Tunnelling design of urban sewerage system – Belgrade Interceptor

Aleksandra Cerović, Nikola Divac, Marko Ćurčić, Anica Jovičić, Miodrag Popović

Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Pinosava, Belgrade, Serbia
(corresponding author: nikola.divac@jcerni.rs)

Article history:
Received: September 16, 2022
Revision: September 19, 2022
Accepted: September 22, 2022

Abstract: This paper presents the overview of the principles of design and construction of tunnel sections of the large sewage collectors in urban areas. Various geological conditions along the route, space occupation, heavy traffic, existing underground and above-ground installations, and numerous existing facilities, represent conditions that must be considered as criteria and limitations for design and construction concepts. These conditions, along with the specific conditions related to the choice of construction technology, represent the basis for the creation of methodological processes whose goal is the collection, unification and expert analysis of all data that can be used in various phases of design and construction. The paper presents methodological procedures that were applied during the design and construction of the tunnel sections of the Interceptor sewerage system in Belgrade, and in particular their use in the stress-strain numerical models.

INTRODUCTION

Designing large-scale sewage infrastructure systems in modern cities, implies dealing with numerous limitations that affect the selection of technical solutions, dynamics, and construction costs. Considering current trends in smart cities design, with an accent on underground urban space, the subject of urban tunnelling is even more in focus [1]. Technical solutions often require use of tunnelling techniques to deal with urban environment constrains, and furthermore Tunnel Boring Machine (TBM) technology is often called for as the most effective solution [2].

Primary design limitation of Belgrade Interceptor Project is represented by the downstream boundary conditions defined by the elevation of the final wastewater discharge destination, location of the wastewater treatment plant, the priority restriction concerning the hydraulic engineering principles itself (which imply that if there is a need to pump wastewater it is optimal to pump the water either at the entrance or at the tunnel exit) and the already built sections of the sewage system, to which the new sewage network is to be connected. Another type of limitation is the existing infrastructure (water supply, electric power, telecommunication, traffic, gas pipelines, etc.). The existing infrastructure is mostly placed at shallow depths in urban areas, which requires the planning of new sewage collectors at greater depths to avoid crossings and relocation, and hence additional work, costs, high possibility of damage to the infrastructure and interruption of service.

Lastly, existing urban architectural solutions, cultural monuments and other protected asset are most often positioned in the city centre in densely populated areas, thus representing limitations in the positioning of collectors [3]. Consequently, there is often very limited space and area for construction sites needed for large city collectors.

Meeting the criteria, tunnelling is generally the optimal construction method of the large-diameter collectors at greater depths in urban areas, especially in urban conditions and the terrain configuration that is characteristic of the city of Belgrade, which is rather hilly type. As to choosing of the tunnelling technology, multiple approaches are considered for different sections of the system with most of them designed to be excavated and built with TBM technology.

As part of this paper, on the example of the central sewage system of the city of Belgrade - Interceptor, a review will be given of the methodology for calculating tunnel sections, strategy for selection of geotechnical and monitoring data, as well as correlation and importance of this data for numerical simulations of TBM tunnelling that has been imposed as the optimal solution for the main city collectors, with the example of previously built sections.

PARTICULAR FEATURES OF THE PROJECT INTERCEPTOR-WWTP VELIKO SELO

The City of Belgrade does not have an adequate solution to the issue of sewerage and wastewater treatment. Central Sewerage System of the City serves about 1,200,000 residents of the central city municipalities, which covers about 85% of the area of the Belgrade Sewerage System.

All wastewater from the Central Sewerage System is discharged without treatment into the Sava and Danube rivers. The existing outlets are mostly located on the banks of the rivers in the wider area of the confluence of the Sava and the Danube, practically in the centre of Belgrade.

The concept of the development of the Central Sewage System is based on the construction of a system of main inlet collectors (Interceptor) and a wastewater treatment plant at the Veliko Selo location (WWTP "Veliko Selo").

The presentation of the scope of the Project is given in Figure 1 and in Table 1 below.

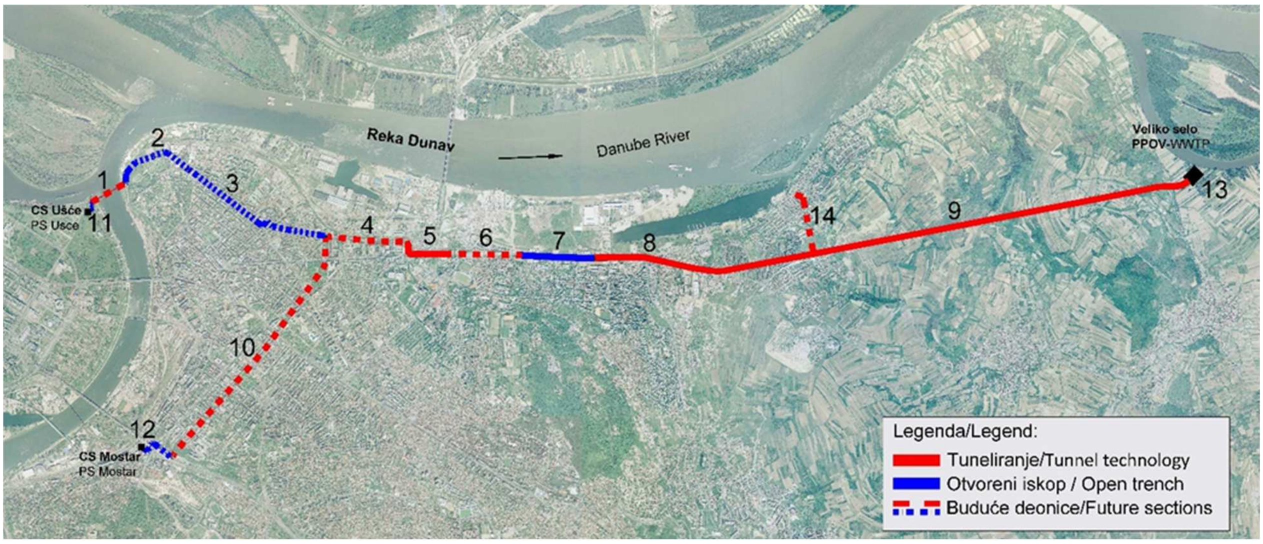

Figure 1. *Scope of the Project*

Table 1. *Scope of the Project*

Scope of the Project	Description	Construction technology
Section 1	Tunnel "Passage under the Sava River", two pipelines in a protective concrete gallery length aprox. 450 m	Tunnel (TBM)
Section 2	Pressure line along Donjogradski Bulevar, lenght aprox. 1010 m	Open excavation
Section 3	"Small Interceptor", length aprox. 1,810 m	Open excavation
Section 4	Tunnel "Extension of Interceptor", length aprox .940 m	Tunnel (TBM)
Section 5	Extension of the Interceptor along Višnjička street, aprox. 524 m long (existing part)	Built section
Section 6	Tunnel "Karaburma", length aprox. 860 m	Tunnel (TBM)
Section 7	Tunnel "Karaburma", length aprox. 780 m (existing section)	Built section
Section 8	"Višnjica" tunnel, length aprox. 933 m (existing section)	Built section
Section 9	"Višnjica" tunnel, length aprox. 5,839 m (existing section)	Built section
Section 10	Tunnel "Hitna Pomoć- Venizelosova", length aprox. 3,080 m	Tunnel (TBM)
Section 11	SPS "Ušće Nova"	Above-ground building
Section 12	SPS "Mostar"	Above-ground building
Section 13	WWTP "Veliko Selo" including inlet and outlet collectors and facilities (capacity aprox. 1.500.000 PE)	Above-ground building
Section 14	Tunnel "Mala Višnjica", lenght aprox. 680 m	Tunnel (NATM)

Existing collector sections of the Interceptor, built in the period from 1980-2012. are the "Interceptor Extension", the "Karaburma" tunnel and the "Višnjica" tunnel, with a total length of over 8,000 m and representing the most downstream sections of the Interceptor (Sections 5, 7, 8 and 9).

