SHAPING THE FUTURE OF TUNNELLING
Innovation, Sustainability and Safety

PROCEEDINGS OF THE SOUTHEASTERN EUROPE TUNNELLING CONFERENCE (SETC-2025)

Papers on Technical Subjects Related to Tunnelling and Underground Space Planning and Engineering

EDITED BY
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ITA SERBIA
Serbian Association for
Tunnels and Underground Structures

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SHAPING THE FUTURE OF TUNNELLING

Innovation, Sustainability and Safety

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety contains the contributions presented at the ITA Awards & SETC-2025, held in Belgrade, Serbia, from 1 to 3 October 2025.

The papers cover a wide range of topics in the fields of tunnelling and underground engineering, including:

1. Advanced construction techniques
2. Use of new materials and machinery
3. Geological investigation and prediction
4. Numerical modelling
5. Instrumentation and monitoring/testing and inspection
6. Digital and information technology in design and construction
7. Strategic planning
8. Operational safety
9. Impact of climate change on tunnel infrastructure

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety aims to provide a useful resource for everyone engaged in tunnelling and underground engineering, from students and young researchers to experienced professionals and engineers.

PREFACE

The ITA Tunnelling Awards and the Southeastern Europe Tunnelling Conference (SETC-2025) were held from the 1st to the 3rd of October 2025 in Belgrade, Serbia.

The Serbian Association for Tunnels and Underground Structures (ITA Serbia) was honoured and proud to host this outstanding event of the international tunnelling community. Bringing together hundreds of distinguished experts, researchers, and industry leaders from across the globe, the event served as a dynamic platform for sharing knowledge, presenting innovations, and advancing scientific and technical excellence in the field of tunnelling and underground construction.

Serbia, with Belgrade as its dynamic capital, is experiencing a period of intensive infrastructure development, particularly in the domain of underground construction and sustainable urban mobility. Landmark projects such as the Belgrade Metro, tunnel connections, and urban underground infrastructure systems are transforming the city’s transport network and enhancing its connectivity and sustainability. These projects demonstrate Serbia’s growing expertise in modern tunnelling technologies, geotechnical engineering, and integrated urban planning, positioning Belgrade as a regional hub for innovation and progress in underground construction.

The conference proceedings encompass a diverse range of nine thematic areas, reflecting the multidisciplinary nature and technological depth of modern tunnelling. Topics include advanced construction techniques, the use of new materials and machinery, geological investigation and prediction, numerical modelling, instrumentation, monitoring, testing and inspection, the application of digital and information technologies in design and construction, strategic planning, operational safety, and the impact of climate change on tunnel infrastructure. Together, these themes highlight the conference’s focus on innovation, sustainability, and resilience in underground construction.

It is our sincere expectation that these proceedings will contribute meaningfully to the professional and scientific community, providing valuable insights for engineers, researchers, and decision-makers engaged in the development of underground infrastructure. The knowledge and experiences shared during SETC-2025 aim to foster innovation, collaboration, and sustainable practices, encouraging the continued advancement of tunnelling and underground construction in the years ahead.

Belgrade, October 2025

Prof. Dr Dejan Divac

Chair of the ITA Awards & SETC-2025 Organising and Scientific Committee
President of the ITA Serbia

ACKNOWLEDGEMENT

The Editors would like to thank and express their sincere gratitude to all members of the Scientific Committee for their effort and the valuable time devoted to reviewing the abstracts and manuscripts.

The SETC-2025 Organizing Committee, Scientific Committee, and Editors wish to express their sincere gratitude to the conference sponsors and exhibitors for their generous support and valuable contribution to the success of this Event.

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NUMERICAL MODELLING

Southeastern Europe Tunnelling Conference (SETC-2025)
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Optimal Shield TBM Face Pressure for Surface Settlement Control: Belgrade Metro Case Study

Uroš Mirković[a], Nikola Mirković[a], Slobodan Radovanović[a], Nikola Divac[a], Jovan Šaponjić[a], Nikola Milivojević[a] and Dejan Divac[a]*

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Abstract: Precise control of face pressure is essential in shield TBM tunneling to limit surface settlements and ensure the stability of surrounding structures, particularly in densely built-up urban environments. This study focuses on determining the optimal shield TBM face pressure for the specific geotechnical conditions of Phase 1, Line 1 of the Belgrade Metro, along the section from Bele Vode Station to Trgovačka Station. Three-dimensional numerical models, developed using a staged construction approach, realistically simulate sequential excavation, shield advancement, and segment installation, while incorporating representative ground properties and structural characteristics. A sensitivity analysis is conducted by systematically varying face pressure values to assess their influence on the magnitude and distribution of surface settlements. The results identify an optimal face pressure range that minimizes surface settlements while maintaining excavation stability. These findings provide practical guidance for shield TBM operation in urban tunneling, contributing to more effective settlement control and improved risk mitigation in shallow urban tunnel construction.

Keywords: shield TBM; face pressure; surface settlement; numerical modelling; sensitivity analysis; urban tunneling

1. Introduction

The rapid growth of urban areas has increased the demand for infrastructure solutions that are both sustainable and space-efficient, leading to a greater reliance on underground construction. With surface space becoming increasingly limited, metro and other subsurface transit systems offer an effective way to reduce congestion and meet rising transportation needs. Mechanized tunneling, and in particular the use of shield tunnel boring machines (shield TBMs), enables excavation with minimal disruption to surface activities while maintaining high safety standards in densely populated environments.

In shield TBM tunneling, face pressure is one of the most critical parameters influencing ground stability. Inadequate control of this parameter can cause excessive surface settlements, posing serious risks to buildings, utilities, and other surface infrastructure. Establishing the optimal face pressure is therefore a key requirement for ensuring excavation stability and controlling ground movements, especially in shallow tunnels and geologically variable conditions. In addition, maintaining appropriate confinement pressure around the shield, ensuring face stability, and controlling the annular overcut while continuously backfilling the tail void are recognized as critical factors for effective ground control. Real-time monitoring of these operational parameters is essential for minimizing volume losses and surface settlements, further highlighting their significance in shield TBM tunneling (, 2018). Previous research has investigated settlement mechanisms, employed numerical modeling techniques, and evaluated shield TBM operational parameters to manage ground deformation. Building on this foundation, the present study concentrates on determining the optimal face pressure for shield TBMs under the specific geotechnical and urban conditions of the Belgrade Metro. This is achieved through detailed three-dimensional numerical simulations and sensitivity analysis, applied to the site-specific

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conditions of Phase 1, Line 1, along the section from Bele Vode Station to Trgovačka Station.

Extensive studies have examined how key operational and geotechnical factors influence ground behavior during shield tunneling. Fargnoli et al. (2013) investigated how face pressure, grouting pressure, and machine thrust affect settlement patterns in earth pressure balance (EPB) tunneling through coarse-grained soils, and introduced a translated Gaussian cumulative curve to more accurately describe subsidence trough development. Do et al. (2021) demonstrated that face pressure, grouting pressure, and shield geometry significantly influence settlements, and identified critical parameter values for the Hanoi Metro case. Similarly, Ter-Martirosyan et al. (2022) found a strong correlation between TBM face pressure and increased surface settlement during EPB tunneling in the Moscow Metro. Beghoul and Demagh (2019) used 3D numerical modeling to show that moderate face pressure, shield conicity, and tail grouting pressure can effectively control settlement and prevent face instability in soft ground. Similarly, Kavvadas et al. (2017) confirmed through 3D finite element analysis that while moderate face pressure reduces ground loss, cutterhead overcut and shield geometry significantly affect surface settlement, which can be further minimized with optimized tail grouting.

Advanced numerical models are widely used to simulate TBM-ground interaction and optimize excavation parameters. Ring and Comulada (2018) employed a 3D iterative model to simulate TBM face and grouting pressures, achieving results that closely matched field data from Rio de Janeiro's Line 4 tunneling project. Luo et al. (2023) studied surface settlement from shield tunneling using grey relational analysis and numerical simulations, identifying thrust force, grouting pressure, earth pressure, and soil elastic modulus as the key factors influencing ground deformation during metro tunnel construction. Numerous studies have used numerical modeling to examine factors influencing ground and structural responses during TBM tunneling. Comodromos et al. (2014) employed a 3D numerical model to evaluate ground and building movements during TBM-EPB tunneling, demonstrating the effects of face pressure, gap grouting, and slurry on settlement, with findings validated on the Thessaloniki metro. Alsirawan et al. (2023) created a numerical model to evaluate TBM-induced settlements, highlighting tunnel diameter, eccentricity, and overburden depth as key factors, and proposed a validated equation to predict maximum structural settlement.

