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Geotechnical dimensioning of TBMs and new technological challenges

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ABSTRACT: The ever-growing need of transportation networks has led to considerable development in tunnelling works. Mechanized excavation is increasingly being applied, especially in the presence of high overburdens and squeezing rock-mass conditions. The advantages of the method are mainly to be found in an industrialization of the construction process, which enables greater excavation rates, as well as safer working conditions. The application of mechanized tunnelling in geotechnically complex contexts, however, forces to deepen the geotechnical dimensioning, considering the behaviour of the core-face, the face chamber-pressure and the interaction between the rock mass and the tunnel system, mainly the shield during excavation, to avoid jamming. These geotechnical analyses allow the design of the technical requirements for the TBM construction, in terms of chamber-pressure, shield conicity, over-excavation, and total thrust. The Authors will present a methodology approach to define in detail the correct technical specification for the TBM. A risk assessment must address the most critical aspects, towards which to choose the most appropriate risk mitigation interventions. The focus will refer to squeezing and geological complex conditions, where recent experiences have allowed projects to define very high-performance TBMs, according to the state-of-the-art. Numerical modelling is presented to analyse the problem and as a tool to help designers in defining with key technical specifications for the TBM advance. Based on monitoring data, specific "guidelines" will allow projects to calibrate operative parameters during excavation and to manage residual risks.

Keywords: geotechnical dimensioning, TBM, mechanized excavation, critical contexts

1 INTRODUCTION

The ever-growing need of transportation networks has led to considerable development in tunnelling works, with increasing excavation diameter requirements and facing adverse geological and geotechnical conditions. Mechanized tunnelling is increasingly being applied, not only in urban areas where it has always been preferred over conventional excavation, but also, nowadays, in the presence of high overburdens and, sometimes, in severe squeezing rock-mass conditions. The advantages of the mechanised system are mainly to be found in its industrialization of the construction process, which determines greater excavation rates, as well as safer working and better environmental conditions. However, the application of this excavation methodology in geotechnically critical contexts, by means of EPB-TBMs or hydro-shield TBMs, forces projects to carefully deepen the geotechnical dimensioning, considering in detail the behaviour of the core-face, according to the ADECO-RS Approach (Lunardi, 2008), and the interaction between the rock mass and the tunnel system, mainly the shields. The definition of the correct pressure value, to be adopted in the excavation chamber to assure face-stability, as well as the TBM thrust, are crucial elements for the success of the advancement excavations. Jamming conditions must be especially avoided, which can lead to excavation stops or the shield's ovalization.

In this paper, a methodological approach to examine the problem and to define the correct technical requirement for the TBM to be used is described. In the design stage, once the geological and geotechnical model has been defined (survey phase), a risk analysis must be developed in order to identify the critical issues regarding TBM excavation (diagnosis phase). Regarding each risk, the TBM design strategies must be identified, according to the potential offered by the TBM manufacturing market, and numerical analyses must be performed to size in detail the technical specifications to be envisaged (therapy phase). Finally, in the construction stage, specific "guidelines" should be adopted, to monitor the key parameters of the TBM advance with respect to each risk, and to calibrate the excavation system according to design variabilities.

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2 GEOLOGICAL INVESTIGATIONS AND GDM MODEL

An accurate geological, geotechnical and hydrogeological model along the tunnel axis has to be constructed. This requires an investigation campaign with boreholes deepened 10 m down the future tunnel invert, in addition to desk studies of the area and relevant bibliographic research. All of the collected stratigraphic and piezometric data must be inserted in the GDM and used to produce an accurate predictive geomechanical profile considering geological sequences, contacts between formations, presence of faults or sliding structures and landslides. Lithological and geotechnical properties (strength and deformability parameters) of the rock-mass should be defined; it's also important to detect the presence of boulders or mixed face conditions. Finally, hydrogeological context should be assessed, that is to define distribution of aquifers, rock permeability values and groundwater levels.

3 RISK ASSESSMENT

Based on the GDM model, a risk analysis for TBM advance must be developed. The main typical risks, linked to geotechnical and hydraulic conditions, are described in the following and must be investigated with respect to TBM behaviour during excavation.

3.1 *Squeezing or swelling phenomena*

In poor rock-mass conditions, mainly in clays or argillitic shales, especially in the presence of high overburden (>80-100 m, with geostatic stresses greater than 2.0-2.5 MPa), it's very frequent to encounter the risk of squeezing conditions. These generate large convergence of the excavation profile, extensive plastic yielding around the cavity, and swelling phenomena due to the volume and stress variation in the rock-mass during excavation. The risk is the activation of high ground pressures on the TBM shields, which could exceed their static resistance, with ovalization and/or deformations. These high pressures on the shield, combined with the need to operate adequate balancing pressures at the face and to impart the cutters' energy to advance the excavation, can generate high thrust values for the TBM, exceeding the capabilities of the machine. The consequential risk is the TBM becomes trapped.

3.2 *Core-face instability*

When the state of stress in the ground is considerably greater than the strength properties of the material, even in the zone around the face, an unstable core-face condition occurs (category C, referring to ADECO-RS Approach), coupled by the risk of face collapses. Moreover, deformation of the core-face, in terms of extrusion and pre-convergence, could cause decay of the strength parameters of the ground, if it's affected by "strain-softening" behaviour, further deepening the band of plastic yielding. So, it's necessary to enact pre-confinement operations at the core-face, by proper pressure in the TBM excavation chamber, minimising ground deformation and strength decay. This is clearly stated by extrusion tests, specifically applied to the sizing of the pressures to be maintained at the TBM face (Gatti, 2011 and Lunardi, 2013).