To these constructed tunnel sections, it is necessary to connect the newly designed, i.e. missing sections of the Central Sewerage System of the City of Belgrade. The full functionality of the Central Sewerage System of the City of Belgrade and the establishment of the wastewater treatment system will be achieved after the construction of the "Passage under the Sava River", the "Interceptor Extension" tunnel, the "Karaburma" tunnel and the "Hitna Pomoć - Venizelosova" tunnel (Section 1, 4, 6 and 10), as well as the construction of the "Small Interceptor" collector, intended for excavation in an open trench in Cara Dušana Street (Section 3).

In this paper, an overview of the design methodology of the tunnel sections of the Interceptor is given, with an emphasis on geotechnical investigation works, observation program and elements of numerical modelling, with a selected presentation of experiences in these aspects from the previously performed TBM (Tunnel Boring Machine) sections.

SCOPE AND TYPES OF GEOTECHNICAL INVESTIGATION WORKS

According to the recommendations of the International Association for Tunnelling and Underground Space (ITA) [4], given as part of the Strategy for tunnelling project investigations, the first step is the proper selection of relevant data, because of the analysis of the geotechnical conditions of the project, with an understanding of the general geology, character, and previous area purpose, in relation to previously acquired knowledge of the area. The work program is defined as to provide this data using the most appropriate method, with the possibility of adapting to unforeseen situations in the field. The main objectives are preparation of the appropriate design of the tunnel and accompanying underground facilities, verification and adjustment of the execution technology, identification of difficulties or risks that may arise, assessment of potential mitigation measures, assessment of the impact on the environment, existing facilities, and the local population.

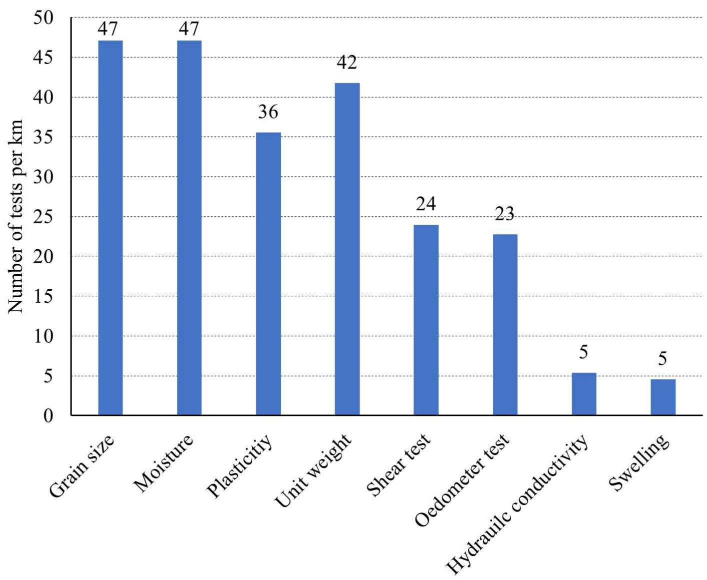

Figure 2: *Overview of investigation works for soil testing per km of tunnel*

Components of geotechnical investigation works are:

- Desk study, which consists of the collection and analysis of existing data, topographical, geological, seismic, hydrological, and other bases and maps, data on the occupation of areas above the route and in the influence zone of the tunnel excavation.
- Geological terrain mapping, determination of geotechnical units.
- Investigation works: boreholes drilling, in-situ testing, geophysical tests, topographical survey, survey of buildings and foundations, installations, infrastructure.
- Laboratory tests: identification and classification of materials, tests for determination of mechanical and physical parameters of materials, groundwater chemistry.

- Systematization of results and presentation of geotechnical construction conditions.

The type and scope of geotechnical investigation works for the tunnel sections of the Interceptor were defined considering the degree of previous exploration of the terrain. The fund of available data on previous investigation works is of significant scope and level of detail. In relation to that, a program of investigation work was defined, which includes the required elements to produce high-quality geotechnical data for the design and construction of tunnel sections. The program of exploration works is in accordance with the Law on Mining and Geological Research, domestic legal and technical regulations, as well as current international practice [4] [5]. When defining the program of works, an additional limitation for the execution of investigation works is the occupation of areas in an urban environment.

The investigation works refer to the new tunnel sections (1, 4, 6 and 10), with a total length of about 5400 m.

The extent of geotechnical investigation work, quantified as the number of laboratory tests per kilometre of Interceptor tunnel section length, is shown in Figures 2 and 3, for soil and rock mass tests, respectively. Table 2 shows the types of investigation work performed in-situ, as well as the number of performed tests.

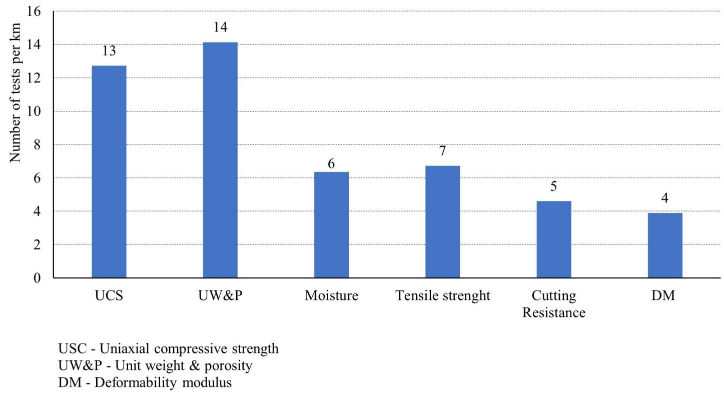

Figure 3: *Overview of investigation works for rock testing per km of tunnel*

Table 2. *Overview of in-situ tests*

Type of in-situ test	Number of tests
Probing dilatometer	8
Seismic tests "down hole"	6
Seismic refraction tests	3
Deformability testing with a pressuremeter	2
In-situ water permeability test	8
SPT	32
CPT	6

The data of investigation works correspond to the world-wide experiences [5], noted they are adapted to the requirements of the specific project of the Interceptor tunnel sections.

Detailed knowledge of the parameters of geotechnical categories enables the possibility for adequate modelling of the environment and the mutual relationship between the environment and the tunnel lining, as well as the appropriate specific requirements related to the TBM and its advancement. Based on the results of laboratory and in-situ research, the values of the parameters of the constitutive models are defined [6], describing the mechanical behaviour of the rock mass and soil. An illustration of the example of a pressuremeter test, from which the deformation and elasticity moduli are obtained, is given below (Figure 4).

Based on the geological and geotechnical documentation and through a detailed analysis some possible problems during the construction of the tunnel can be foreseen, e.g., possible appearance of high pressure on the tunnel liner. If there are sections along the route of the tunnel with a low bearing capacity of the surrounding rock, it is possible that during the excavation there will be significant pressures on the lining, convergence, and an increased plasticized zone around the excavation. The consequence of this can be overloading of concrete segments or even jamming of the TBM machine [7].