Accurate prediction of ground settlement has been a central focus of previous research, aiming to enhance tunnel design and tailor excavation parameters to site and geometric conditions. Kim et al. (2020) found modest statistical correlations between surface settlement and various geotechnical, geometrical, and operational factors, concluding that settlements result from the combined effect of multiple parameters. Zhu and Li (2017) improved settlement prediction by incorporating six operational and soil parameters into a modified gap parameter model, validated on the Xi'an Metro project. Bogusz et al. (2021) investigated the empirical variability of settlement trough parameters in EPB tunneling, highlighting the importance of deriving these values from data under similar ground and operational conditions.

Numerous studies have also examined the influence of soil types and time-dependent behaviors on settlement during mechanized tunneling. Ayasrah et al. (2020) found that slurry shield tunneling in granular soils usually produces maximum transverse settlements within a zone about 2.6 times the tunnel diameter. For sandy soils, Chen et al. (2022) developed a new analytical method that accounts for soil arching to predict subsurface settlement along the tunnel centerline. In clayey soils, Hashimoto et al. (1999) proposed a two-phase deformation model for shield tunneling, separating immediate deformations during shield passage from later, delayed deformations. Building on this, Meng et al. (2022) applied 3D finite element analysis to examine soil disturbance in various clays, identifying characteristic disturbance zones influenced by soil properties and cover-to-depth ratios.

Effective control of shield TBM tunneling-induced settlements requires an integrated approach combining realistic operational parameters, advanced soil models, and numerical methods. When supported by analytical assessment, these tools enable accurate simulation of soil behavior, TBM mechanics, and tunnel lining response, which is essential for safe urban tunneling. The most important factor, however, is ensuring proper control of machine performance through an experienced team supported by a comprehensive monitoring program. Equally important is the selection of an experienced contractor and an appropriate machine type. In this context, the primary goal of this study is to develop and validate a methodology based on staged 3D numerical simulations and sensitivity analysis of face pressure for controlling surface settlements. The proposed framework provides practical guidance for managing shield TBM operations, enhancing ground stability, and minimizing risks to adjacent and overlying structures, streets and underground utilities.

In addition to the introductory Chapter 1, the paper includes four further chapters. Chapter 2 provides a technical overview of Belgrade Metro - Phase 1, Line 1. Chapter 3 presents the proposed methodology, including the development of numerical models and the calculation procedures. Chapter 4 details the results of the numerical simulations and provides a discussion of them. Chapter 5 summarizes the main findings and presents the conclusions.

2. Technical Overview of Belgrade Metro - Phase 1, Line 1

Belgrade, the capital of Serbia, is experiencing rapid urbanization and population growth, which is placing significant strain on its public transportation network. This has underscored the need for a high-capacity and sustainable mass transit system. To address this, the city has initiated the construction of a modern metro as part of its long-term urban mobility plan, starting with Phase 1 of Line 1.

This chapter presents a comprehensive overview of the route alignment, subsurface and geotechnical conditions, tunnel design characteristics, shield TBM specifications, constructability and risk management considerations for Phase 1 of Line 1 of the Belgrade Metro. These aspects form the basis for the numerical modeling and optimization methodology described in the subsequent section.

2.1. Route alignment

Route of Phase 1, Line 1 of the Belgrade Metro covers about 15.4 km, extending from Železnik Station in the south to Pančevački Most Station in the north (Fig. 1). Along the route, there are 15 metro stations and 10 ventilation and evacuation shafts.

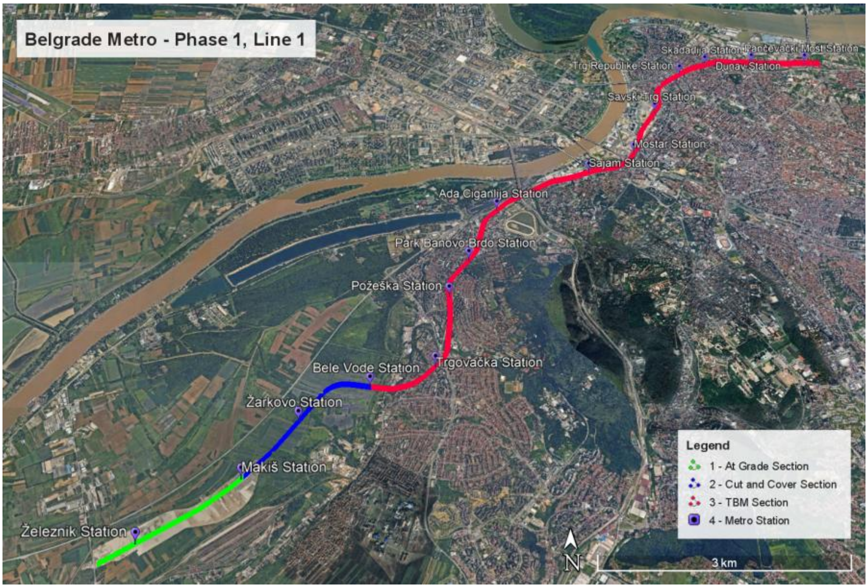


Fig. 1. Route of Phase 1, Line 1 of the Belgrade Metro, showing sections and stations.

Approximately 11.3 km of Phase 1 of Line 1 (from km. 4+174.98 to km. 15+441.15) will be constructed using shield TBMs, divided into southern (Bele Vode Station to Sajam Station) and northern

(Karaburma Launching Shaft to Sajam Station) sections. The remaining sections will use cut and cover (from km. 2+066.45 to km. 4+174.98) and at grade construction (from km. 0+000 to km. 2+066.45).

The geometric parameters of the route alignment are carefully defined to optimize construction and operational performance. A minimum horizontal curve radius of 350 m is adopted on mainline tracks to ensure consistent shield TBM performance during tunnel excavation. The vertical alignment includes a minimum curve radius of 2500 m, while the maximum longitudinal gradient is set at 4.5% (Figure 2).

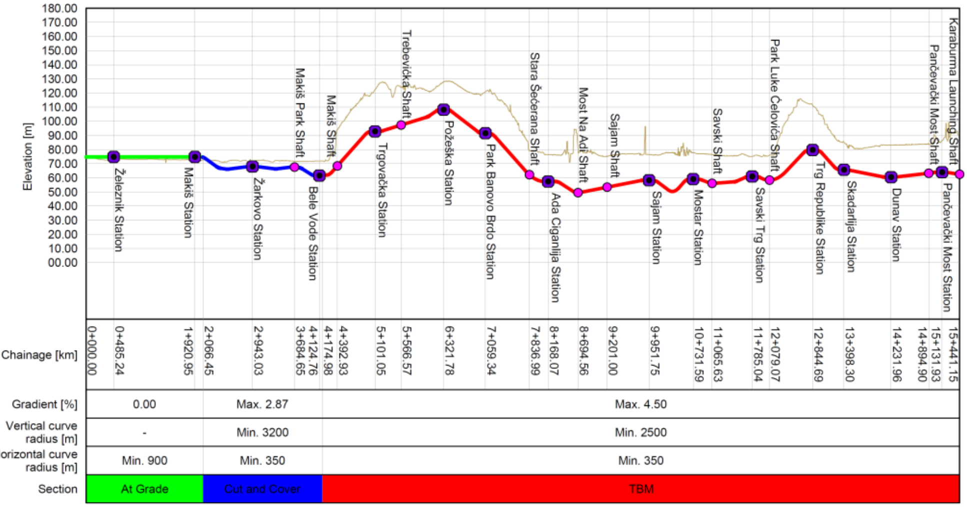


Fig. 2. Vertical alignment of Phase 1, Line 1 of the Belgrade Metro.

2.2. Subsurface and geotechnical conditions

The TBM tunnel alignment traverses a geologically complex urban corridor characterized by alternating soil and rock units, tectonic discontinuities, and variable groundwater conditions, all of which significantly influence tunneling performance.

The shield TBM excavating the southern section begins at Bele Vode Station and advances toward Sajam Station. From Bele Vode to Trgovačka, the alignment includes 150 m of shallow, water-saturated fluvial deposits, then passes through compact interbedded marls, limestones, sandstones, and claystones with weathered rock and cavernous fractures. From Trgovačka to Požeška, it crosses tectonically deformed, highly permeable Cretaceous rocks with karstification and multiple discontinuities. From Požeška to Park Banovo Brdo, geology consists of coarse conglomerates, breccias, and fractured porous karstified limestones. From Park Banovo Brdo to Ada Ciganlija, the tunnel passes layered conglomerates, breccias, fractured reef limestones, and tectonized clays and marls. From Ada Ciganlija to Sajam, it crosses clay deposits, gravelly sands, marls, friable clays, and karstified limestones.

