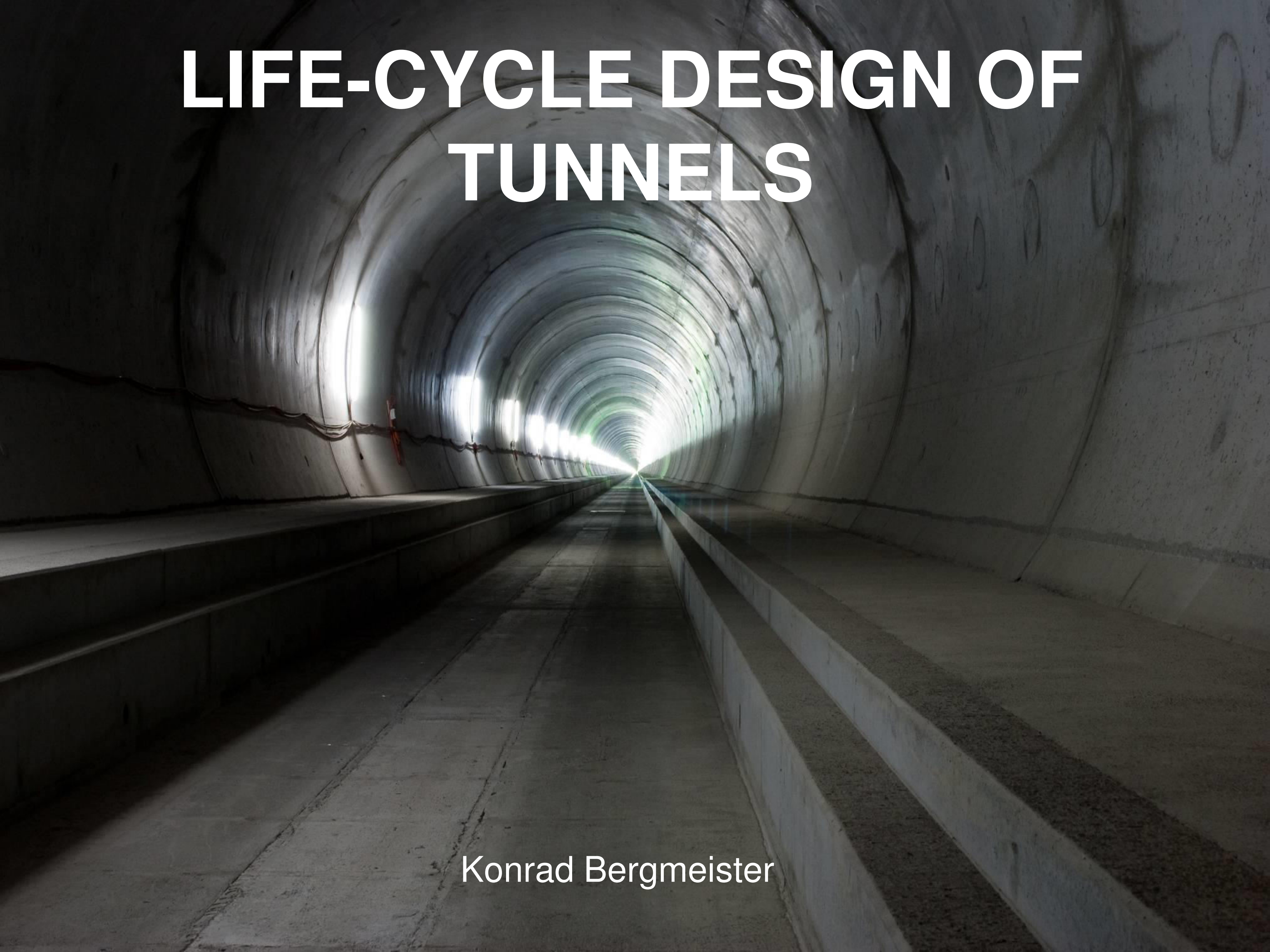
LIFE-CYCLE DESIGN OF TUNNELS



Konrad Bergmeister

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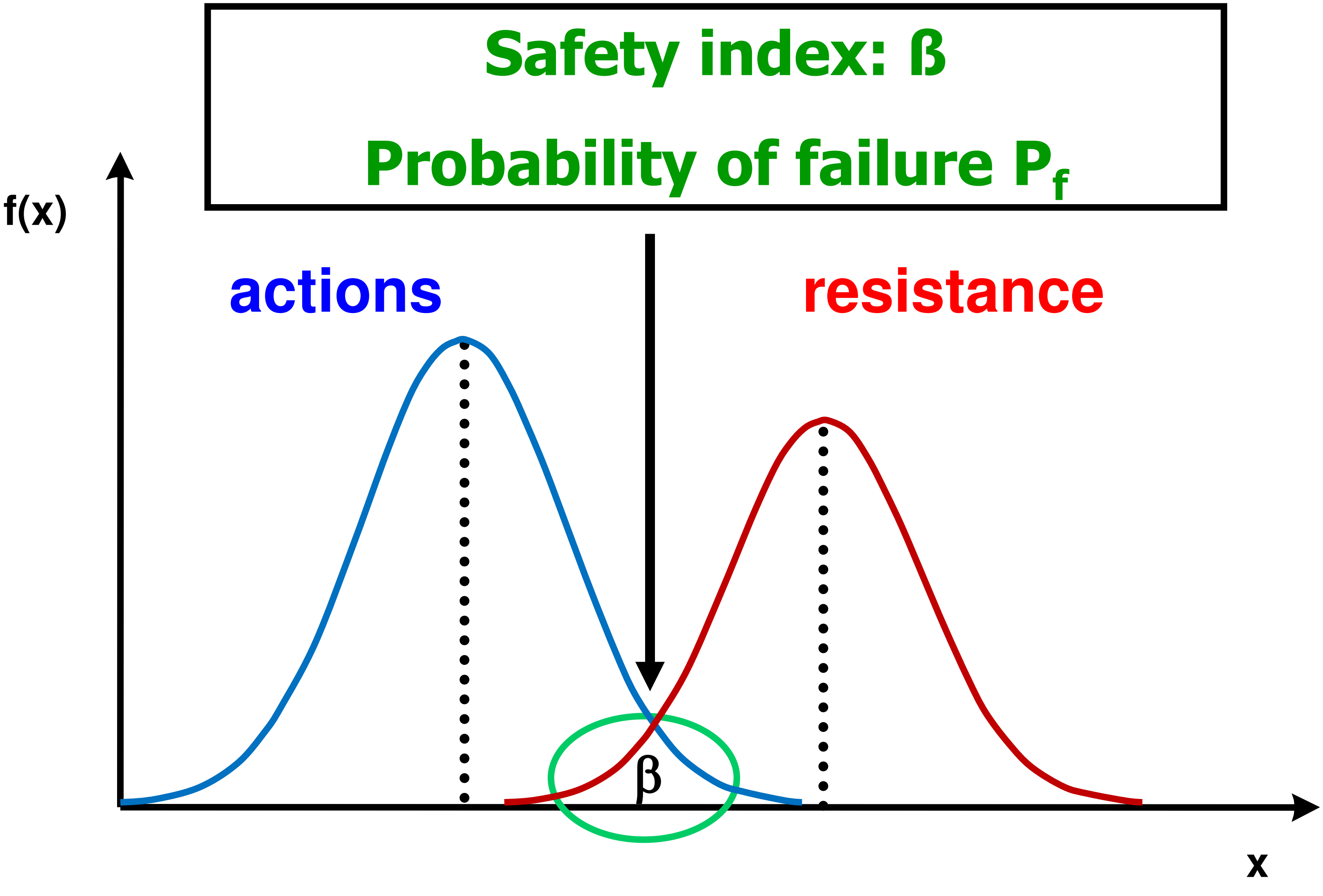
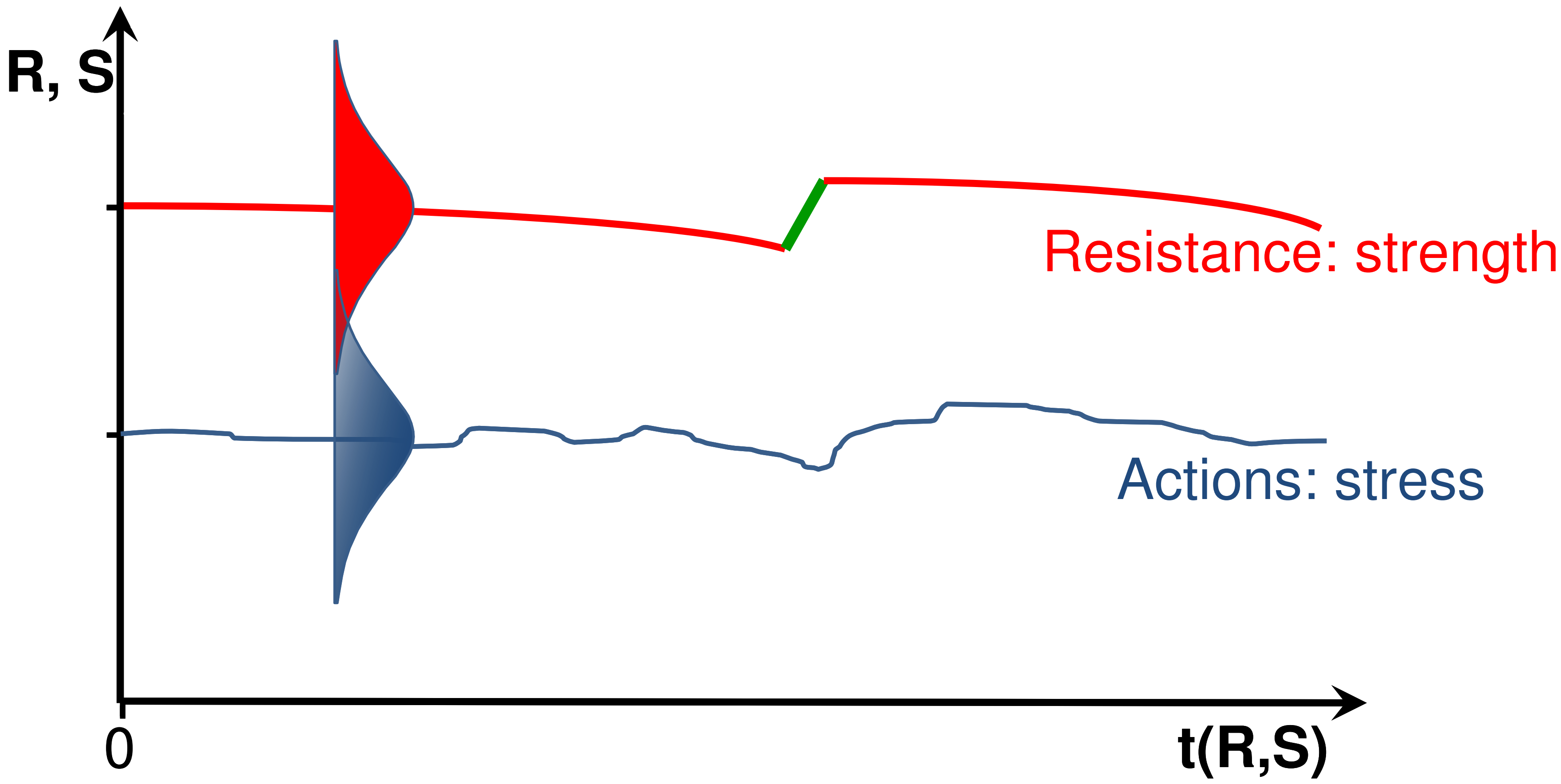
SOME THEORETICAL BACKGROUND



TIME RELATED BEHAVIOR



SAFETY INDEX VS. PROBABILITY OF FAILURE

	Reliability Index, ß or Safety Index	Probability of Failure, p_f
	5.19	10^{-7}
ULS / year	**4.75**	$\mathbf{10^{-6}}$
	4.26	10^{-5}
ULS / lifetime	**3.72**	$\mathbf{10^{-4}}$
SLS / year	3.09	10^{-3}

Valid for Normal PDF

CONSEQUENCE CLASSES AND RELATED SAFETY INDICES FOR LIFETIME

Reliability Classes	Consequence Classes		
	CC1 Low	CC2 Medium	CC3 High
RC1 Low Costs	3.1	3.3	3.7
RC2 Medium Costs	3.6	3,8	4.4
RC3 High Costs	4.2	4.3	4.7

