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Control of EPB TBM tunneling parameters to mitigate the effects on Dambovita river structures

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Abstract. This paper presents an assessment of the impact of tunnelling of the M5 Metro line in Bucharest, and its associated risks on Dambovita river development located in the influence zone of tunnelling operation. During the metro performance the undercrossing of the hydraulic works related to the Dambovita River was required. The Dambovita River hydraulic development is made of 2 main components – the upper clean water channel and the sewage/drainage system cassette, placed below (the base slab of the channel representing the roof of the cassette). On the left river bank, the B0 collector is an old structure with uncertain technical condition Tunnelling in proximity of existing development introduces deformations in both structures and in turn induces additional axial and bending forces. In modern mechanized tunnelling, ground convergence is controlled through balancing the earth pressure at the tunnel face. Reducing ground deformation can consequently lower the additional deformations and forces and lessen the associated construction risk. In this paper, a detailed finite element modelling was performed to simulate the sequence of construction works. The model was calibrated based on the measured settlements behind the face. Based on model results the undercrossing area of influence is revealed. Recommendations regarding the tunnelling works are made in order to avoid any damages to the existing facilities.

Keywords: EPB TBM tunnelling, FEM model, surface settlements, undercrossing

1. Introduction

The increasing demand for new transport routes led to the need of improving the current Bucharest underground system. The control of ground movements induced

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by tunnel excavation in urban areas is a key issue of concern for designers and many techniques are used in practice to minimize the effect of the excavation on existing buildings. Therefore, the analysis of induced tunneling displacements on ground surface and at depth is required.

The impact of tunnel construction on existing structures has been investigated through field measurements on instrumented structures, as well as numerical modeling [1], [2]. Empirical methods have been developed on the basis of experimental data as to define the displacements field induced by tunneling in greenfield hypothesis. However, numerical analyses can be used when more complex situations have to be analyzed. Several Finite Element analyses have been performed, by Plaxis 3D Tunnel, in reference to the Line 6 tunnel in Naples in order to understand the soil behavior and to back-analyze the observed induced displacements [3].

On the basis of collected monitoring data concerning the ground and the buildings displacements, as the machine applied pressures (front and grout pressure), the real tunnel excavation process has numerically been simulated by means of construction stages. Moreover, parametric studies on soils parameters and machine pressures have been performed in order to observe their influence on induced displacements field, in terms of volume loss and maximum settlement at the ground surface.

A number of Finite Element Analyses has been performed with Plaxis 3D Tunnel, as to predict the tunneling induced displacements field and the role played by both soil and machine parameters on it. The monitoring data will then be compared with the numerical analysis results in order to verify and validate them simplified two-stage methods. The finite element method is getting more attention due to its generality and combined treatment of the problem.

One such model is presented in the current paper – the analysis of the M5 metro line tunnelling works and their effect on the hydraulic structures of the Dâmbovița River. The software was ANSYS, offering several advantages concerning the interaction modelling. A 3D linear-elastic model was built which encloses the entire interaction area and simulates the execution steps by activating and deactivating different sets of elements. The rate of advance was established based on the model results.

2. Structures involved

The development of Dâmbovița River (completed in 1988 [4]) is made of 2 hydraulic structures, placed one on top of the other – on the surface there is a clean water channel and beneath, a sewage/drainage system cassette (figure 1 medallion).

