Design of segmental lining for TBM tunnels

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Design of segmental lining for TBM tunnels

Premise

TBM technology is currently the most applied method of tunnelling, with performance indexes impossible to be reach with any of traditional methods.

Tunnels with diameters up to 16m, executed with excavation rate up to 20 m/day, perfectly watertight and fire-resistant are the state of the art.

Those impressive results are also due to the continuous technological improvement of the core of this industrial process: the segmental lining design and production.

The contents hereinafter has the scope to focus on the main important design aspects and provide a wide layout of the design scenarios and applications.

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Contents

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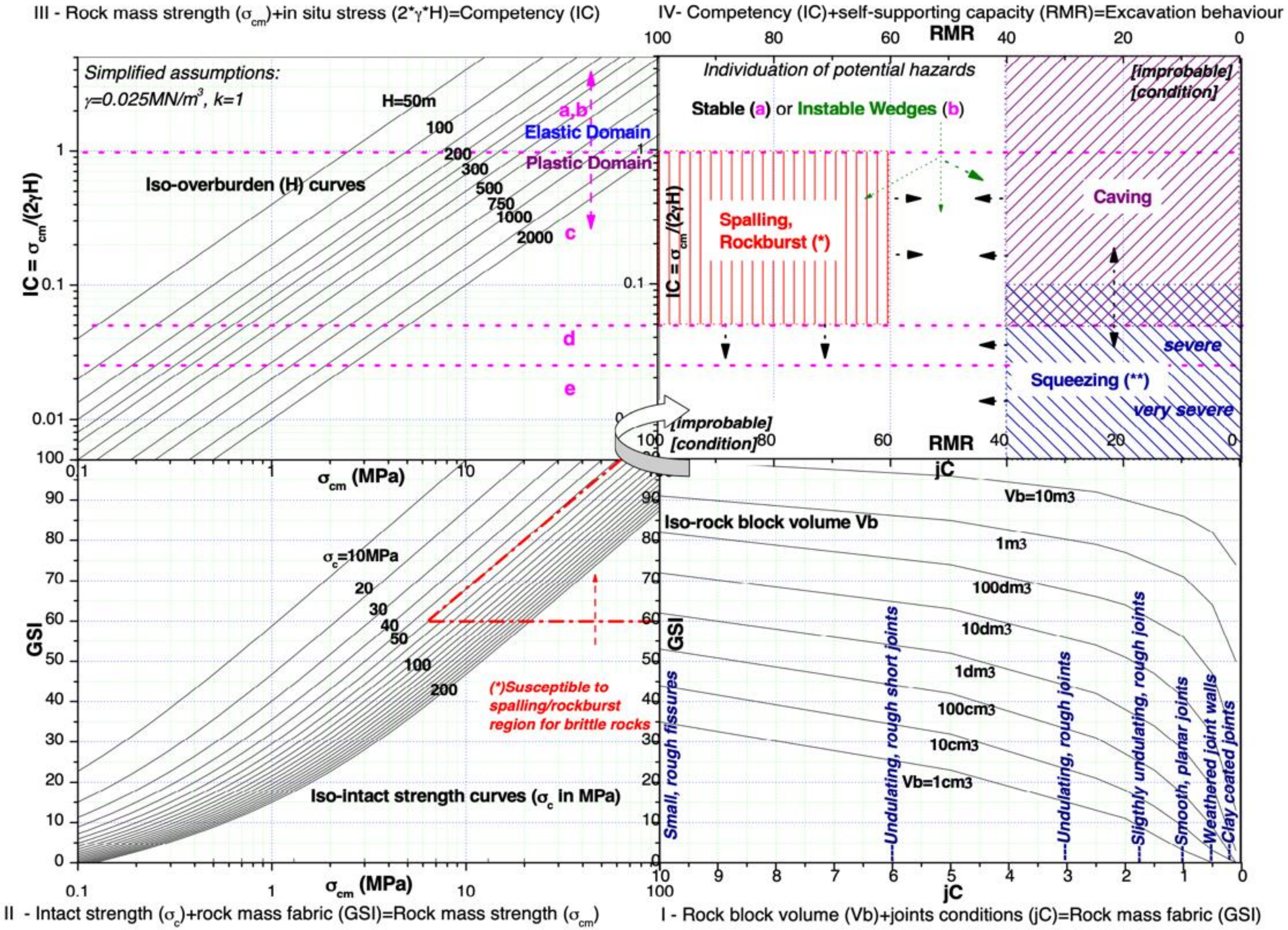
TBM Tunnel – Feasibility assessment

Geological framing

- Soil/rock parameters
- Tectonized zones analysis
- Hydrogeological conditions

Risk assessment



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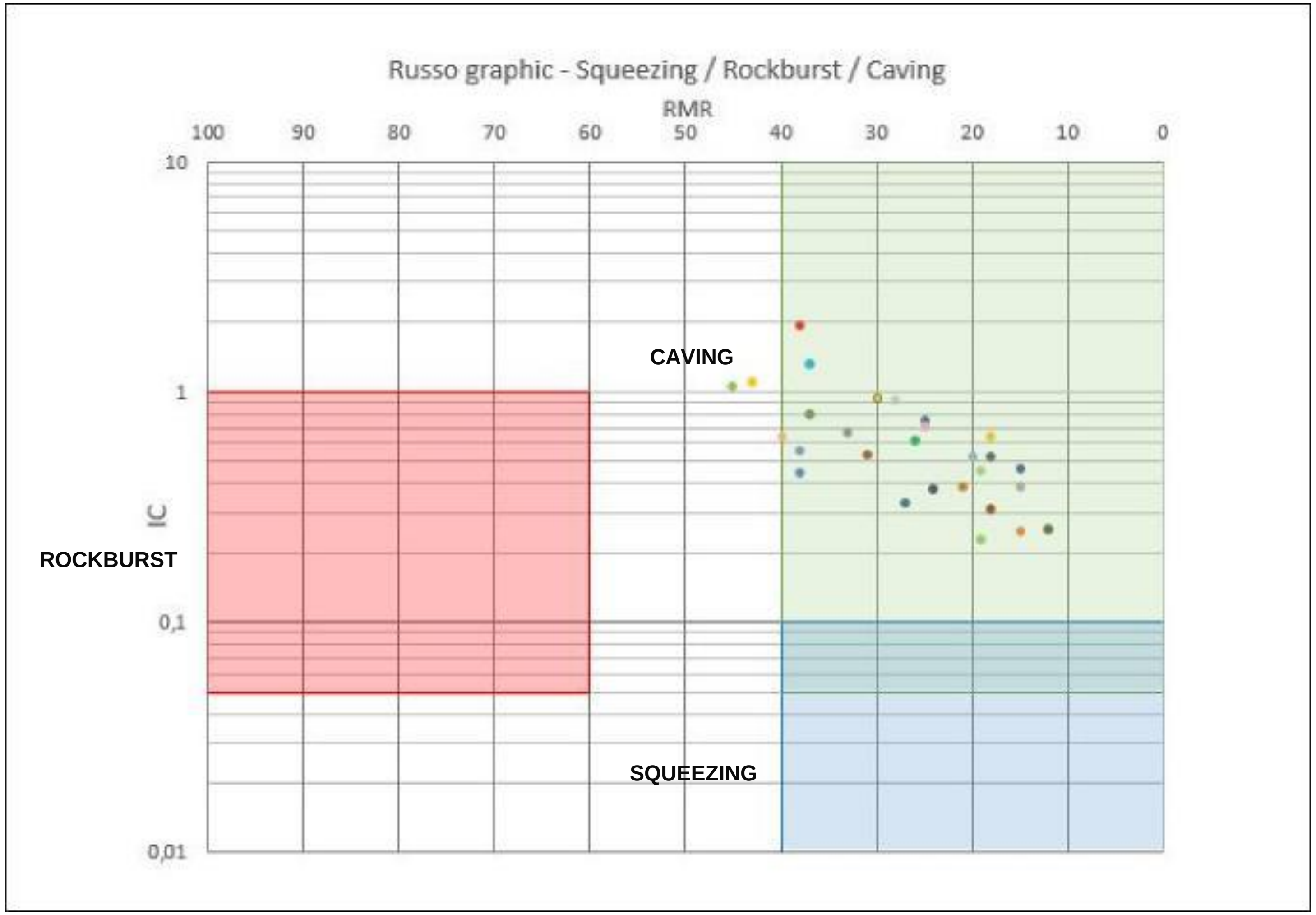
TBM Tunnel – Feasibility assessment

An application template of Multigraph application for large diameter tunnel in Carpathian Flysch.