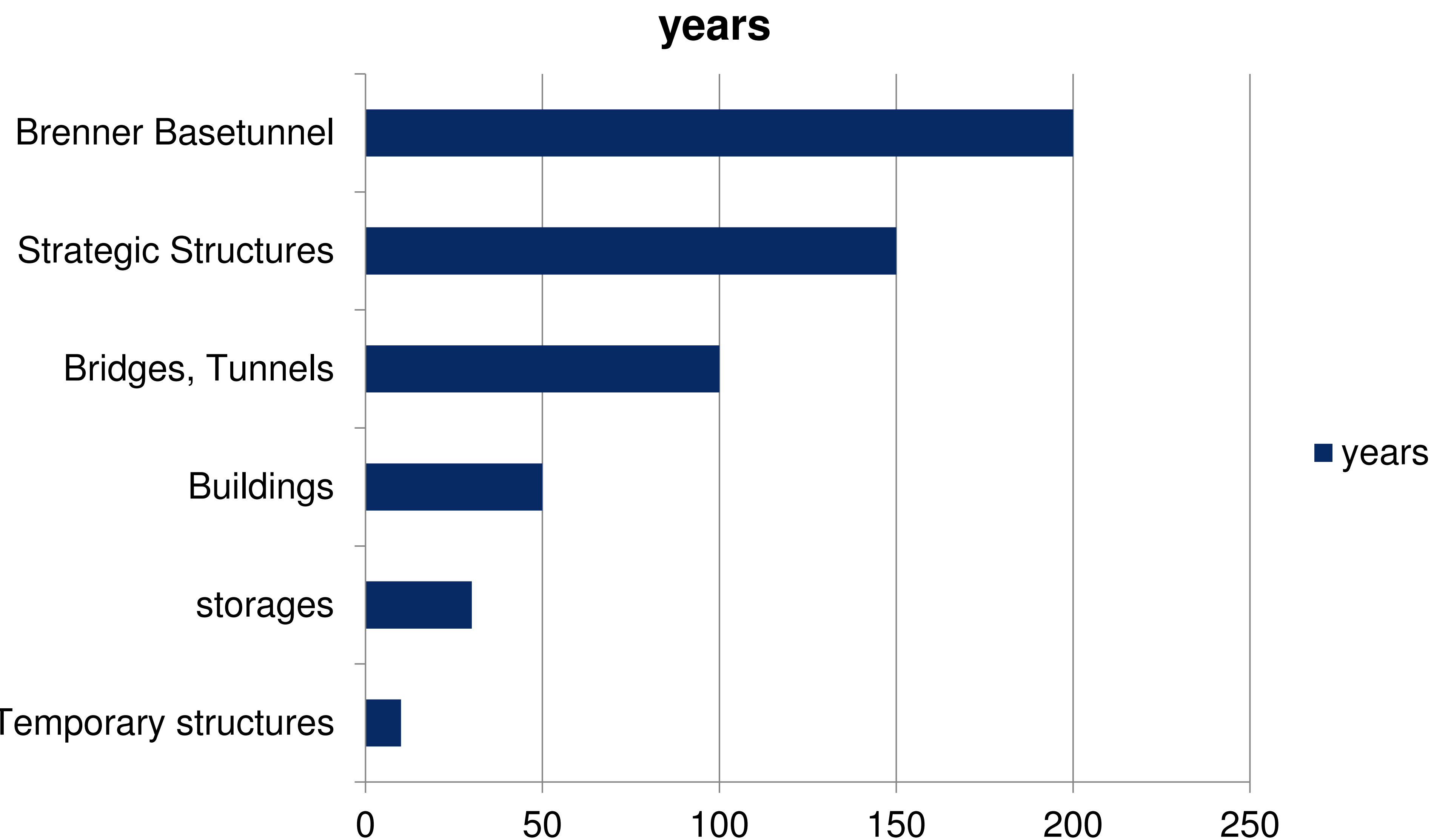
Eurocode 1

SAFETY CONCEPT - DESIGN

Material: $\gamma_R = \exp [v_R (\alpha_R \cdot \beta \cdot v_R - K_{f,R})]$

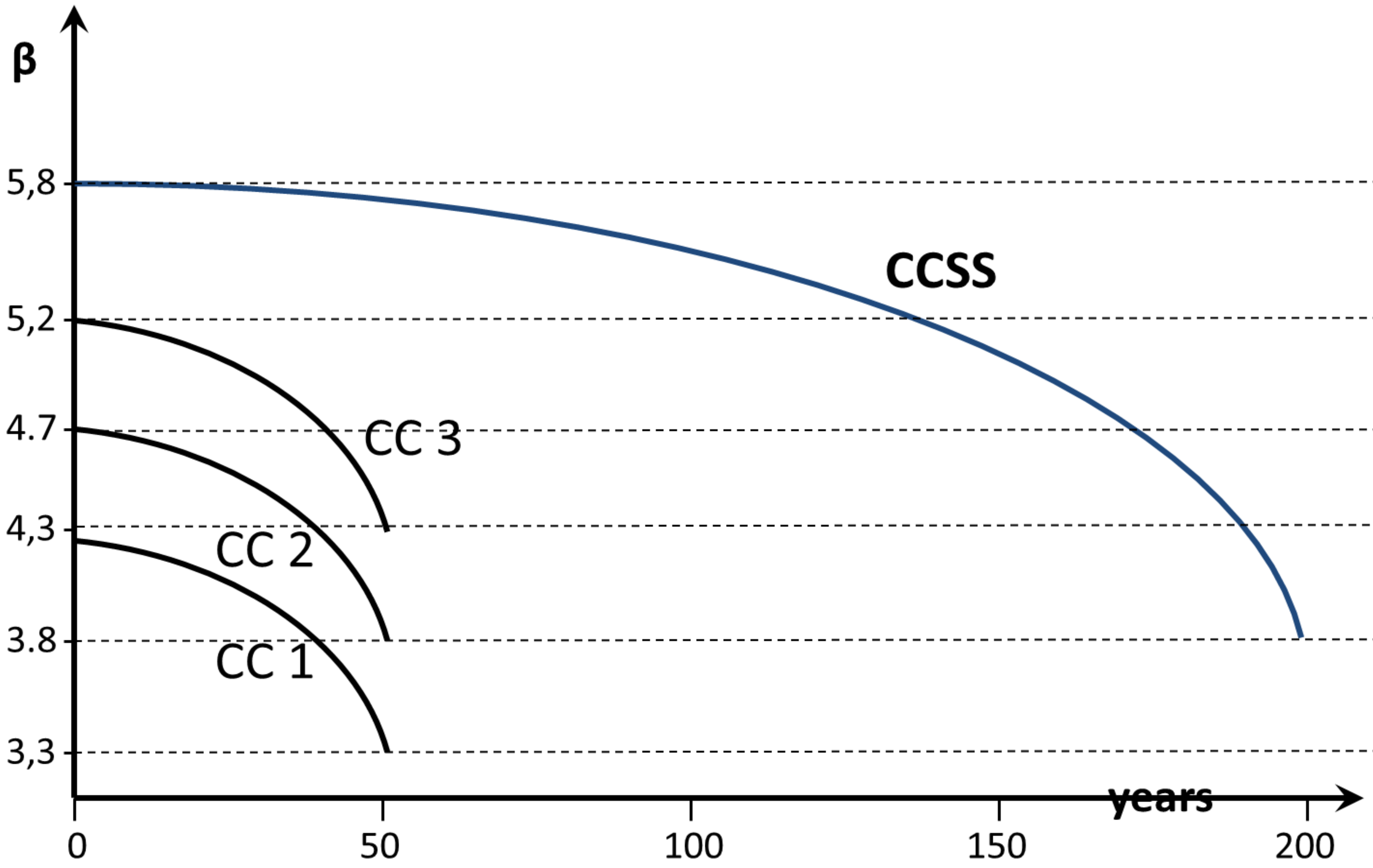
Action: $\gamma_S = [1 + \beta \cdot \alpha_S \cdot v_S] / [1 + K_{f,S} \cdot v_S]$

HOW LONG SHOULD THE LIFE OF STRUCTURES BE?