The northern section excavated by the shield TBM starts at Karaburma Launching Shaft and progresses toward Sajam Station. Initial excavation passes through porous, karstified limestones and firm to semi-firm marls. From Pančevački most to Dunav Station, the alignment includes marl-limestone sediments, compressible clays, and silty sands, with fossil landslide deposits near Dunav Station. Between Skadarlija and Savski Trg, the TBM advances through gravelly sands, silty and marly clays, and laminated limestones. From Savski Trg to Mostar and Sajam, it passes fractured karstified limestones, coarse sandstones, gravelly sands, local marls and clays, with faults and stabilized landslide zones.

Based on the geological assessment conducted through investigative works along the metro alignment, distinct macro-zones were identified within the TBM excavation (Figure 3). The analysis focuses on macro-zones B1 and B2, along the section from Bele Vode to Trgovačka Station, which will be constructed first, with the experience used to adapt excavation for the remaining sections.

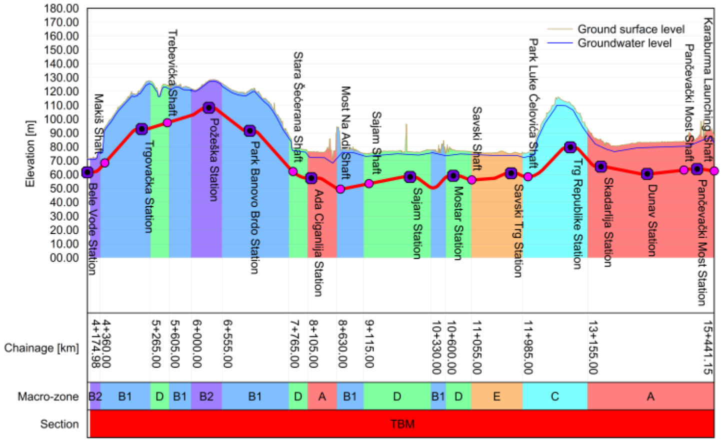
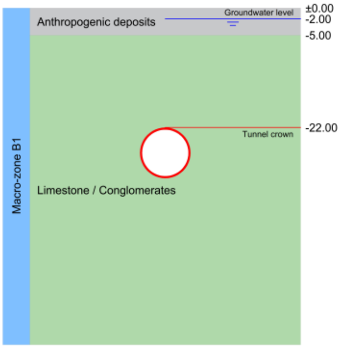


Fig. 3. Macro-zone distribution along the TBM section of Phase 1, Line 1 of the Belgrade Metro.

The stratigraphic distribution and corresponding geotechnical parameters for macro-zone B1 and B2 are presented in Table 1, providing essential data for tunnel design and construction planning.

Table 1. Stratigraphic distribution of ground layers by macro-zones B1 and B2 of Phase 1, Line 1 of the Belgrade Metro, along the section from Bele Vode Station to Trgovačka Station.

<table>
<tr><th>Macro-zone</th><th>Geotechnical parameters</th></tr>
<tr><td>
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<table>
<tr><th>Ground layer</th><th>γ [kN/m³]</th><th>c [kPa]</th><th>ϕ [°]</th><th>E [GPa]</th></tr>
<tr><td>1</td><td>19</td><td>5</td><td>21</td><td>0.003</td></tr>
<tr><td>2</td><td>26</td><td>100</td><td>40</td><td>0.300</td></tr>
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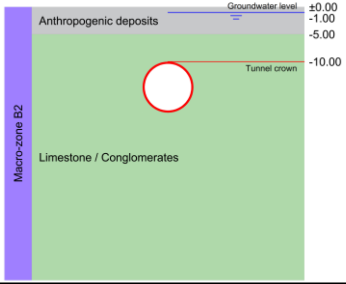
<tr><td>
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<tr><th>Ground layer</th><th>γ [kN/m³]</th><th>c [kPa]</th><th>ϕ [°]</th><th>E [GPa]</th></tr>
<tr><td>1</td><td>19</td><td>5</td><td>21</td><td>0.003</td></tr>
<tr><td>2</td><td>26</td><td>90</td><td>45</td><td>0.600</td></tr>
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2.3. Tunnel design characteristics

The TBM tunnel has a nominal internal diameter of 8.55 m and a minimum functional diameter of 8.35 m. The segmental lining is 40 cm thick, with each tunnel ring consisting of seven segments and having a ring width of 1.6 m. Figure 4 illustrates a typical cross-section of the TBM tunnel, showing the tracks, the structure gauge based on rolling stock clearance requirements, and the arrangement of tunnel equipment.

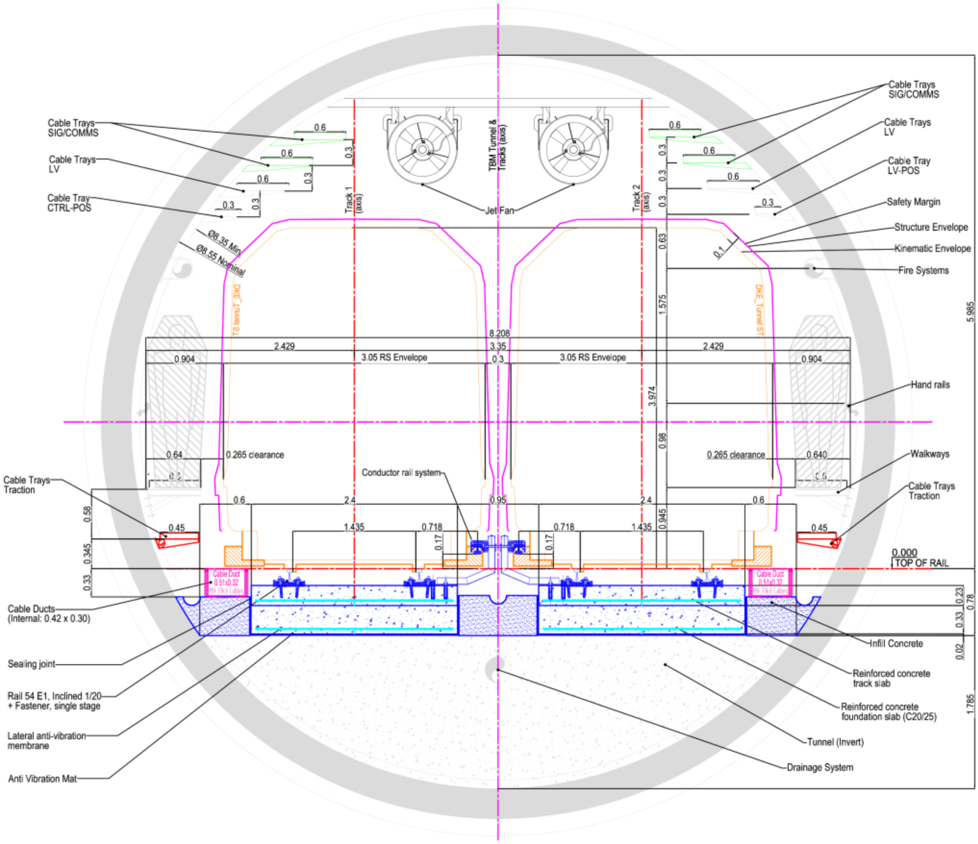


Fig. 4. Typical cross-section of the TBM tunnel on the main line (Alstom, 2025).

2.4. Shield TBM specifications

The TBM used for this project is an EPB machine with a total system length of approximately 100 m, while the main body, which includes the cutterhead and screw conveyor, measures around 12.3 m (Fig. 5). It is engineered to navigate horizontal curves with a minimum turning radius of 300 m and to manage vertical gradients of up to 5.0%, ensuring adaptability to complex tunnel alignments.

The cutterhead features a robust structure designed for balanced load distribution and efficient excavation. With a diameter of 9.6 m, an overall opening rate of 38%, and a center opening rate of 32%, it facilitates effective soil removal and stable face pressure. Its main components are fabricated from high-strength Q355 steel, providing the necessary durability for challenging urban tunneling environments.

The shield structure is optimized for excavation in mixed ground conditions, with the front shield featuring an outer diameter of 9550 mm and a plate thickness of 70 mm, while the tail shield measures 9520 mm in diameter with 60 mm thick plating. The average shield diameter is 9535 mm, and the entire structure is fabricated from high-strength Q355 steel to ensure durability and rigidity. The TBM features a synchronous bi-component grouting system with 8+8 tail shield pipes for precise annular gap filling, alongside a probe drilling and injection unit for targeted pre-excavation grouting, enhancing ground stability in challenging geology.