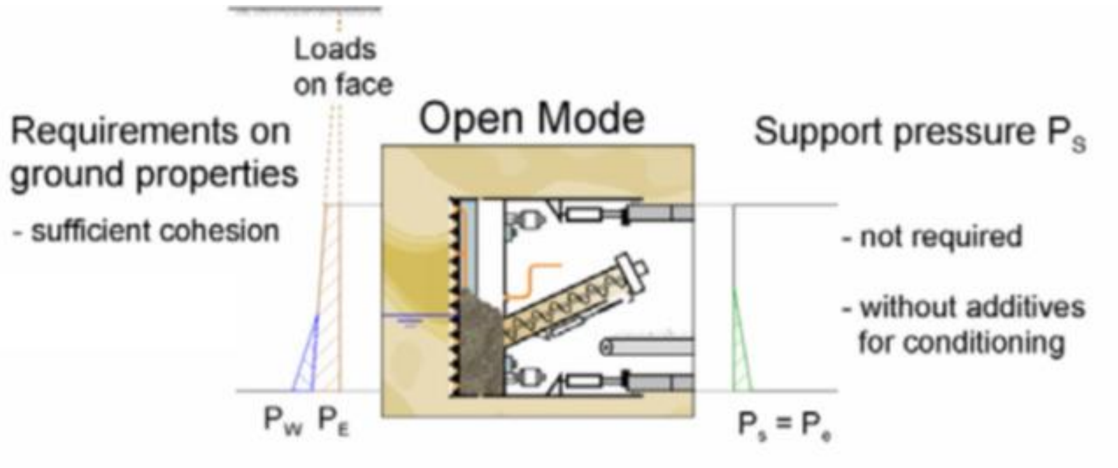


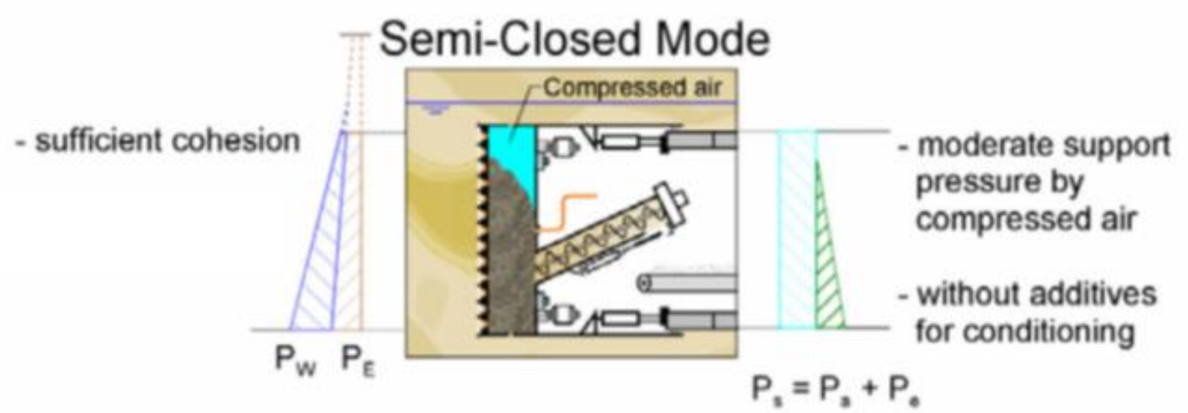
TBM Tunnel – Feasibility assessment

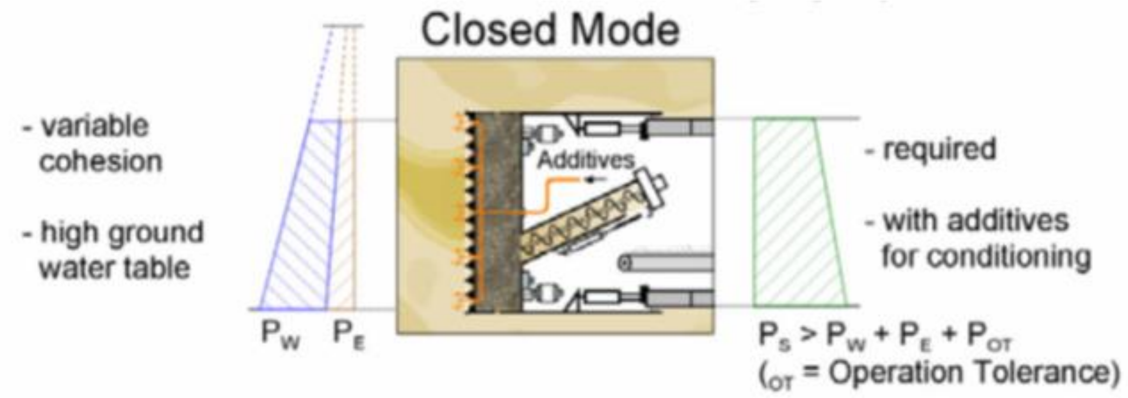
The TBM Competitiveness formula

$$TBM\colon \frac{Tunnel\ Length\ [m]}{Tunne\ Diameter\ [m] \cdot (Unconfined\ compressive\ strength\ [Pa])^{1/3}} > 1{,}5$$

TBM-EPB machine workflow







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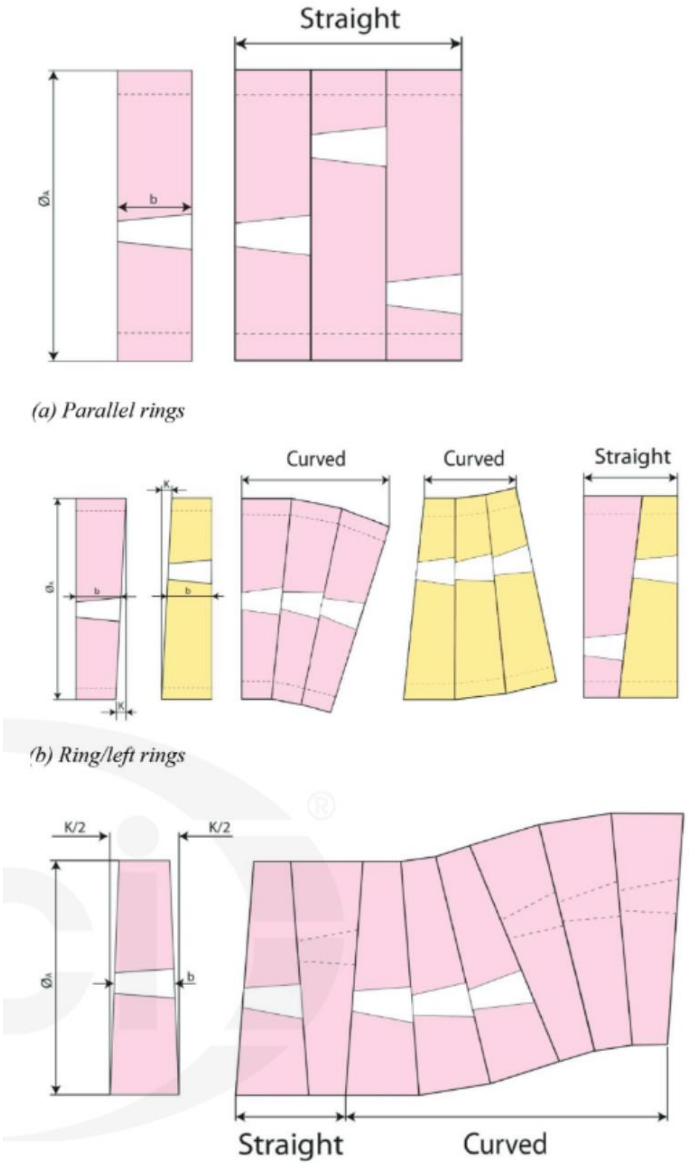
The pre-casted lining and the Universal Ring

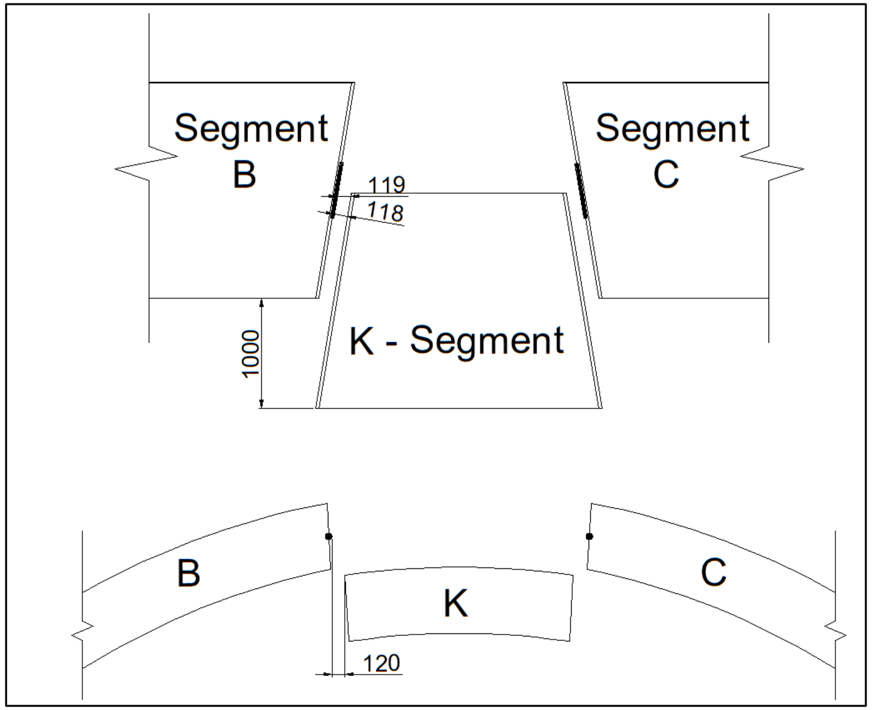
Two ring types have been designed for the project:

- Light reinforced ring: to be used generally in the tunnel alignment.
- Heavy reinforced ring: to be used in those special sections where maximum or operational TBM thrust is required as well as for opening sections for cross passages and niches. They will also be used in the first 20 m of the tunnels at both portal areas.