3.3 *Presence of boulders or mix-face condition*

Homogeneous face conditions, characterized by uniform stiffness and strength of the material to be excavated, allow regular and efficient advancement of the TBM. Otherwise, the presence of stone boulders, especially inside a weak rock-mass, or mixed face conditions characterized by different rock components can be critical for the TBM excavation. Some examples are reported in Figure 1.

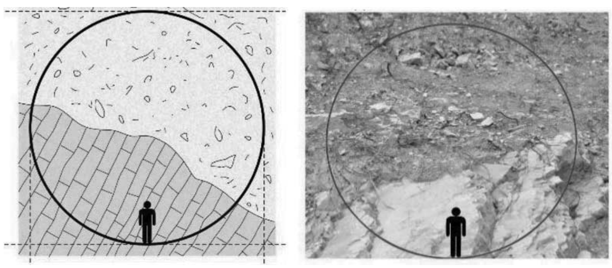

Figure 1. Example of mix-face conditions.

Thus, the excavation tools of the TBM must guarantee adequate flexibility in relation to the variety of stiffness and strength of the excavated materials, providing suitable devices for their easy replacement in relation to the lithological variability of the rock-mass to be excavated.

3.4 *Landslides or existing superficial interferences*

The presence along the tunnel alignment of landslides or pre-existing interferences, such as buildings, roads or utilities, requires to limit the "lost volumes" during the excavation, in order to avoid subsidence at ground level and consequently damage to the pre-existing structures or accelerations to the movements of landslide. Generally, this risk occurs with low overburdens (with limited geostatic stresses), so that it is possible to maintain pressures in the TBM excavation chamber close to geostatic pressures, and drastically reduce deformations during the excavation phase. Similarly, care must be taken to backfill the segmental lining, in order to avoid settling at the tail of the TBM (Gatti, 2007).

3.5 *Water leaks and high hydraulic heads*

With reference to the hydrogeological context, the main risks are linked to the interception, during excavation, of high-water inflows and to the presence of high groundwater pressure. The first risk can be mitigated through consolidation and/or drainage systems to be carried out at the face of the TBM and through the shield (dewatering system). For the second one, if the hydrostatic pressures exceed the static resistance of the concrete linings, drainage systems must be used, generally installed along the base of the sidewalls, so as to facilitate easy collection and disposal of the drained water (Figure 2).

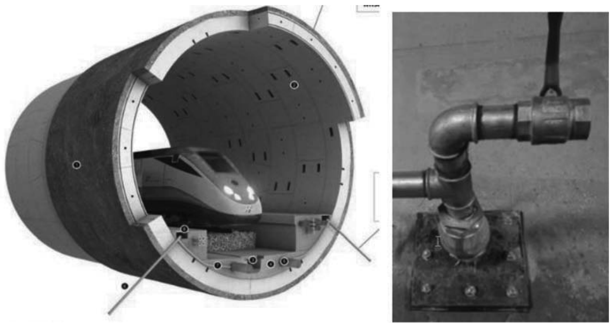

Figure 2. Drainages systems.

The effectiveness of the drainage action can be verified, in the long term, by pressure monitoring systems mounted behind the segmental lining.

3.6 *Presence of in-situ gas*

The presence of in-situ gas can be identified through detailed analysis of the geostructural context (i.e., lithological and fault successions) and according to the results of boreholes that identify gas emissions. The gas risk is very high in mechanized excavations, considering that not all TBM equipment can be ATEX, such as the cutterhead. The Italian "Interregional Note 44" (NIR, 2009) provides useful advice to mitigate the risk of operating excavations with TBMs in a gas context. The TBM must be compartmentalized by sectors, to avoid the diffusion of gas in the different working environments. In the presence of gas, the excavation must be carried out with a full chamber (closed mode) to prevent possible formation of a "combustion chamber", and a special gas-proof duct to enclose the top of the screw conveyor and the conveyor belt, for approximately the first 80 m, up to the protected tunnel sectors should be provided. Systems for monitoring and controlling the concentration of gas in the atmosphere must also be activated, coupled with ventilation systems (Lunardi, 2012).

3.7 *Clogging phenomena*

Clogging phenomena are linked to the presence of clayey soils, which are difficult to condition and subject to "cooking" and packing. The resulting risk is not allowing the correct pressures to be maintained at the face and the correct extraction of material from the screw. It may be necessary to use anti-clogging additives in addition to ordinary foaming agents.

3.8 *Other risks*

Other risks may be linked to structural geological conditions, such as the crossing of fault zones or highly fractured rock, as well as anomalous thrust conditions (for example of a tectonic nature or due to schistosity). These risks present similar problems to those already discussed in Section 3.1. Sometimes, in very sound rocks, problems may arise related to difficulties in penetrating and breaking the rock, with high wear of the cutting edges due to abrasiveness.

To identify the magnitude of the described risks, it is necessary to determine the frequency (F_E) of occurrence of the events identified above, evaluating the length of the tunnel sections in which they will have to be addressed. Furthermore, the impact (I_E) of each event must be assessed considering the possible consequences, in terms of health/safety, effects on the development of works to be carried out, economic and environmental impacts during construction. The risk will be identified as the impact for the probability of occurrence ($R = F_E \times I_E$).

