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Adaptation of tunnelling technical solutions to urban conditions: Case study Sava - Danube slope Tunnel

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Abstract: Tunnelling in urban conditions is often met with demanding criteria for surface settlement control, the limitation which is arising from the fact that most of the urban area is occupied by structures which are sensitive to deformations, such as buildings, roads, communal infrastructure etc. Another important necessity in any project is to deliver the project in shortest amount of time possible. Temporary occupation of public areas for construction sites and traffic congestions alleviate social pressure which further emphasizes these requirements. If planned correctly, TBM technology promises to deliver on these requirements more readily than conventional tunnelling techniques. In this paper a Case study of Belgrade's double tube traffic tunnels is presented, in which project design went through significant conceptual transition, led by the designer's idea to change the technology of excavation from conventional to TBM, as well as to adjust the project in multiple ways to accommodate for this major turn of tides. Most notable historic background of the project is presented. Geotechnical profile of tunnels and data are shown and calculations for both TBM and conventional variants are presented and discussed.

Keywords: shield TBM; urban tunnelling; numerical modelling; sensitivity analysis; ground settlement; structural response

1. Introduction

The construction of tunnels in urban areas is the only way to transfer traffic underground in order to reduce congestion and pollution in cities that face increasing growth of population. Geological conditions affect the behavior of the tunnel during construction, as well as the impact of construction on surrounding structures and the environment. Major difficulty in urban tunneling is to minimize the impact of construction on surrounding structures and the environment, to avoid damaging the buildings and infrastructure. In modern tunnel construction, various structural and technological measures are applied for ensuring safety of operations during tunnel construction and to reduce the ground disturbance. Contractor, Designer and Investor get to choose between conventional construction methods such as NATM or ADECO-RS, and Tunnel Boring Machine (TBM method). At an increasing rate, especially in urban environments choice is made to use TBM method due to its undeniable advantages over conventional construction methods as a more reliable option which allows for safer operations and improved control over soil disturbance.

A project development of Belgrade traffic tunnels connecting Sava and Danube slope is examined and discussed as an example of mutual influence of tunnelling technology choice and design solution. A name "tunnel connection of Sava and Danube banks" describes the purpose of the project, which is to relieve traffic on main streets (Kneza Milosa and Takovska) in the city core that currently serve as a connection between New Belgrade, a major part of the city on the left bank of Sava river and Karaburma and other city districts both South and North of the Danube river. Urban plans call for two tunnel tubes, each with two traffic lanes. City core plan is shown from the orthophoto plan view in Fig. 1.

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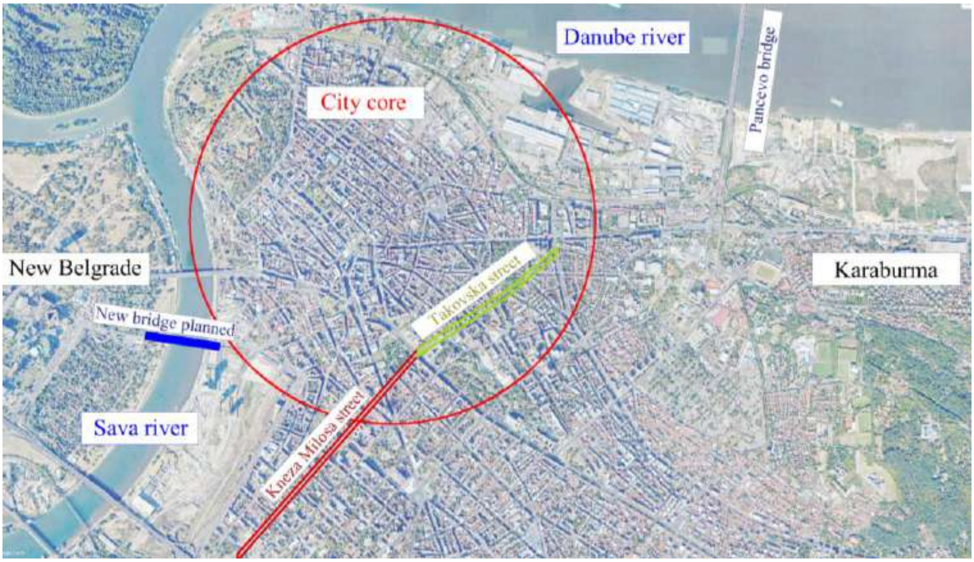


Fig. 1. Belgrade city core disposition.