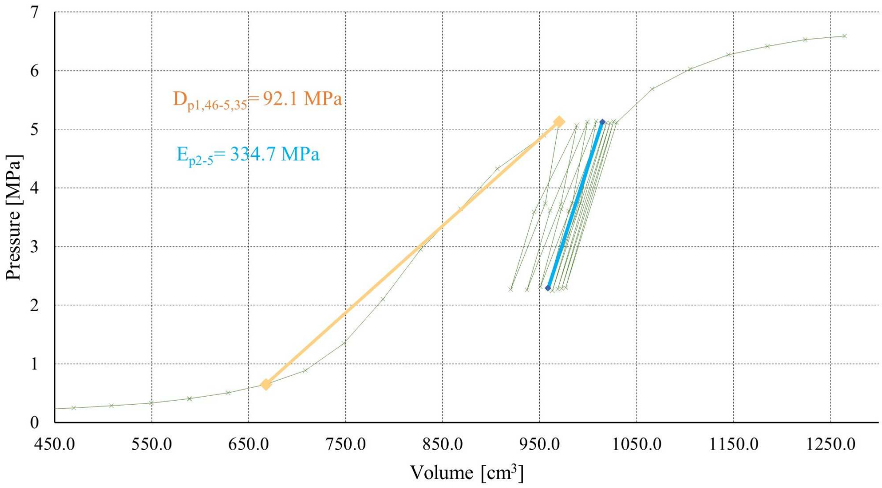

Figure 4. *Illustration of in-situ pressuremeter test results*

The level of accuracy and the quality of the results of geotechnical investigation work is in direct proportion to the accuracy of the calculations, considering it is the key input data for all tunnel calculations. In the case of TBM technology, the situation is even more complexed, because based on geotechnical data, the TBM type is selected and the basic parameters of the machine are defined, including thrust force, torque, cutting resistance, pressure on the face of the excavation and injection pressures. Geotechnical investigations should also provide a whole range of information needed for modelling during calculations, e.g., layering of the terrain, physical and mechanical characteristics of individual layers, hydrogeological characteristics, etc., therefore representing the basic input data for all calculations.

The results of geotechnical investigations are closely related to the Tunnel Monitoring Design [8], because the selection of measurement profiles is made based on the defined geotechnical environments. It is very important to make such a selection of measuring profiles that will represent all the different geotechnical sections, characterized by their geological conditions, expected loads, etc. Each geotechnical category is represented by at least one measurement profile.

MONITORING

According to [8], measurements and observations during tunnel construction aim to fulfil:

- Checking of calculation assumptions made during design,
- Making possible to take timely measures to adapt tunnel excavation to actual conditions,
- Monitoring the state of the tunnel during exploitation.

The results of instrumental measurements should enable the following data to be obtained [8] [9]:

- The position of the zone around the tunnel that is affected by disturbances in the rock mass,
- Size and trend of deformation development in the rock mass around the tunnel opening as a function of time,
- Magnitude and development trend of stress at the contact of the rock/soil and the lining, stress in the lining,
- Magnitude and trend of development of tunnel lining deformations (convergence, strains, displacement),
- Magnitude and trend of development of deformation on the surface of the terrain - subsidence and rotation, possible heave,
- The magnitude and trend of changes in external factors (temperature of water, air...), which can affect the state of the tunnel in operation,
- Groundwater level.

Measuring points outside the tunnel consist of a system of benchmarks installed on existing buildings, on sidewalks and road surfaces, and vertical inclinometer boreholes. In addition, the measuring system consists of a series of measuring instruments and measuring points that are placed inside the tunnel itself: convergency reference bolts for measuring convergence, strain gauges in concrete, rock extensometers, fissuremeters, pressure cells, pore water pressure cells.

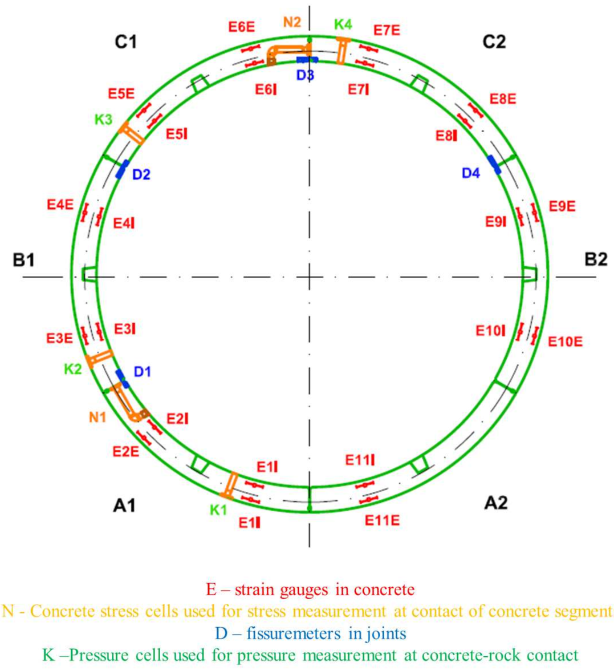

Figure 5: *Layout of measuring points in tunnel cross-section*

Monitoring of Parameters for TBM Work Coordination

In the case of TBM tunnelling, it is necessary to define and monitor operational parameters of TBM, which are the basis for the functioning and coordination of the TBM tunnelling process. The main set of data is the following: pressure at the face of the excavation, grouting pressure, soil/rock pressure on the machine shield, overcut size, press pressure. In the assembly of the TBM, there is a whole series of measured values that are necessary for the proper and safe operation of the machine, but not listed here because it is beyond the scope of this paper.

Observations and monitoring of following parameters: pressure on the face of the excavation, injection pressures, excavation, and compression pressure, are in conjunction with the geotechnical conditions of tunnelling and the modelling methodology. The measurement results represent input data for back-analysis and at the same time confirmation of the calculation methodology and assumptions about the geotechnical conditions.

Special Requirements for Urban Tunnelling Monitoring

Special requirements set within urban tunnelling projects include strict criteria for limit displacement of existing structures. In the case of exceeding one of the permitted criteria, it is necessary to undertake timely activities to strengthen and reconstruct such objects, so that no damage occurs during the construction of the tunnel. In such conditions, proper monitoring and analysis of deformations is of key importance, both in the design phase and during the execution of works. The correct application of monitoring enables timely taking of necessary measures in case of unexpected circumstances, which are not rare during tunnelling works.

The instruments are installed according to the schedule defined within the Tunnel Monitoring Design, for each section separately, so that a set of relevant results is obtained. The data is monitored during the progress of the excavation, in the influence zone, defined in the direction and perpendicular to the direction of the tunnel. The results are relative displacements, in relation to the reference point, or the referenced direction. These displacements are monitored during the progress of the excavation.

For a correctly defined plan for observing the deformations of the terrain surface, first step is to define the zone of influence of the tunnel construction and define all objects located within this zone. Then, it is necessary to assess the potential risk of damage due to ground movement during tunnel excavation, based on some of the assessment methods given in the reference literature [10].

After determining the degree of damage risk, structures evaluated as important or risky are defined. Risk classification is performed based on empirical formulas and diagrams derived from the analysis of cases of subsidence and resulting damage.

According to Boscardin and Cording (1989) [11], the category of possible damage to masonry structures is defined as a function of limit tensile strain, according to Table 3.

Table 3: *Damage categories [10]*

Category of damage	Degree of severity	Limiting tensile strain (εlim) (%)
0	Negligible	0 - 0.05
I	Very Slight	0.05 - 0.075
2	Slight	0.075 - 0.15
3	Moderate	0.15 - 0.3
4 to 5	Severe to Very Severe	> 0.3

Limit tensile strain is defined as a function of the horizontal movement of the ground, because of the excavation convergence.

In practice, the approach proposed by Burland and Mair (1996) [12], which classifies possible damage to structures based on the ratio of rotation and horizontal displacements, is often and successfully used, as shown in Figure 6.

