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A parametric 3D advanced numerical model for Single Shield TBM simulations

A. Marchioni
Systra S.p.A., Rome, Italy (Former Pini Group)
amarchioni@systra.com

F. Mangaretto & V. Floria
ARX, Turin, Italy

Abstract

Three-dimensional numerical analyses allow to simulate Tunnel Boring Machine (TBM) advancement and its operations. Despite the recent progress of modelling techniques, significant time and efforts are still needed to properly set up the model, calibrate the mesh density, and develop routines for simulating tunnel excavation and the ground-shield-lining interaction. Therefore, an appropriate simulation tool in the form of a three-dimensional advanced numerical model is required for TBM projects.

This paper presents the results obtained through a parametric model developed using the Finite Difference Method computer code FLAC3D employing an innovative numerical approach to simulate the gap between the ground and the shield. Shell-type structural elements, available in the library of the software and generally used for other engineering problems, have been leveraged to simulate the interaction between the ground, the TBM shield and the segmental lining. The current case study refers to a numerical exercise performed under axisymmetric conditions already presented in the literature.

The comparison of the results demonstrates the capability of our parametric model to consider the main factors governing the ground-shield-lining interaction for a Single Shield TBM. The excellent agreement of the results also suggests the potential use of the same model for real projects, despite the anisotropy of in-situ stress and ground conditions.

Keywords

Mechanised Tunnelling, Ground-shield interaction, TBM simulation, Squeezing ground, FDM model

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1 Introduction

Nowadays, mechanized tunnelling is considered the most appropriate excavation method for long drives due to its high advance rate, and enhanced operating conditions. Although tunnelling is a three-dimensional problem (3D), in the current design practice the ground-shield-lining interaction is addressed using two-dimensional (2D) approaches. The latter are useful for preliminary estimations of ground displacements and loads on the supports but do not provide a complete understanding of the out-of-plane arching effect and spatial stress redistribution associated with the advancing tunnel face (Lombardi 1973). Additionally, the actual evolution of the stress state during the excavation cannot be captured using plane strain conditions (Cantieni and Anagnostou 2009). When shielded TBMs are involved, further assumptions are also required to model the main features of the TBM and the distance of interaction (Barla et al., 2014).

Several authors have emphasized that accurate simulation of the ground-shield-lining interaction must consider: i) the TBM geometry, including the cutterhead and shield conicity, ii) backfilling, grout hardening, and injection pressure, iii) face support pressure, and iv) the structural system of the segmental lining (Barla et al. 2011; Ramoni and Anagnostou 2010; Dias et al. 2009; Schiena et al. 2020). In recent years, many researchers have focused on detailed analyses of TBM-rock mass interaction (Barla 2018), and fully 3D numerical models have been developed to account for all the major factors influencing the interaction by introducing different numerical strategies.

For instance, a 3D finite element parametric model was developed at the Politecnico di Torino to investigate the feasibility of a Double Shield TBM for the excavation of the Lyon-Turin Base Tunnel (Zaho et al. 2012). The numerical formulation is based on the small-strain assumption and the gap between the ground and the extrados of the shield is modelled using special interface elements with zero elastic stiffness. The TBM advancement is simulated using the step-by-step method. A distributed pressure over the gripper shoes is applied to the tunnel wall to model TBM bracing, and edge pressure is applied to the last installed segmental ring to simulate the push rams. The shield and the lining are modelled as plate elements, while the backfilling is modelled using continuum elements with an elastic modulus that increases along the tunnel to simulate the hardening process.