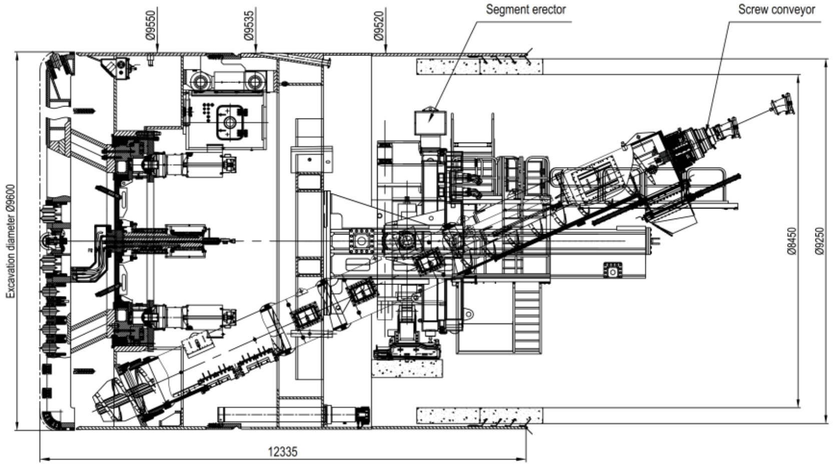


Fig. 5. Longitudinal section of the EPB TBM (main machine only) (CRCHI, 2025).

The propulsion system comprises 38 thrust cylinders (Φ300/260-2600 mm), delivering a maximum thrust force of 94,012 kN at 350 bar and a propulsion speed of up to 80 mm/min. This configuration ensures reliable advance through varying geological formations.

Material removal is handled by a screw conveyor with a 1120 mm internal cylinder diameter and a maximum discharge capacity of 900 m^3/h. The excavated material is then transferred to a belt conveyor system featuring a 1000 mm wide belt and an approximate length of 70 m, enabling spoil transport at rates of up to 1000 m^3/h.

2.5. Constructability and risk management considerations

The construction of Phase 1 of Line 1 of the Belgrade Metro presents a complex engineering challenge due to its integration into an urban environment characterized by diverse subsurface and geological conditions, dense infrastructure, and a high population density. To ensure the project's success, a comprehensive approach to constructability and risk management is essential.

The alignment crosses karstified limestones, fractured rocks, and water-saturated deposits, necessitating thorough geotechnical investigations to inform tunnel design and TBM selection. The southern section of route is relatively favorable for TBM excavation, while the northern section presents greater challenges due to complex geology. Macro-zones B1 and B2 are suitable, whereas other zones are less optimal. In some segments, the overburden is only around 10 m, complicating surface settlement control, while the high groundwater level presents a significant engineering challenge.

For the approximately 11.3 km TBM tunnel section, feasibility is challenged by a minimum horizontal curve radius of 350 m and a maximum longitudinal gradient of 4.5 %. Although the TBM can navigate curves as tight as 300 m and gradients up to 5.0 %, these conditions approach its design limits and may require careful management in demanding sections.

Furthermore, while the conceptual design for the TBM-driven tunnel follows standard practices for double-track metro tunnels, issues related to emergency evacuation, fire safety, and smoke management in a single-bore bi-directional tunnel remain crucial importance. These aspects will need to be carefully addressed through detailed analysis by specialized teams and integrated into the overall tunnel safety and emergency planning framework.

Advanced technologies are key to managing constructability and risks in Phase 1 of Line 1. Digital tools such as Building Information Modeling (BIM) and Geographic Information Systems (GIS) support detailed planning and help identify potential conflicts before construction. Real-time monitoring systems track ground movements, structural integrity, and environmental conditions to enable proactive management of anomalies.

Managing risks during tunnel excavation with a shield TBM requires both qualitative and quantitative assessments. Identifying potential hazards, such as ground instability, water ingress, or equipment failure, allows for prioritizing mitigation measures. The following risk assessment scale (Table 2) provides a framework to evaluate risk severity and guide appropriate actions before excavation begins.

Table 2. Risk assessment level with corresponding scores and descriptions.

Score	Level	Description
1	Insignificant	No immediate action needed; risks should still be monitored, and procedures for the construction phase must be in place.
2	Moderate (acceptable)	Work may proceed; risks should be monitored, and construction phase procedures must be maintained.
3	Important (to monitor)	Work cannot begin until risks are mitigated; resolution may require minor adjustments to the project.
4	Unacceptable	Work cannot begin until risks are mitigated; resolution requires significant project changes.

From a quantitative analysis perspective, the preliminary design of Phase 1 of Line 1 of the Belgrade Metro evaluates the sensitivity of existing structures, classifying them into six categories, with Category F covering infrastructure. Example thresholds (e.g., 10 mm settlement) are provided, but actual allowable limits must be set by the asset owner. Applying a single settlement value to all structures is oversimplified and ignores risk analysis, which is essential in modern tunnelling design. Strict adherence to low thresholds would slow TBM progress and increase costs, whereas risk-based assessments indicate that higher settlements (up to 20 mm) may be acceptable for some buildings.

Lake et al. (1996) associated slope values and maximum absolute settlement in structures with defined categories of damage, thereby providing a framework for assessing the potential impact of ground movements on the structural integrity of buildings. This classification, summarized in Table 3, serves as a practical guideline for engineers to evaluate the severity of tunnelling-induced deformations in urban environments.

Table 3. Damage classifications with typical values of maximum building slope and settlement for risk assessment (Lake et al., 1996).

Risk category	Maximum building slope	Maximum building settlement [mm]	Risk description
I	< 1/500	< 10	Negligible: Superficial damage is unlikely.
II	1/500 - 1/200	10 - 50	Slight: Superficial damage is possible but unlikely to have structural significance.
III	1/200 - 1/50	50 - 75	Moderate: Superficial damage is expected, with possible structural damage to buildings and potential damage to relatively rigid pipelines.
IV	> 1/50	> 75	High: Structural damage to buildings and rigid pipelines is expected, with possible damage to other types of pipelines.

3. Methodology

This chapter presents the methodology for simulating sequential excavation, shield advancement, and segment installation of the Belgrade Metro Phase 1, Line 1. The approach enables systematic evaluation of face pressure variations and their effects on the surrounding ground, providing a basis for defining optimal operational parameters to ensure safe tunnel construction and effective control of surface settlements.

3.1. Numerical modeling of shield TBM excavation

Three-dimensional Finite Element Models (FEMs) were developed using Midas GTS NX (2025), including the shield TBM, tunnel segmental lining, and surrounding soil and rock mass (Figure 6). The rock and soil mass were represented by solid elements defined according to the macro-zones described in the previous chapter, enabling realistic simulation of ground settlements and stress-strain behavior during tunnel excavation. The constitutive behavior of the rock mass was modeled using the Mohr-Coulomb model, which has been adopted as the initial framework for this study. In subsequent design phases, and as required by the results of additional geological investigations, the model may be adjusted or replaced with other suitable models, depending on the geological conditions along the tunnel alignment.

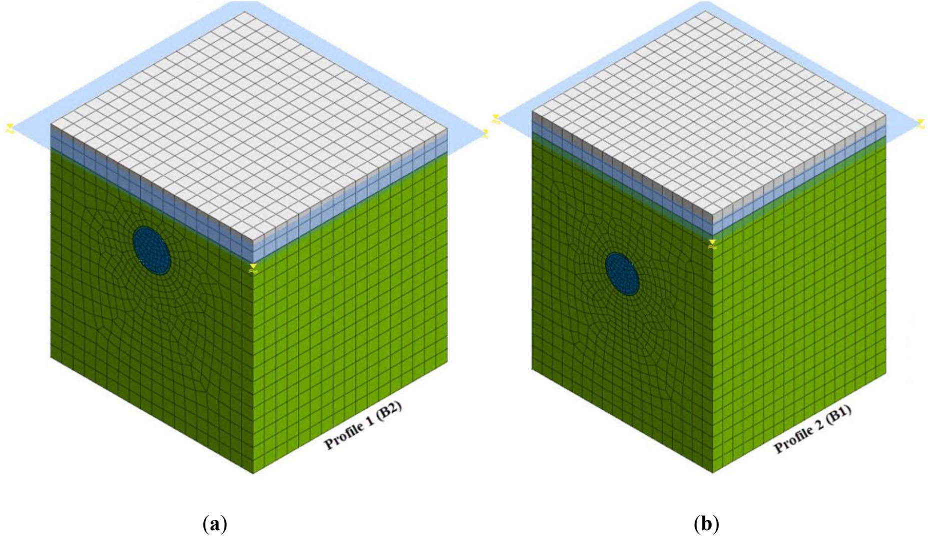


Fig. 6. Three-dimensional FEMs with macro-zones B2 (a) and B1 (b) for Phase 1, Line 1 of the Belgrade Metro, along the section from Bele Vode Station to Trgovačka Station.