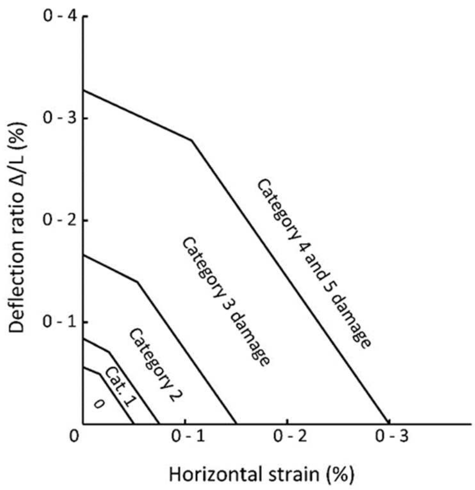

Figure 6. *Damage category [12]*

For identified structures, an observation plan is defined, which includes the type and arrangement of instruments and the time schedule of observation. According to the recommendations given in [11, 13], a number of authors propose the following classification: structures in categories 1 and 2 are not of the interest for further monitoring, while structures in categories 3 and 4 require a detailed monitoring program. For category 5, before the start of tunnelling, the structure must be adapted so that it can withstand additional loads caused by tunnelling, which includes strengthening the structure and foundation, or reconstruction of the object to the required extent.

CALCULATION METHODOLOGY AND USE OF NUMERICAL MODELS

Tunnelling with TBM is a complex process which integrates several aspects of classic tunnelling method, with addition of phenomena specific to TBM:

- Simultaneous excavation and progress of the machine
- Stabilization of the excavation face with pressurized earth or bentonite slurry (present in Pressure Balance type of machines)
- Formation of overcut and stabilization of over excavation with grouting fluid and bentonite slurry
- Formation of prefabricated segment rings beneath shield protection and its mobilization achieved by machine transition.

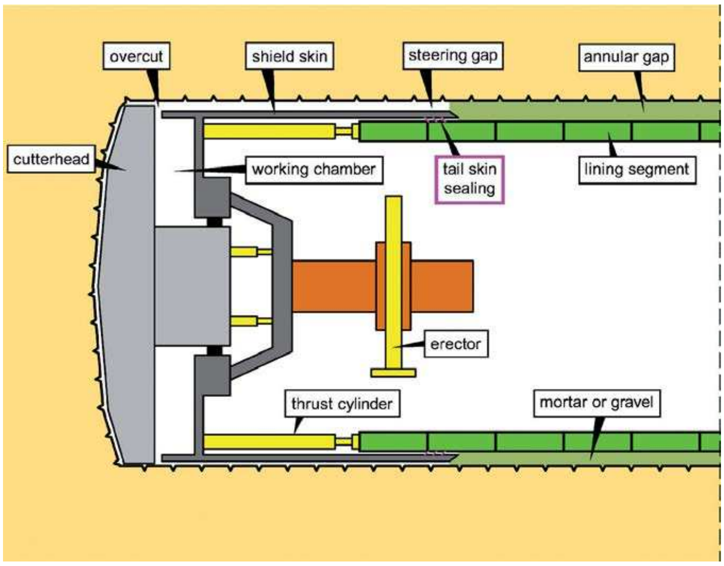

Figure 7. *Schematic view of most important parts of SPB (Slurry Pressure Balance) machine type [14]*

Processes that have been described can be different to a degree, in dependence to the machine type. Nevertheless, they are used to illustrate the importance of harmonizing all the activities inside the machine and their significance on TBM tunnelling approach.

Designing of support structure and formulating the criteria that machine assembly must meet, and then designing the machine itself, is an elaborate task. In course of demonstrating viability of proposed solutions and assumptions, variety of numerical methods and models are used for the purpose.

Depending on the challenge that the model is supposed to tackle, a different numerical approach may be used. Some are based on Discrete Element Method (DEM), others on Finite Element Method (FEM).

DEM is primarily used to simulate mechanisms that are deployed inside machine cutter head. Key considerations of these calculations are interaction of [9]:

- Rotational force (Torque)
- Pressure inside cutter head chamber
- Thrust forces (progression speed of the machine)
- Rotational speed of screw conveyer (discharge rate of excavated muck), etc.

These models are essentially only used to simulate very specific parts and operations of a machine. They are useful in optimizing these operations and subsequently for defining a set of rules that will guide machine driving, be it manual or automatic.

FEM is more commonly used approach when precise modelling of operations inside machine are not essential in simulation. This is especially true on large scale models where most of the interest regarding the machine are based on its geometrical characteristics, such as diameter, shield length, conicity and overcut. Focus of these models is put on broader area of interaction between surrounding soil, tunnel support structure and other structures of importance.

It is common to conduct prediction calculations before construction begins. Such analysis is called Class A prediction. Calculations are then revised or verified during and after tunnelling (Class B and C predictions), based on corrected model assumptions (geotechnical data, machine operation) and often using the monitored data that is collected through the process of tunnelling [15].

3D Tunnelling simulation using FEM

Tunnelling is in principle three-dimensional problem, with excavation face advancing progressively and lining getting erected behind it. This implies the usefulness of 3D models, which became common due to availability of commercial software and computational resources.

Tunnelling technology, as explained, has very significant effect on soil reaction to excavation, as reflected in soil settlement, stress-strain field, as well as support structure of the tunnel. When TBM is used, all of technology is related to characteristics of the machine assembly. In order to simulate a tunnelling routine, it is crucial that all the important processes and phenomena are considered and formulated into the model. The most important of them are:

- Excavation volume loss
- Injection pressure grouting
- Excavation face pressure
- Thrust forces acting on segmental ring lining.

Further descriptions of these processes and phenomena that occur with them are given below, as well as possibilities on how to approach them in finite element modelling.

Excavation volume loss

Shield of the machine is usually constructed in conical shape so that diameter at the face of the machine is larger than on the tail. This is done so that forces acting on shield of the machine are reduced, and space is given for the manoeuvrability. It allows machine to move itself with lesser thrust forces in hydraulic jacks that are pushing off concrete lining.

Besides conical shape of the shield, another factor that amounts to overall excavation area is due to cutterhead overcut. Often retractable knives are incorporated into machine cutterhead with the purpose like that of a conical shape, and that is to relieve shield of the machine of excessive forces and increase manoeuvrability. In addition, over excavation can be done in an eccentric manner so that overcut is larger (for example on upper vault) in some zones of the tunnel face.

Difference in excavated volume and final tunnel volume (defined by concrete segment ring geometry) is increased by another gap between outer diameter of the tail of the shield and outer diameter of segmental lining.

All these gaps may or may not be accounted for in numerical calculations, bearing in mind that volume difference is mostly replaced by either grout injected on the back of the shield or pressurized slurry on front of the cutter head.

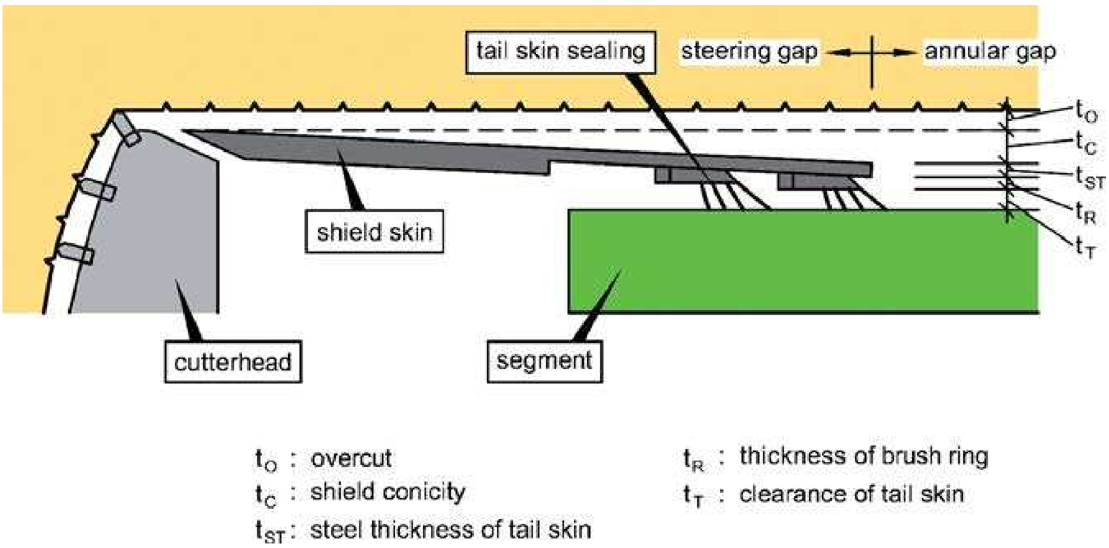

***Figure 8**. Excavation area and gaps that occur during TBM tunnelling [14]*

Shield is usually modelled as two-dimensional shell (2D elements) using linear elastic material model. Appropriate parameters such as weight and rigidity are assumed, but not for the purpose of calculating stress-strain field of the shield, which is irrelevant for these kinds of calculations.