Other researchers have proposed the use of large-strain formulations, available in most of the commercial codes, to update the deformed grid nodes at the end of each calculation step. Graziani et al. 2007 developed a Finite Difference Model (FDM) applicable to different tunnel lining and TBM types. To allow contact between the deforming ground and the shield, an interface is modelled along the extrados of the shield. The shield is simulated using continuum elements, while the lining is modelled with elastic shell elements linked to the excavation boundary via special spring elements. To consider the backfilling compressibility, the stiffness of these elements is calibrated based on the oedometer modulus and the thickness of the annular grout. In a similar framework, Hasanpour et al. 2014 presented a large-strain FDM, which also implements the step-by-step method for the excavation and TBM advancement. This model can be adapted to various rock masses and TBM types. In this case, the shield, segmental lining and backfilling are modelled with continuum elements. The contact between shield and rock mass has been modelled by using interface elements on both tunnel and shield boundaries. To avoid the overlap of the grid meshes a routine code (FISH language Itasca) was developed to control the displacements against the overcut at each calculation step. Interfaces elements are also placed between the tunnel perimeter and the grouting as well between the grouting and the lining. Increasing stiffness of the backfilling is assumed to model the hardening of the grout along the tunnel. De Lillis et al. 2018 presented another example of an advanced 3D FDM model. In this model, the TBM shield, lining, and backfilling are modelled with continuum elements, and the stiffness of the grout is increased along the tunnel according to a time-dependent hardening rule. The pushing rams are simulated as a distributed pressure, while a support pressure is applied at the tunnel face throughout the entire simulation.

Due to the relevant numerical difficulties in simulating the radial gap and the closure of the ground on the shield, other authors introduced simplified assumptions. For instance, Wittke et al. 2007 assumed a priori the closure of the gap 4 m behind the tunnel face; Floria et al. 2008 considered the length of the shield as unsupported span and applying a radial pressure; Tyrer et al. 2023 simulated all the shield attached to the tunnel perimeter. Nevertheless, the proper assessment of the distance from the tunnel face where the interaction occurs is fundamental for the simulation of the ground-shield-lining interaction (Marchioni and Di Carlo 2023). Graziani et al. 2007, on the base of the comparison of the results obtained with and without modelling the TBM shield, showed the pre-support effect of the TBM shields in squeezing ground conditions lead to significant increase of load on the segmental lining.

Assuming isotropic mechanical ground behaviour and isotropic lithostatic state of stress, extensive 3D parametric studies were performed by Ramoni and Anagnostou 2011 in axisymmetric conditions. Even assuming axisymmetric conditions the simulation of the gap closure is still difficult to be modelled. In fact, operating under small-strain assumptions, the latter authors developed an algorithm aimed to apply mixed boundary conditions to the excavation profile. An alternative numerical procedure was proposed by Marchioni 2021. It is based on the existing relationship between the overcut and the interaction distance and it allows to overcome the difficulties in simulating the closure of the radial gap between the ground and the shield. The procedure has been recently refined by Marchioni and Di Carlo 2023 to also consider the length of the TBM shield and the different stiffness of the structures (TBM shield and lining) and validated in Marchioni et al. 2024.

This paper presents the validation of a fully 3D advanced numerical model by comparing the results of a case study with the data presented in Ramoni and Anagnostou 2011 and Marchioni et al. 2024. The model is set up in FLAC3D and routine code has been developed to perform parametric studies for different ground conditions, in-situ stress and TBM operations (i.e., grouting injection, support pressure at the face and around the shield). The interaction between the ground, the shield and the lining are accurately assessed by using liner elements that are shell-type structural elements available in the library of the software. These formulations allow to consider the structural response of the liner elements and the gap between the ground and the shield.

2 Case study

The case study addressed in this paper (Fig. 1) refers to the numerical example presented in Ramoni and Anagnostou 2011 and reutilised in Marchioni et al. 2024. This application involves full axial-symmetric analyses of a cylindrical tunnel through a homogenous and isotropic ground subjected to an isotropic lithostatic state of stress (S=10MPa). It consists of a tunnel of 5 m boring radius (R=5 m) excavated with a TBM single shield with a shield length L=10 m and without face support pressure. The ground behaviour is assumed elastoplastic with a Mohr-Coulomb strength criterion defined by the Young Modulus (E=1000 MPa), Poisson ratio (ν=0.2), friction angle (φ=25 °), cohesion (c=956 kPa) and dilatancy (ψ=5°). The annular gap is supposed to be backfilled just behind the tail shield. The stiffness of the shield and of the segmental lining are K_S=1008 MPa and K_L=360 MPa, respectively. Three different values of the overcut (ΔR = 50, 100, 150 mm) are considered.