The finite element mesh was generated from the model geometry in accordance with the TBM construction method. Excavation was simulated in phases, with each step representing a separate stage of tunnel advancement. A hybrid mesh was employed, resulting in models with approximately 25,000 elements and 155,000 nodes for Profile 1 (B2), and about 26,000 elements and 165,000 nodes for Profile 2 (B1). Figure 7 shows the basic elements of the models, including the overburden layer, which ranges in thickness from 10 m at Profile 1 (B2) to 22 m at Profile 2 (B1).

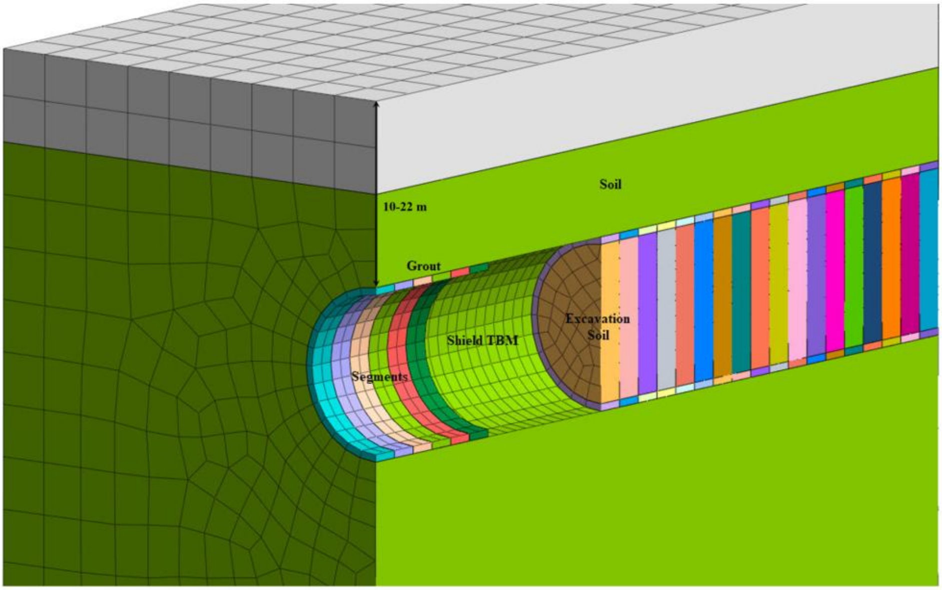
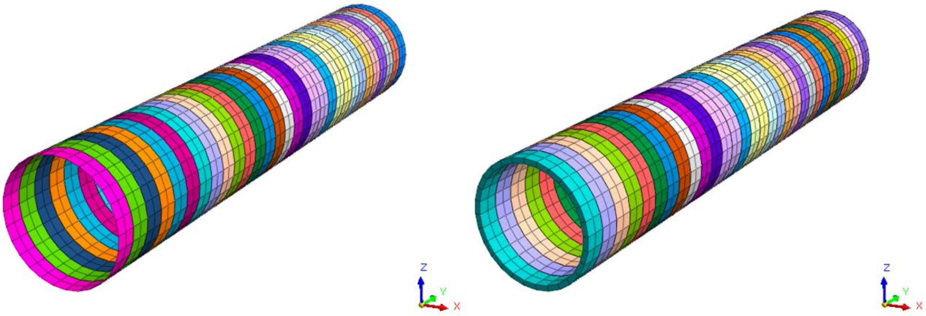


Fig. 7. Vertical cross-section of the model elements.

The steel shield of the TBM, 6.5 cm thick, together with the injection grout of equal thickness, is modeled as a surface element, while the segmental concrete lining, 40 cm thick and 1.60 m wide, is modeled as a volumetric element. All components are represented using linear elastic material models (Figure 8).



(**a**) (**b**)

Fig. 8. Shield / injection grout (a) and segmental lining (b) in the model.

Displacement boundary conditions are defined such that displacements are fully restrained at the bottom boundary of the rock mass, while at the lateral boundaries, displacement is restricted in the direction perpendicular to the model plane (Figure 9). This setup ensures a realistic representation of rock mass behavior and its deformation under self-weight. The groundwater level is 1.0 m below the ground surface at Profile 1 (B2) and 2.0 m below the ground surface at Profile 2 (B1).

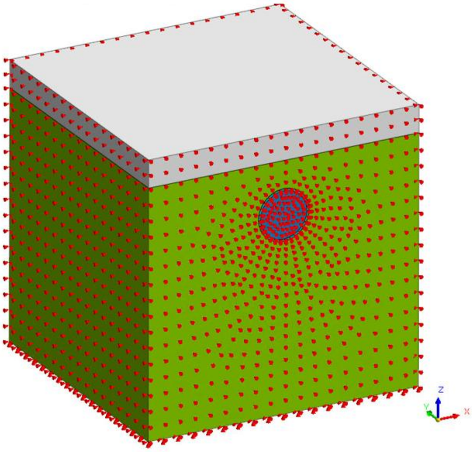
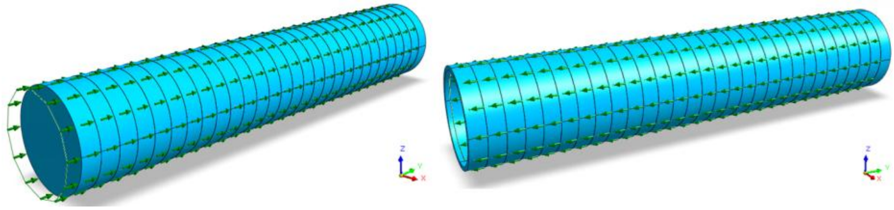


Fig. 9. Applied boundary conditions of the model.

The shield of the TBM in the model has a length of 12.8 m and a diameter of 9.35 m. The machine advances through the model in increments of 1.6 m, corresponding to the length of one concrete ring. Shield movement is simulated by sequentially activating elements at the front and deactivating elements behind the shield. During the analysis, the load due to self-weight is automatically generated in the FEM model based on the adopted geometry of the structure and surrounding soil. Self-weight is considered the initial load, establishing the initial stress state of the model.

A key feature of excavation with an EPB TBM is the continuous application of pressure on the tunnel face (Figure 10(a)). The pressure is controlled within the cutterhead chamber and depends on the design profile, including the mechanical properties of the ground, pore pressure, and overburden height. Face pressures were varied within a range of 75.0 - 350.0 kPa for Profile 1 (B2) and 200.0 - 750.0 kPa for Profile 2 (B1) to evaluate their influence on ground surface settlements.

In addition to face pressure, the model included the following loads: thrust pressure from the thrust cylinders acting on the surface of each concrete ring (4500.0 kPa, see Figure 10(b)), and the combined effect of grouting pressure at the interface between the ground and the concrete lining together with ground pressure acting directly on the lining (1000.0 kPa). A volume loss of 0.35% was also included in the numerical model to account for ground deformation associated with tunnel excavation, ensuring a more realistic representation of soil-structure interaction.



(**a**) (**b**)

Fig. 10. Shield TBM loads: excavation face pressure (a) and thrust pressure (b).

Stress-strain analyses were performed for the design scenario corresponding to the tunnel construction phase. The analysis is steady-state and encompasses all excavation and concreting stages occurring during the construction process. The first calculation phase represents the initial state. After computing stresses and deformations, displacements are reset. From the second phase onward, tunnel lining excavation is carried out in 45 steps over a total length of 48.0 m. The excavation sequence is simulated through the sequential activation and deactivation of model elements, representing the TBM advancing through defined quasi-homogeneous zones. Tables 4 and 5 present the construction stages of the tunnel using the shield TBM, showing the activation/deactivation of model elements as well as the applied loads and boundary conditions.

Table 4. Activation and deactivation of model elements during construction stages.