Currently, the project is in transitioning state, awaiting annex of the contract between Government of Serbia and contractor PowerChina which would set up the project for both the new tunnel trajectory and TBM tunnelling technology instead of existing contract which planned a solution based on conventional tunnelling approach.

The sequence of events and prime motivators for this course change of the project are shown in following order:

- Project history – most notable moments in the long-lasting background of the project are described.
- Geotechnical conditions – objectively most influential factor when deciding on tunnelling technology.
- Conventional tunneling analysis showcase – detailed 3D FEM analysis of variant solutions that greatly influenced the adoption of TBM solution.
- TBM proposal – derived from two most recent documents, a Study which formally initialized the idea and set up an organizational pathway towards TBM-based solution agreement, and Technical Design which serves as a baseline document for the forthcoming contract annex.

2. Project history

A substantial history can be traced back to the development of the idea of the traffic tunnel beneath the heart of Belgrade in the era after World War 2. First geological investigations and even tunnel excavation works took place in 1950s. This infamous tunneling attempt was stopped early after only a few dozen meters had been breached, as observations on the surface indicated too much deformation that threatened to collapse the existing buildings above the tunnel (Stepanovic and Perić, 1961).

During 1960s more investigation works and more than one geotechnical study was conducted as an attempt to restart the construction works. These studies often criticized results of the studies which predated them, most likely due to severity in the atmosphere imposed by the failure of the first tunneling attempt. One of the interesting notations from the critics in these reports emphasized importance to reduce ground disturbance and even stated as the fact that the tunneling in most critical zones must be done with the shield technology. Nevertheless, ambition to construct a single tunnel tube, soon to be followed by another one, still existed. Moreover, the plans suggested that a third tunnel should be built to accommodate tram traffic. None of these plans came to fruition and the project was abandoned during the nation's prosperous decades of 1970s and 1980s, likely as the result of common opinion between the experts in the field of tunneling from the time, being that the project risk was too high. Succeeding decade of 1990s was marked by wars and nation's decline during which little infrastructure was developed, while 2010s transitional years saw the idea of the tunnel only as a distant memory with no real effort put into its materialization.

Fig. 2. Portal zone of the tunnel from 1950s (Source: Kaldrma, 2023).

In recent history of 2010s, the idea is brought back to the table by the City authorities, and with a fresh start the decision was made in 2015 for the city planners to analyze the variant solutions of the tunnel trajectory and portal position on the Danube slope side (Figure 3), with more or less fixed location of the portal on the Sava slope side, which through further project development, proved to have become a prerequisite governed by the trajectory of the new bridge connecting left and right bank of Sava river (Krstić and Mihajlović, 2015).

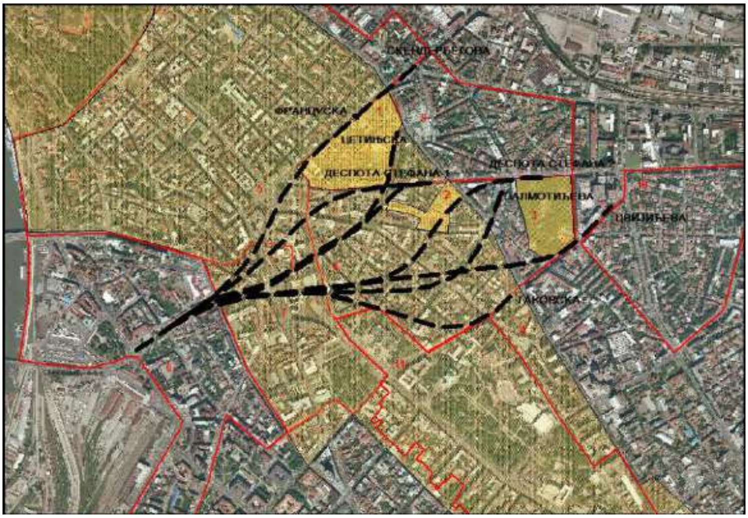


Fig. 3. Tunnel variant solutions (Source: (Krstić and Mihajlović, 2015).