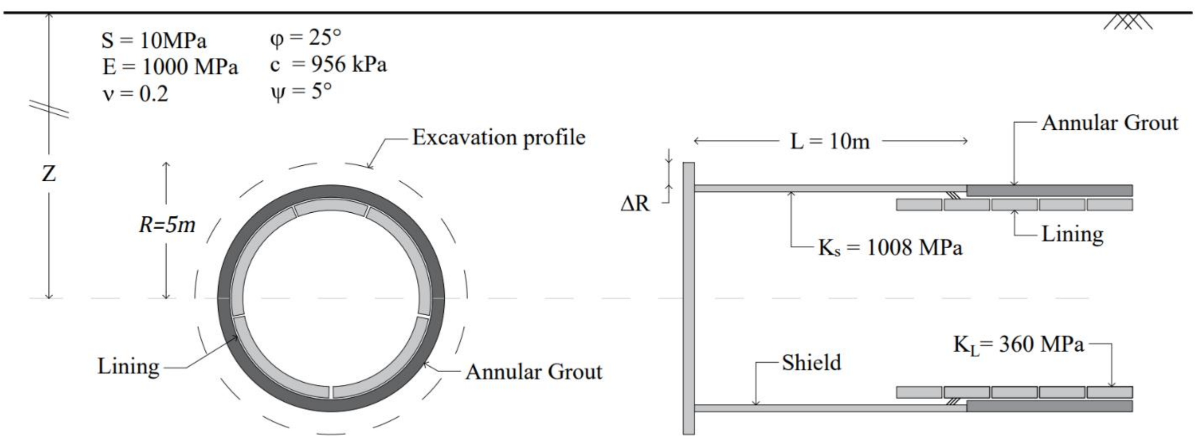

Fig. 1 Scheme of the application example (Marchioni, 2025).

3 Parametric model

A parametric model was developed to account for the main factors governing the ground-shield-lining interaction in a Single Shield TBM using the FDM software code FLAC3D (Itasca 2024). The text-based file represents a design tool in the form of a three-dimensional advanced numerical model to be used for challenging TBM problems where is paramount to accurately assess the closure of the ground on the shield.

Fig. 2 illustrates the model domain, mesh density, and boundary conditions. The size of the ground elements and the model extent are scaled proportionally to the excavation radius to ensure that the quality of the results remains independent of the tunnel dimensions. Due to axisymmetric conditions, only a quarter of the tunnel was simulated to reduce computational time. Two primitive-based grids were used to enable a smooth transition from the circular to linear boundary shape. The tunnel is surrounded by a cylindrical-shell mesh (green block), followed by a radial-cylinder mesh (red block).

It is important noticing that the tunnel itself is modelled by using a cylindrical-shell mesh, where the central portion of the tunnel is excluded from the initialization to avoid the generation of tiny ground elements. This assumption certainly introduces minor errors reducing computational time. Indeed, according to the Manual Code (Itasca 2024), the characteristic time (t_c^m) is proportional to the characteristic length (L_c) of the continuum elements (i.e., the average dimension of the zones). The following formula can be used to derive the approximate time scales for *FLAC3D* analyses:

$$t_c^m = \sqrt{\frac{\rho}{K + 4/3\, G}} * L_c \tag{1}$$

Where ρ is the mass density, K is bulk modulus and G is the shear modulus.

Proper boundary conditions were set to simulate axisymmetric conditions. Normal displacements were restrained along all surfaces except the top and right boundaries, where a tension equal to the initial in-situ stress is applied. The extent of the model was determined through parametric studies to minimize the effects of the boundary conditions while maintaining manageable computational time.