Construction stage	Excavation / Element removal			Element installation		
	Internal circle	External ring	Shield	Shield	Segment	Grout
0	-	-	-	Ground, Internal circle 1-30, External ring 1-30		
1	1	1	-	1	-	-
2	2	2	-	2	-	-
3	3	3	-	3	-	-
4	4	4	-	4	-	-
5	5	5	-	5	-	-
6	6	6	-	6	-	-
7	7	7	-	7	-	-
8	8	8	-	8	1	-
9	9	9	1	9	2	-
10	10	10	2	10	3	-
11	11	11	3	11	4	-
12	12	12	4	12	5	-
13	13	13	5	13	6	-
14	14	14	6	14	7	-
15	15	15	7	15	8	-
16	16	16	8	16	9	1
17	17	17	9	17	10	2
18	18	18	10	18	11	3
19	19	19	11	19	12	4
20	20	20	12	20	13	5
21	21	21	13	21	14	6
22	22	22	14	22	15	7
23	23	23	15	23	16	8
24	24	24	16	24	17	9
25	25	25	17	25	18	10
26	26	26	18	26	19	11
27	27	27	19	27	20	12
28	28	28	20	28	21	13
29	29	29	21	29	22	14
30	30	30	22	30	23	15
31	-	-	23	-	24	16
32	-	-	24	-	25	17
33	-	-	25	-	26	18
34	-	-	26	-	27	19
35	-	-	27	-	28	20
36	-	-	28	-	29	21
37	-	-	29	-	30	22
38	-	-	30	-	-	23
39	-	-	-	-	-	24
40	-	-	-	-	-	25
41	-	-	-	-	-	26
42	-	-	-	-	-	27
43	-	-	-	-	-	28
44	-	-	-	-	-	29
45	-	-	-	-	-	30

Table 5. Application and removal of loads and boundary conditions during construction stages.

Construction stage	Load application				Load removal		Boundary condition			
	Face pressure	Shield pressure	Segment pressure	Thrust pressure	Shield pressure	Thrust pressure	Displacement	Shield contraction	Change segment property	Change grout property
0	-	-	-	-	-	-	Foundation displacement constraint	-	-	-
1	HP 1	S 1	-	-	-	-	-	C 1	-	-
2	HP 2	S 2	-	-	-	-	-	C 2	-	-
3	HP 3	S 3	-	-	-	-	-	C 3	-	-
4	HP 4	S 4	-	-	-	-	-	C 4	-	-
5	HP 5	S 5	-	-	-	-	-	C 5	-	-
6	HP 6	S 6	-	-	-	-	-	C 6	-	-
7	HP 7	S 7	-	-	-	-	-	C 7	-	-
8	HP 8	S 8	E 1	J 1	-	-	-	C 8	1	-
9	HP 9	S 9	E 2	J 2	S 1	J 1	-	C 9	2	-
10	HP 10	S 10	E 3	J 3	S 2	J 2	-	C 10	3	-
11	HP 11	S 11	E 4	J 4	S 3	J 3	-	C 11	4	-
12	HP 12	S 12	E 5	J 5	S 4	J 4	-	C 12	5	-
13	HP 13	S 13	E 6	J 6	S 5	J 5	-	C 13	6	-
14	HP 14	S 14	E 7	J 7	S 6	J 6	-	C 14	7	-
15	HP 15	S 15	E 8	J 8	S 7	J 7	-	C 15	8	-
16	HP 16	S 16	E 9	J 9	S 8	J 8	-	C 16	9	1
17	HP 17	S 17	E 10	J 10	S 9	J 9	-	C 17	10	2
18	HP 18	S 18	E 11	J 11	S 10	J 10	-	C 18	11	3
19	HP 19	S 19	E 12	J 12	S 11	J 11	-	C 19	12	4
20	HP 20	S 20	E 13	J 13	S 12	J 12	-	C 20	13	5
21	HP 21	S 21	E 14	J 14	S 13	J 13	-	C 21	14	6
22	HP 22	S 22	E 15	J 15	S 14	J 14	-	C 22	15	7
23	HP 23	S 23	E 16	J 16	S 15	J 15	-	C 23	16	8
24	HP 24	S 24	E 17	J 17	S 16	J 16	-	C 24	17	9
25	HP 25	S 25	E 18	J 18	S 17	J 17	-	C 25	18	10
26	HP 26	S 26	E 19	J 19	S 18	J 18	-	C 26	19	11
27	HP 27	S 27	E 20	J 20	S 19	J 19	-	C 27	20	12
28	HP 28	S 28	E 21	J 21	S 20	J 20	-	C 28	21	13
29	HP 29	S 29	E 22	J 22	S 21	J 21	-	C 29	22	14
30	-	S 30	E 23	J 23	S 22	J 22	-	C 30	23	15
31	-	-	E 24	J 24	S 23	J 23	-	-	24	16
32	-	-	E 25	J 25	S 24	J 24	-	-	25	17
33	-	-	E 26	J 26	S 25	J 25	-	-	26	18
34	-	-	E 27	J 27	S 26	J 26	-	-	27	19
35	-	-	E 28	J 28	S 27	J 27	-	-	28	20
36	-	-	E 29	J 29	S 28	J 28	-	-	29	21
37	-	-	E 30	-	S 29	J 29	-	-	30	22
38	-	-	-	-	S 30	-	-	-	-	23
39	-	-	-	-	-	-	-	-	-	24
40	-	-	-	-	-	-	-	-	-	25
41	-	-	-	-	-	-	-	-	-	26
42	-	-	-	-	-	-	-	-	-	27
43	-	-	-	-	-	-	-	-	-	28
44	-	-	-	-	-	-	-	-	-	29
45	-	-	-	-	-	-	-	-	-	30

3.2. Analytical assessment of optimal shield TBM face pressure

Analytical approaches for determining the optimal shield TBM face pressure are mainly based on limit equilibrium and limit state methods, both aimed at evaluating the critical conditions for tunnel face stability.

Limit equilibrium methods assume a predefined kinematic failure mechanism at the tunnel face, commonly represented as a sliding wedge subjected to the weight of the overlying soil and surcharge, which acts as destabilizing forces. These forces are counteracted by stabilizing contributions from the applied face pressure and the shear resistance along the boundaries of the wedge. The classical concept, introduced by Horn (1961), was later extended to mechanized tunneling by Anagnostou and Kovári (1994) and Jancsecz and Steiner (1994).

Limit state methods, derived from plasticity theory, define two reference values for tunnel face stability: an upper bound (kinematic) and a lower bound (static). The upper bound represents an optimistic, theoretically unsafe estimate, as it predicts a lower face pressure than what is actually required to prevent collapse. In contrast, the lower bound provides a conservative, safe estimate, yielding a higher value of the necessary support pressure. In practice, the tunnel face is stable if the applied pressure exceeds the lower bound, will collapse if it falls below the upper bound, and may be conditionally stable if the applied pressure lies between these two limits. This framework allows engineers to assess face stability under varying geotechnical conditions while providing a clear understanding of the safe and unsafe operating ranges.

In summary, analytical methods therefore provide a theoretical basis for estimating optimal face pressures, offering insight into safe and unsafe conditions, and can be further refined and validated through detailed numerical simulations under site-specific geotechnical conditions.

Table 6 presents the values calculated using selected analytical approaches, illustrating the range of face pressures estimated through different methodologies. These results provide a reference for comparison with numerical simulations and help evaluate the reliability and applicability of the analytical methods under varying geotechnical conditions.

Table 6. Face pressures for shield TBM calculated using selected analytical approaches.

Analytical approach	Profile 1 (B2)	Profile 2 (B1)
	Face pressure [kPa]	
Cone of bearing	183	230
Jancsecz and Steiner	139	210
DIN 4085 (2017)	62	235
Blow out limit pressure	410	1150

4. Results and Discussion

Figures 11 and 12 present the vertical displacement results obtained from the developed numerical models at Phase 28. Two representative cases are illustrated: Profile 1 (B2), simulated with a face pressure of 250.0 kPa, and Profile 2 (B1), simulated with a face pressure of 450.0 kPa. For Profile 1 (B2), face pressures were varied within the range of 75.0 - 350.0 kPa, while for Profile 2 (B1) they were varied within 200.0 - 750.0 kPa, in order to evaluate their influence on ground surface settlements. The comparison between profiles highlights the sensitivity of surface and subsurface displacements to the applied face pressure, emphasizing the importance of careful pressure control in shield TBM tunneling. In the presented results, negative displacement values indicate ground settlement, whereas positive values correspond to ground heave.

From the presented diagrams, it can be seen that along the ground surface cross-section following the shield TBM excavation axis, ground heave occurs at the tunnel face and along the shield, partially counteracting the settlement induced by volume loss. For Profile 1 (B2), the maximum heave reaches 0.17 mm, whereas for Profile 2 (B1), the settlement is reduced to -1.64 mm. In contrast, ground settlement occurs in the zone of the installed concrete lining, with a minimum settlement of -4.86 mm for Profile 1 (B2) and -3.38 mm for Profile 2 (B1).