From eleven proposals, the solution was adopted which differentiated somewhat from the one proposed several decades ago. For once, a portal on Danube slope side was put further away. Secondly, the tram idea was put away and solutions called only for two tunnels, each with two traffic lanes.

Conceptual Design was at first trusted to Ces-Cowi consortium (2016) and subsequently to GEOPUT (2022). As an aftermath of the proposed technical solutions, a minor position adjustment of portal on Sava slope was examined. A working group was formed and strategic decision was made which moved the portal slightly closer to the river, thus avoiding substantial expropriation obligations and costs. The secondary strategic move was to formally consider development of the project in conjunction with another important project – namely replacement of old Sava Bridge that is of cruical importance in connecting New Belgrade on one side of the river and the tunnel connection on the other side.

Based on the existing Conceptual Design and the strategic decisions made by the Working Group, a contract between Government of Serbia and PowerChina corporation as a design and build type of contract has been made.

Further development of the project, in the form of another Conceptual Design, is showcased more closely in section 4 and latest advancements in section 5 as a Study and Technical project that pose to adapt the design towards TBM construction.

3. Geotechnical conditions

Geotechnical investigation works were carried out on several occasions, dating back to 1950s attempt at the project. Latest works were carried out as part of the active contract agreement between Serbia Government and PowerChina Corporation (2023). Contractor assigned Jaroslav Cerni Water Institute for execution of investigation works and delivery of geological study (JCWI, 2023). Geological study consists of, among others, reports on geotechnical conditions from which some of the results will be interpreted in this chapter.

Majority of soil is composed of uneven layers of marly sediments mostly in loose form with some of the layers had hardened into marlstones. This implies to all possible tunnel trajectories, though depending on proposed trajectories, appearance of very porous Miocene limestones may happen sporadically on the tunnel path. Quaternary deposits occurrence is present only in portal zones. For tunneling phase, the focus is set on marly-clayey soil type. Ranges of soil physical and mechanical properties are shown in Table 1 and geotechnical profile in Figure 4. These properties come as the interpretation of laboratory and in situ investigations published in the Geological Study. Mohr-Coulomb failure criterion is used and Modulus of elasticity for both load and unload-reload stress path are extracted to be further used in numerical analysis as main input data necessary to define Hardening Soil constitutive model. All properties are for the drained conditions. Other parameters such as Poisson's ratio ν, Coefficient of earth lateral pressure K_0, constitutive model specific parameters such as reference pressure p_{ref}, stiffness/stress power factor *m* are also important for proper interpretation of the problem. The scope of this work though, is mainly to present the most important influencing factors, results and methodology that played part in decision making throughout the project.

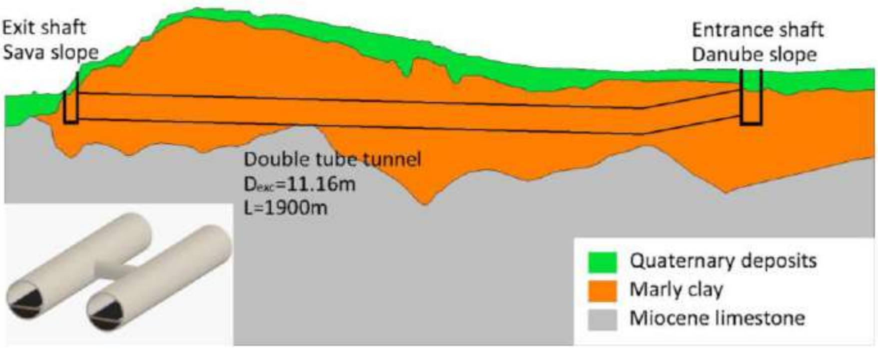


Fig. 4. Simplified presentation of geotechnical profile for one of the solutions. The profile shown in the Figure corresponds to the latest trajectory proposed for the TBM tunnel.

Table 1. Range of mechanical properties for each type of soil in drained conditions.

Soil type	Marly clay	Quaternary deposits	Limestone
c (kPa)	5-100	0-10	200-500
φ (°)	18-30	30-35	30-35
E (kPa)	20-100	100-500	100-500
E_{ur} (kPa)	50-300	400-1500	300-1500
Permeability	Low	Medium-High	High

4. Conventional tunnelling analysis showcase

A Conceptual Design (JCWI, 2023) mentioned in the last paragraph of chapter 2 took the existing premises of conventional tunnelling approach. In this endeavour, 6 structural types (with additional subtypes) were analysed in various soil conditions using 3D Finite Element Analysis. Each structural type implied using different reinforcement type, excavation and reinforcement installation sequences. All structural types and subtypes are shown in Fig. 5.