Ring type	Universal ring
Ring configuration	9 standard segments +K segment (1/2)
Inner diameter of lining	13.45 m
Outer diameter of lining	14.65 m
Segment thickness	0.60 m
Ring length	2 m
Ring taper/conicity	100 mm (taper on one side). Minimum theoretical tunnel radius of 293 m.
Segment slenderness ($\lambda seg = Lseg/thickness$)	7.74
Minimum ring length	1.95 m (at the K segment)

The pre-casted lining and the Universal Ring





The lining design

Standards and main references

- Eurocode 7
- ACI 533.5R-20 Guide for Precast Concrete Tunnel Segments
- BTS Tunnel lining design guide
- ITA-AITES – Guidelines for the Design of Segmental Tunnel Lining
- The design, sizing and construction of precast concrete segments installed at the rear of a tunnel boring machine (TBM)

The lining design

Set of partial safety factors and design approach

Load case		Unfavourable	Favourable
Transient load cases	Demoulding (*)	1.35·1.50 = 2.025	-
	Stacking	1.35	-
	Transport (*)	1.35·1.50 = 2.025	-
	Handling (*)	1.35·1.50 = 2.025	-
TBM thrust	Maximum	1.10	-
	Operational	1.20	-
Primary grouting (**)		1.25	-
Ground forces		1.35	1.0
Variable load		1.50	0
Gasket compression		1.35	-

(*) - Extra safety factor of 1.50 is applied for dynamic load cases.

(**) - Safety factor recommended in ACI 544.7R-16 [24].

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The lining design

Load combination and load cases

1. Temporary construction loads
2. TBM Thrust forces
3. Primary grouting
4. Final state
5. Fire load

The lining design

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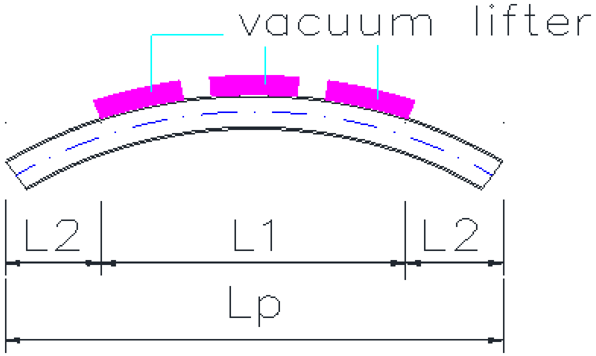

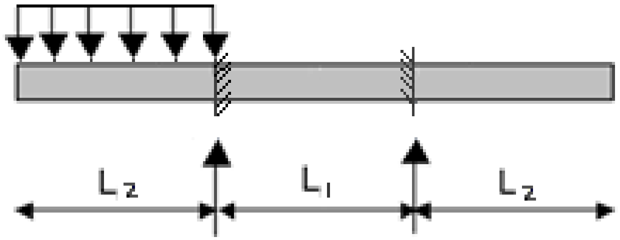

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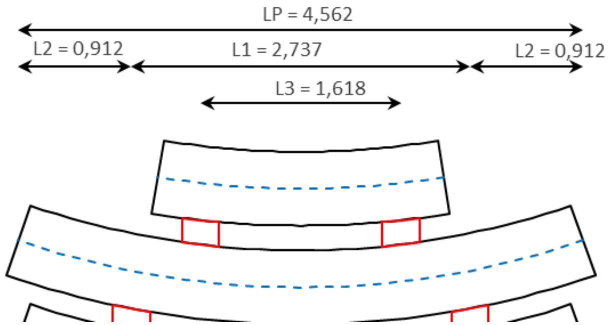

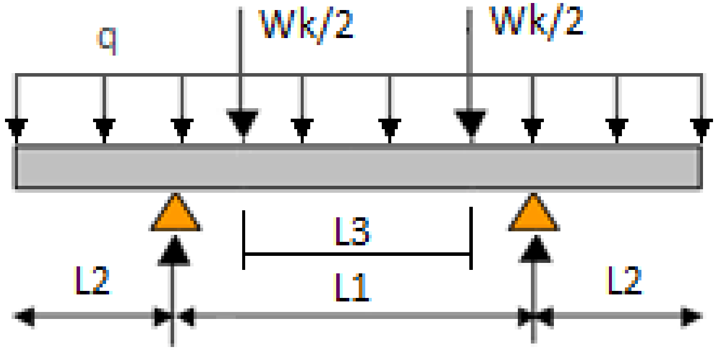

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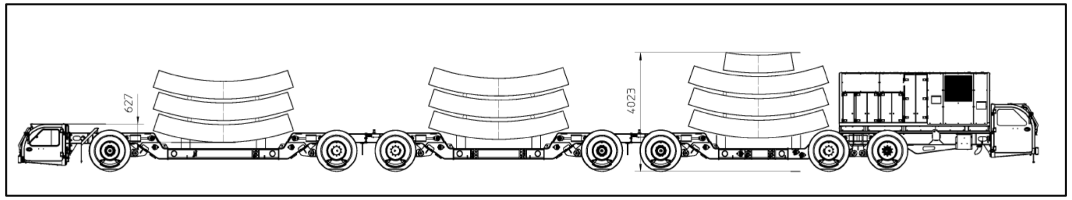

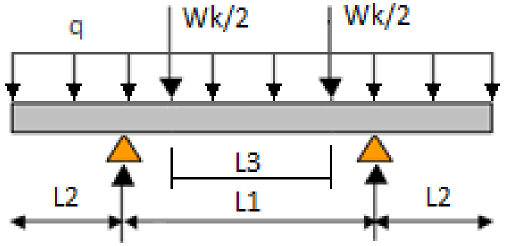

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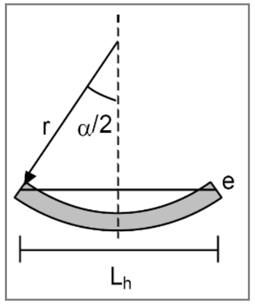

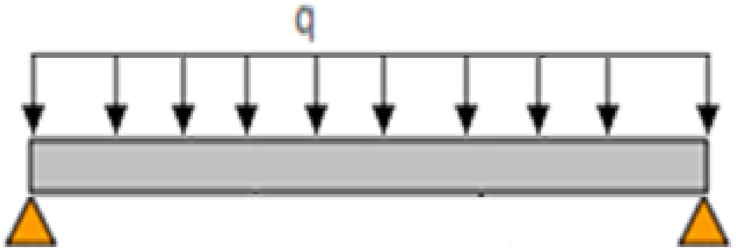

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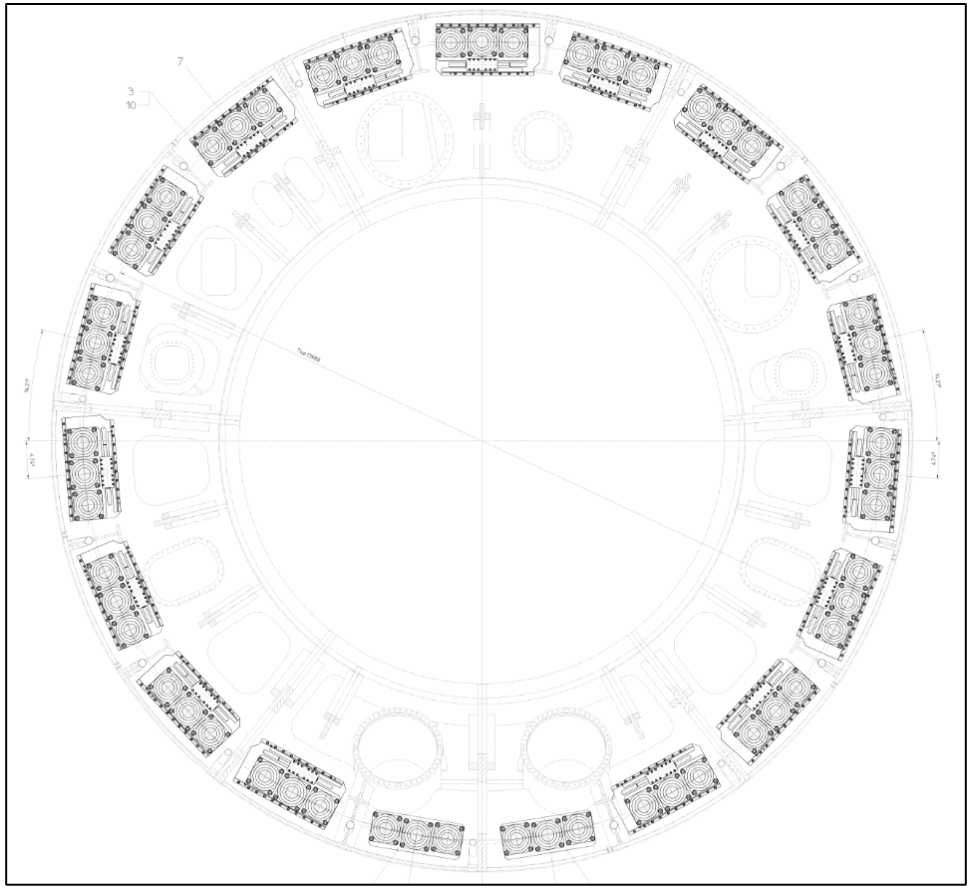