4 DESIGN APPROACH AND TBM REQUIREMENT

The TBM design strategy is to consider mitigation measures, which will have the aim of mitigating the risks within residual acceptable values. With reference to risks of geotechnical nature, mainly linked to squeezing or complex geological conditions, it is necessary to adopt measures capable of governing the stress-strain distribution into the rock-mass all around the TBM, keeping the pressures on the shields below fixed values. This can be achieved by avoiding the relaxation of the rock-mass by applying counterbalancing pressures at the TBM's face and along the contour of the shield, as well as by preparing a gap around the TBM by overcutting in order to accommodate the inevitable convergence of the rock-mass. It is therefore necessary to define the pressure value to adopt in the chamber pressure and choose the correct excavation diameter, coupled with TBM's shield conicity. Modern TBMs can operate pressures at the excavation face of up to 5-6 bar, thanks to the maintenance of conditioned soil in the excavation chamber in the case of EPB or by means of bentonite slurry in the case of hydroshield. At the same time, they can inject bentonite along the gap between the shield and the excavation profile, using pressure injectors of up to 5 bar. Modern TBMs have also the possibility of modulating the excavation diameter during advance, to face different geotechnical contexts, and increasing the excavation diameter in the presence of squeezing conditions. This can be achieved both through the adoption of fixed "overcutting", which is managed along the perimeter of the cutterhead, and through temporary "copy-cutters", with hydraulic opening. Radial fixed overcutting values of up to 100-150 mm can be achieved, for single steps of 20-40 mm; additional copy-cutters can further increase the excavation radius by a further

50-60 mm. Typical shield conicities are between 50 mm and 130 mm. Considering that the shields, with a total length of 10-12 m, are generally divided into three sections (front, intermediate and tail shields), the conicity is guaranteed by providing a first step between the excavation diameter and the front shield (20-30 mm) and two reductions in diameter between the intermediate and the tail sectors (30-50 mm each), as represented in Figure 3.

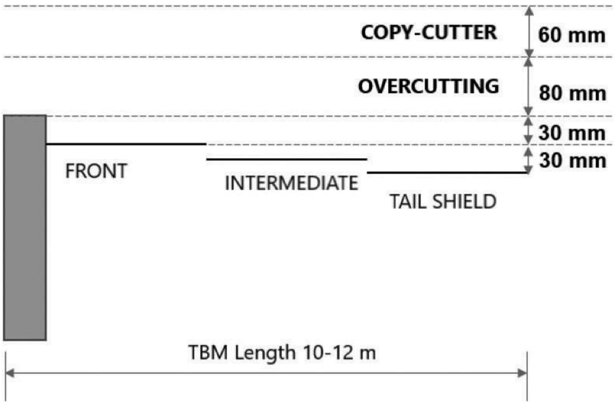

Figure 3. Typical TBM shield conicity.

It follows that the maximum radial over-excavation can reach up to 250-300 mm. It is therefore necessary to equip the TBM with measures to facilitate driving if the expected convergences do not occur and the driving position may be lost. For example, 4 to 6 fin stabilizers are placed around the lower part of the shield and 2 to 4 round stabilizers in the upper part. It could also be useful to provide an “active articulation system” of the head, located in the front-shield, so as to manage the vertical guidance of the TBM. If a significant gap, between the excavation profile and the extrados segments is present, it’s necessary to make sure it is perfectly filled with bicomponent backfilling; the filling systems, carried out by 8-10 injection lines, must be able to guarantee an injection volume of 50-60 m^3/hour.

The ground pressures, which will be active around the shield, will generate frictional forces that must be overcome by the thrust of the jacks. It is therefore necessary to size the overall thrust of the TBM to take into account all the necessary components: mainly the pressure to be maintained at the face, the force of the cutters for excavation, the friction forces along the shields, the weight of the machine and the back-up (Maidl, 1996 and Gatti, 2011). In the squeezing context, a total thrust in the range of 200-300 MN is recommended, depending on the TBM’s diameter. Numerical modelling must be performed to define in detail the proper chamber pressure, the excavation diameter (using overcutting and/or copy-cutter) and the total TBM thrust. A proposal is described in Section 5.

Another important strategy in managing mechanised excavations in squeezing conditions is to guarantee regular and continuous advances, avoiding prolonged stops, which can generate the release of ground pressure on the shields and considerably increase the friction forces. This is the situation in which trapped TBMs most frequently occur. Some modern TBMs are equipped with the “continuous mining” system (CMS), which allows the installation of the segmental lining at the same time as the advancement. During the installation of a segment, the corresponding thrust cylinders must be temporarily retracted while the remaining pistons remain actively pushing on the rest of the ring; the TBM’s PLC manages the necessary redistribution of pressure in the active cylinders, to keep the centre of the thrust unchanged during the advancement of the TBM, as showed in Figure 4.

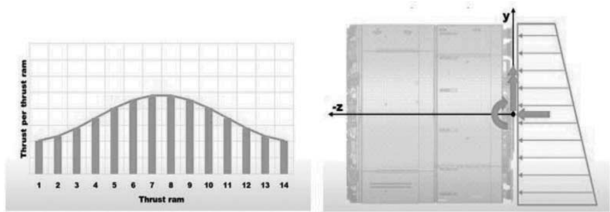

Figure 4. Redistribution of pressure in the active cylinders.