4.1. Finite element model

All structural types but type 6 were tested in multiple conditions that varied both mechanical characteristics of the soil and overburden and water level above tunnel. Structural type 6 was analysed after the fact, being the most complicated and rigorous tunnelling sequence, with the idea to analyse the best-case scenario in terms of safety and surface settlement reduction regardless of efficiency of excavation, which in case of sequential excavation of type 6 is quite poor.

Soil is modelled with Hardening Soil constitutive model. Terrain surface is simplified as flat. Dimensions of the model are L x W x H(varied) = 140 x 100 x (70-100) m. One soil material is used for the whole volume of the model, the one which mostly represents Marly-Clayey soil, though by varying parameters in the analysis within the specified range does allow for perceiving a wide palette of possible ground conditions and soil varieties.

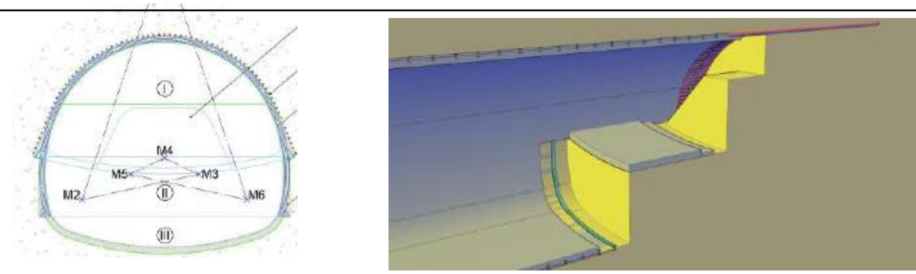
Table 2. Varied parameters in numerical analysis of different structural types.

	Varied Hardening Soil parameters				
Parameter set	Modulus at 50% of peak triaxial strength E_{50}^{ref} (kPa)	Oedometer Modulus E_{oed}^{ref} (kPa)	Unload-Reload Modulus E_{ur}^{ref} (kPa)	Cohesion c'_{ref} (kPa)	Friction angle φ (°)
1	20 000	20 000	60 000	10	20
2	40 000	40 000	120 000	20	25
3	60 000	60 000	180 000	40	27
4	100 000	100 000	300 000	70	30
	Varied overburden [water level] height measured from top of the tunnel (m)				
1	10m overburden [-20, 7m water level over top of the tunnel]				
2	25m overburden [-20, 13, 20m water level over top of the tunnel]				
3	40m overburden [-20, 20, 33m water level over top of the tunnel]				

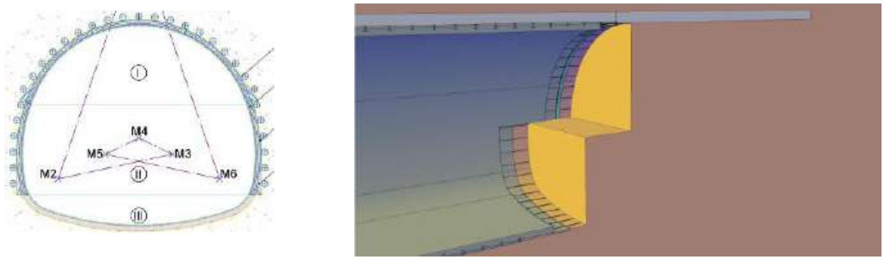
Type 1 – Sprayed concrete 30cm, Steel braces IPB200 at 1m, Radial steel anchors d=32mm L=6m, Fiberglass anchors at the face L=12m. Used only for tunneling in rock conditions.

Type 2 – Sprayed concrete 30cm, Steel braces IPB200 at 1m, Grouted Steel pipe umbrella arch Ø114 (t=6mm) L=12m, Fiberglass anchors at the face L=12m. Used only for tunneling in rock conditions.