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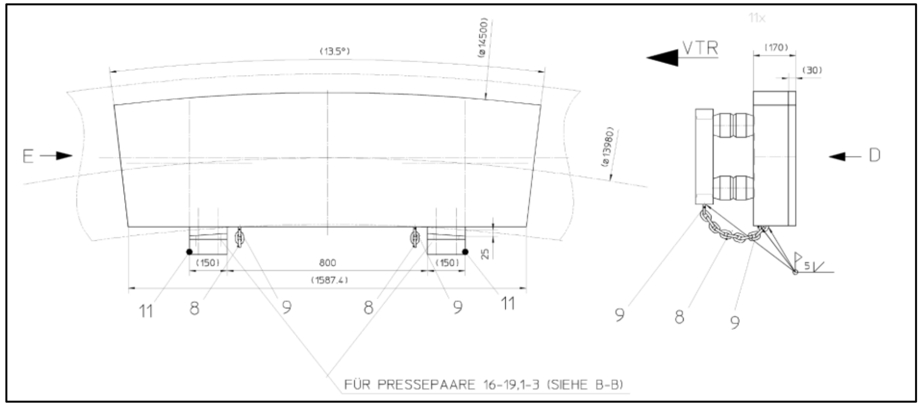
TBM light ring thrust: 175000 kN.

For TBM light ring thrust the partial safety factor applied is 1.20.

$$F_{d,light,rams} =\cdot \frac{F_{TBM,light} \cdot \gamma_{light}}{Number\ of\ ram\ shoes} = \frac{175000 \cdot 1.20}{19} = 11052.6\, kN/ram\ shoe$$



The lining design

Load combination and load cases

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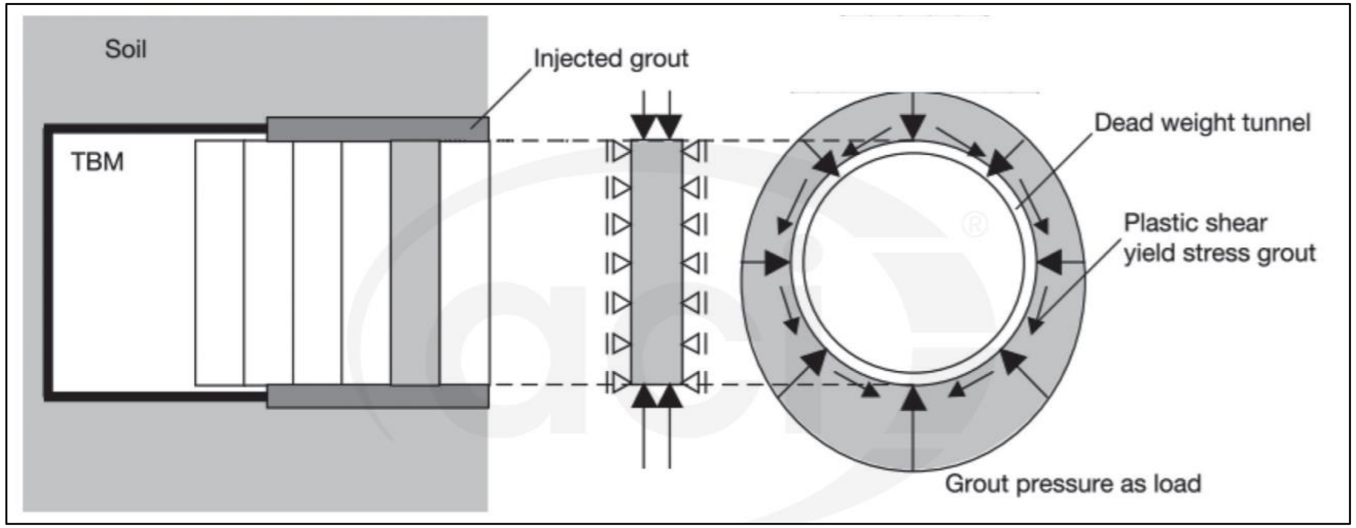

The lining design

Load combination and load cases

1. Temporary construction loads
2. TBM Thrust forces
3. Primary grouting
4. Final state
5. Fire load

- Self-weight of segments
- Ground pressure
- Water pressure
- Creep and shrinkage loads
- Seismic loads
- Live load
- Accidental load

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The lining design

Load combination and load cases

1. Temporary construction loads
2. TBM Thrust forces
3. Primary grouting
4. Final state
5. **Fire load**

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Geotechnical model

Analythical method

Muir Wood's Method:

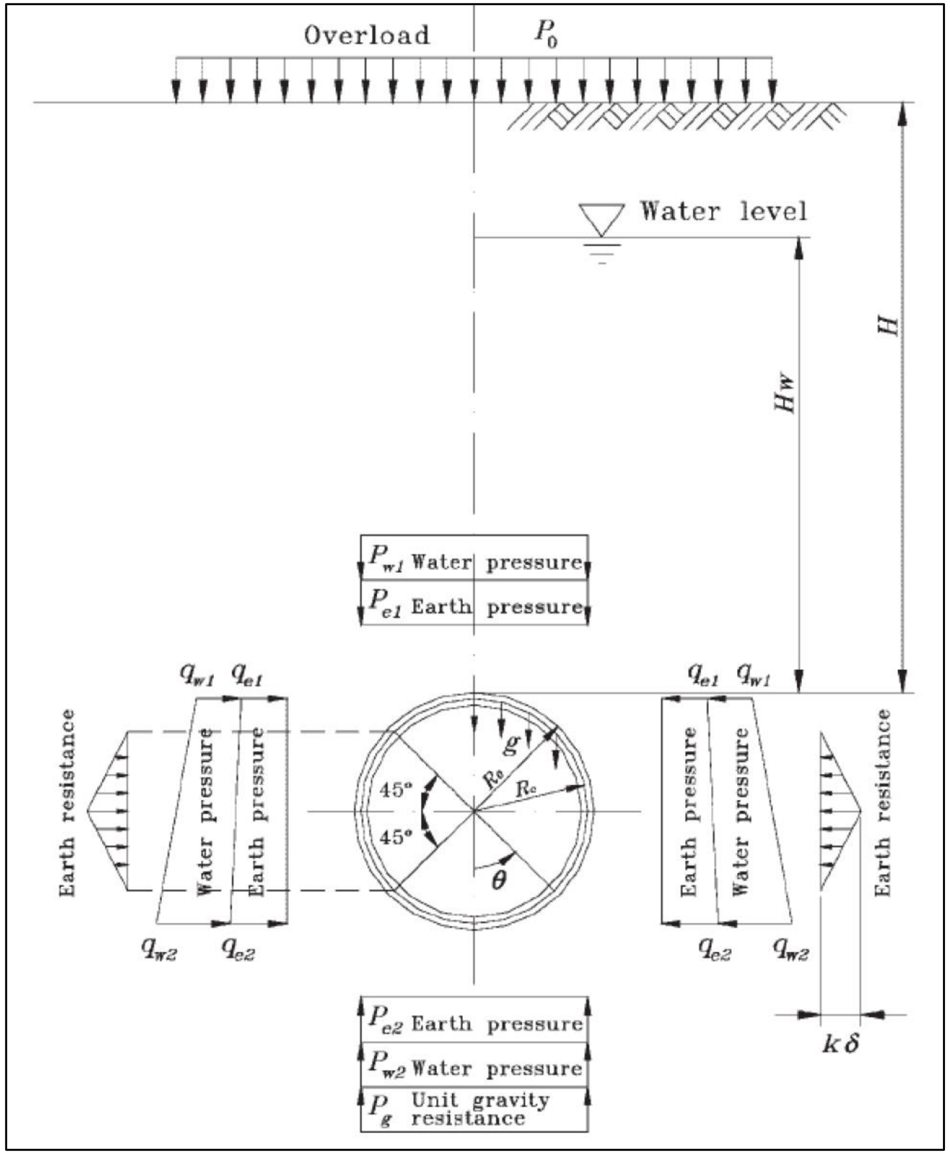
$$I_e = I_j + \left(\frac{4}{n}\right)^2 \cdot I \qquad for\ n > 4$$

I_e: Effective moment of inertia of segmental lining.

I_j: Second moment of area at the joint.