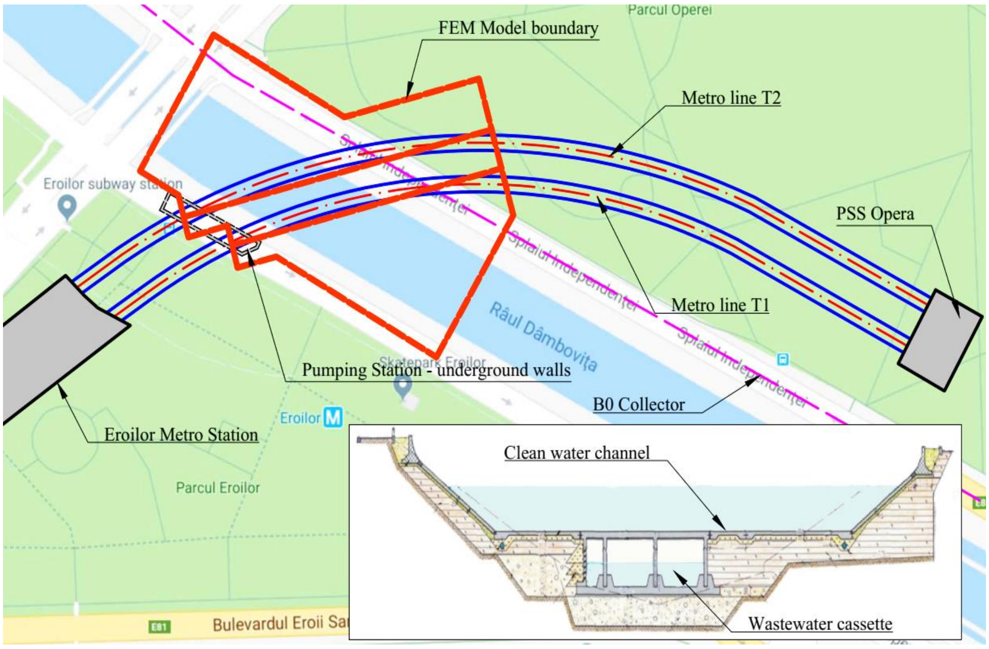


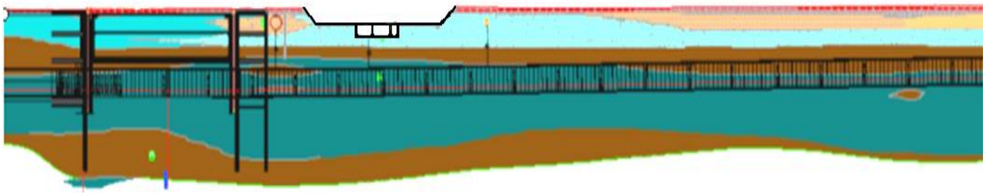
Fig. 1. Plan view of the undercrossing area and the Dambovita hydraulic structures (cross section).

The clean water channel is lined with concrete slabs in order to create a new river bed in downtown area. Its length is approximatively 17 km and it is divided into 10 sectors by flap-gated dams. The sewage/drainage cassette is situated underneath the clean water channel and is made of 3 covered, parallel chambers (the roof of the cassette is part of the base slab of the channel). It represents the main sewerage network component in Bucharest – 12 main collectors and 11 secondary collectors discharging into the cassette. It provides the gravitational water flow to Glina Wastewater Treatment Plant.

Along these hydraulic structures there are 2 main collectors – A0 and B0 (one on each side of the river). On the left river bank, the B0 collector is an old structure with uncertain technical condition. The collector has an ovoid shape (w/h – 1.10/1.65 m) made of plain concrete, padded with bricks in the lower part.

Tunnelling works are located in Dâmboviţa's floodplain area which is characterized by the geological profile in figure 2.

The hydrogeological conditions of the site are characterized by the presence of 2 aquifers: the Colentina aquifer (the upper one) separated from the Mostiștea aquifer by a thick layer of clay. The piezometric elevation of the upper aquifer is situated between 2 and 8.50 m under the surface level, meaning that the tunnelling works will be executed in the presence of water.



Layer	Elevation	Color[a]	γ [kN/m^3]	k_0 [-]	Φ' [°]	c' [kPa]	cu [kPa]
1	Silty clay complex made of loessoidal deposit with sandy seams		20.0	0.645	25	10	100
2	Granular complex made of gravel and sand with fossorial seams		19.5	0.540	32	0	0
3	Clay complex made of clay, silty clay and sandy - clayey silt		20.0	0.660	24	20	0
4	Mostiştea sand complex made of fine and medium sand		20.0	0.496	35	0	0

Fig. 2. Longitudinal profile along the metro tunnels axis with geology.