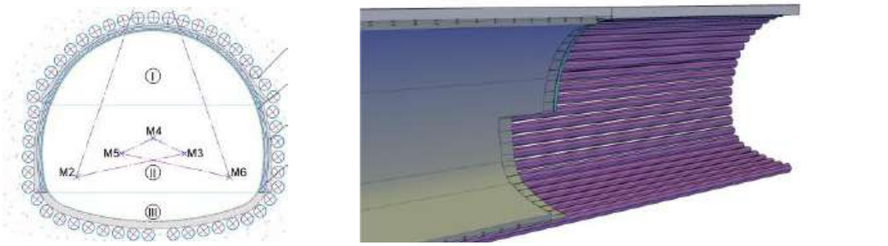
Type 3 – Sprayed concrete with 30cm or 40 cm thickness, Temporary invert for upper bank excavation, Steel braces IPB200 at 1m, Grouted Steel pipe umbrella arch Ø88 or Ø250 (t=6mm) L=14m, Fiberglass anchors at the face L=12m



Type 4 – Sprayed concrete 30cm or 40cm, Steel braces IPB200 at 1m, Grouted Steel pipe umbrella arch Ø300 or Ø600 (t=6mm) L=16m, Fiberglass anchors at the face L=12m



Type 5 – Sprayed concrete 30cm or 40cm, Steel braces IPB200 at 1m, Grouted Steel pipe umbrella arch Ø300 or Ø600 (t=6mm) L=16m, Fiberglass anchors at the face L=12m. Similar to Type 4, except that pipes encircle the excavation face completely and bigger piles of Ø600 are analyzed as well.



Type 6 – Sprayed concrete 40cm, Steel braces IPB200 at 1m, Grouted Steel pipe umbrella arch Ø250 (t=6mm) L=12m, Fiberglass anchors at the face L=12m, 6 excavation steps in a sequence.

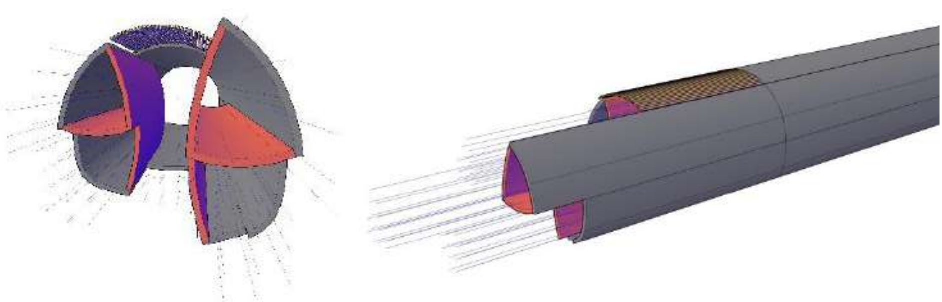


Fig. 5. Structural types parametrically analyzed in the design.

Numerical models consider one tube and are mostly modelled as symmetrical models. Structural elements are all modelled in following manner:

- Sprayed concrete – plate elements
- Fiberglass face anchors – linear beam elements
- Steel braces – linear beam elements
- Radial Anchors – linear beam elements
- Pipe umbrella – linear beam elements or combination of 3D elements (grouted pipe interior) and plate elements (steel pipe wall)

Calculation steps are designed in a way that realistically represents sequencing of operations during tunnelling, i.e. activation and deactivation of each structural element in conjunction with volume excavation (deactivation). Analysis was done with Plaxis 3D software. Detailed modelling and procedure will not be explained thoroughly since the purpose of the model showcasing in this article is only to present results in a manner which gives better perspective on broader picture of project development.