GRADUAL SAFETY APPROACH

4 CONSEQUENCE CLASSES



LIFE-CYCLES OF TUNNELS

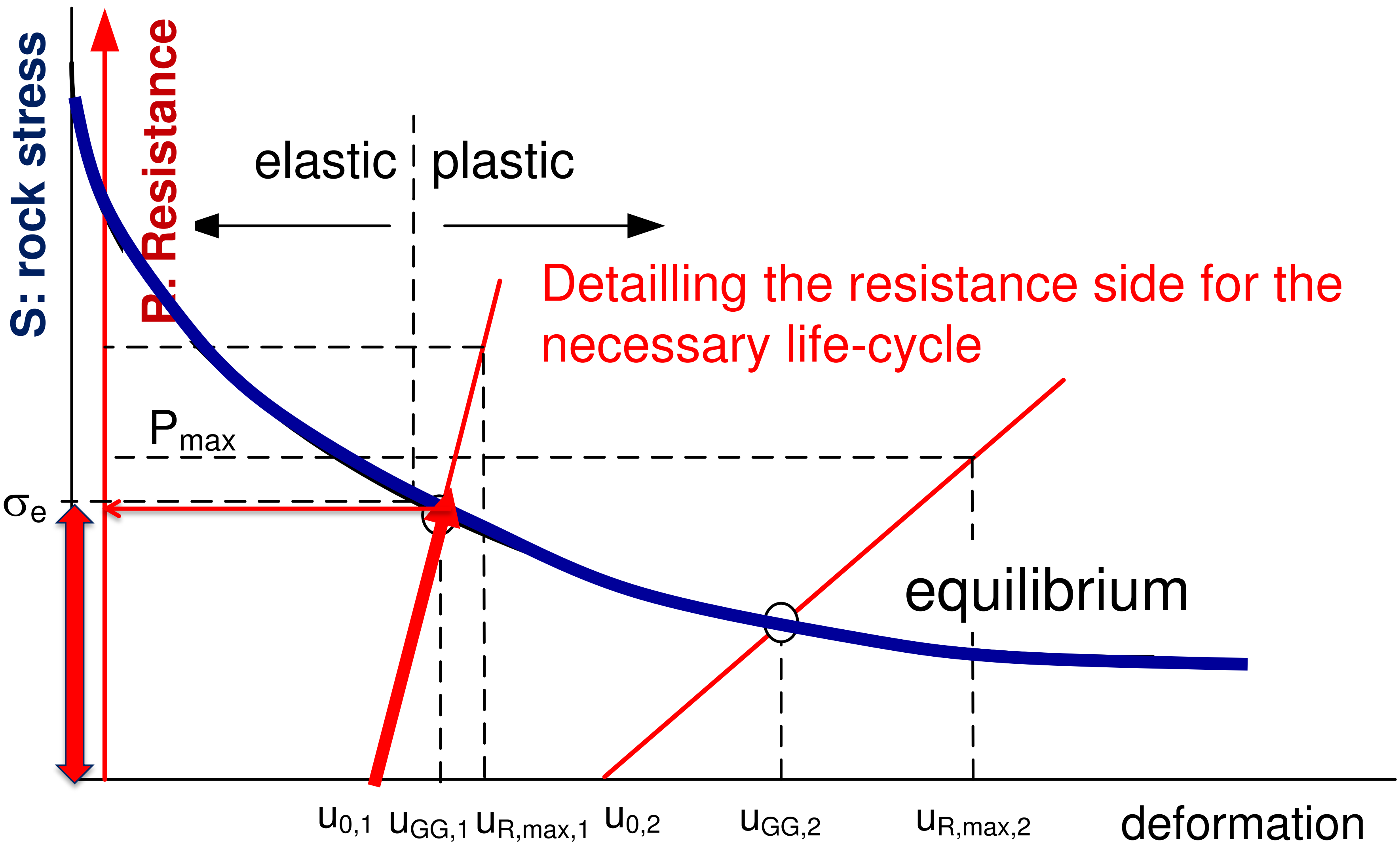
Structure, equipment	Life-cycle [years]	Inspections, maintenance
Tunnel structure	> 100	periodical Inspection – min every 5 years
Rails	> 100	periodical Inspection
Rail equipment	➢ 50	periodical Inspection
Ventilation-system	> 25	yearly Inspection
Illumination-system	> 15	yearly Inspection

3. THE BRENNER BASETUNNEL PROJECT

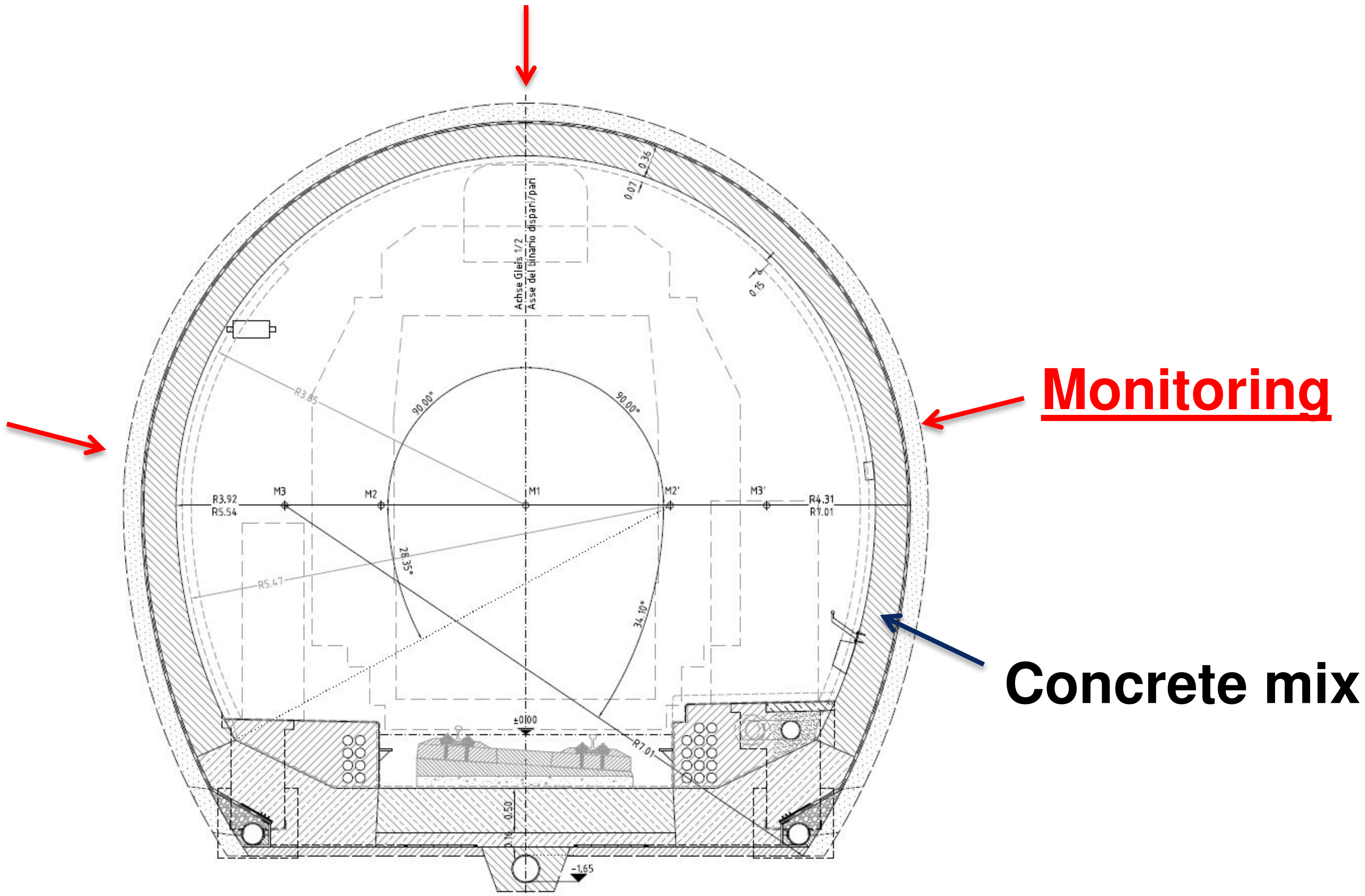
Video: *The Brenner Base Tunnel in 5 minutes*