Another important tool is the “sliding continuous conveyor” system (SCC) and service extension. This solution consists of the installation of a single sliding belt of 1000 m in length with a bridge function between the machine belt and the ordinary tunnel belt, capable of advancing autonomously while following the TBM. Finally, it’s necessary to reduce as much as possible the maintenance interventions. This can be achieved by increasing the cutter positions of the cutterhead, adopting anti-wear protections on the cutterhead, on the edge of the shield and on the screw. It may be useful to install two high-pressure water injections of 300 bar (10 l/s) at the face to break up the rock-mass and foam injection points to lubricate the screw conveyor. With reference to the equipment for backfilling injection at the back of the segments, it could be useful to adopt a greater number of injection lines in the tail shield (10-12), with additional lines installed as spares. These can provide an automatic high-pressure washing system that will be activated on each line at the end of each excavation stroke of the TBM, to avoid blockage of the lines. The main TBM mechanical parts must be designed with a view to facilitating replacements and maintenance interventions.

5 NUMERICAL AXIAL-SYMMETRIC MODELLING

The interaction analysis between the rock-mass and the TBM shield during the excavation can be conveniently carried out with an axisymmetric model created with the software FLAC 2D ver. 8.0 by

Itasca. The result in terms of pressure on the shield can be considered as an upper limit because the axisymmetric model is not gravity oriented and the convergence along the tunnel boundary is the same on the whole circumference. In the analyses presented in the following, the mesh has a width of 50m and a height of 125m, to avoid boundary effects during the calculations of the stresses in the rock-mass; the mesh is composed of 25000 square elements, sized 0.5m. Excluding the boundary of the axisymmetric model, the geostatic load is applied on the other three boundaries from the initial phase of the model (the geostatic step), and, in the first excavation step, the lower boundary is fixed to avoid movements in the longitudinal direction of the excavation, due to the increase of stresses in that direction.

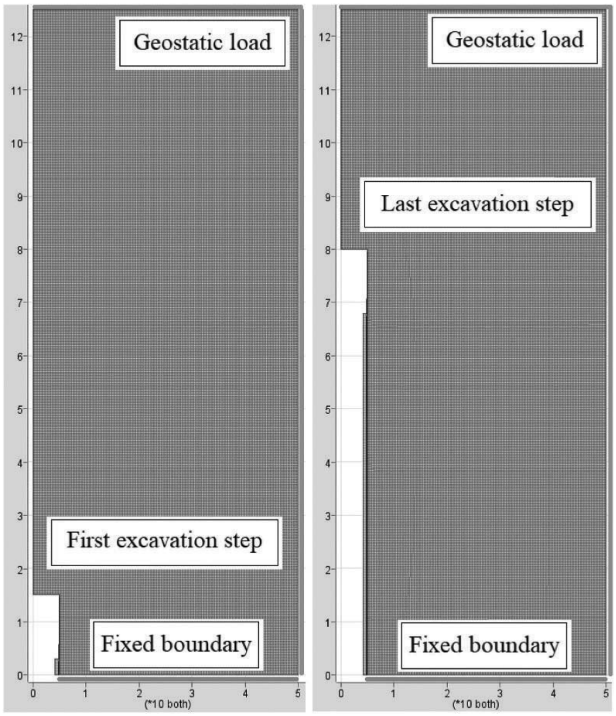

Figure 5. Axisymmetric model.

The model includes excavation steps of 1m each to simulate the advance of the excavation face from 15m to 80m, in the middle of the mesh. In each step, the geometry of the mesh is updated as a function of the calculated displacements, using the “set large” command in the software, to correctly evaluate the progressive contact between the rock-mass and the shield and the tunnel lining.

In each step, following the advance of the excavation face, one additional meter of the TBM shield, of the tunnel lining and of the backfilling is activated. The TBM pressure, which is constant at the face and decreases linearly to null pressure in the first 4 meters of the tunnel, is moved forward 1 meter too.

Mesh elements representing the steel TBM shield and the concrete tunnel lining, concrete class C35/45, are modelled with an Elastic behaviour. For the backfilling, the Mohr-Coulomb criterion is applied. In Table 1, properties of the structural parts are reported. Mesh elements of the rock-mass and of the backfilling are fully connected (“attached”), while the interaction between the rock-mass and the shield is managed by an “interface” which is activated only in the case of contact between the two elements.