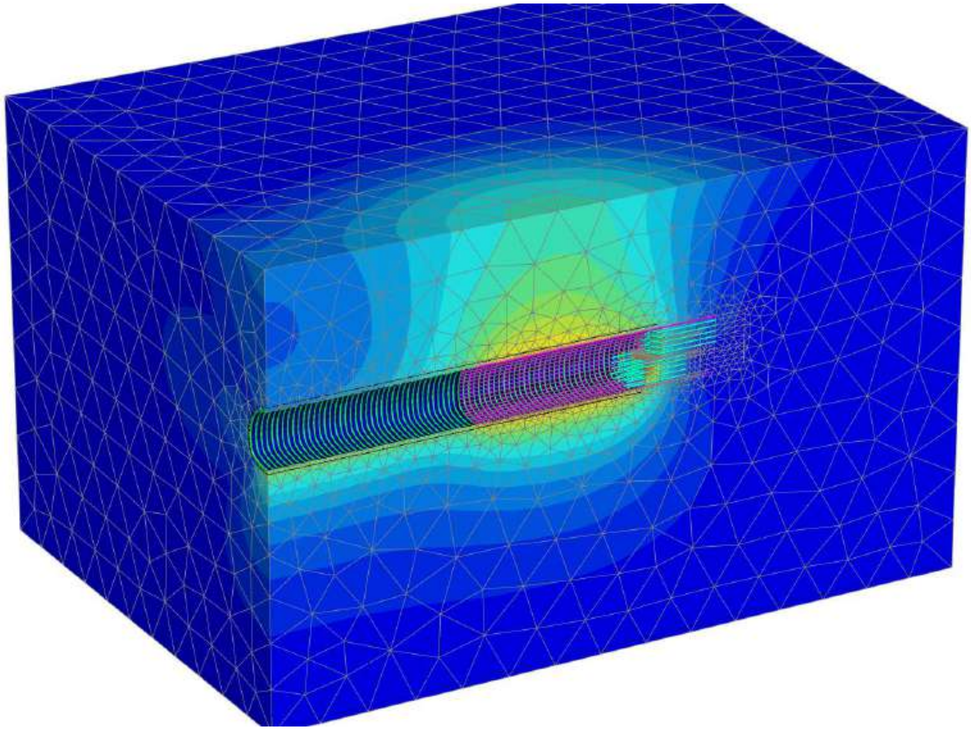


Fig. 6. 3D Numerical model of structural type 5 showing total deformations in the model.

4.2. Analysis results

In Table 3 the surface settlement and structural type dependency is shown for:

- Overburden height of 40m
- No groundwater
- Soil parameter set 2

Table 3. Settlement dependency on structural type used in calculations.

Structural type	Maximum surface settlement (mm)
3a	56
3b	49
4	47
5a	44
5b	37
6	30

The most rigorous method of tunnelling show significantly increased the safety of excavation and excavation volume loss, resulting in lesser surface settlements. One of the most influential factors on surface settlement is of course strength of the soil. Results of settlements shown for parameter set 2 are agreeable to a degree, given the proper choice of excavation sequence and structure.

In Table 4 is shown how different overburden and parameter set influences settlement, for a given structural type (type 3a) and no groundwater conditions.

Table 4. Settlement dependency on parameter set and overburden used in calculations.

Parameter set	Overburden (m)	Maximum surface settlement (mm)
1	25	166
	40	151
	10	124
2	25	67
	10	59
	40	56
3	25	39
	10	37
	40	34
4	25	23
	40	20
	10	20

The results are further greatly influenced by groundwater level which has been considered in numerical models through coupled seepage analysis with the assumption that steady state draining conditions are formed on face surface of the tunnel. Surface settlement dependency on groundwater conditions is shown through Table 5.

Table 5. Settlement dependency on groundwater conditions.

Parameter set	Water level height from top of the tunnel	Structural type	Maximum surface settlement (mm)
2	20	5 (liner 40cm, pipes 300mm)	119
	13		82
	below tunnel		47
2	20	5 (liner 40cm, pipes 300mm)	65
	13		47
	below tunnel		28
3	20	5 (liner 40cm, pipes 600mm)	62
	13		45
	below tunnel		25
4	20	5 (liner 40cm, pipes 300mm)	35
	13		25
	below tunnel		18

While resulting settlements vary greatly on adopted parameters, such parametrically generated models give broad impression on project's possible outcomes and are very representable for the whole project in which soil material can mostly be generalized as one soil type with different ranges of mechanical properties.

Ground movement has been used for this purpose as the main indicator for quality of tunneling solutions in urban areas. In different conditions, i.e., where no threat exists to damage the urban infrastructure such information provides little value. Considering the unsuccessful historical attempts, very dense urban conditions along tunnel trajectories, complexity of proposed solutions and possible outcomes of the analysis which suggest likeliness that significant further expenses and effort should be put in ensuring that no damage is dealt to the existing infrastructure, the decisions and actions were made to convert the tunneling technology to TBM.

5. TBM proposal and analysis showcase

Similar approach to NATM analysis was adopted for TBM. In this manner, soil parameters were adopted and are shown in Table 6. It can be noted that parameter sets coincide with previously used sets with addition of parameter set with even lower properties and exclusion of parameter set with highest properties.