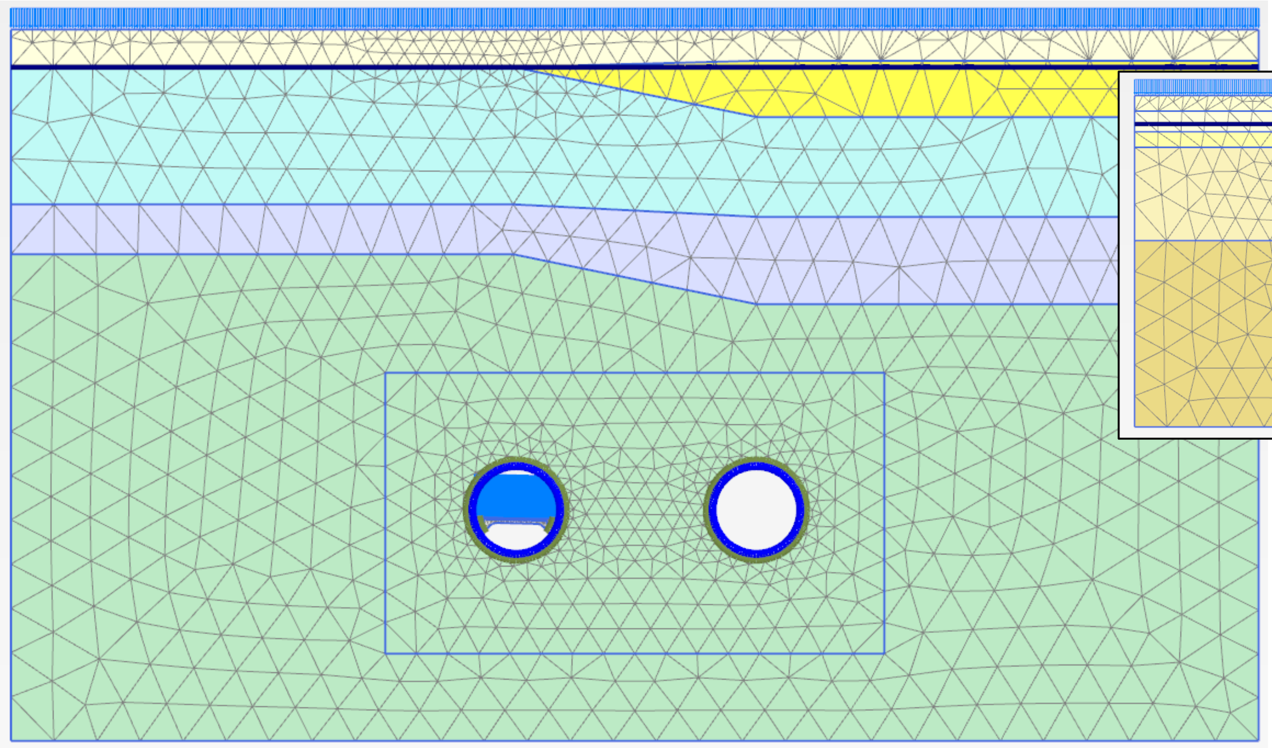
n: number of segments.

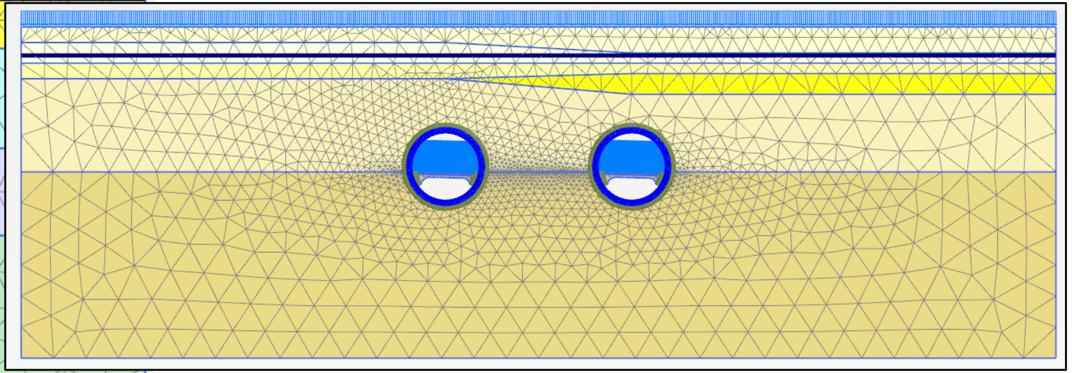
I: moment of inertia of segment complete section.