3. EPB TBM tunnelling

For the M5 metro line performance the EPB TBM method was selected. The **E**arth **P**ressure **B**alance Shields (EPB) turn the excavated material into a soil paste that is used as pliable, plastic support medium. This makes it possible to balance the pressure conditions at the tunnel face, avoids uncontrolled inflow of soil into the machine and creates the conditions for rapid tunneling with minimum settlement.

A rotating cutting wheel equipped with tools is pressed onto the tunnel face and excavates the material. The soil enters the excavation chamber through openings, where it mixes with the soil paste already there. Mixing arms on the cutting wheel and bulkhead mix the paste until it has the required texture. The bulkhead transfers the pressure of the thrust cylinders to the pliable soil paste. When the pressure of the soil paste in the excavation chamber equals the pressure of the surrounding soil and groundwater, the necessary balance has been achieved (figure 3). The front excavation is followed by concrete segment lining and back-fill grouting to minimise the surface settlements.

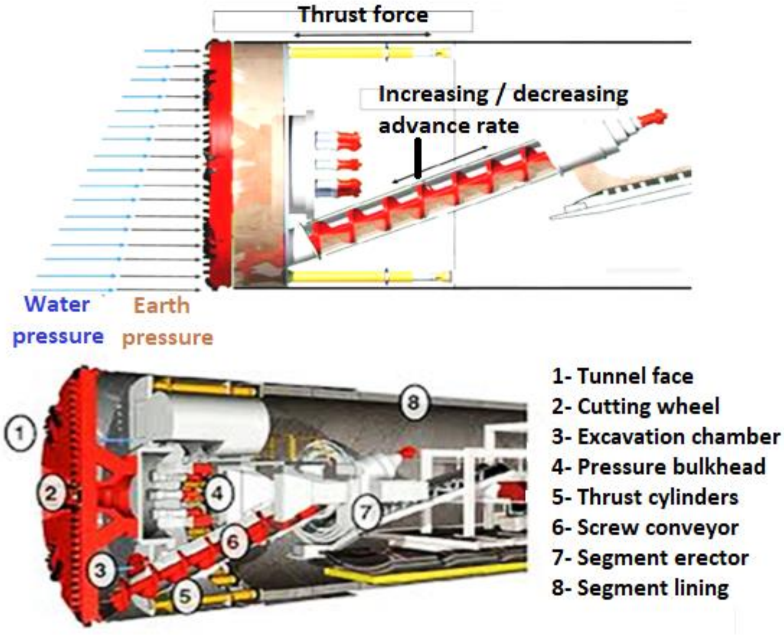


Fig. 3. EPB TBM - excavation performance and shield components.

In order to complete the first sector of M5 line the two metro tunnels, with a diameter of 6.3 m and a distance between their axes of 16.50 m (figure 1) must go undercross the Dambovita River. The curved route of the undercrossing has a radius of 250 m and total length of 56 m. The tunnels are placed at 13.5 m beneath the ground surface level, between them and the wastewater cassette slab being a minimum distance of 6.30 m. The vertical distance between the tunnels and the B0 collector is almost 8.70 m.

For the annular gap filling two-component mixes are used: a super fluid mortar with an accelerator mixture, added at the injection point. The metro tunnels will be executed one after the other, from Eroilor Station, starting with Line 1. Once the works for Line 1 are finalized, the second TBM starts towards PSS Opera. The rings of the segmental lining (5 current blocks + 1 keystone block) have a length of 1.5 m along the axis and a thickness of 30 cm. The rings are connected with the adjacent ones through 16 longitudinal bolts and to ensure the sealing, all blocks are provided with neoprene gaskets.

4. **Tunneling parameters that control the effects on existing structures**

Back-filling grout in tunnel boring machines operating under face pressure has to achieve the instantaneous filling of the “annulus”, which is created behind the segment lining at the end of the shield tail (figure 4).