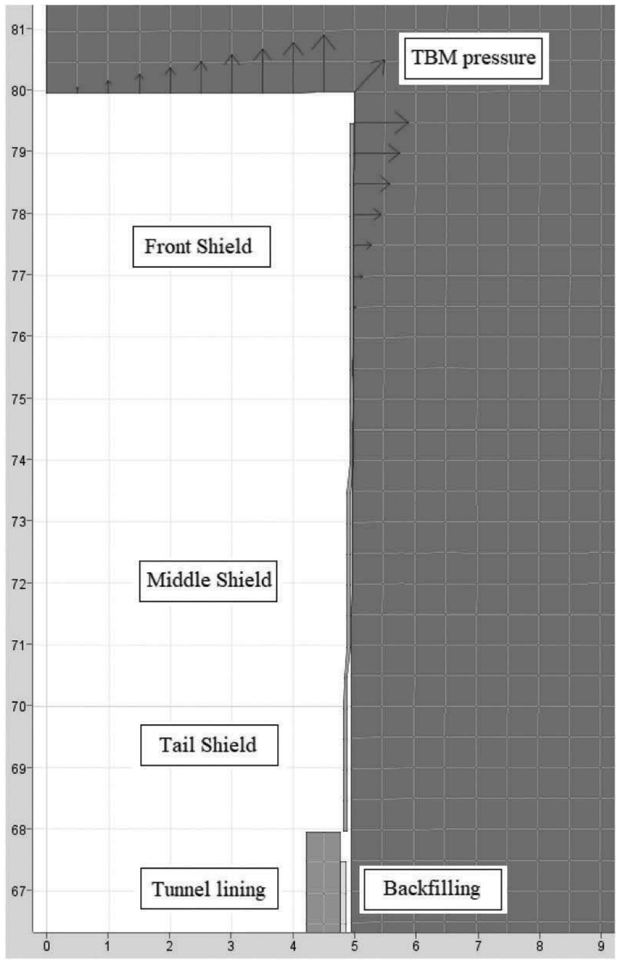

Figure 6. Detail of the FDM model for the high conicity TBM.

Table 1. Properties of the structural components.

Structural part	Thickness [m]	γ [kN/m^3]	E [GPa]	c’ [kPa]	Φ [°]
TBM shield	0.05	78.5	200		
Tunnel lining	0.55	25	34		
Backfilling	≥ 0.1	20	0.5	0	25

The considered TBM shield has a typical length of 12 m and the nominal excavation diameter is equal to 10 m. Two types of TBM shapes are evaluated: one with “low conicity” (40 mm), for the excavation in good rock, and one with “high conicity” (130 mm), where relevant convergence is expected during excavation at the tunnel boundary (see Table 2). The evaluation of how far from the front face is the contact zone between the rock-mass and the shield and its extension is surely more reliable with respect to what can be found with a simplified closed-form solution, such as the one used by Panet (1982). A geostatic isotropic pressure of 5.125 MPa is initialised in this application, for each of the cases studied below, considering a tunnel overburden of 200 m and a rock-mass unit weight γ equal to 25kN/m^3. Three geomechanics contexts are analysed, with a different response of the core-face, as classified by the ADECO-RS approach (Figure 7):

A – good rock, with "stable" behaviour
B – fault zone with "short term stable" behaviour
C – weak rock with "unstable" behaviour.

In the geomechanics context A, a TBM with a low conicity (Model 1) is compared with a high conicity TBM (Model 2), varying the TBM pressure from 1 bar (a) to 3 bars (b) and up to 5 bars (c).

Table 2. Geometry of the TBM.

TBM type	Low conicity	High conicity
Cutterhead		
R_{nom} [m]	5	5
ϕ_{nom} [m]	10	10
TBM Front shield		
R [m]	4.98	4.97
ϕ [m]	9.96	9.94
L [m]	6	6
gap from Cutterhead	0.02	0.03
TBM Middle shield		
R [m]	4.96	4.92
ϕ [m]	9.92	9.84
L [m]	3	3
gap from Front shield (m)	0.02	0.05
TBM Tail shield		
R [m]	4.96	4.87
ϕ [m]	9.92	9.74
L [m]	3	3
gap from Middle shield	0	0.05
gap from Cutterhead (m)	**0.04**	**0.13**
Tunnel lining		
R_{int} [m]	4.2	4.2
ϕ_{int} [m]	8.4	8.4
Thickness [m]	0.55	0.55
R_{ext} [m]	4.75	4.75
ϕ_{ext} [m]	9.5	9.5
gap from Tail shield (m)	0.21	0.12
gap from Cutterhead (m)	0.25	0.25

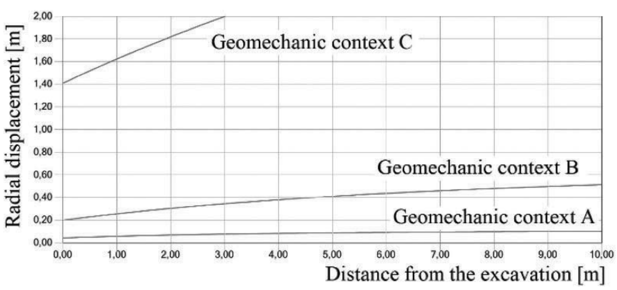

Figure 7. Radial tunnel displacement along the shield.

The analyses' results are reported in Figures 8 to 11, representing:

– Radial displacement along the tunnel,
– Deconfinement rate, equal to the ratio between radial stresses at the tunnel boundary and geostatic pressure,
– Pressure along the interface between medium and shield, and
– Axial – circumferential stress in the TBM shield.

It can be noticed that different levels of pressure, always less than 10% of the geostatic load, have a slight impact on the tunnel convergence at the core-face and at the tunnel boundary. With the high conicity TBM, bigger radial displacements are allowed and a lower pressure acts on the shield, even avoiding the contact with the middle and tail shield (Figure 10), thus reducing both the friction force on the shield and the thrust force required by the TBM to advance.

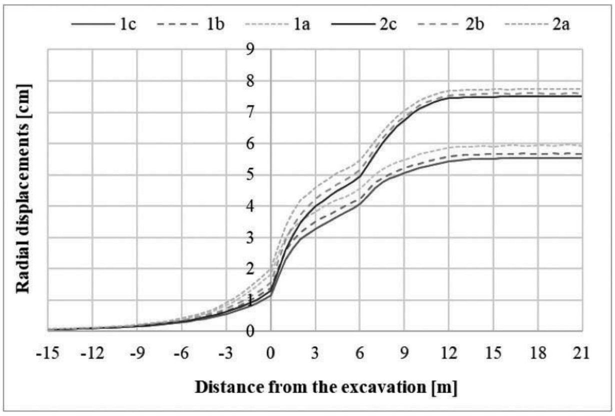

Figure 8. Geo-context A – Models 1 and 2 - Radial displacement.