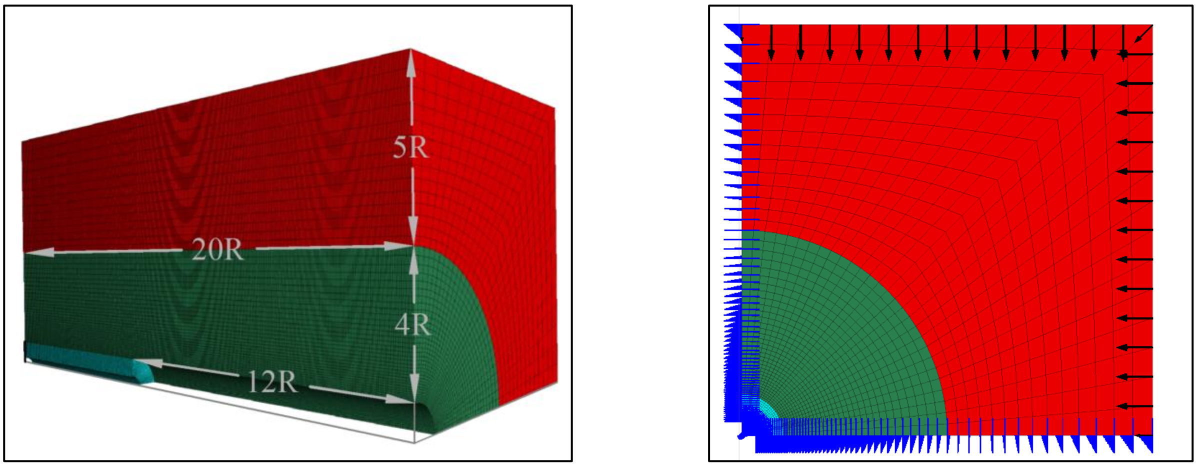

Fig. 2 Model details and mesh.

Excavation and TBM advancement are simulated using the step-by-step method, with each analysis stage deactivating a slice of ground elements while simultaneously installing a new shield and lining ring strip. This approach, utilizing a longitudinal discretization of 0.05R, accurately replicates the continuous excavation process performed by a TBM. The total excavation length is 12R, involving 240 numerical stages. During the initial 15 excavation stages, a radial pressure is applied to the tunnel wall to support the excavation and to minimize the unbalanced forces. This pressure, equal to the in-situ stress at the first excavation round, is progressively reduced up to zero after 15 stages.

The numerical formulation is based on the small-strain assumption. The shield and lining are modelled using liner-shell elements, a type of shell structural element available in the software code library. Their formulation allows to capture both the structural response of the shell elements (shield and lining) and their interface behaviour with the model grid. Such elements are commonly used in engineering to simulate ground-supports interaction in other applications, such as shotcrete-lined tunnels or retaining walls (Itasca 2024), while in this case we leveraged these features to simulate the overcut of the TBM and the backfilling injection behind the shield.

Fig. 3 shows the normal stress behaviour of the interface versus the relative normal displacement of the shield (left) and the lining (right). The interface behaviour is represented numerically at each liner node by a linear spring. The normal behaviour is controlled by the tensile strength ($f_t = 0$) and the spring stiffness (K_N), which has been calibrated according to the guidelines provided in the Manual (Itasca 2024). At every excavation stage the grid nodes of the new shield slice are automatically attached to the grid of the ground (Point A in Fig. 3). To model the gap between the ground and the shield, a radial displacement equal to the overcut (Point B in Fig. 3) is applied to the interface of the new liner element slice ($u_n = - \Delta R$).

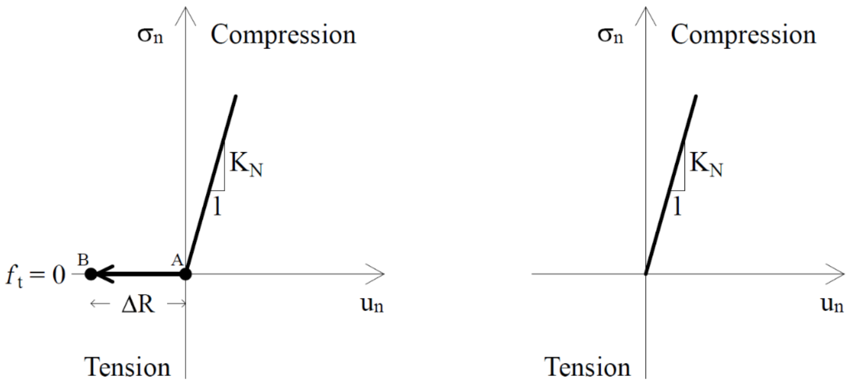

Fig. 3 Normal stress vs relative normal displacement for the shield (left) and for the lining (right).