Please find the link at www.bbt-se.com

SEARCHING FOR EQUILIBRIUM

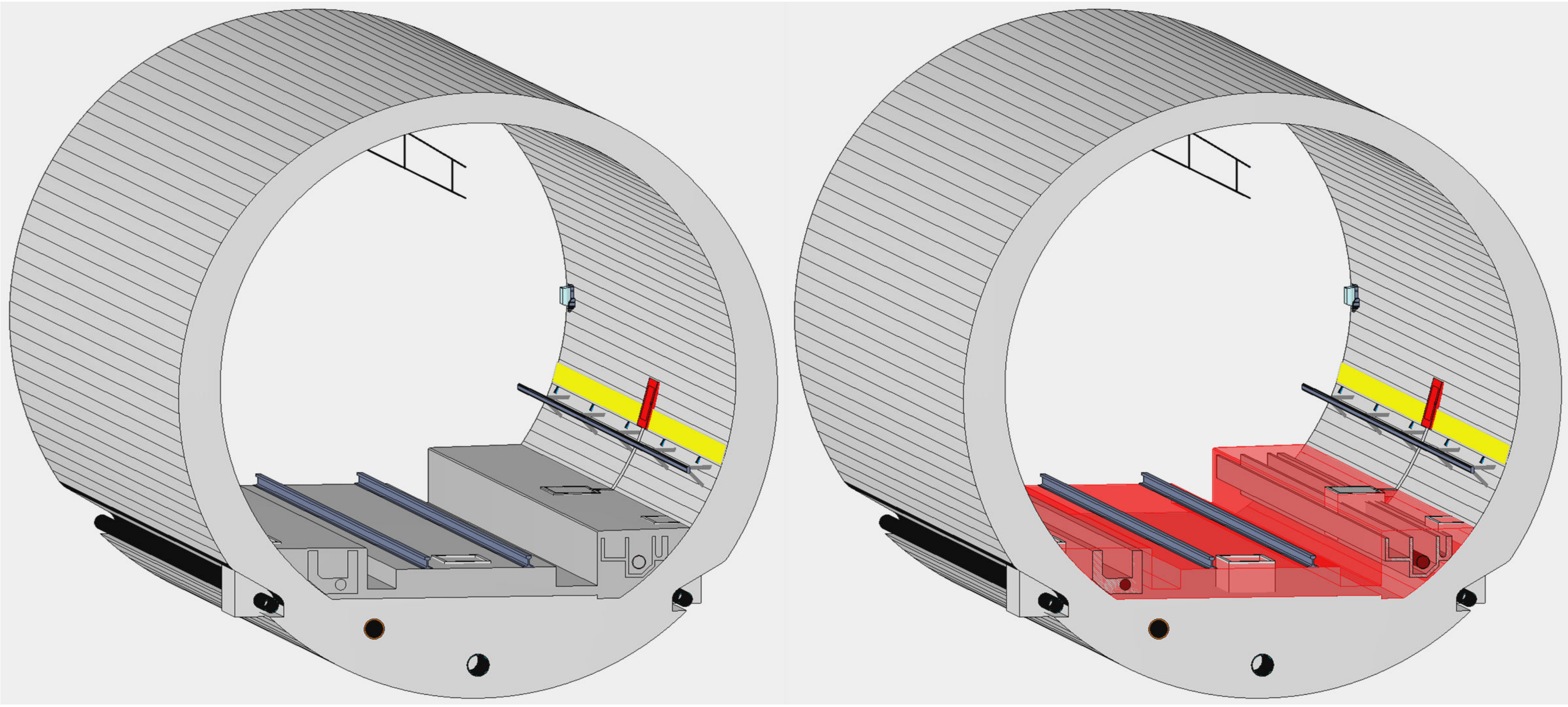


STRUCTURAL DETAILLING FOR THE LIFE-CYCLE



STRUCTURAL COMPONENTS

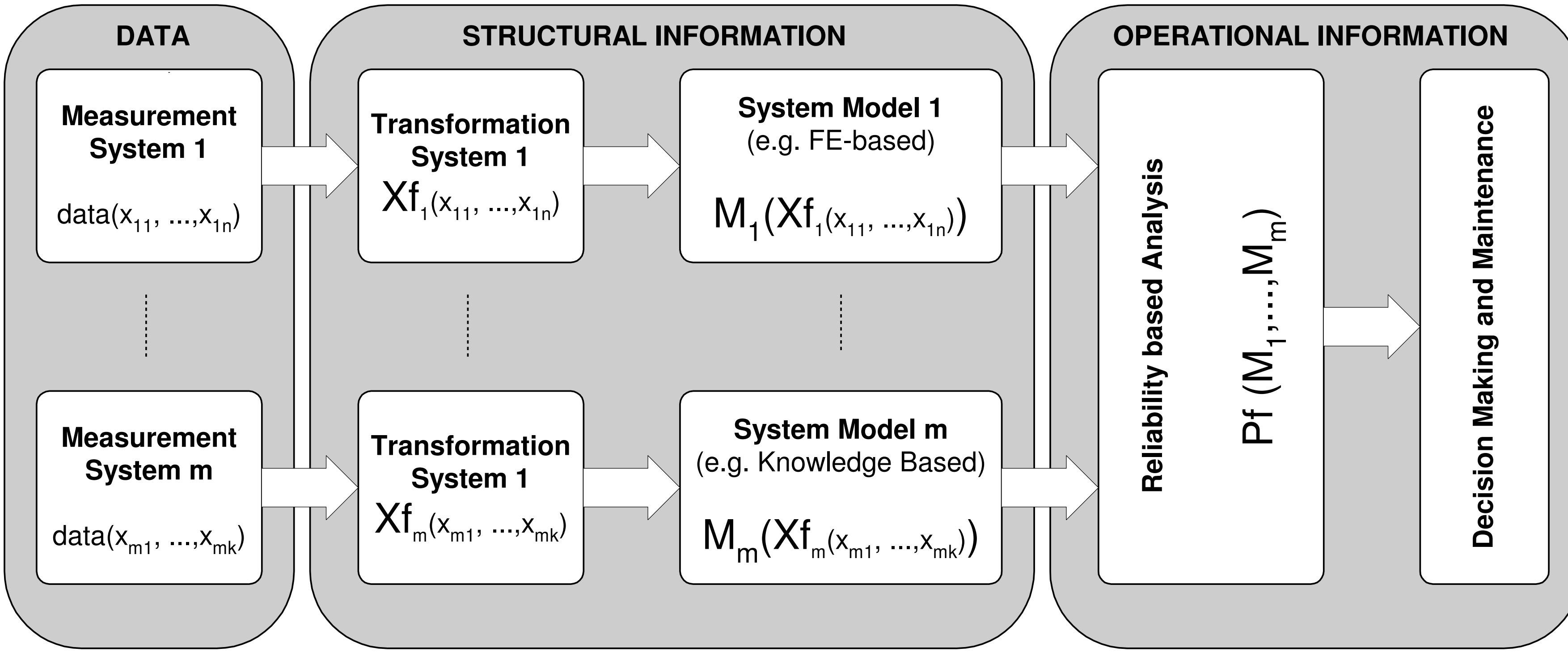
«AGING?»



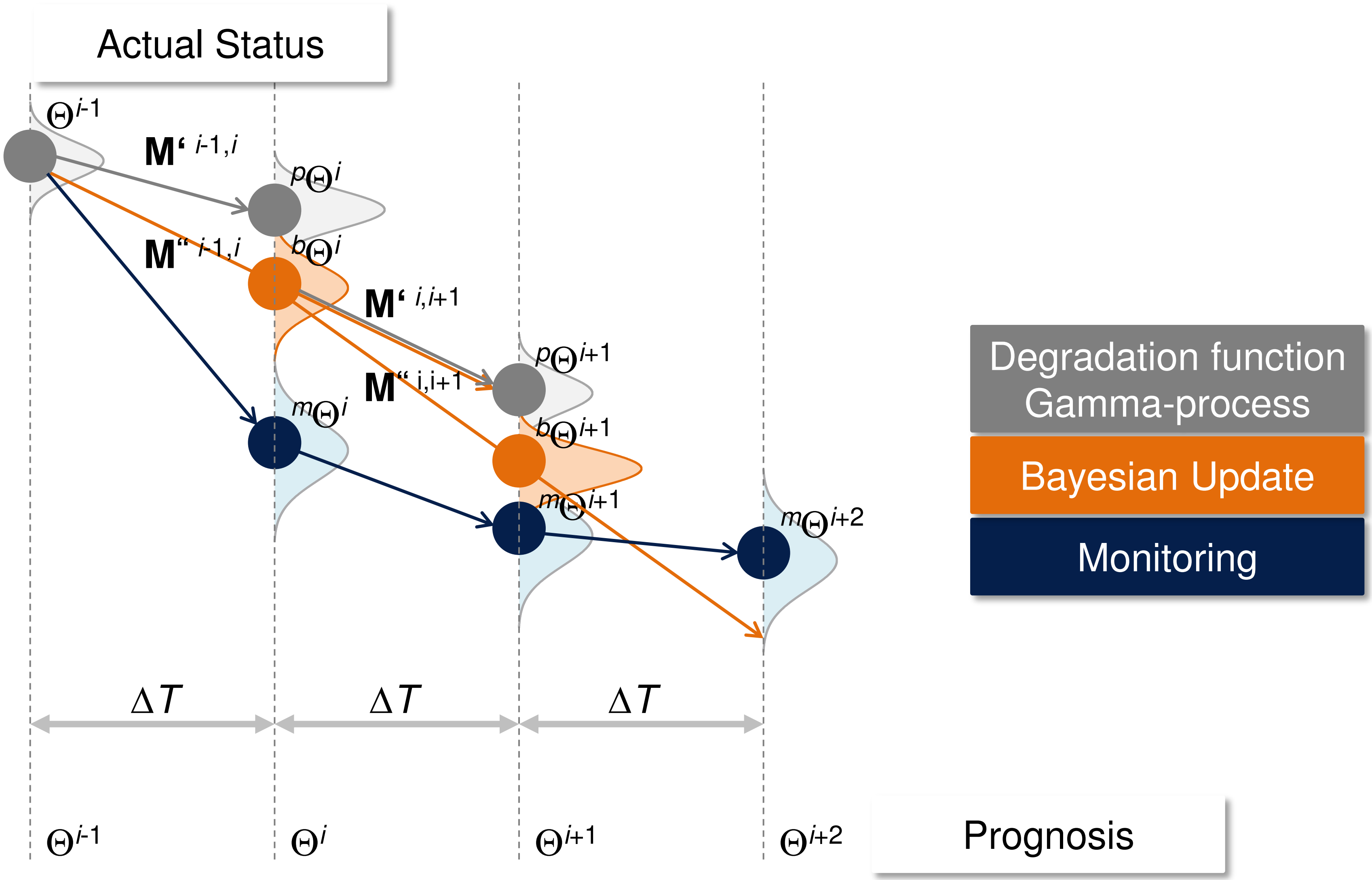
LIFE IS DEFINED BY EXTERNAL CONSTRAINTS

ALBERT EINSTEIN - 1905

RELIABILITY BASED MONITORING + INSPECTION



MODELS FOR DEGRADATION + AGING



MARKOV-PROCESS WITH MONITORING

Permanent ***monitoring information*** requires a continuous adjustment of the prior information θ^n of **M** = **M'** by short-term monitoring information

$$P(\theta_{i,t} | m_{ei,t}) = \frac{P(m_{ei,t} | \theta_{i,t}) \cdot P(\theta_{i,t})}{\sum_{i=1}^{n} P(m_{ei,t} | \theta_{i,t}) \cdot P(\theta_{i,t})}$$