In the ground surface cross-section perpendicular to the shield TBM excavation axis, settlement occurs above the tunnel crown zone, with minimum values of -1.08 mm for Profile 1 (B2) and -2.78 mm for Profile 2 (B1). Meanwhile, ground heave is observed outside the tunnel crown zone, reaching a maximum of 0.47 mm for Profile 1 (B2) and without heave for Profile 2 (B1).

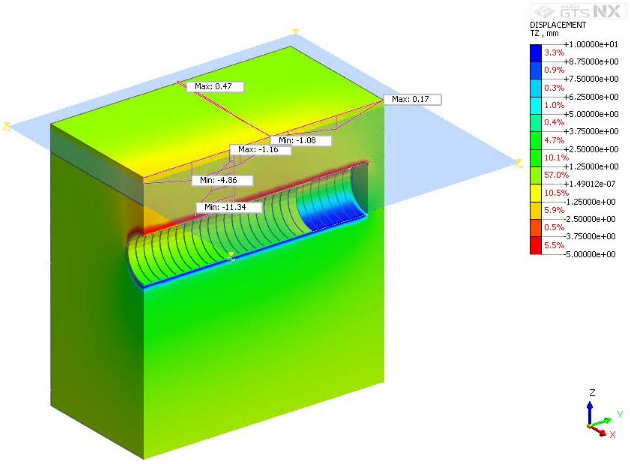


Fig. 11. Vertical displacement (Tz, mm) of Profile 1 (B2) at Phase 28.

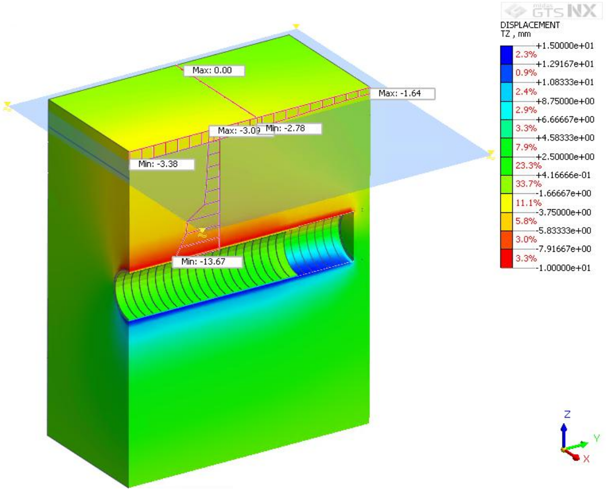


Fig. 12. Vertical displacement (Tz, mm) of Profile 2 (B1) at Phase 28.

It is also evident that settlement at the tunnel crown is significantly greater than surface settlement. For Profile 1 (B2), the crown settlement reaches -11.34 mm, compared to a surface settlement of -1.16 mm. For Profile 2 (B1), crown settlement reaches -13.67 mm, whereas the surface settlement is only -3.09 mm. This difference clearly indicates that the maximum ground deformations are concentrated in the immediate vicinity of the tunnel, while the effects transmitted to the surface are considerably smaller. Such behavior is consistent with the stress redistribution around the excavation and highlights the importance of accurate modeling of tunnel-soil interaction when predicting surface impacts in urban environments.

Figures 13-16 show the vertical displacements at the ground surface for each phase of the calculation models, considering all analyzed face pressure scenarios. These diagrams allow a detailed comparison of settlement and heave along the tunnel alignment, highlighting how variations in face pressure influence both the magnitude and spatial distribution of ground movements. Systematic examination of the results helps identify deformation trends and evaluate the effectiveness of different shield TBM face pressures in controlling settlements.

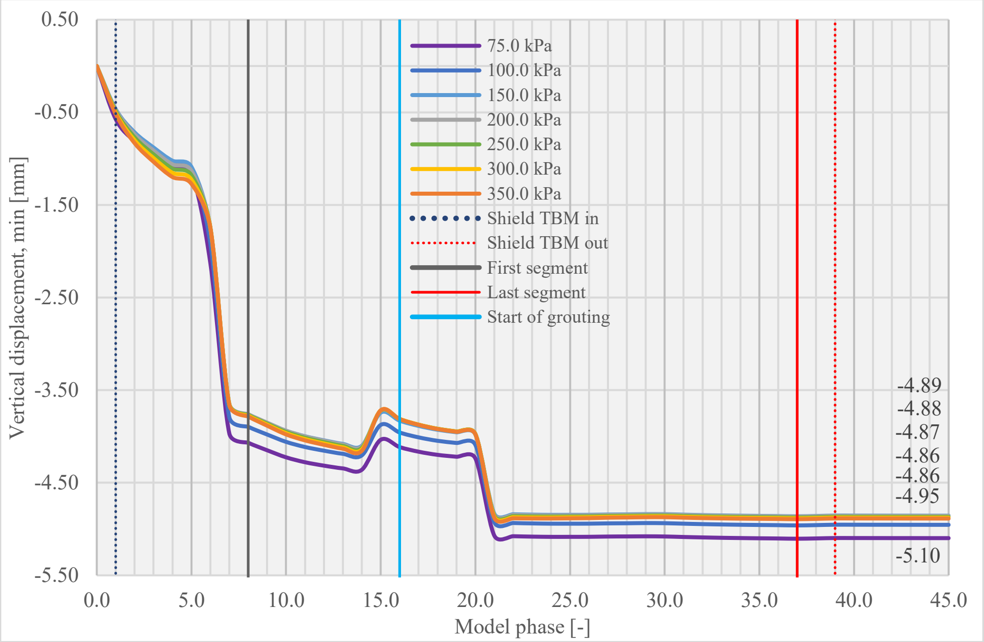


Fig. 13. Minimum ground surface vertical displacements for each calculation model phase of Profile 1 (B2).

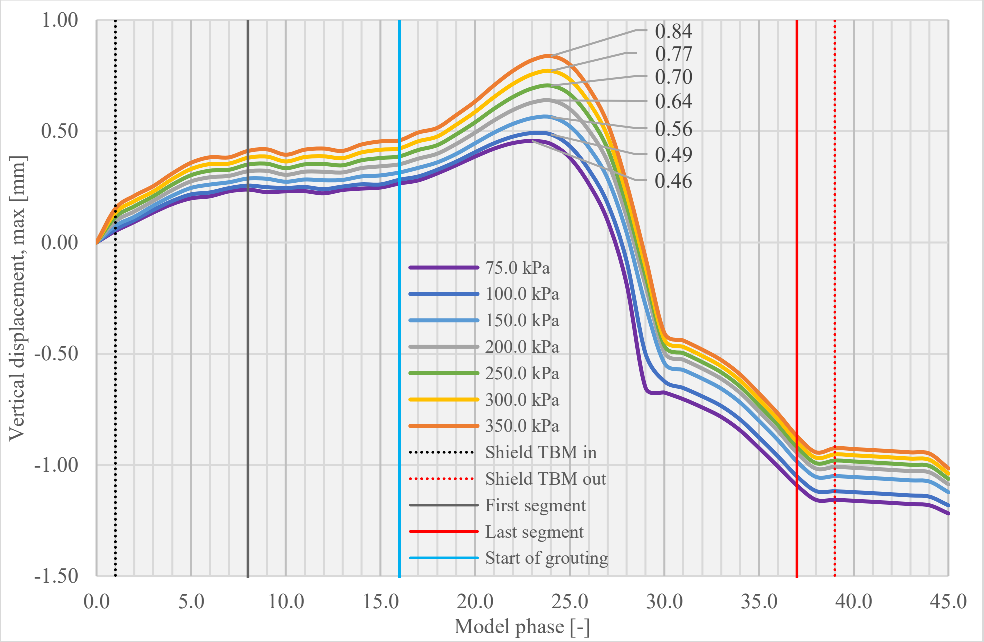


Fig. 14. Maximum ground surface vertical displacements for each calculation model phase of Profile 1 (B2).