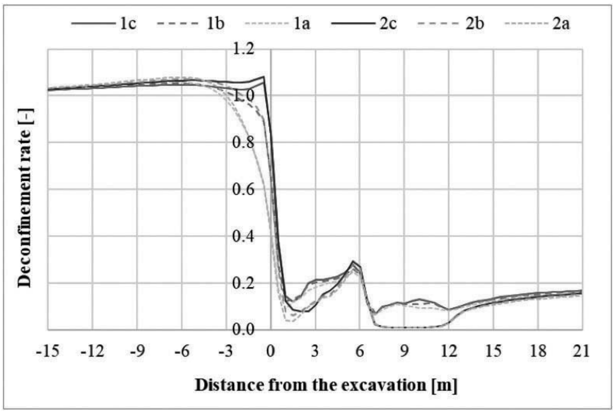

Figure 9. Geo-context A – Models 1 and 2 – Deconfinement rate.

In Model 1, preconvergence at the tunnel face is around 1.5 cm and along the shield the entire gap of 4 cm, between the cutter-head and tail shield, is used. In Model 2, preconvergence at the tunnel face is around 1.5-2.0 cm and along the shield only 6 cm of the available 13 cm is used (Figure 8).

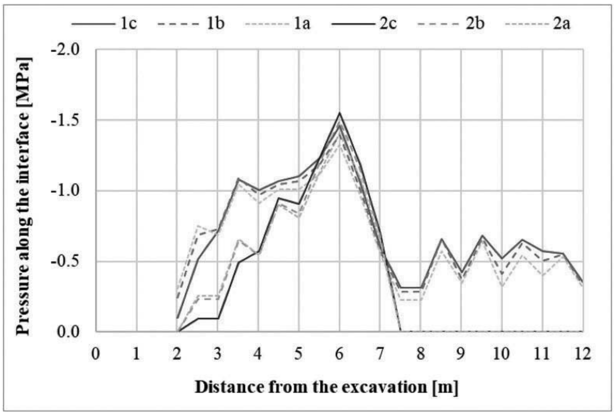

Figure 10. Geo-context A – Models 1 and 2 – Pressure along interface.

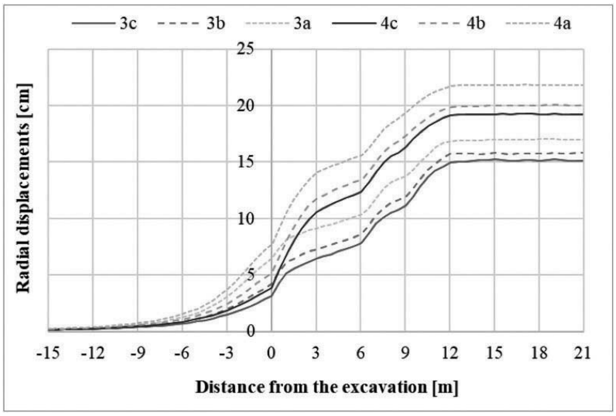

Figure 12. Geo-context B – Models 3 and 4 - Radial displacement.

In the geomechanics context B, the high conicity TBM (Model 3) is compared with the same geometry but with the activation of a copy-cutter (Model 4), which increases by 5 cm the excavation diameter. The copy-cutter, allowing higher tunnel convergence, significantly reduces the contact zone between the soil and the shield, maintaining the average pressure along the interface around 1.5MPa (Figure 14), which means a maximum axial stress of about 150MPa at the end of the front shield and lower stress in the tail shield. Considering that the tail is the weakest part of the shield, it is difficult to put structural reinforcement in the inner part, where segments are to be placed (Figure 15). Even in this case, different front-face pressures have a small impact on the tunnel convergence and on the TBM shield, especially in Model 3.

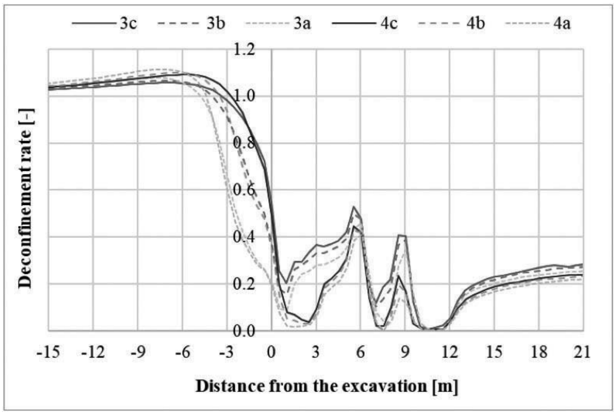

Figure 13. Geo-context B – Models 3 and 4 – Deconfinement rate.

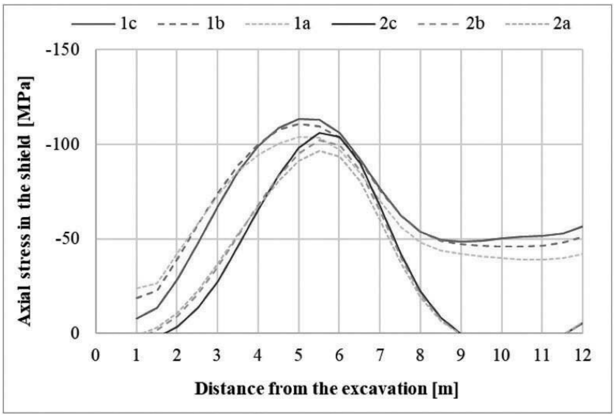

Figure 11. Geo-context A – Models 1 and 2 – Axial stress in the shield.