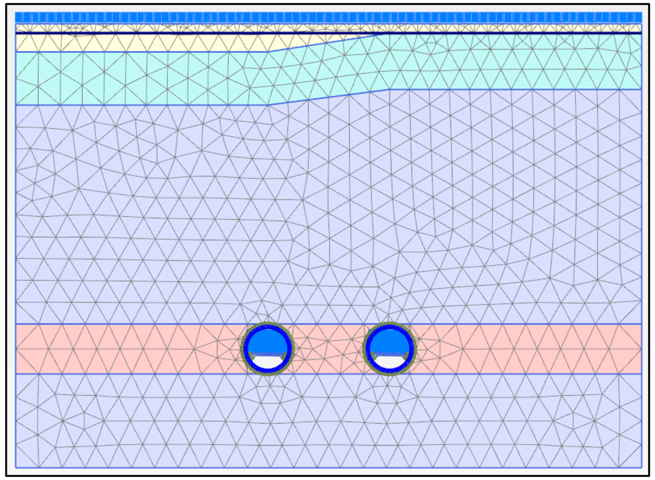


Geotechnical model

Numerical method – 2D

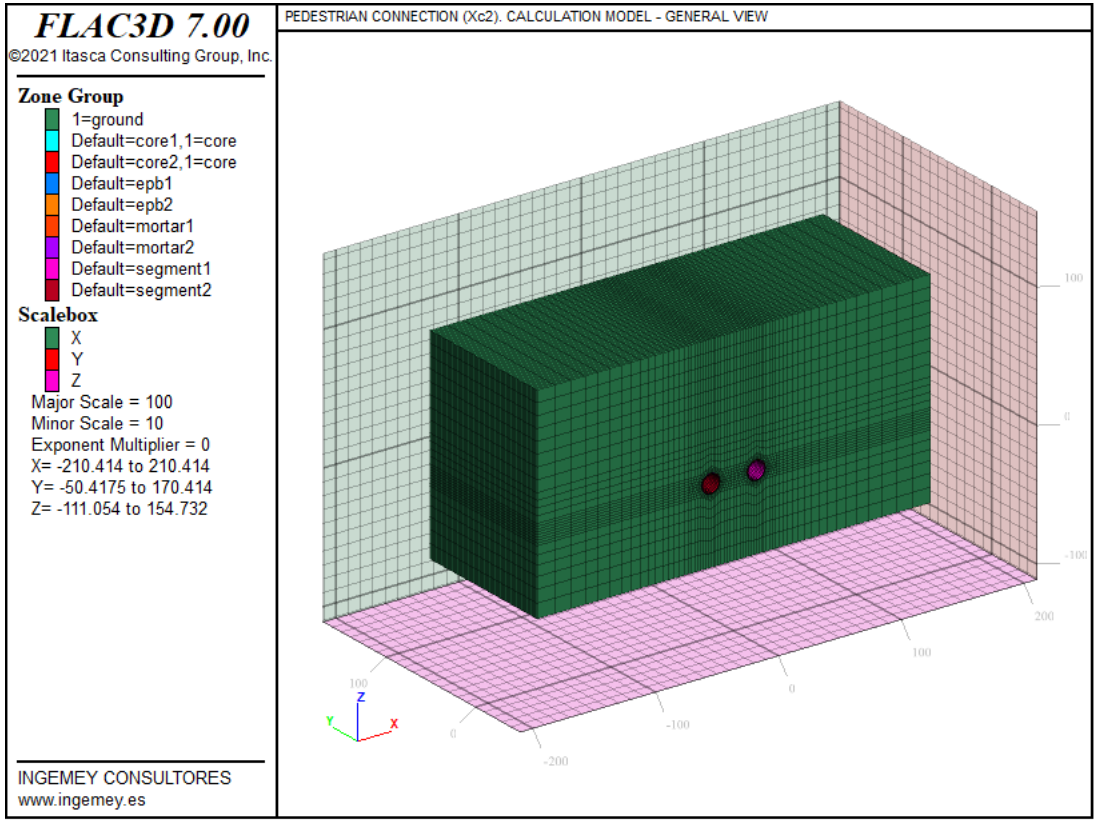


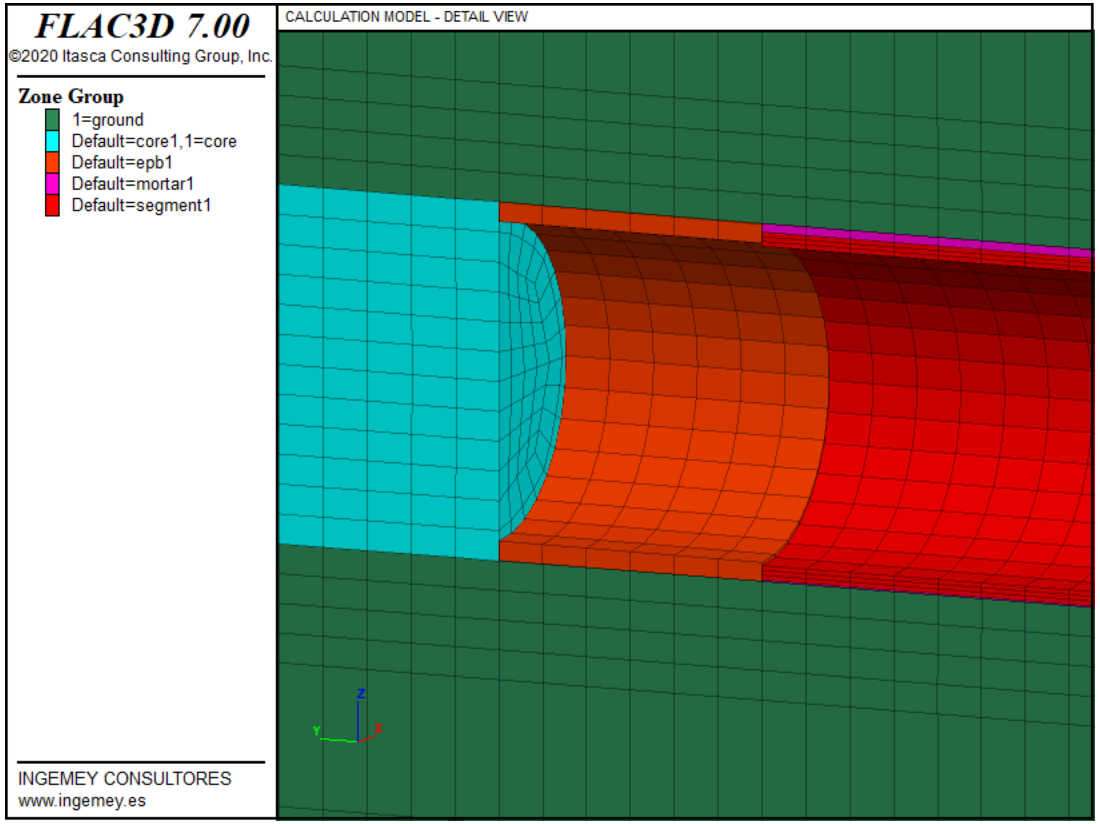




Geotechnical model

Numerical method – 3D





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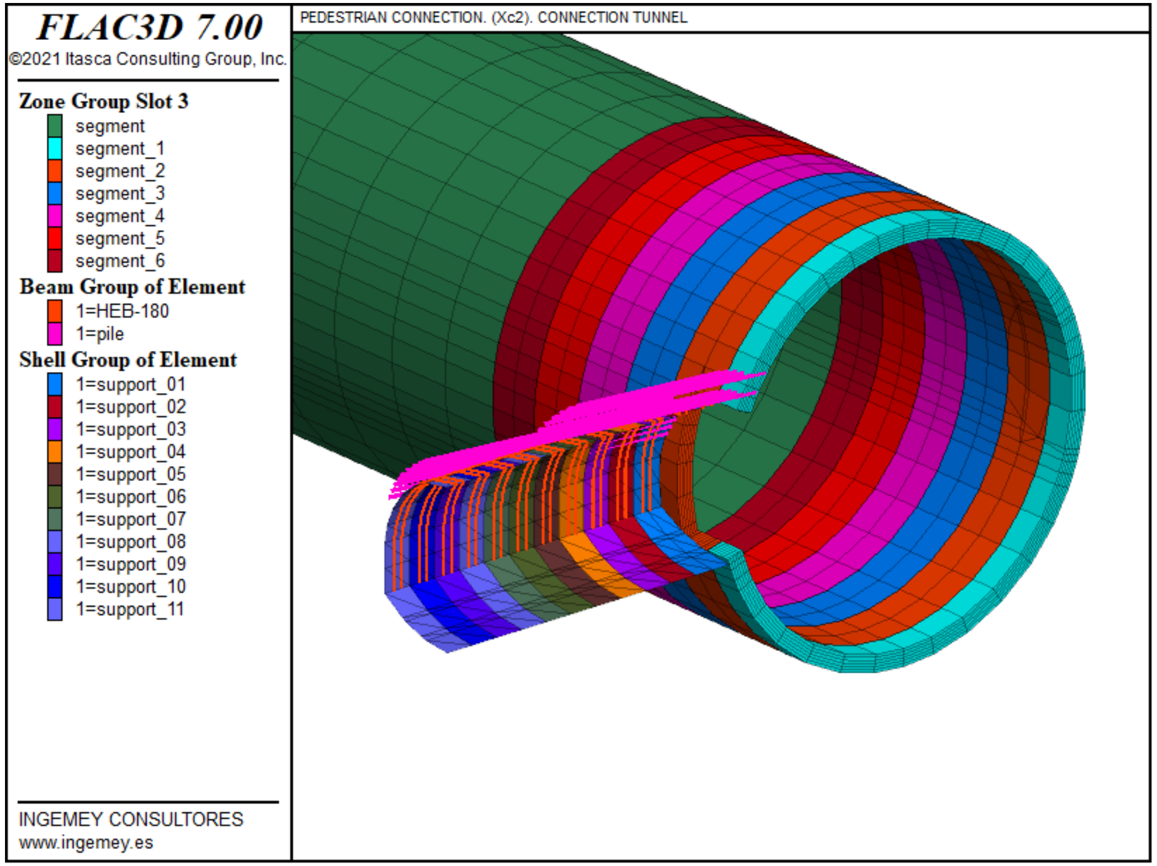
Geotechnical model

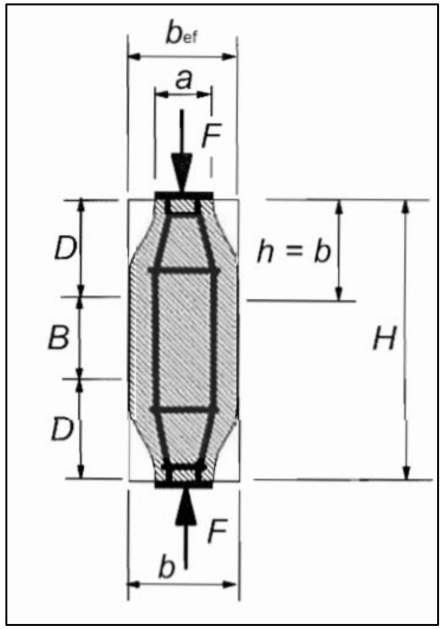
Numerical method – 3D



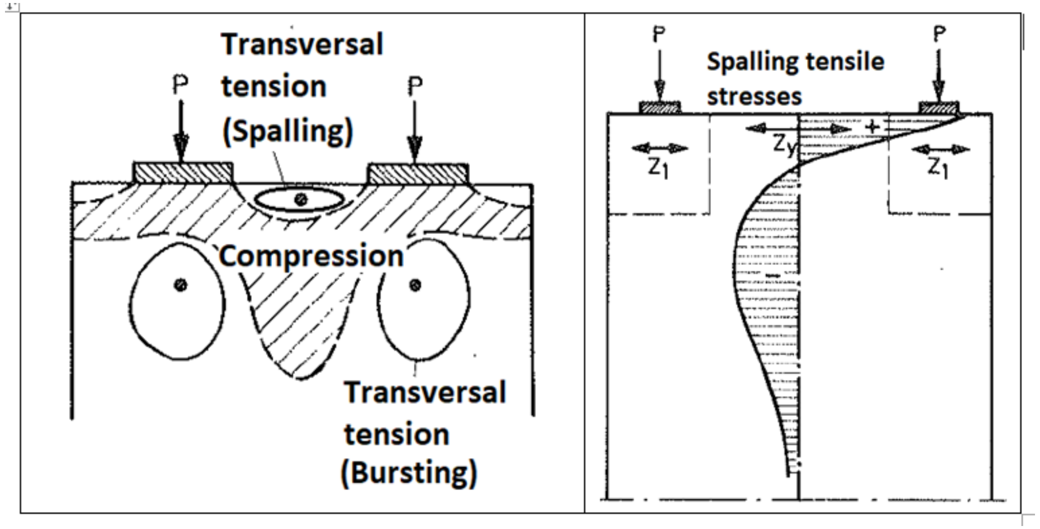
The 3D numerical modeling has the skill to analyze also advanced boundary conditions. E.g. the construction stages of transversal cross passages.

Structural model

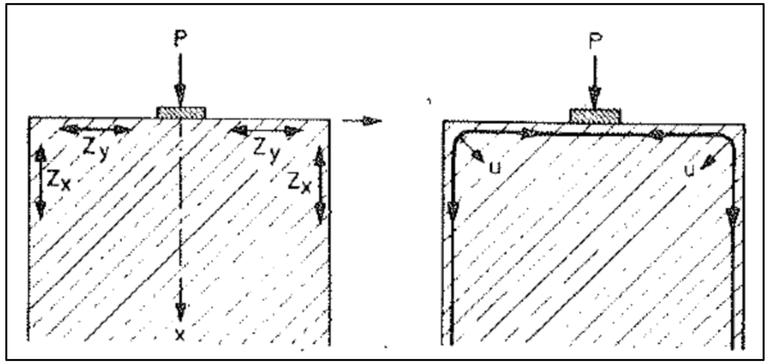
Analytical structural model



Strut and tie model for bursting analysis



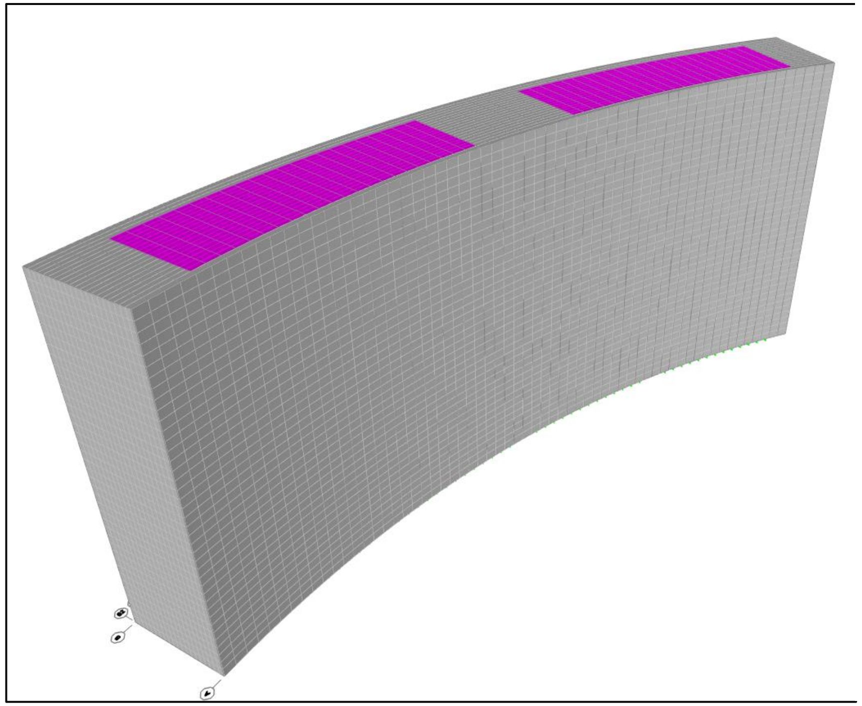
Tensile stresses in concrete due to TBM thrust in circumferential direction