It is important noticing that, from a numerical perspective, the application of a constant radial displacement induces an unrealistic axial force in the liner. To address this issue, the Young's modulus of the shield is temporarily reduced before applying the displacement and restored afterward before the computation. Following this procedure, the gap can be initialized without inducing tension in the springs and axial forces in the shield at each excavation stage. Finally, the ground is free to move during the model solve without loading the shield until the gap closes (from B to A in Fig. 3). The sequence of the commands and the main features of the model are summarised below using a scaled deformed mesh to better understand the ground displacement and the gap between the shield and the tunnel perimeter:

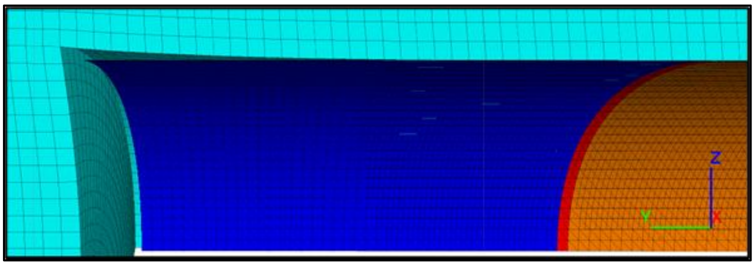

Fig. 4 Reference stage

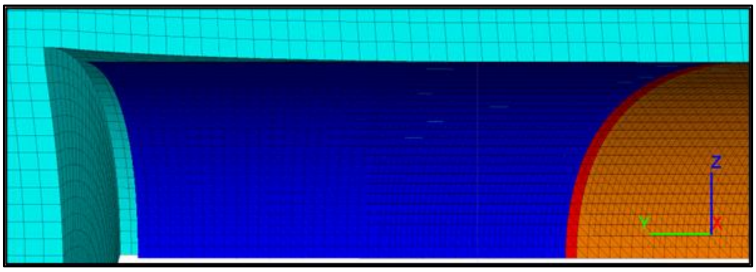

Fig. 5 Removal of one ground slice

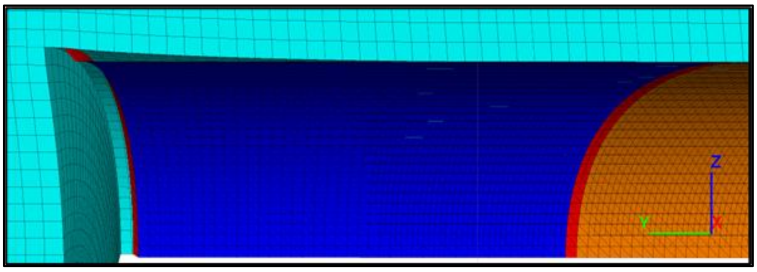

Fig. 6 Installation of a shield liner strip with zero stiffness attached to the ground by default

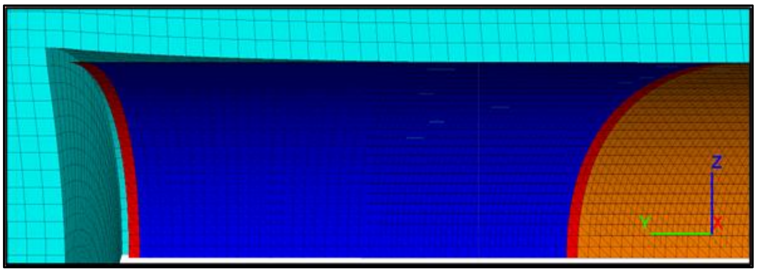

Fig. 7 Initialization of the overcut through application of a radial displacement to the structural nodes

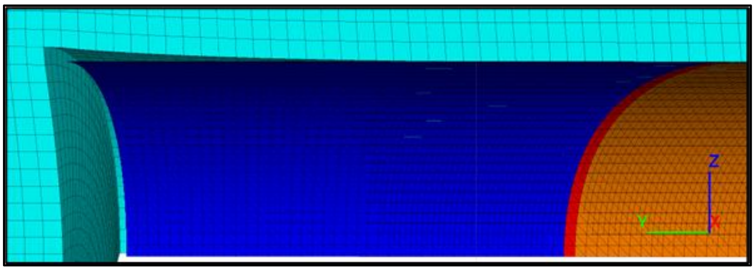

Fig. 8 Restoring of shield stiffness and installation of a segmental lining slice