Table 6. Settlement dependency on groundwater conditions.

Varied Hardening Soil parameters					
Parameter set	Modulus at 50% of peak triaxial strength	Oedometer Modulus	Unload-Reload Modulus	Cohesion	Friction angle
	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	c'_{ref} (kPa)	φ (°)
1	10 000	10 000	30 000	1	20
2	20 000	20 000	60 000	10	20
3	40 000	40 000	120 000	20	25
4	60 000	60 000	180 000	40	27
Varied overburden [water level] height measured from top of the tunnel (m)					
1	10m overburden [-20, 7m water level over top of the tunnel]				
2	25m overburden [-20, 13, 20m water level over top of the tunnel]				
3	40m overburden [-20, 20, 33m water level over top of the tunnel]				

Pressure balance TBM technology relies on actively keeping soil in balance by exerting pressure both on face of the excavation through pressure chamber of the cutterhead and by injecting grout inside the annular gap between the erected concrete structure and soil surrounding the structure. Grouting operation takes place immediately behind the shield, as the machine moves and "reveals" latest erected segmental ring behind the steel shield of the machine. If needed, additional pressure can be applied through holes on the shield with bentonite medium to further help in keeping the soil in balance and reduce the volume loss of the excavation. These actions act in conjunction with other processes that also need to be precisely controlled, such as torque application, hydraulic pistons advancement rate, screw conveyer extraction rate etc.

Applying the right actions in right amount at the same time is the task of the TBM machine and TBM operator, one that can be extremely complex and sensitive to error if soil conditions are challenging and urban tunnelling requirements rigorous. If done properly though, TBM technology promises to achieve better results in controlling volume loss during excavation and thus provide better alternative for tunnelling in urban areas.

Numerical (or analytical, for that matter) modelling of such complex processes often requires certain assumptions to be made. Depending on the required output of the analysis, these assumptions can lead to results which can be both conservative and non-conservative at the same time, i.e. calculations which lead to overestimated volume loss often underestimate forces in the structure. As so, few modelling assumptions have been made in an endeavour to simulate TBM tunnelling process for the design of this project. It is shown how some of these assumptions can achieve results which represent somewhat conservative application of TBM tunnelling from the standpoint of surface settlements. The model is briefly described prior to presentation of the results in order to supplement the manner in which the realistic problem of TBM tunnelling sequence is interpreted in the model.

Firstly, pressure on the face of the excavation is achieved with surface load. This parameter was varied through parametric analysis and is always active on the face of the tunnel excavation, as shown on Figure 7.

Secondly, gap between tail shield external diameter and excavation diameter is achieved by radial contraction of the shield as the shield advances through sequences (each step being equal to length of segmental ring). This is achieved with gradual application of tangential contraction on plate elements that are used as shield structure (Figure 7). Interface elements are used on surface elements of the shield. This allows for different displacements on nodes which coincide on both surface elements and soil elements so that no bogus tension forces are induced, neither in shield nor in soil elements.

Lastly, grouting pressure is induced in a single step behind the tail of the shield as radial pressure. With this, assumption is made that pressure as such has effect on surface settlements while it is in fluid form and while pressure in fluid exists. This pressure is parametrically varied along with face pressure. As soon as advancement is made and the next calculation step is started, the pressure is removed and it is assumed that the grout has hardened enough so that its strength is greater than the properties of the soil, which in the case of the project is very likely considering ranges of possible properties of the soil and hardening time of two component grout.

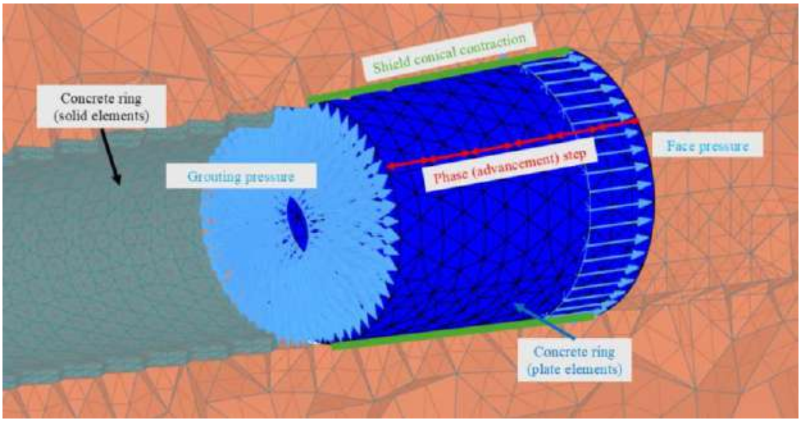


Fig. 7. TBM numerical model components.