Movement of TBM and face excavation is progressing in steps with the length of step corresponding to the length of the segment. This step length is usually used in numerical calculations when discretizing movement and defining sets of routines, which simulate the advancement of the machine. Routines are made so that tunnelling processes are "moved" in steps inside the model space and in this way simulating excavation advancement.

Each step can account for certain amount of time, which can be taken into consideration for processes that require such information, such as grout hardening.

Movement of the TBM shield is therefore achieved by activating shield elements in front of the excavation, while deactivating soil elements representing the excavation done by the machine. At the same time tail elements of the shield are deactivated.

Routine must also include all the other important processes, most importantly injection grouting, face pressure and concrete lining activation for which more will be said later.

Number of steps necessary to define all routines that describe machine movement through soil depends mostly on ratio between shield length and step length, but also on how processes that are happening in front and behind TBM shield are defined.

Commonly used approach in modelling gap between shield and surrounding soil is by using surface contraction on 2D shield elements (or volume contraction on 3D elements). Radial deformation is induced by introducing tangential contracting deformation in shield elements. These deformations should account for either conicity or overcut gap, or both. Conicity gap routines are formulated in such a way that for any given section, deformation is achieved gradually from the front of the shield to the back of it (starting from zero to at most 1% surface contraction of the machine section area, for most of the machines).

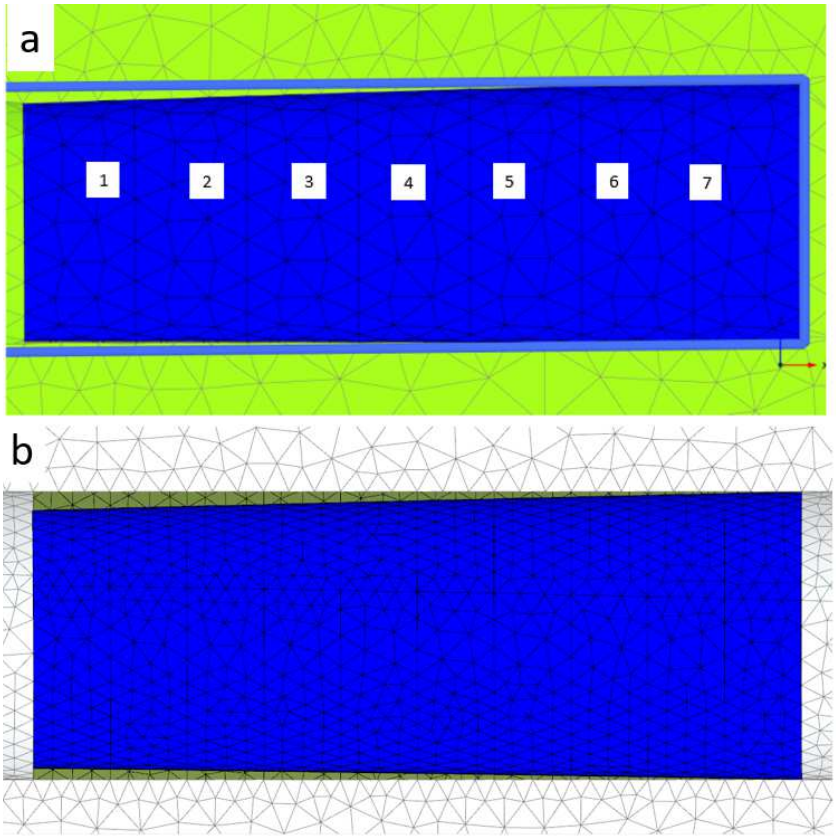

Figure 9. *Discretization of steps and conicity of shield: a) Deformation of shield elements in weak soil which are same as soil deformation b) Deformation of shield elements in strong soil which are not the same as soil deformation*

Deformed mesh of a model around shield can be seen in Figure 9. Deformations are scaled up 20 times for better visibility. Gradual deformation of the shield elements can be observed depending on calculation step of the defined contraction routine.

Contact between shield and surrounding soil (also between concrete segments and soil) is modelled with interface elements. These elements double the number of nodes on contact by duplicating existing nodes and establishing numerical relations between them, allowing for difference in deformation of soil elements on one side, and concrete and shield elements on other.

Another approach in modelling overcut and conicity uses thin layer of elements with "softened" parameters and then limits their deformation by allowing only certain amount (width of gap).

Adopting either approach is a matter of designer’s choice and availability of numerical tools.

Injection grouting

All the gaps are filled with grout that is injected under pressure at the tail of the machine. Grout goes through the process of hardening, effectively transferring load from soil to concrete structure and preventing excessive displacements.

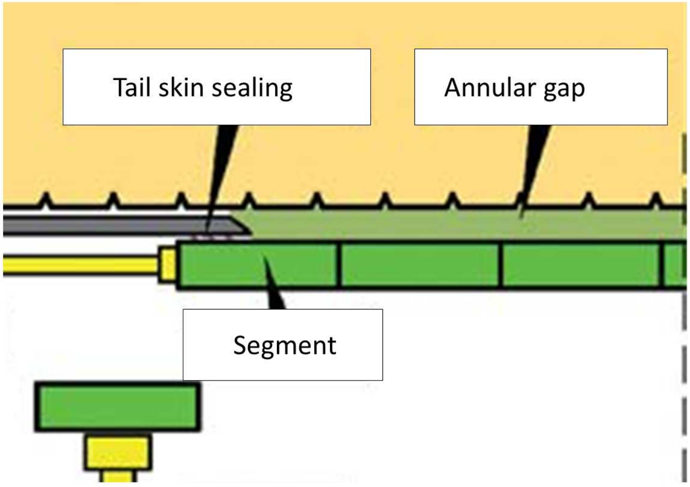

Figure 10. *Schematic view of grouting process [14]*

Grouting process is modelled in one of two ways. In less detailed model, only surface load perpendicular to excavated wall is used. Intensity of the load matches that of an injection pressure. If this method is used, the grouting only acts as a stabilizing component during injection of grout and immediately behind shield. Physical and mechanical properties of the grout are not taken accounted for, nor the time relevant in achieving these properties.

Another approach is to use physical elements to represent a layer that surrounds concrete liner. They are usually time dependent which can be easily incorporated into calculation steps as a routine. Solidifying of grout can be modelled in this manner by changing mechanical properties through calculation steps.

Excavation face pressure

Most significant characteristic of a Pressure Balance (PB) type of machine is that it continually provides pressure on the excavation face. This pressure is modelled as surface load that acts perpendicular to the cutterhead face. Intensity of the pressure is very important in controlling soil displacement. Defining this pressure is often one of the main purposes of the model, with prediction analysis often giving significant sensitivity of results in response to change in face pressure. Desirable pressure is closely related to overburden above tunnel and water level, but also other geotechnical properties of the soil (layering, mechanical properties, initial stress, etc.)