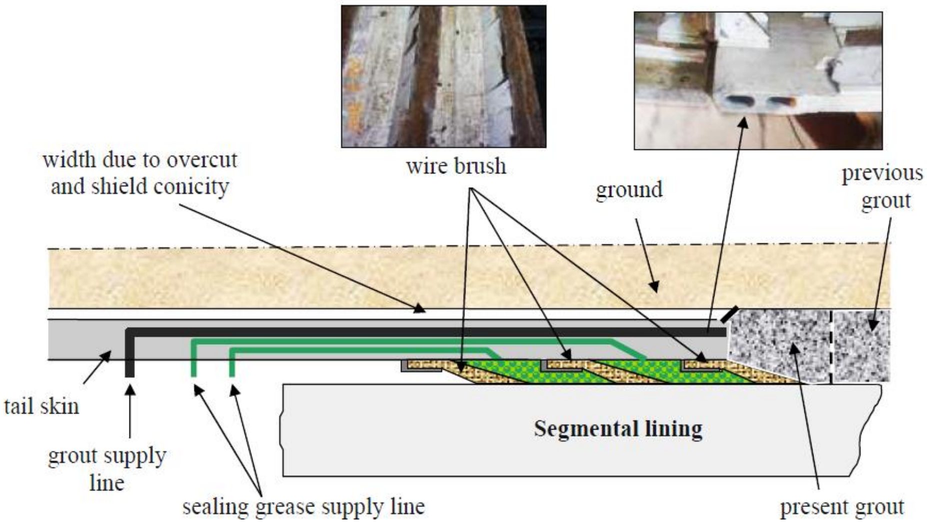


Fig. 4. Scheme of the back-filling grouting (after [5]).

Its main goal is to minimize surface settlements due to over-excavation generated by the passage of the TBM [5]. Furthermore, the backfilling operation has to:

- lock the segmental lining into position, avoiding movement owing to both segmental self-weight and the thrust forces, hoop stresses, generated by the TBM;
- bear the loads transmitted by the TBM back-up weight;
- ensure a uniform, homogeneous and immediate contact between ground and lining;
- avoid puncture loads by ensuring the application of symmetrical and homogeneous loading along the lining;
- complement the waterproofing of the tunnel with the concrete lining and gasketry (i.e. if the lining has cracks due to wrong installation, back-fill grout should help to mitigate any water inflow).

As the injected material for two-component system is an ultra-fluid liquid which, thanks to the addition of an accelerator admixture just before its injection, gets a thixotropic consistency in a few seconds, and as it is made up of a huge amount of water (approximately 800 liters per cubic meter of material), it is without doubt an uncompressible fluid, just like water. The consequence is that the annulus void that is created, after the TBM tail skin passage, has to be considered as a closed annular bubble that is filled, instant per instant, with an uncompressible fluid. Therefore, the uncompressible ball of gel confines perfectly and completely everywhere the concrete rings already installed and the new concrete ring which has to be installed.

It is of paramount importance that the mix creates a gel after a few seconds and so an uncompressible closed ball is generated: therefore, the gel creation must be tested. The main features of such a material are: super-fluid initial consistency, creation of a gel after a few seconds from the injection, compressive strengths from approx. 0.1 to 1 MPa at early stages.

Effectively the goal of the back-filling is carried out in the first minutes after its injection, therefore it is important to focus the attention on the last 2-3 installed rings and not more. Consequently, it is important to verify that the mix actually makes a gel quickly, in order to confine homogeneously the segment ring. The latter stages are meaningless, because the gel mechanical strength does not influence the structural behavior of the tunnel lining if the “annulus” is actually completely filled in.

The main parameter that has direct links to the soil deformation along the TBM passing is the deformation modulus of the back-fill grout and the length of gel phase. The actual length of the gel phase depends on the rate of advance having in mind that the final stiffness of the grout is achieved in approximately 6 hours. The advancement speed corresponds to the number of installed rings in which the gel-phase grout is activated before it is changed with the hardened grout. In this study the length of the gel-phase grout was chosen 3, 6 and 9 m (corresponding to 2, 4, and 6 lining rings).