All models, unlike in NATM analysis, consist of two tunnel tubes. Each tube advances for amount of 20 steps, which equals 40 meters in terms of length. This makes each calculation take 40 advancements steps, since tunnels start one after the other rather than at the same time.

Presented as a chart on Figure 8 are maximum surface settlements for different soil conditions and pressure/grout pressures. Results are shown for overburden of 40m and with no groundwater present above tunnel. First three columns for each soil parameter set represent results of surface settlements for conicity of the shield modelled as per manufacturers specification. Fourth, fifth and sixth column represent results of surface settlements in which conicity is zero i.e. if no convergence is allowed to happen either by the use of bentonite or actually designing the shield with zero conicity and no overcut.

Machines are generally not designed with zero clearance since this clearance is necessary for the machine to turn efficiently.

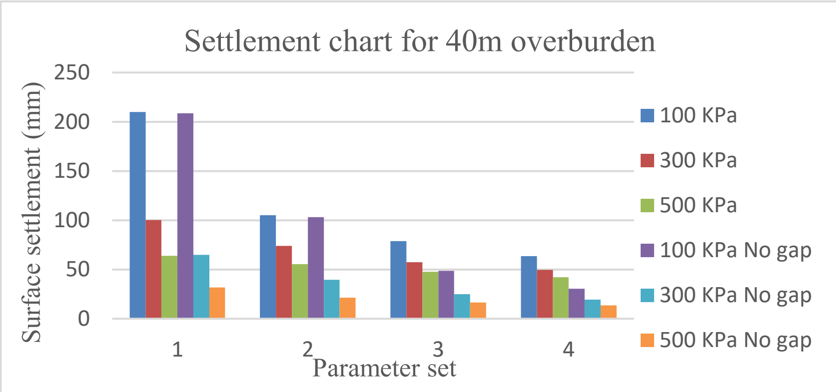


Fig. 8. Surface settlements for different soil conditions and face/grouting pressure.

It can be observed that with pressure increase, the settlements decrease significantly, especially in the case of very weak soil. However, for the case of models with specified conicity of the shield, at certain point there is little improvement with increasing soil pressure as the settlement converges to approximately 50 mm, which basically represents convergence that happens because of the shield conicity and the fact that bentonite injection effect is not modelled and for this reason the soil collapses onto the shield because it does not have enough bearing capacity. In real scenario such collapsing effect should be controlled by allowing bentonite muck or clay shock material to be injected through designated openings on the shield. If assumption is made so that the bentonite injection process is achieved in full effect, results of models with no conicity would present a good simulation of the effect and influence it has on surface settlements.

Results obtained from TBM analysis further influence the opinion that for the given conditions, the TBM method is superior to conventional method of construction.

6. Conclusion

The design and construction of tunnels in urban areas is complex and requires detailed and studious analysis that should define adequate technical solutions that will enable the safe and successful implementation of the tunnel construction project.

Risks in urban tunneling are often governed by ground settlements. In order to minimize these risks, TBM technology offers substantial advantages when dealing with weak soil conditions.

The development of the tunnel project presented in this paper began more than several decades ago. The project underwent a large number of changes that primarily related to the traffic solutions of the route and access zones and fitting into the traffic solution of the City of Belgrade. However, the essential issue with this project is the construction technology, which was obviously wrongly selected and considered in previous studies and analyses. This was to be expected at the time when the development of the project began, because the knowledge and construction practice at that time in Serbia did not recognize the application of mechanized TBM methods in the construction of tunnels. Nowadays, the advantage of TBM technology is undeniable and the further realization of the project will take place using TBM. It is expected that by the end of 2025 works on the construction of the launch shaft will begin and that the beginning of the construction of the tunnel should start at the beginning of 2027. The tunnel connection project is one of the largest infrastructure projects in the City of Belgrade.

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