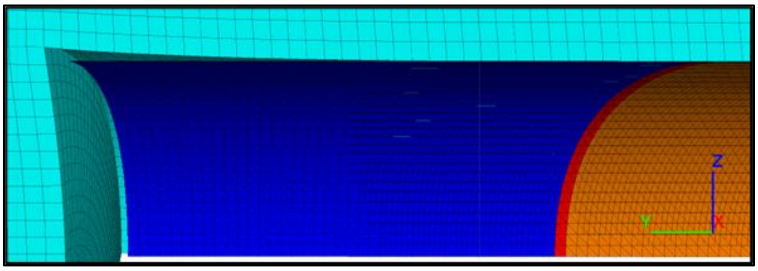

Fig. 9 Model solve

As shown in the previous figures, no liner is installed immediately behind the tunnel face to prevent stress transfer in the longitudinal direction. Additionally, to simulate the physical disconnection between the shield and the lining, a dummy element with no stiffness is introduced between the two liners throughout the simulation (red liner elements). This assumption implicitly accounts for the very low stiffness of the grout just behind the shield. While a pressure boundary could have been introduced to simulate the injection pressure, this is not considered for the purpose of this application. However, the primary grouting is considered by attaching the liner immediately to the ground at a distance from the tunnel face equal to the length of the shield. Although shear resistance could have been easily considered for the interface, it was neglected for this application.

4 Results and validation

The use of the liner-shell elements allowed to initialize the overcut of the TBM that generally demands advanced numerical expertise (Marchioni & Di Carlo, 2023). Fig. 10 shows the deformed mesh and the normal stress contours of the springs assuming 10cm overcut. The results demonstrate the ground is free to move up to a certain distance from the tunnel face (normal stress of the springs is nil). The interaction begins once the total relative displacement of the interface is equal to the overcut and a pressure build up on the shield. Since the gap is an intrinsic property of the liner, the closure of the gap is inherently considered without the need to monitor displacements at each calculation cycle reducing numerical complications.