5. The mathematical model

In order to analyse the undercrossing effect of the metro tunnels a 3D linear-elastic model was built [1].

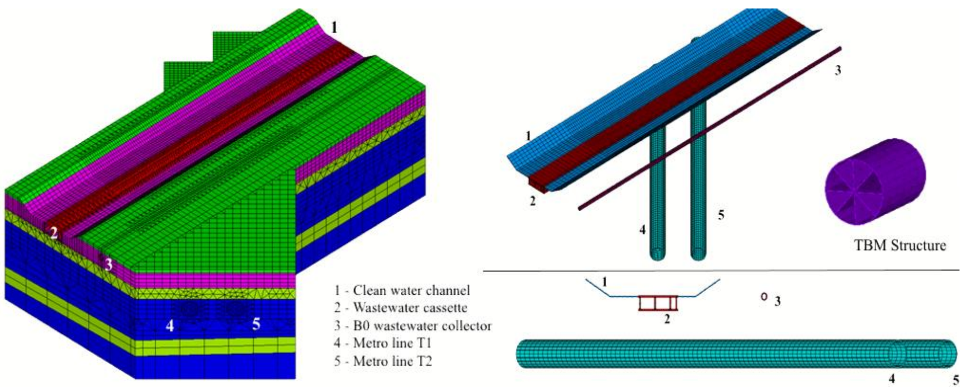


Fig. 5. Mathematical model (view from downstream), shell elements in model (axonometric and front view from downstream) and TBM modelled structure (after [1]).

The model includes the whole interaction area – the wastewater cassette, the clean water channel, the B0 collector, the 2 metro tunnels and the surrounding earth mass. The model extends 150 m along the Dambovita river and has a width of 64 m. In the oblique direction of the tunnels, the length of the model is 120 m and 60 m wide. Vertically, the model extends up to 45 m below the surface. The stratification was adopted in accordance with geotechnical studies.

Two simplifying assumptions were considered: 1. a linear route of the metro tunnels oriented at 45^{o} from the cassette axis (the radius of curvature being long enough not to influence the results – figure 1); 2. the B0 collector's cross section was assimilated with an ellipse with equivalent area.

The excavation, assembly works and grouting of the concrete lining are simulated from the moment when TBM T1 penetrates the model limit (on the right river side) until all works of TBM T2 passing the area are concluded (on the left river side). The simulation was made considering the designed technology, meaning that the works for L2 start after the completion of the works for L1.

For good results, a fine mapped mesh made of elastic shells was adopted for all structural components. This mesh was connected with the terrain volumes using free or mapped meshes, automatically generated. 3D solid elements were used for terrain and the back-fill grout. The model contains 171593 elements from which 148845 solids and 22748 elastic shells. All assigned shell thickness corresponds to the actual dimensions. For the TMBs, the real geometrical and mass properties of the machine were considered: a tail skin roughly 10 m in length and a total weight of 400 tons.

The simulation of the execution technology (excavation and segmental lining assembly) was made for each phase by elements activation and deactivation in subsequent load steps. Each load step corresponds to a length of 1.5 m (the length of a concrete lining ring) and the sequence adopted in the model is presented in figure 6:

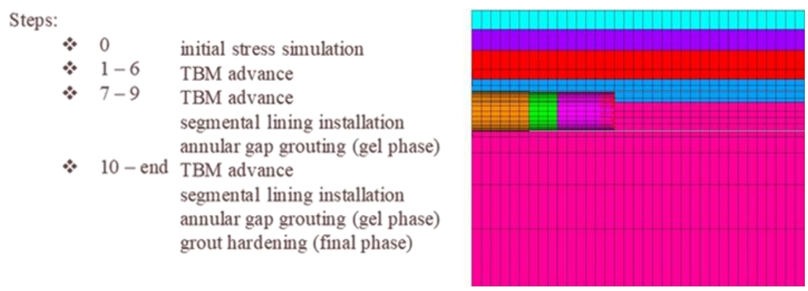


Fig. 6. Main FEM model – adopted step sequence.