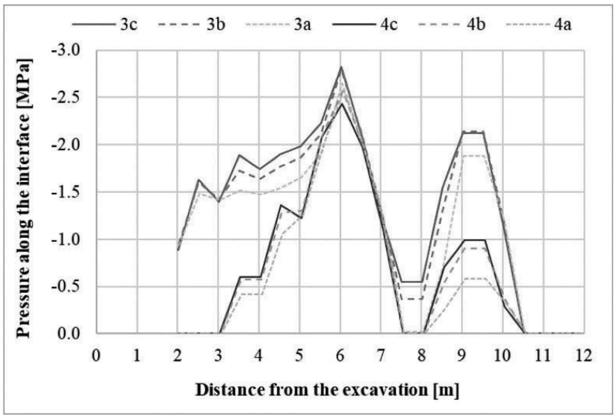

Figure 14. Geo-context B – Models 3 and 4 – Pressure along interface.

Finally, in the geomechanics context C, the comparison is between the high conicity TBM (Model 5) and the same geometry but with an excavation diameter increase of 15 cm (Model 6), due to overcutting. With low pressure at the tunnel face (case a, Figure 16), the support given by the soil ahead the excavation face tends to be null causing a significant increase in the preconvergence at the tunnel face and subsequent tunnel convergence, with a higher risk of instability of the excavation.

The increase of the excavation diameter has a positive impact, reducing the contact zone between the soil and the shield (Figures 18 and 19). The contact zone has to be adequately evaluated to assure the feasibility of the excavation, even in terms of stresses in the shield and TBM thrust needed to advance.

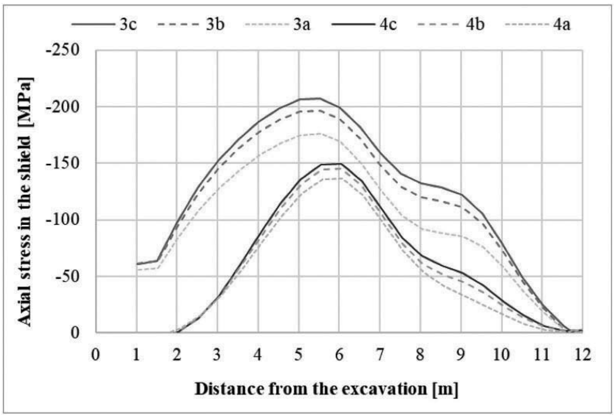

Figure 15. Geo-context B – Models 3 and 4 – Axial stress in the shield.

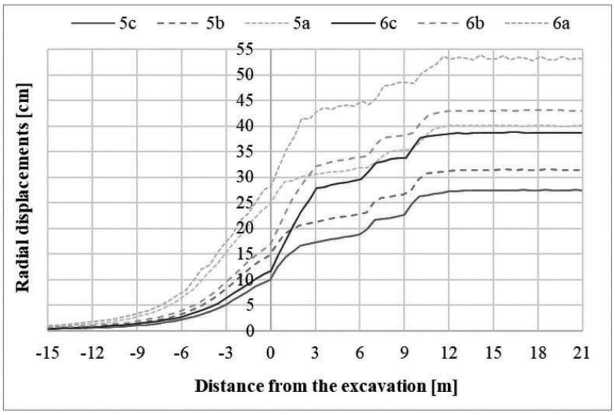

Figure 16. Geo-context C – Models 5 and 6 - Radial displacement.

6 GUIDELINES FOR THE CONSTRUCTION STAGE

Once the risks have been defined and the mitigation measures have been identified for the TBM project, it is also important to define “guidelines” for the management of the TBM advance and to calibrate the interventions during construction. The main design inputs, such as the chamber pressure at the face and the actual excavation diameter, can be varied during advancement and adjusted according to the evidence collected. Other parameters to be collected during advancement in order to verify the processes are being carried out efficiently, are the pressures on the shields, the annular gaps around the shield, the thrust values and the volumes of backfilling injected.

It should be noted that to record the annular gap around the shields and, in the event of contact, the acting ground pressures, it is necessary to equip the shields with fonti-meters and pressure cells. Generally, three control sections are arranged, one in the central position of each shield sector; 3 instruments are provided for each section, corresponding to the crown and the lateral sidewalls. The TBM control system allows the systematic recording of the pressures at different levels in the excavation chamber, the total TBM thrust, and the volumes of back-filling

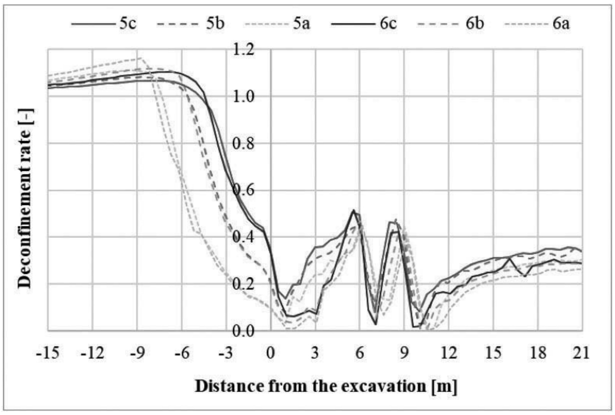

Figure 17. Geo-context C – Models 5 and 6 – Deconfinement rate.