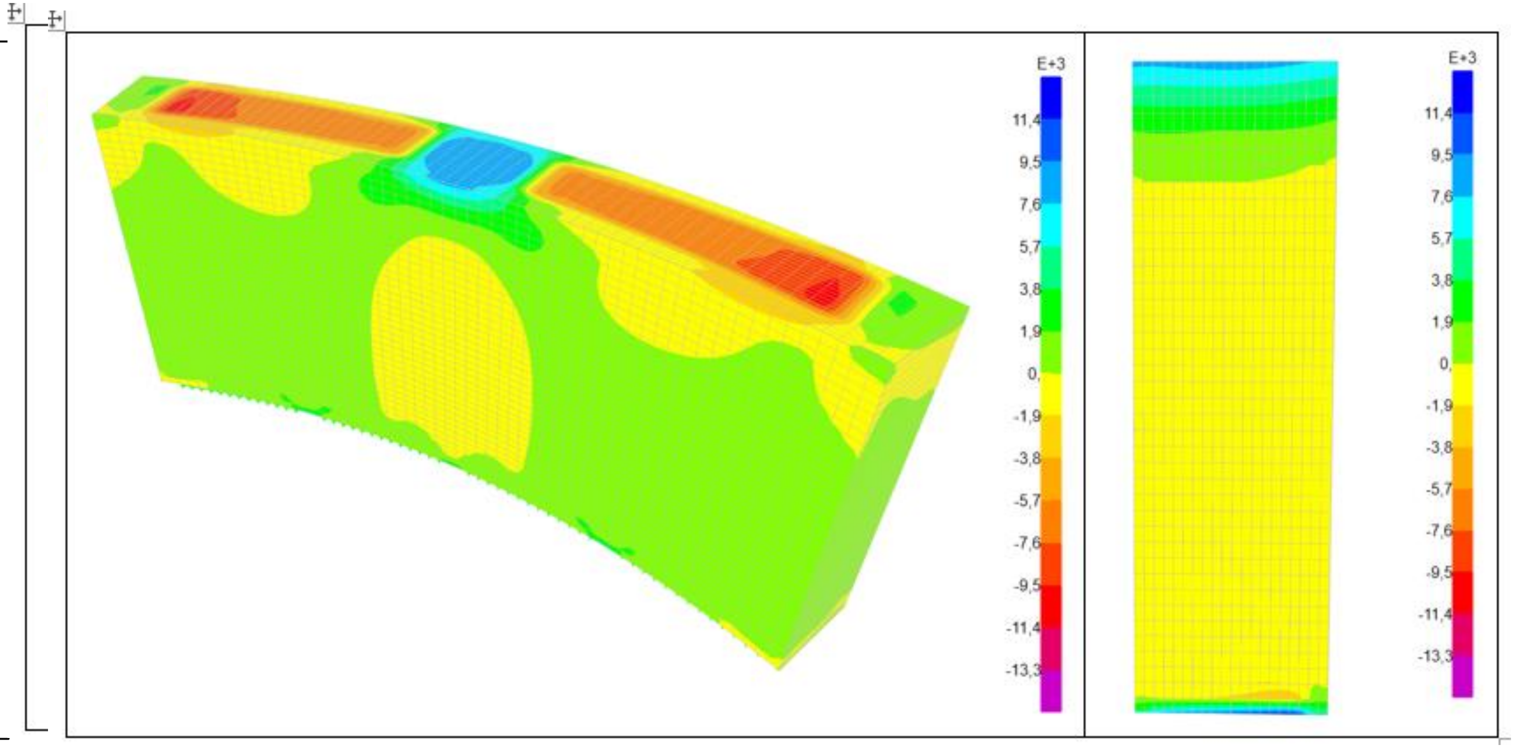


Tensile force Zy and Zx in edge and vertex zones (left) and reinforcement in vertex zones