The posterior transition matrix **M''** with $\theta_i^{n''}$ and to the comprehensive transition matrix

$$\mathbf{M}_t'' = \mathbf{M}'' \cdot \mathbf{A}_{an}$$

Strauss, Bergmeister (2012)

Ahrens, Strauss, Bergmeister, Mark, Stangenberg (2013)

MODELLING OF GAMMA PROCESS

- A continuous-time stochastic process $\{X(t),\ t \geq 0\}$ is characterized by independent increments

- Probability distribution function of $X(t)$,
  with the time variable t:

$$f_{X(t)}(x) = Ga\left(x, \alpha(t), \beta\right)$$

- The expected value:

$$E\left(X(t)\right) = \frac{\alpha(t)}{\beta}$$

- Variance:

$$Var\left(X(t)\right) = \frac{\alpha(t)}{\beta^2}$$

$$COV\left(X(t)\right) = \frac{\sqrt{Var\left(X(t)\right)}}{E\left(X(t)\right)} = \frac{1}{\sqrt{\alpha(t)}}$$

GAMMA PROCESS MODELING OF DETERIORATION PROCESS

Degradation model $$\alpha(t) = ct^b$$

The deterioration rate X(t) at the time t, with t ≥ 0 can be described by:

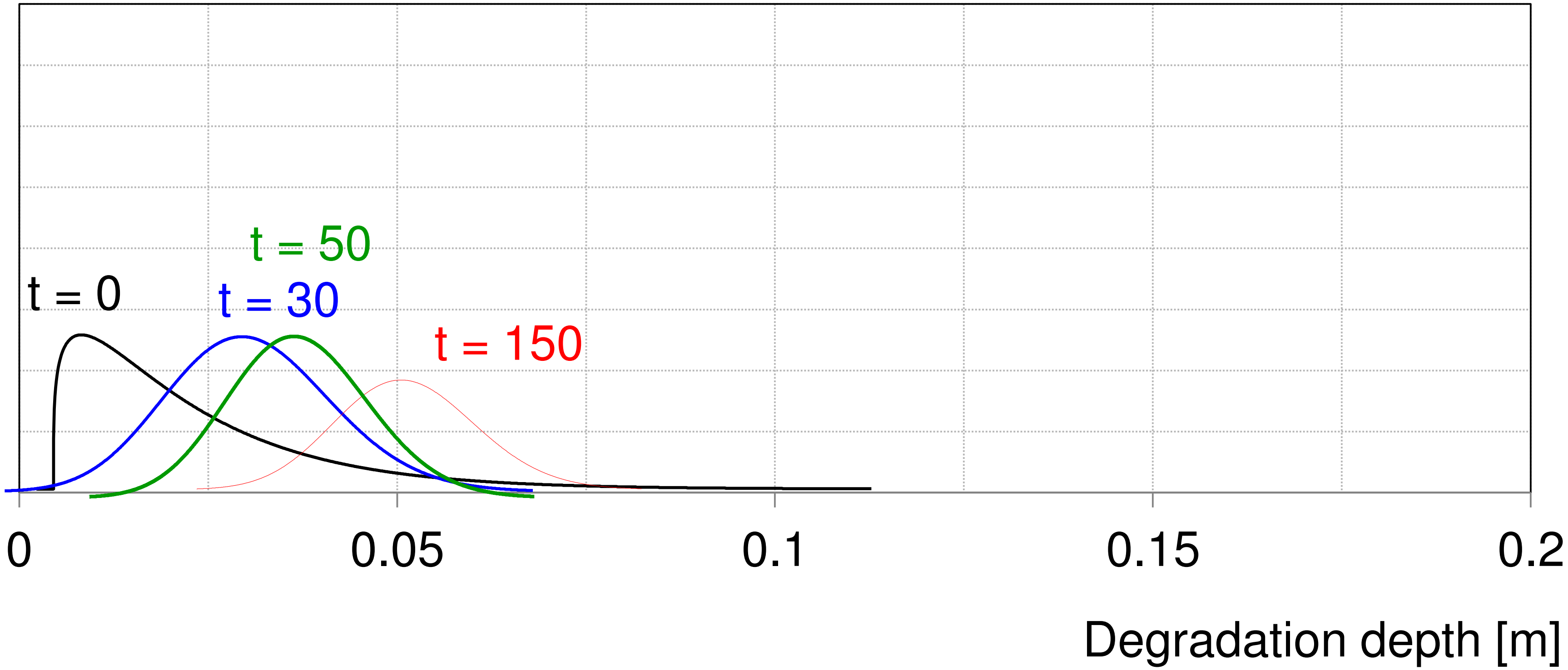
- the shape parameter $\alpha(t) = ct^b$
- the scale parameter

C = random rate of degradation (unknown)

b = scale parameter (unknown)