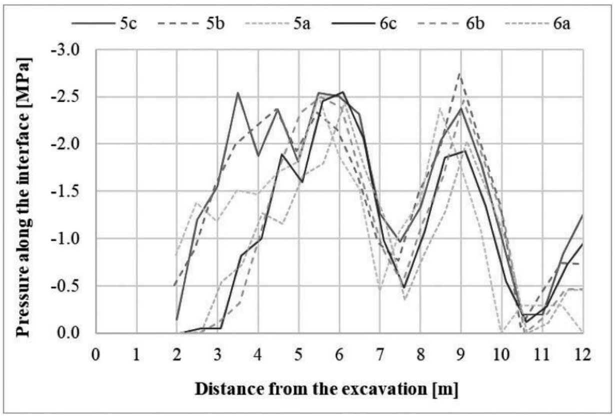

Figure 18. Geo-context C – Models 5 and 6 – Pressure along interface.

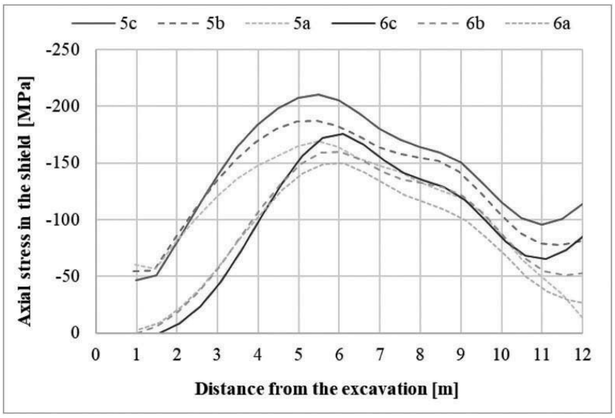

Figure 19. Geo-context C – Models 5 and 6 – Axial stress in the shield.

injected for each advance stroke of the TBM. Furthermore, to ensure that the annular gap has been perfectly filled, the backfilling will be verified continuously by means of Pulse-Echo ultrasonic tomography based on the reflection of short pulses of elastic waves at the extrados of the tunnel lining segments, and by adopting the Ground Penetrating Radar (GPR) technique.

For each control parameter, a reference value (design value) and a range of possible excursions must be set. The limits of this range represent threshold, attention and alarm values. For some parameters which refer to the most critical risks, such as for example the gap at the intermediate shield or the pressure on the tail shields to control the jamming risk, it is advisable to set a maximum limit, so as to implement urgent corrective actions in its proximity; warning and alarm values can be suggested at 70% and 90% respectively of the set value. The following scenarios can be identified:

1. If the values of the measured control parameters are consistent with the design value, within a minimum expected variability (+/- 10%), it's possible to proceed with the project operating parameters.
2. If the values of the control parameters are lower than expected, for example fewer thrusts, less convergence of the excavation profile and, therefore, less pressure on the shields, it will be possible to reduce the operating parameters (reduction of overcutting, pressure values at the front, etc.).
3. Vice-versa, if the values of the control parameters are greater than expected, or if there is a tendency towards greater difficulty in TBM advance, with thrust values higher than expected, higher ground pressure on the shields, it will be necessary to increase the operating parameters (increase in the excavation diameter with insertion of overcutting and/or copy-cutters, increase the pressure at the face, etc.).

Any change in the operating parameters must arise from an analysis of the monitoring data considering the trend over time on a significant number of readings and data collections. The analysis must therefore be conducted considering at least the values deriving from 2-3 strokes, before leading to variations during construction. If the planned actions are not able to resolve the problems, it's necessary to implement further measures to mitigate the residual risk, especially with reference to the risk of high pressures acting on the shields and therefore trapping the TBM. Some useful solutions to keep in mind relate to the use of the "clay-shock" mixture or hydro-demolition. To apply both solutions it is necessary to leave provisions in the shields for additional injectors. In the first case, a mud containing bentonite, fillers and additives is injected which has the property, when activated with a component B, of rapidly thickening so as to reduce, even partially, the convergences of the soil, and drastically reduce the friction of the shields facilitating the start/restart of excavation. In the second case, the hydro-demolition of the ground around the shields is carried out through the nozzles, to unlock the shields and allow the TBM to restart.

7 CONCLUSION

In this paper, a methodological approach to examine TBM excavation, especially in squeezing and complex geological contexts, is presented, to define the correct technical requirement for the TBM to be used. Once the geological and hydrogeological model has been defined, a risk assessment is necessary to address the critical issues to be carefully investigated in the design stage. The main parameters to be considered are the pressure to maintain in the excavation chamber and the modulation of the TBM diameter during excavation. Indeed, the nominal TBM diameter can be increased by overcutting and using copy-cutter systems, so as to calibrate the gap between the shields and the surrounding rockmass and to control the ground pressure on the tail shield. These pressures and the correlated friction forces are responsible for the most important risk related to ovalization and/or deformations of the shield, and trapping the TBM. A proposal of using a numerical axial-symmetric model is presented, through which an understanding of the behaviour of the TBM excavation is gained and used to define the design aspects in detail. The examples presented allow focus to be placed on how different excavation radii can affect the static of the shields.

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