- Step 0 – initial stress state simulation – items modelled: terrain and Daboia's associated hydraulic structures with their loads (gravity and hydrostatic pressure).

- Steps 1 – 6: the advance of the TBM structure (the length of the TBM was approximated with 6 × 1.5 m) – the excavation of the terrain by gradual deactivation of the associated elements, the simultaneous activation of the TBM elements and applying the pressure on the excavation front.
- Steps 7 - 9: the advance of the TBM machine according to the previous sequence, the segmental lining assembly and grouting of the annulus, done by deactivating the last row of TBM elements simultaneously activating the segmental lining elements (in steps of 1 ring) and the grouting elements in gel state (material with reduced stiffens – represented in green colour).
- Steps 10 to end of the simulation: the advance of the TMB into the terrain and segmental lining assembly as in steps 7 - 9, with the difference that the appropriate distant elements of the grouted region are hardening (represented in orange colour).
- After the execution of the first tunnel the entire pattern is repeated for the second one.

For mathematical model calibration 5 different ground stratification were selected. They correspond to actual geological profile of the soil along a sector of tunnels that has monitoring data used for calibration (figure 7).

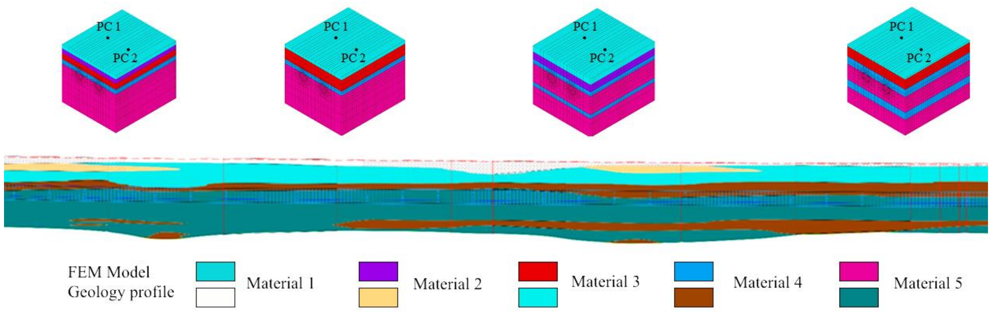


Fig. 7. Calibration area with geology (after [1]).

For each model, several simulations with different values for the elastic modulus of the gel-phase back-fill grout and different lengths were carried out (E = 100 … 400 kPa; length between 1.5 and 9 m). The evolution of the vertical displacement was checked in 2 points placed at the surface, in the middle of the models in the vertical plane of the tunnels' axes (PC1 and PC2 in figure 7).

The results on the calibration models indicated a reduced influence of the geotechnical stratification, the settlements having similar values in all 5 models. It was also found that the pressure applied at the excavation front has little influence, the final results being similar with or without the applied pressure. The main parameters which influence the final vertical displacements are the elastic modulus of the grout in gel phase and its length (translated as advancement speed – i.e. number of steps in which the gel-phase grout is activated before it is changed with the hardened grout).

Based on these foundings, in order to obtain similar settlements as the ones recorded at the surface, the value for the elastic modulus of the gel-phase grout has to be in the range of 300 kPa and 400 kPa. Considering the results on calibration models and the fact that the in-situ measurements were made in circumstances in which at the surface some layers with a higher stiffness are present (the road structure), the chosen value for the elastic modulus for the gel-phase grout was E = 250 kPa. Concurrently, for the main model, the length of the gel-phase grout was chosen 3, 6 and 9 m (2, 4, and 6 lining rings).