The unknown is determined by using experts' judgment and statistic

SIMULATED DEGRADATION TAKING INTO ACCOUNT MONITORING + MAINTENANCE



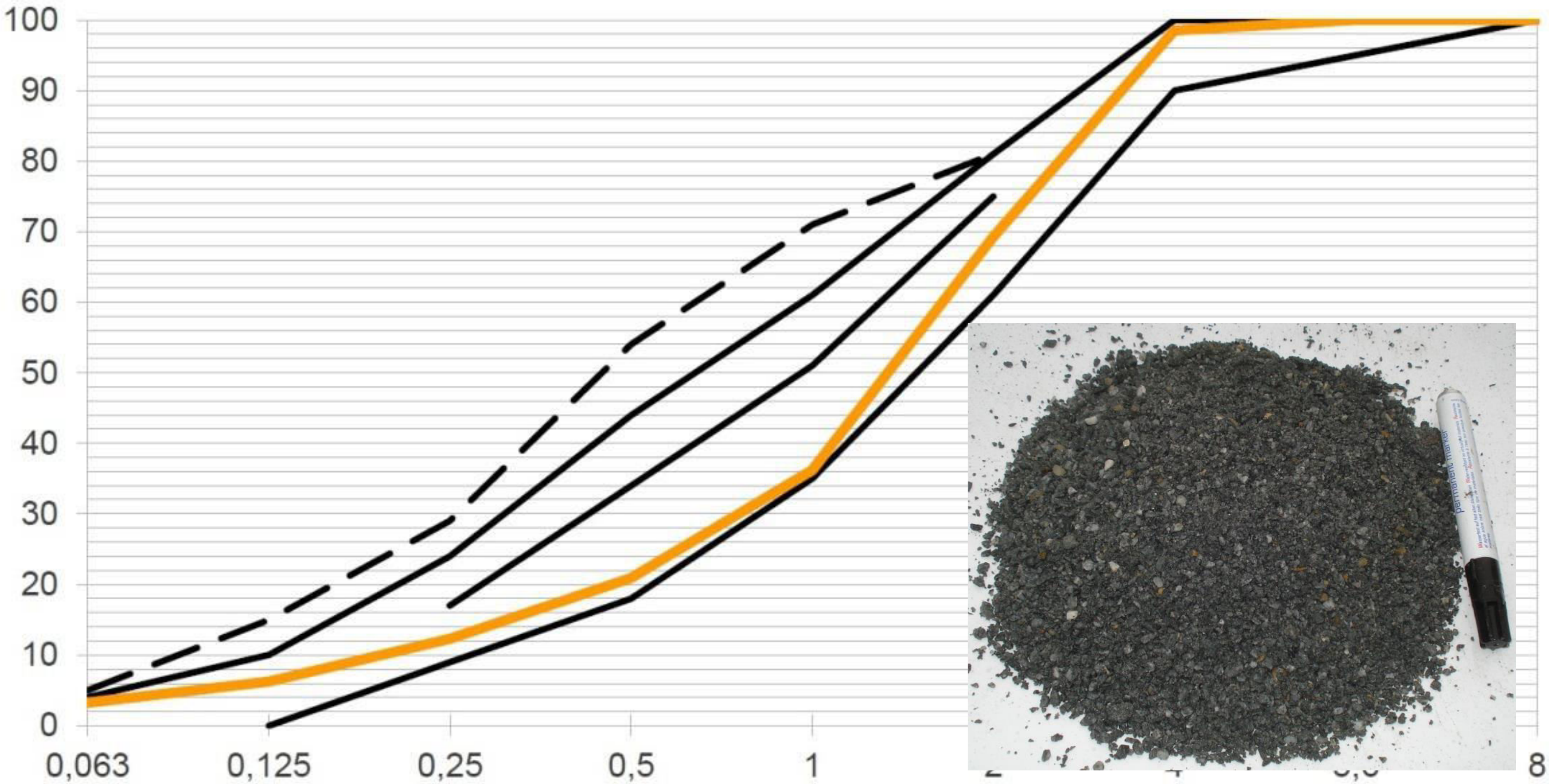
Defining the minimum concrete cover > 50 mm

CONTROLLED CONCRETE PREPARATION WITH EXCAVATION MATERIAL

- stone resistance ca. 75 Mpa
- geometrical form

GRADING CURVES

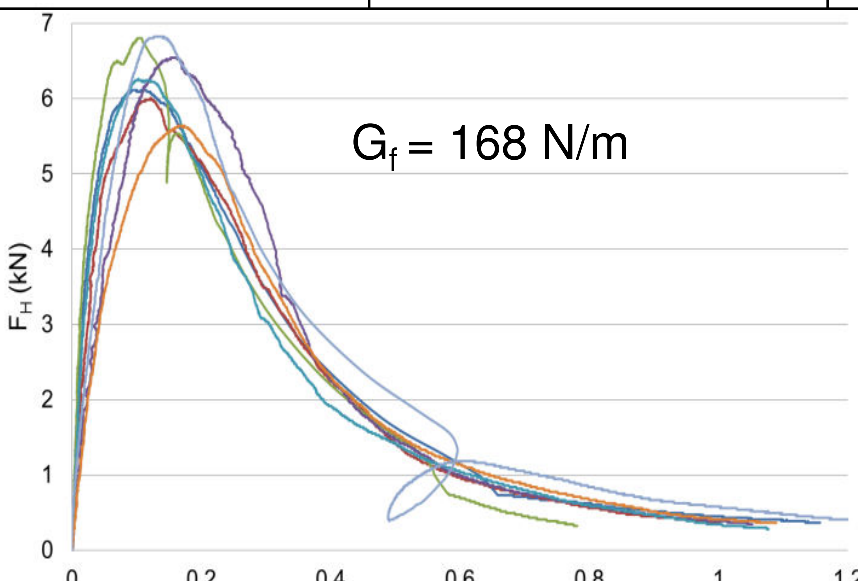
Fine sand (< 0,063 mm): < 3,2 %



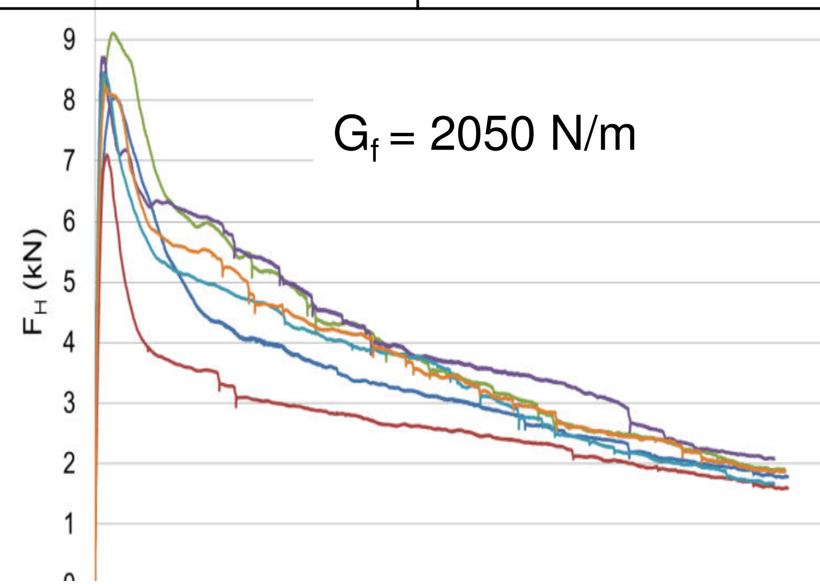
STRENGTH PARAMETERS - 28DAY

- **Schist** (0/4 sand)

	compression (N/mm²)	flexural strength (N/mm²)	fracture energy (N/m)
concrete	48	3,5	168
with steel fibers	58	4,7	2050



plain concrete



steel fiber reinforced concrete

LIFE-CYCLE DESIGN PROCEDURE FOR TUNNELS

1. Defining the lifetime
2. Defining the safety index for the various levels, consequence classes and exposure classes
   - Structure
   - Equipment, etc.
3. Calibrating the partial safety factors
4. Structural detailling (concrete mix, concrete cover, etc.)

BRENNER BASETUNNEL: LIFE-CYCLE 200 YEAR

F(design, structural detailling, monitoring)

Partial safety factors

concrete: $\gamma_c = 1{,}6$

reinforcement steel: $\gamma_s = 1{,}2$

Concrete Cover

C_{nom} 50 mm

THANKS + GOOD LUCK !

1. Tunnels are strategic structures
2. Lifetime must be defind
3. Gradual safety approach with integrated monitoring + inspection
4. Quality controlled structural detailling
5. Life-cycle based maintenance plan