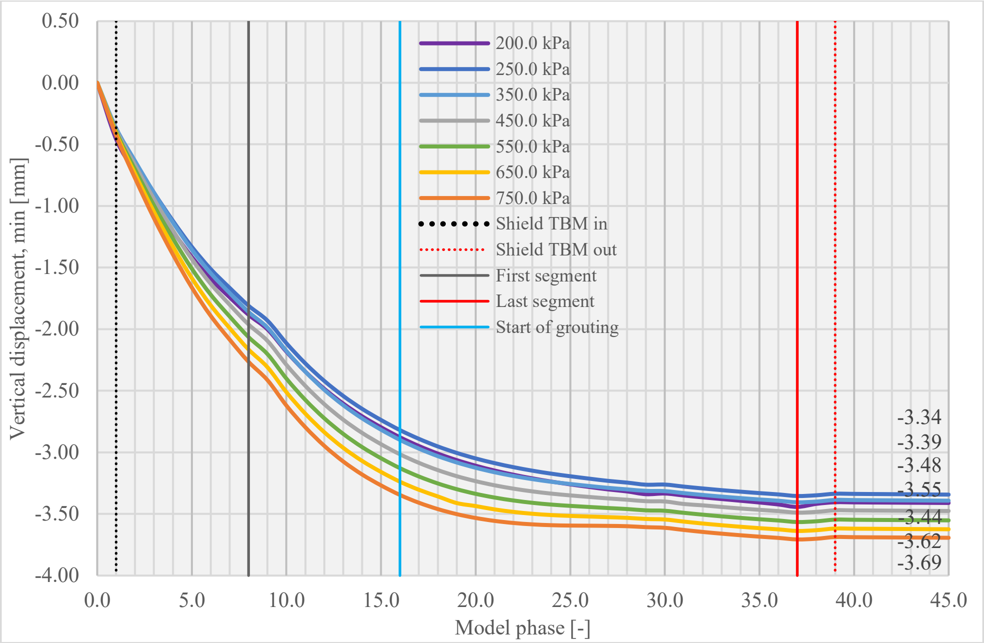


Fig. 15. Minimum ground surface vertical displacements for each calculation model phase of Profile 2 (B1).

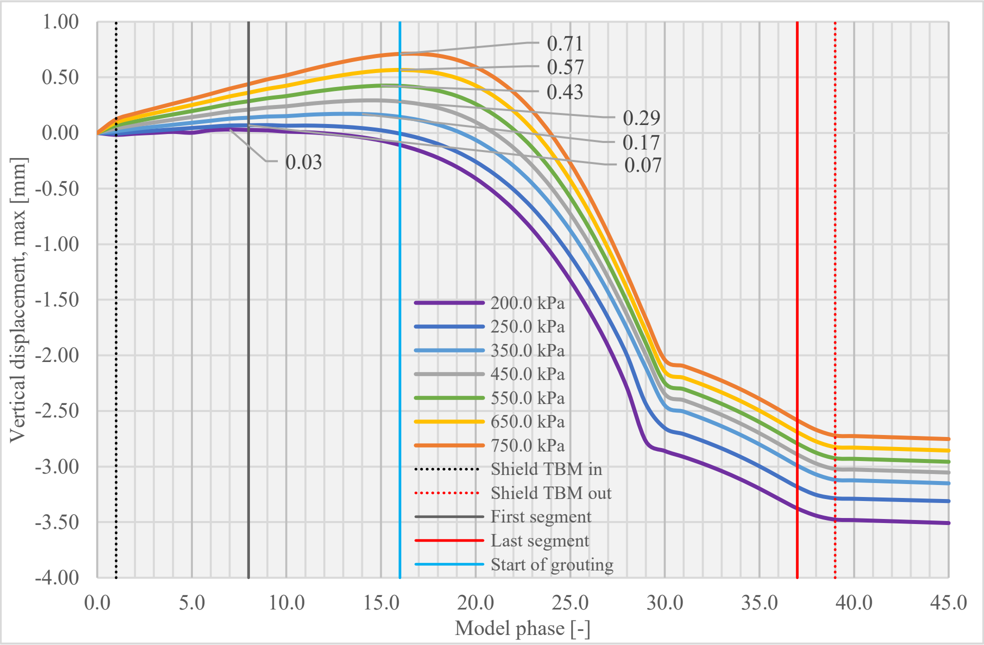


Fig. 16. Maximum ground surface vertical displacements for each calculation model phase of Profile 2 (B1).

Tables 7 and 8 present the ground surface vertical displacement values corresponding to the different face pressure scenarios analyzed in the study. These results provide a quantitative basis for evaluating the influence of face pressure on settlement and heave behavior, offering insights into the optimal operational range for minimizing ground displacements during shield TBM tunneling.

Table 7. Ground surface vertical displacements for Profile 1 (B2).

Face pressure [kPa]		75.0	100.0	150.0	200.0	250.0	300.0	350.0
Surface vertical displacement [mm]	Minimum	-5.10	-4.95	-4.86	-4.86	-4.87	-4.88	-4.89
	Maximum	0.46	0.49	0.56	0.64	0.70	0.77	0.84

Table 8. Ground surface vertical displacements for Profile 2 (B1).

Face pressure [kPa]		200.0	250.0	350.0	450.0	550.0	650.0	750.0
Surface vertical displacement [mm]	Minumum	-3.44	-3.34	-3.39	-3.48	-3.55	-3.62	-3.69
	Maximum	0.03	0.07	0.17	0.29	0.43	0.57	0.71

Tables 9 and 10 present the vertical displacements at the tunnel crown obtained from the numerical models for the full range of considered face pressures, providing a direct measure of the deformation around the tunnel excavation, where the crown represents the most critical point in terms of settlement and structural response. These results highlight the sensitivity of crown displacements to variations in face pressure and can be used to guide TBM operational strategies for minimizing excessive ground movements and ensuring tunnel stability.

Table 9. Vertical displacements at the tunnel crown for Profile 1 (B2).

Face pressure [kPa]		75.0	100.0	150.0	200.0	250.0	300.0	350.0
Crown vertical displacement [mm]	Minimum	-12.23	-11.76	-11.45	-11.52	-11.53	-11.53	-11.50
	Maximum	0.47	0.51	0.60	0.68	0.76	0.84	0.93

Table 10. Vertical displacements at the tunnel crown for Profile 2 (B1).

Face pressure [kPa]		200.0	250.0	350.0	450.0	550.0	650.0	750.0
Crown vertical displacement [mm]	Minimum	-17.19	-15.56	-14.30	-14.08	-14.02	-14.00	-13.99
	Maximum	0.04	0.08	0.18	0.30	0.46	0.67	0.91

5. Conclusion

The present study focused on assessing the optimal face pressure for shield TBM tunneling along Phase 1, Line 1 of the Belgrade Metro using staged three-dimensional numerical simulations. The results indicate that both surface and subsurface vertical displacements show limited sensitivity to the applied face pressure. For Profiles 1 (B2) and 2 (B1), maximum vertical displacements were observed in the immediate vicinity of the tunnel crown, while surface vertical displacements remained significantly smaller. The analysis also showed that surface ground heave develops at the tunnel face and along the shield, whereas settlements are primarily concentrated in areas with installed concrete lining. Furthermore, the observed differences between Profiles 1 (B2) and 2 (B1) reflect the influence of varying geotechnical conditions and overburden thickness along the alignment, underlining the importance of site-specific analysis for reliable shield TBM operation.

The numerical results indicate optimal face pressure ranges that minimize both crown and surface vertical displacements, providing practical guidance for shield TBM operation (Tables 7-10). Compared to analytical methods proposed by various authors, the numerical approach offers several advantages: it accounts for complex ground-structure interaction, simulates sequential excavation stages, and allows detailed sensitivity analyses under varying operational parameters. Unlike analytical methods, which provide single-value estimations, numerical modeling can capture the spatial and temporal distribution of deformations, offering a more reliable and risk-informed basis for operational decisions. The obtained results indicate that the analyzed calculation profiles (macro-zones) are located within relatively competent limestone and conglomerate formations, which exhibit limited sensitivity to variations in applied face pressure, suggesting favorable conditions for shield TBM tunneling.

Future research will cover all calculation profiles (macro-zones) along the entire alignment of Phase 1, Line 1 of the Belgrade Metro, with particular focus on zones characterized by less favorable ground conditions. A more comprehensive sensitivity analysis will be conducted using Midas GTS NX in conjunction with PEST++ (2025), incorporating not only face pressure but also other key shield TBM operational parameters. While contact elements between the tunnel lining and the surrounding ground were not included in the current numerical models, they could be implemented in future, more detailed studies to account for soil-structure interaction. In Midas GTS NX, interface elements with defined frictional behavior can be used to model the interaction between lining segments and the surrounding soil or rock. Incorporating such elements would allow for more accurate predictions of lining stresses, deformation patterns, and load transfer mechanisms during tunnel excavation. This methodology will enable a detailed evaluation of the combined effects of multiple operational variables on both surface and subsurface settlements, thereby supporting the development of robust risk mitigation strategies and providing enhanced operational guidance for shield TBM tunneling in complex urban environments.

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