6. Selection of tunnelling rate of advance

The simulation of tunnelling progress has included different length of the gel-phase grout, to highlight the effects of the tunnelling works on the existing hydraulic structures. The most significant settlements and thus, the most detrimental situation is created by the highest advancing speed, i.e. 36 m/day, that corresponds to the longest gel-phase of the grout – 9 m (6 rings) considering that the final stiffness of the grout is achieved in approximately 6 hours.

In order to underline the structural effects of the tunnel undercrossing on the Dambovita hydraulic development 9 longitudinal profiles were selected, with 18 points on tunnels axes, 7 cross sections on hydraulic structures and 28 cross sections for the waste water cassette (figure 8). For each selected point were analyzed the settlement evolution over time, the final settlements and the longitudinal effect on B0 Collector (bending moment & shear force).

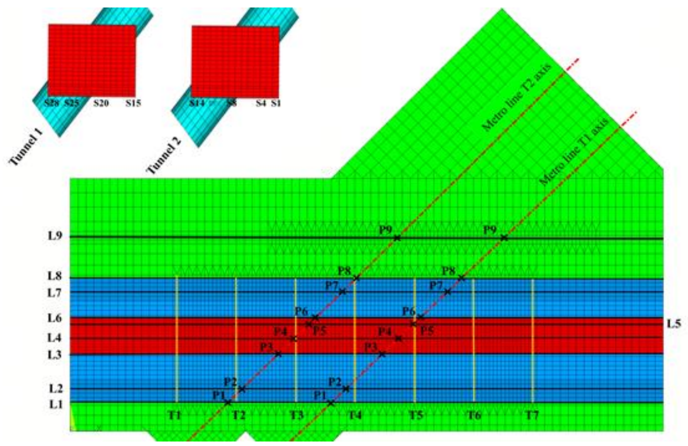


Fig. 8. Selection of profiles and sections included into analysis.

Vertical displacements for both the hydraulic structures and the B0 collector are shown in figure 9. In the same image, the influence area of the tunnelling works is emphasized.

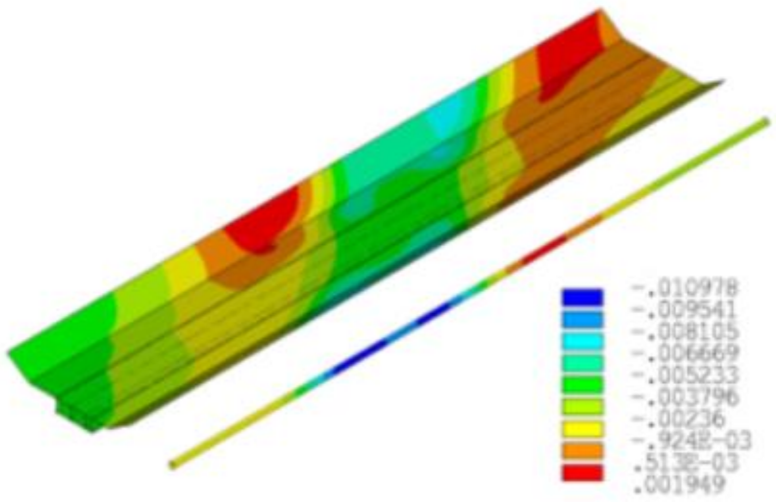


Fig. 9. Final vertical displacements for Dambovita structures and for collector B0.

For the existing structures, the influences of the tunnel performance can be evaluated in terms of imposed displacements. To assess the structural response of the hydraulic structures, the capable values for both bending moment and shear force are compared with the calculated ones. For the present study the main concern was the structural effect on B0 collector.

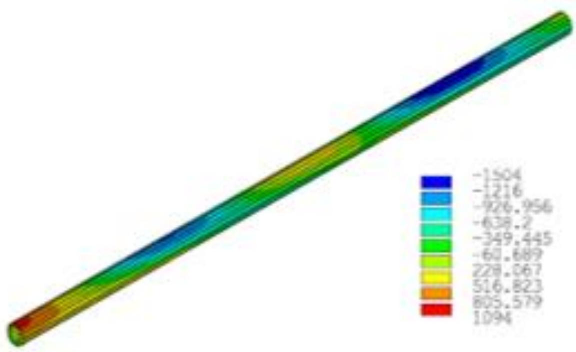


Fig. 10. B0 Collector – axial stresses distribution [kN/m^2].