During excavation, Class B prediction analysis along with monitoring data give basis for machine operation and adjustment of pressure inside pressure chamber.

Prediction analysis after excavation is done (Class C) give valuable information and knowledge about choice of calculation parameters and modelling of processes overall [15].

Thrust force

Machine progresses through soil by getting pushed with hydraulic jacks acting on the back side of the shield (Thrust cylinders). Concrete lining represents support that jacks push against, extending themselves and subsequently moving shield of the machine with cutterhead.

Force which is used to move the machine depends on forces acting on the shield, speed of progression, cutting resistance of the soil, etc. Maximum forces that can act on the segments is limited by the hydraulic capacity of the cylinders (number of cylinders, pressure inside cylinders and section area of cylinder). Maximum force, together with the eccentricities of TBM thrust shoes on the lining induced by the shield drive [16], is used as parameter for determining design of the segments.

Dimensions of three-dimensional FEM model

Tunnels are, in linear nature of their function, of elongated shape. Model that would be able to simulate excavation and construction of such structure in whole would be in most cases very exaggerated length dimension. For the risk of disproportionality and oversizing of the model, it is typical to divide tunnel into sections and model each of the sections independently. Deciding upon number of sections to be modelled is influenced by various factors.

One of the most important is the purpose of the model. If main aim is to investigate influence of tunnelling on any structure in proximity to the tunnel (either underground or on surface) then focus should be put on defining an interaction zone between these structures. When only stress-strain calculations are done, rarely do these zones exceed double or triple the size of the object itself.

If, on the other hand, the goal is to design and optimize structure of the tunnel then it may be purposeful to analyse larger parts or even complete length of the tunnel. As rationalization measure it is common to divide tunnels into sections and group these sections so that all the sections in one group share geotechnical features and tunnelling routines which can then be represented by one numerical model.

Models are of a rectangular shape as a rule because it allows for easier formulation of boundary conditions. It is best to keep all three dimensions of the model in similar proportions, though it is not uncommon that tunnel models tend to have length dimension several times greater than width and height dimensions of the model.

EXPERIENCES FROM DESIGN AND CONSTRUCTION OF SECTIONS 8 AND 9 – "VIŠNJICA" TUNNEL

Monitoring of the "Višnjica" Tunnel

The 6.8 km long tunnel passes through complex geological conditions, with very heterogeneous properties and with a wide range of geomechanical parameters. The height of the overburden is also variable, from about 6 to 200 m. These circumstances caused the tunnel to be constructed using a TBM (Tunnel Boring Machine), i.e., by the EPB mechanized shield method.

The tunnel has a circular cross-section, with an inner diameter of the concrete tunnel lining of 4.1 m and an outer diameter of 4.6 m. The lining of the tunnel is segmental, consisting of 6 parts, with a constant thickness of 24 cm.

It is a very complex object, with a wide scope of works and numerous non-standard problems in the field of monitoring [8].

The chosen technology of tunnel construction (using a TBM machine), according to the geological conditions along the route, imposed limitations in terms of design and performance of technical supervision. The working disposition of the machine is such that during the actual excavation it was not possible to install instruments for observation. Thus, that for a certain period of time immediately during and after the excavation in the selected measuring profile, it was not possible to perform measurements until the entire composition of the TBM machine had passed (about 120 m). Depending on the speed of progress, this means that measurements in a measuring profile could only start about a week after the excavation in the profile itself. In this way, the most important, initial information about the interaction between the installed tunnel lining and the rock would be missing. In order to overcome this deficiency, the so-called "early" measurements on instruments that were installed in the segments during concreting and were connected to the measuring point outside the TBM composition by cables immediately after the assembly of the segments.

In addition to the limitations related to the measurement start time, the selected technology also imposed limitations regarding the installation of the equipment. Given that the tunnel lining is prefabricated, segmented, instruments were selected that are of such dimensions and characteristics that they can be installed in the segments during or after the production of the segments themselves.

The mentioned limitations, which refer to the possibilities of observation inside the tunnel, imposed the need to foresee measurements that can be made from the outside, from the surface of the terrain, and which also provide information on the interaction of the rock/soil and the tunnel lining.

The measurement of ground subsidence on the tunnel route is of interest in the sections where the depth of the overburden is relatively small and where there are residential and other structures on the surface. In this context, the section that represents the urban area of the city towards Višnjička banja is of interest. Geodetic measurement on the surface of the terrain is therefore planned for this part.

Measurements and observations were made in specific, previously selected profiles along the tunnel, called measurement profiles. Measuring instruments are grouped in measuring profiles, so that one profile contains several types of instruments. The type and scope of measurements at measuring profiles are different and related to the geotechnical unit in which they are located. A total of 23 measurement profiles were selected.

The following data were measured at the Višnjica tunnel [8]:

- Excavation volume loss,
- Convergence,
- Relative displacement in the rock mass around the tunnel,
- Inclinometer measurements in existing boreholes,
- Strains in concrete segments,
- Stress at the concrete-rock contact,
- Stress at the joints of the concrete lining segments,
- Displacement at the joints of the concrete lining segments,
- Groundwater pressure on the lining and pore pressure,
- Concrete temperature,
- Air temperature,
- Water temperature,
- Geodetic measurement of displacement on the terrain surface.

For all these measurements, except for geodetic surveys, convergence measurements and measurements from the terrain surface, electric instruments with remote reading were used. This allows monitoring the specified data even after the tunnel is put into service.

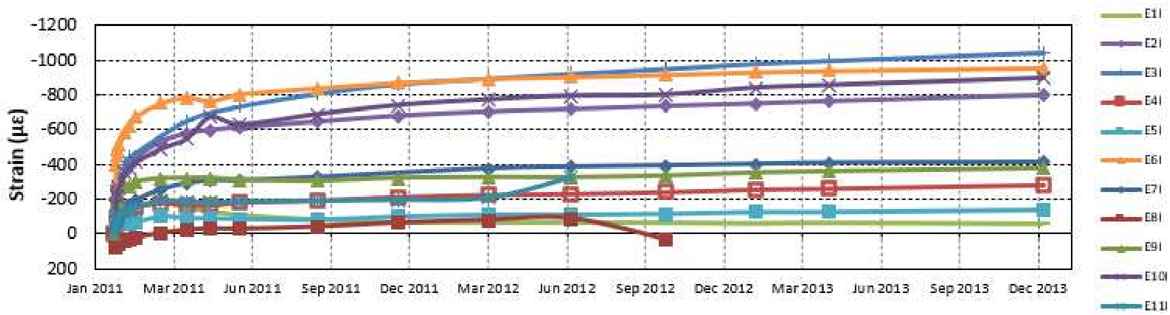

Figure 11. *Diagram of the concrete lining strains change over time*

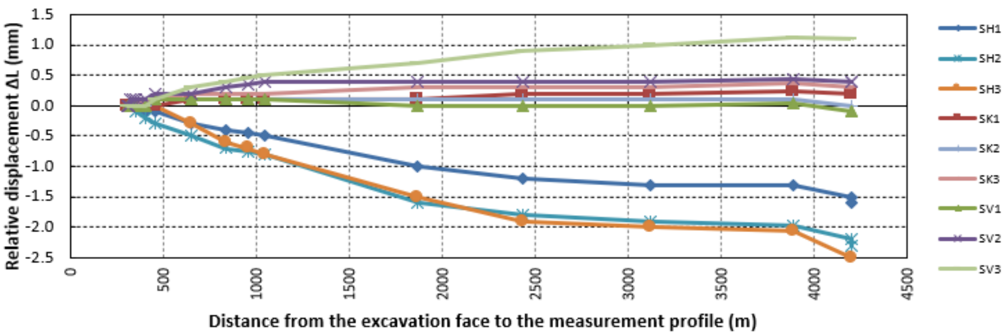

Figure 12. *Diagram of the relative displacement of the rock mass around the tunnel depending on the distance of the excavation face from the measurement profile*

During the monitoring of the "Višnjica" tunnel during construction, it was observed that with the progress of the excavation, the behaviour of the lining first shows a faster and then a slower asymptotic growth of all measured data from the moment of installation of the instruments in the tunnel onwards, with a trend of stabilization of displacement, stresses and other data.