Structural model

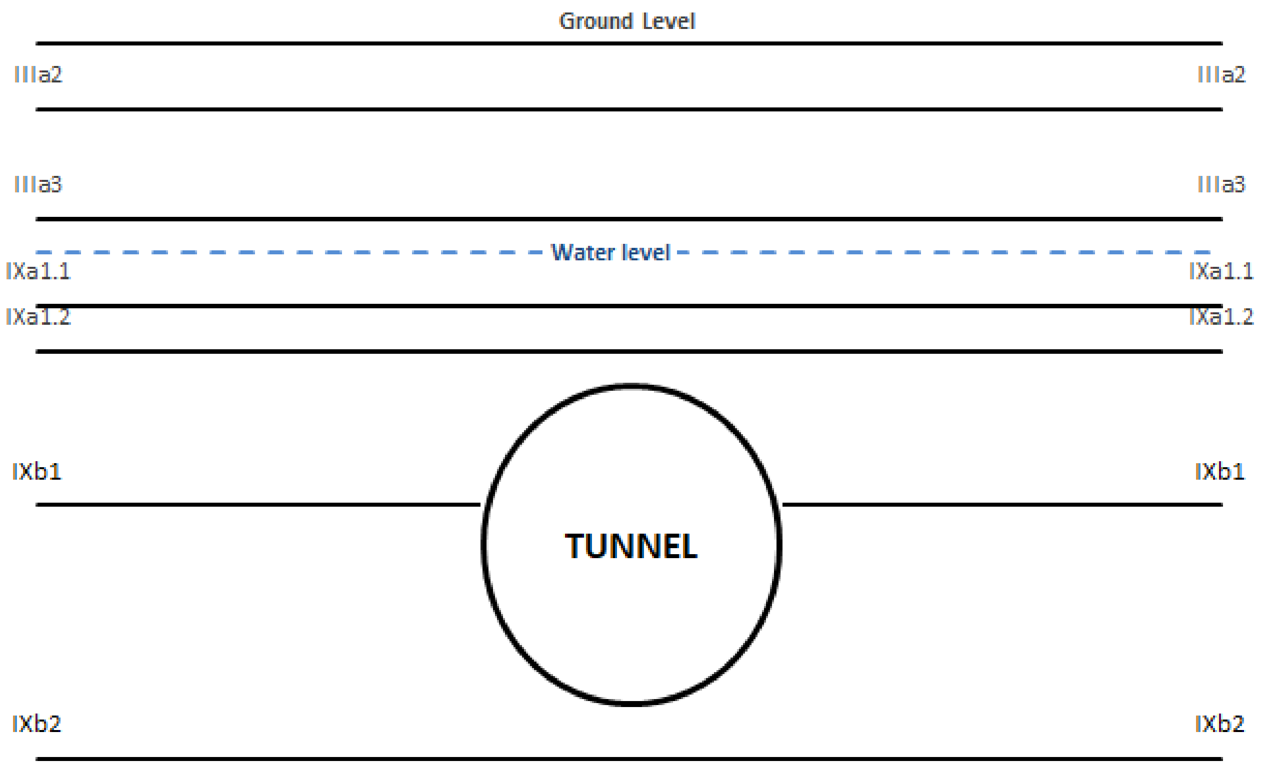
Numerical model





Hydraulic model

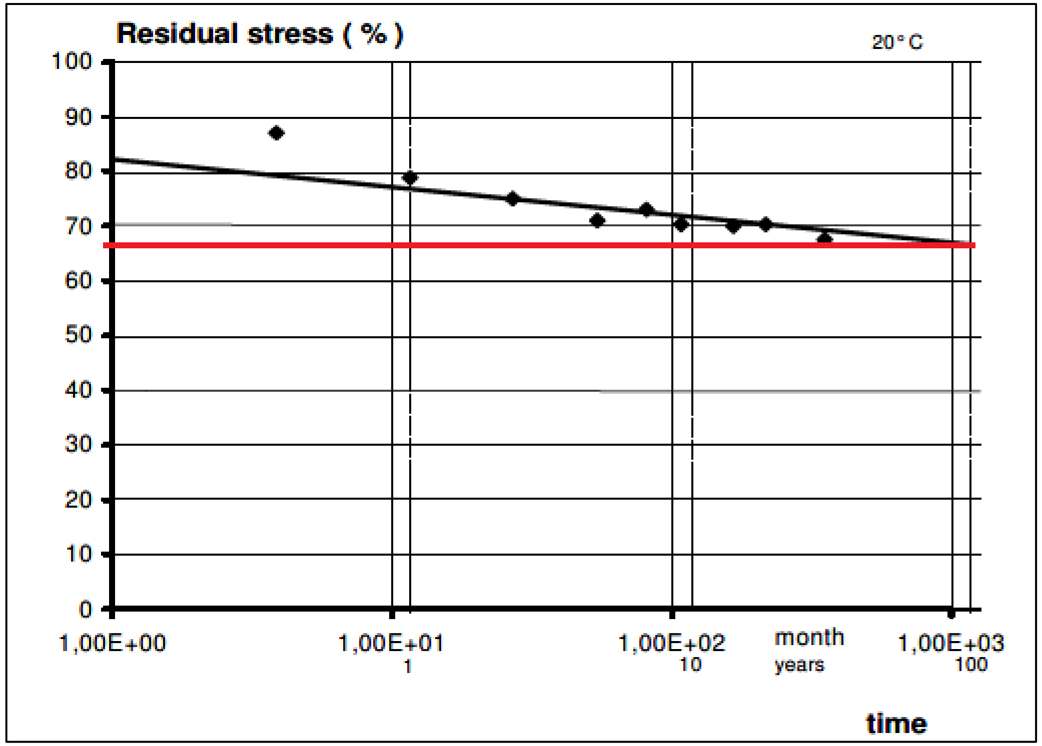
Analythical method

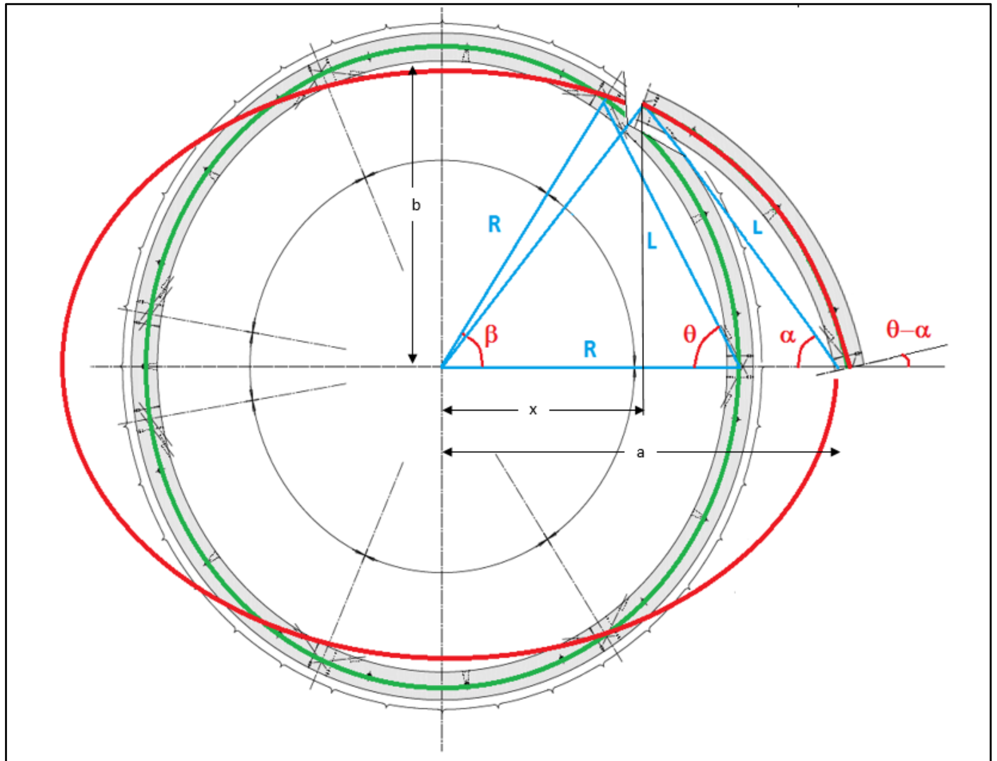


Strata	Top level (m)	Bottom level (m)	Thickness (m)
IIIa2	2,50	-0,50	3,00
IIIa3	-0,50	-5,50	5,00
IXa1.1	-5,50	-9,50	4,00
IXa1.2	-9,50	-11,50	2,00
IXb1	-11,50	-18,50	7,00
IXb2	-18,50	-30,00	11,50

Hydraulic model

Watertightness verification





To obtain x it is necessary to calculate the intersection between the ellipse of centre (0,0) and a-b as major and minor axes, and the circle of centre (a,0) and radius L

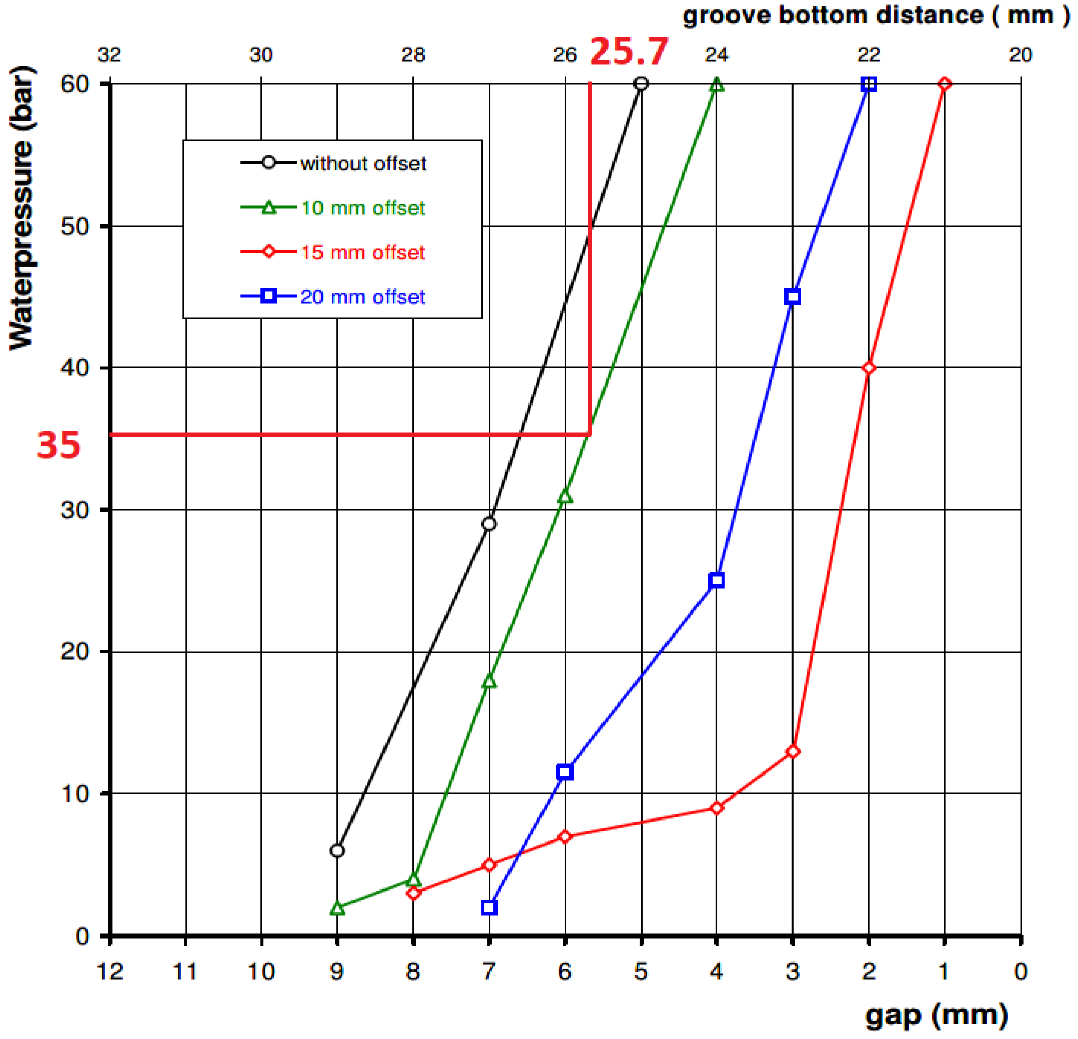
Ellipse equation $x^2/a^2+y^2/b^2=1$

Circle equation $(x-a)^2+y^2=L^2$

Intersection: $x=\dfrac{a^2+\sqrt{b^4+L^2a^2-b^2L^2}}{\dfrac{a^2-b^2}{a}}=$ 5563,52 mm

Hydraulic model

Watertightness verification



Conclusions

- The TBM technology has to be assumed as an on-site industrial process
- The supply chain has the most important ring in the production of segmental lining, that requires a strongly detailed design process, to keep in account the complete lifecycle, since the production, up to the installations, up to the lifetime
- A huge set of scenarios and boundaries conditions takes place in the design process
- Both analytical, bot numerical methods of analysis has to adopted in order to properly resume in a feasible design process the limitless possible scenarios
- The contents presented above have to scope to present a roadmap from the conception up to the execution of the segmental lining elements
- Further aspects of the technological process can be focused with the same approach, among them the segments survey and review and, after it, the repairing actions.