and very weak formations having a total length of....km

A second section in more competent sedimentary rocks (figure 4) under high cover

The present article deals with the excavation of the first section.

Characteristic of this section are the following formations:

.....  
.....  
.....

#### 4- THE TBM PERFORMANCES IN THE FIRST 2 KM SECTIONS IN WEAK ROCK FORMATIONS

After an initial learning curve period, the TBM started to advance at high speed with daily advances over....m and peaks of.....

This despite the argillite formations proved to be in very poor conditions since the beginning of the tunnel.

At chainage ..... however the conditions bad conditions of the argillite formations encountered in the first section of the tunnel negatively affected the TBM performances.

Figure ...shows the tunnelling progress and the encountered geological difficulties in the first section of tunnel excavated

## 5- TBM BEHAVIOUR IN SQUEEZING GROUND

Tunnel convergence was one of the major concerns in the project design phase since the large tunnel diameter and the presence of argillite rock formations under high cover.

The DSU TBM proved however to be able to cope with rapid convergences of the tunnel walls without any problem and without having to use the full overboring capability of the machine, thanks to the particular shield design of this new type of TBM

This capability will allow the utilization of TBMs in many projects under critical conditions that until now had to be executed with conventional methods with huge costs and very low advances..

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A long section of the tunnel in the .....ground formations was characterised by large instabilities of the tunnel face.

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- **Pre-treatment of the ground ahead of the face-** (Figure....)- in the most critical sections the weak argillite was behaving like a flowing gravel and even the above described face stabilization treatments were not sufficient to control the face collapses and the ground itself had to be treated in front of the TBM.  
A pattern of PVC pipes were executed through specific holes in the rear shield of the TBM in order to stabilise the crown of the tunnel. These piles were than grouted with .....chemical grouting mix (wilkit resin) with proved to be very successful in penetrating in the argillite formations and increase the cohesion of the ground enough to avoid face collapses.  
In the worse tunnel sections this treatments had to be repeated every 3-5 mt

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Therefore the TBM was equipped with a standard gas monitoring system.

This system, each time the concentration of gas concentration overpass a given percentage of the explosion mixture, cause the automatic shut down of the electric supply to the TBM and Back\_Up except that for:

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The ventilation system installed on the TBM back-up has been design to flow 37,5 cm/second of air from the back-up rear end to the TBM area.

This amount of air maintain an air speed all along the back-up of 0,61 m/sec.

Despite the forecast important gas inflows occurred almost continuously between chainage .... And chainage..... in the .....rock formations.

A maximum of 11,5 bar of gas pressure was measured in a probe hole.

The extraordinary volumes and pressure of the gas inflows, as well the continuity of the inflows for long tunnel sections, caused major delays and disruption to the TBM advance and required additional installations to increase the air speed in some critical area in the TBM shield area.

To avoid the formations of gassy pockets in the TBM shields several compressed air agitators were installed in critical locations (Figure....) and at the same time several additional gas sensors were installed.

Moreover, the upper limits of admitted gas concentration, initially set up at 20% of the gas explosion mixture, was reduced to 10% in the attempt of increasing the level of safety in the tunnel.

These measures increased substantially the efficiency of the gas control and monitoring system.

However and despite the improvements the power shut downs due to high gas concentrations were frequent and in some sections of the tunnel they were occurring every few revolutions of the cutterhead. The stand by time of each shut down varied depending the volume and pressure of the gas inflow and was ranging from few minutes up to several weeks.

In total ..... hours of stand by had been caused by gas inflows; this despite the particular additional measures implemented on the TBM to increase the air flow in the critical area.

The presence of gas negatively influenced the TBM advance much more than the simple stand by time, this because:

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## **8-POSSIBLE IMPROVEMENTS OF DSU TECHNOLOGY FOR FUTURE APPLICATIONS**

DSU TBM is an evolution of the traditional Double Shield TBM type and therefore many technical solutions and features were already of proved design and efficiency.

The main improvements that can be implemented to DSU TBMS design in order to further increase their capability to cope with extremely adverse ground conditions can be resumed as follow:

- Install on the cutterhead a copy cutter system designed for rock application. SELI has designed and tested in the Torino Metro Project a double copy cutter arrangement that proved to be able to work in soft rock and that could improve the overboring capability of the TBM in squeezing ground formations
- Avoid the possibility of vertical displacements between the inner telescopic shield and the gripper shield
- Further extend the possibility of the TBM to install piles (more positions for probe/piles around periphery) to treat and stabilise the ground ahead of the face.

All the above improvements are relatively easy to be executed.

## **9-CONCLUSION**

The combination of the presence of high concentration of gas and of very bad rock encountered in this first .....km long section until now excavated drastically reduced the advance speed of the TBM.

Despite these extreme tunnelling conditions the DSU TBM was able to advance without having to execute mining works like: by pass tunnels, caverns, etc.

In particular even rapid and important convergence of the tunnel proved not to be a problem for the TBM advance .

Ravelling ground could be treated ahead of the tunnel to an extent to avoid important face collapse.

Even in the weak ground conditions the DSU TBM can be operated in telescopic mode, erecting the segmental lining contemporary with the excavation. This type of machine is therefore able to maintain very high advance speed even in unstable ground were traditional Double Shield TBM would have to advance ins Single Shield Mode.

In good rock conditions DSU TBM is able to advance with a productivity that is basically limited by the segment erection time and by the efficiency of the back-up system.

The DSU TBM technology can be further improved to increase its performance in the most extreme rock conditions