Measurements of convergence and displacement at the joints of concrete segments showed that there was no significant change in the geometry of the tunnel lining, which would threaten its stability. Most of the measured displacements at the joints are expected to take place in the first few days after the concrete segments are installed in the tunnel. The measured sizes of concrete expansions and pressures in the concrete lining are significantly smaller than the limit expansions and compressive strength of concrete segments.

Calculation models and monitoring

According to [3], the pressures on the TM shield and the tunnel lining are calculated using analytical (E. Hoek, 2003) and numerical methods 2D and 2D+ (Phase 2-RockScience). The analysis was done considering the range of parameters of the geotechnical conditions, the overcut and the injection pressure. Figure 13 shows an example of a comparison of analytical and numerical calculation results in a characteristic profile for a overcut of 5 cm.

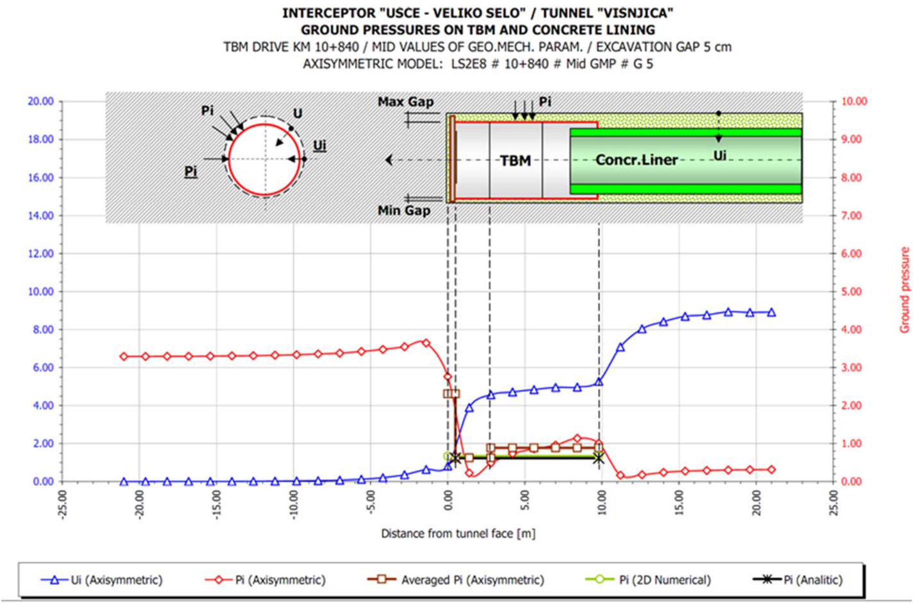

Figure 13. *Comparison of analytical and numerical calculation results: Convergency and pressure at chainage km 10+840, overcut 5 cm [17]*

A detailed analyses were made to assess the possibility of TBM jamming due to reaching the limit pressures on the shield of the machine. Based on this, the predicted critical frictions were calculated (Figure 14) and the appropriate excavation mode was recommended.

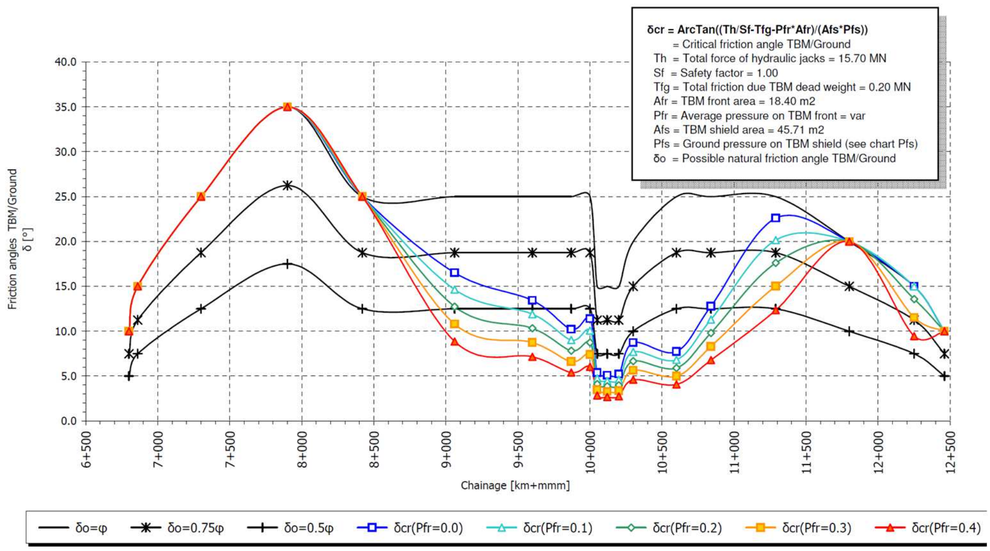

Figure 14. *Estimate of critical friction for TBM jamming in case of independent front and tail shield movement [17]*

For monitoring the pressures on the TM shield during excavation, measuring cells are placed on the shield itself. During the excavation, an analysis was made of the results of forecast and measured pressures on the shield, shown in Figure 15.

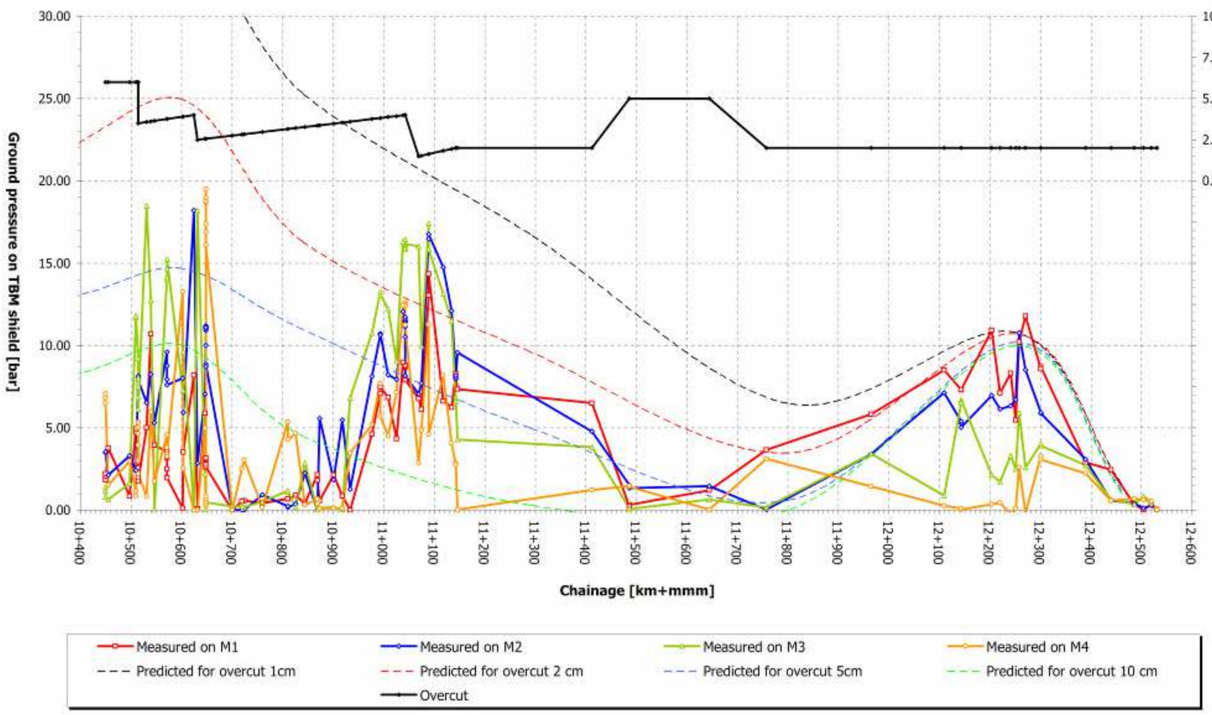

Figure 15. *Measured versus predicted pressures on TBM shield [17]*

CONCLUSION

Densely populated areas require expansion of infrastructure that has no other space, but to be placed underground. This is especially true for wastewater collectors. Challenges on building this infrastructure are related to ensure quality of life for people populating these areas, which requires control of noise, dust and vibration.