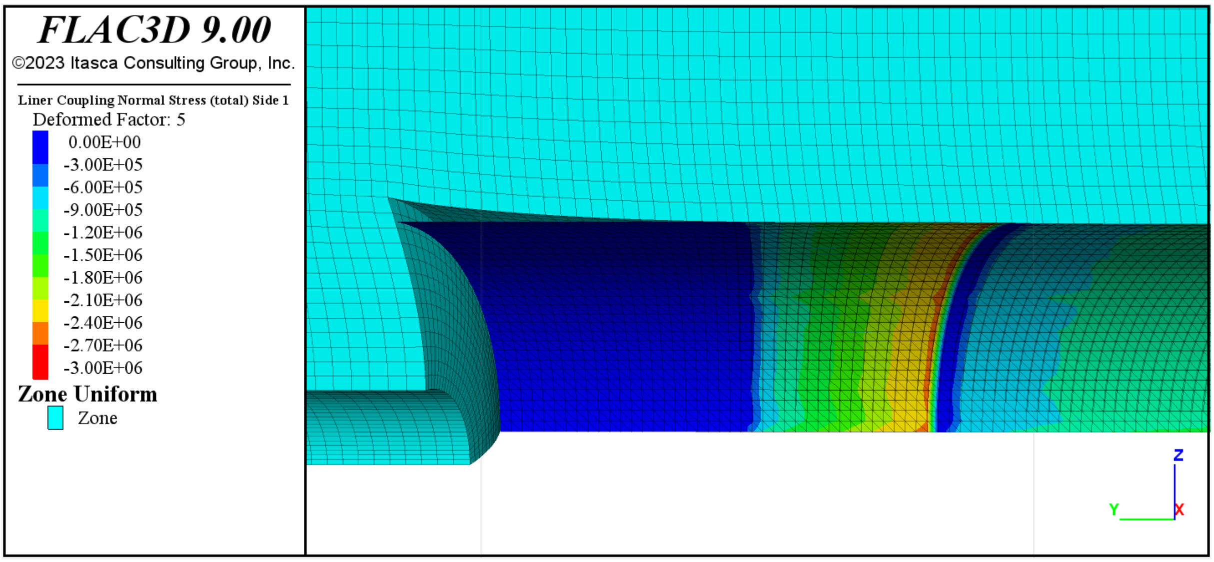

Fig. 10 FLAC3D model (ΔR=10cm) deformed mesh and normal stress contours on the springs

Fig. 11 shows the comparison of the numerical results presented in Ramoni & Anagnostou, 2011, Marchioni et al., 2024 and the outcome of our parametric model in terms of Longitudinal Displacement Profile (LDP) and Longitudinal Pressure Profile (LPP). As shown, the various numerical approaches for simulation of the ground-shield-lining interaction are in excellent agreement.

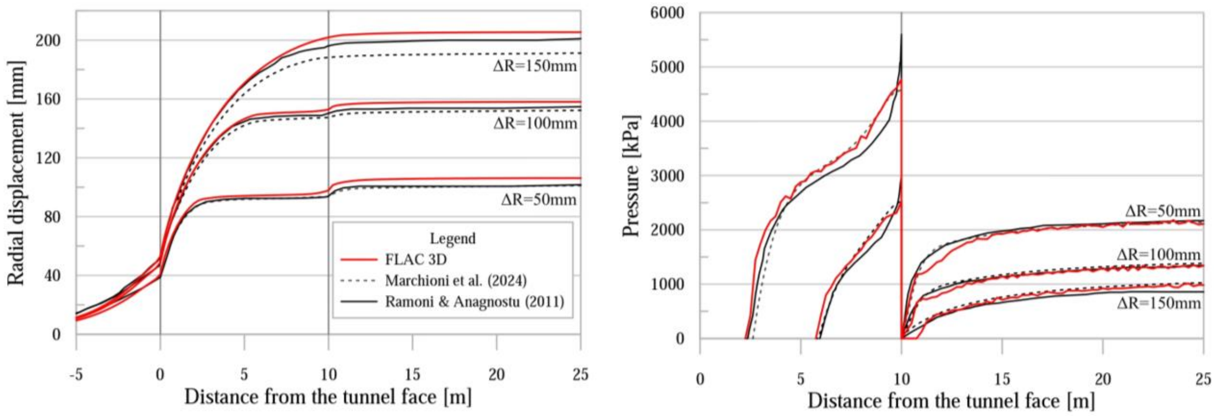

Fig. 11 Comparison of the numerical outcome with data reported in the literature.

Minor differences are observed in terms of displacements, and some numerical noise remains noticeable along the LPP. However, these differences are negligible from a design perspective and can be addressed by increasing the convergence criteria. Additionally, the omission of the central portion of the tunnel and its associated boundary conditions introduced an error that was not quantified in this study. This issue can be resolved by modelling the missing portion, though it would lead to increased computational time.

5 Conclusions

This paper presented a parametric 3D advanced numerical model for simulating Single Shield TBM excavation, developed using FLAC3D. The use of shell-type structural elements, available in the software library, allowed to simulate the radial gap closure and to investigate the ground-shield-lining interaction in a numerical application. The comparison with established results from Ramoni and Anagnostou (2011) and Marchioni et al. (2024) highlights the capabilities of the proposed model to capture the critical features of TBM tunnelling. The excellent agreement among results also demonstrates its potential to address significant limitations of simplified 2D approaches, particularly in challenging ground conditions. Moreover, the routines developed in-house (FISH language Itasca) allow the simulation of non-isotropic initial in-situ stress.

Future enhancements will include the simulation of shield conicity and multiple shield radii. The model will be further refined to consider the variable gap dimensions around the shield, overcoming the current limitation of a constant gap. These advancements will enable the back analysis of void monitoring data around the shield providing insights of ground behaviour and risk of TBM entrapment during the excavation in very short time.

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