As urban areas keep growing in number, so will the need for pressurized face TBMs excavating tunnels for various infrastructure projects: transit systems, rail, sewer networks, highways, power distribution and other functions [3].

The paper presents a methodological approach to the subject of designing tunnel sections in urban areas where there are various limitations in the form of existing infrastructure, existing buildings, cultural monuments, etc. The methodology implies a complex approach based on the collaborative use of various data domain.

Comprehensive geotechnical investigation designed for particular ground and boundary conditions is accompanied by expert interpretation of data. Geotechnical investigations include results obtained during construction works, which are to be used for verification of design.

Instrumentation and monitoring are essential part of the tunnelling project, for several reasons: verification of design, safety control, quality control of construction, defining and correcting operational parameters of TBM, early warning system against potential failures. In stage after construction, monitoring results are the key for back-analyses.

3D numerical modelling is proposed as a contemporary tool for predicting, designing, and analysing upcoming tunnelling challenges of the project, while relying on past knowledge and experiences in TBM design as an invaluable resource. With enough geotechnical data collected through investigation works, careful assessment of risks in urban tunnelling that are more pronounced in upcoming sections, a more detailed modelling approach will certainly provide merits in successful conclusion of the project.

REFERENCES

[1] Peng, F.L. Qiao, Y.K. Sabri, S., Atazadeh, B. Rajabifard, A. (2021). A collaborative approach for urban underground space development toward sustainable development goals: Critical dimensions and future directions. *Frontiers of Structural and Civil Engineering*, 15, 20–45.

[2] Abdullah, R. A. Abdullah, A. (2016). A Review on Selection of Tunneling Method and Parameters Effecting Ground Settlements. *Electronic Journal of Geotechnical Engineering*, 21.14, 4459-4475.

[3] Kovari, K. Ramoni, M. (2004). Urban Tunnelling in Soft Ground Using TBM's. Lecture for International Congress on Mechanized Tunnelling: Challenging Case Histories Politecnico di Torino, Italy.

[4] International Tunnelling and Underground Space Association Working Group 2. (2015). *Strategy for Site Investigation of Tunnelling Projects*. ITA Report No15.

[5] Jakobsen, P.D. Babendererde, T. (2017). Pre-investigations for TBM tunnelling. Proceedings of the World Tunnel Congress 2017: Surface challenges – Underground solutions, Bergen, Norway.

[6] Radovanović, S. Rakić, D. Milivojević, N. Milivojević, V. (2014). Identification Parameters of Modified Cam-Clay Material Model Using FEM. Proceedings of the 5th International Conference Civil Engineering - Science and Practice, Zabljak.

[7] Tričković, M. (2012). Assessment of Risk of TBM Jamming during Construction of Hydro Tunnel in Belgrade, ITA AITES WTC 2012, Bangkok.

[8] Petrović, Lj. Tričković, M. Jovičić, A. (2009). Monitoring of "Višnjica" Tunnel in Belgrade. Monograph "Water resources management in Serbia '09" (p. 317-339). Belgrade: Jaroslav Černi Water Institute.

[9] Lee, H. Choi, H. Choi, S.W. Chang, S.H. Kang, T.H. Lee, C. (2021). Numerical Simulation of EPB Shield Tunnelling with TBM Operational Condition Control Using Coupled DEM–FDM. *Applied Sciences*, 11, 2551.

[10] Sonkar, S. Hayri, A. Singh, T. (2020). Deformational Behaviour of Ground and Control Measures in Urban Tunnelling. ITA-AITES World Tunnel Congress 2020 and 46th General Assembly, Kuala Lumpur.

[11] Boscardin, M. D. Cording, E. J. (1989). Building response to excavation -induced settlement. ASCE*, Journal of Geotechnical Engineering,* 115, 1-21

[12] Burland, J.B., Broms., B.B., de Mello, V.F.B. (1977). Behaviour of Foundations and Structures. Session 2. Proceedings of the 9th International Conference SMFE, Tokyo.

[13] Burland, J.B. Mair, R.J. Linney, L.F. Jardine, F.M. Standing, J.R. (1996). A collaborative research programme on subsidence damage to buildings: prediction, protection, and repair. In: Mair, R. J. Taylor, R. N. (Eds.). Proceedings of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, 773-778.

[14] Wittke, W. (1984). Rock Mechanics Based on an Anisotropic Jointed Rock Model (AJRM). New York: Wiley.

[15] Losacco, N. Viggiani, G.M.B. (2019). Class A Prediction of Mechanised Tunnelling in Rome. *Tunnelling and Underground Space Technology*, 87, 160-173.

[16] Kolić, D. Mayerhofer, A. (2009). Segmental Lining Tolerances and Imperfections. ITA WTC 2009 Symposium, Budapest.

[17] Tričković, M. (2011). Construction of Hydro Tunnel "Višnjica". Lecture for Serbian Association for Tunnels and Underground Structures ITA Serbia, Faculty of Civil Engineering, Belgrade. (in Serbian)

[18] TBM Tunnel Business Magazine. (10 Jun 2019). Cover Stories: Advances in Tunneling Overcome Challenges in Urban Areas. Retrieved from the website: https://tunnelingonline.com/advances-in-tunneling-overcome-challenges-in-urban-areas

Editors

Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20, 2022, Belgrade, Serbia

EDITORS
Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20 2022, Belgrade, Serbia

Publisher

Jaroslav Černi Water Institute
Jaroslava Černog 80, 11226 Belgrade, Serbia
www. jcerni.rs, office@jcerni.rs

For the Publisher

Prof. dr Dejan Divac, Director General

Editors

Prof. dr Dejan Divac

dr Nikola Milivojević

Prof. dr Srđan Kostić

Cover page design

Tanja Jeremić

Printing

M&G Marketing, Belgrade

Circulation

1000 copies

PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

CONTENTS

HYDROINFORMATICS SYSTEMS IN WATER MANAGEMENT

WATER AND UNDERGROUND STRUCTURES

WATER QUALITY MANAGEMENT

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

556(082)
626/628(082)

INTERNATIONAL Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute (2022 ; Belgrade)
Contemporary Water Management : challenges and research directions :
proceedings of the International Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute, October, 19-20, 2022, Belgrade, Serbia / editors Dejan Divac, Nikola Milivojević, Srđan Kostić. - Belgrade : Jaroslav Černi Water Institute, 2022 (Belgrade : M&G Marketing). - 430 str. : ilustr. ; 30 cm

Tiraž 1.000. - Bibliografija uz svaki rad.

ISBN 978-86-82565-55-0

a) Хидрологија - Зборници b) Хидротехника - Зборници

COBISS.SR-ID 76403977

9 788682 565550