The axial stresses on longitudinal direction caused by the vertical bending were checked. In figure 10 the axial stresses distribution is presented (a detail from the undercrossing area). In figure 11 the longitudinal bending moments assessed by the axial stress integration for 3 different advancing speeds are shown (3 m, 6 m and 9 m of gel-phase grout).

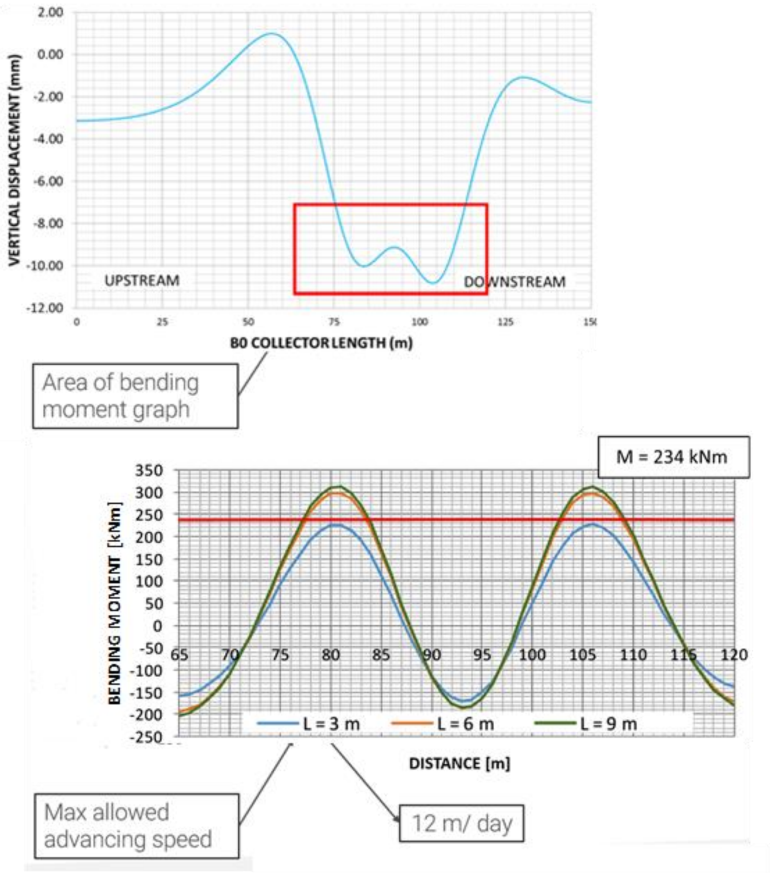


Fig. 11. Settlement and bending moment diagram along the B0 Collector longitudinal profile.

For an increased advancing rate (6 or 9 m the length of the gel-phase grout), the capable bending moment of the collector is exceeded. This was the reason why the advancing speed of the TBMs was restricted at maximum 12 m/day, in order to avoid the risk of plain concrete cracking. Regarding shear force in the collector, all the calculated values are under the capable ones (for any advancing speed).

7. Conclusions

In order to complete the first sector of M5 line the two metro tunnels, with a diameter of 6.3 m and a distance between their axes of 16.50 m must under cross the Dambovita River. EPB TBM method was selected. This paper presents an assessment of the impact of tunneling of the M5 Metro line in Bucharest and its associated risks in the influence zone of tunneling operation during the undercrossing of the hydraulic works related to the Dambovita River.

The control of ground movements induced by tunnel excavation in urban areas is a key issue of concern for designers and many techniques are used in practice to minimize the effect of the excavation on existing buildings. Therefore, the analysis of induced tunneling displacements on ground surface and at depth is required.

A detailed finite element model calibrated based on the measured settlements was performed to simulate the sequence of construction works. Based on model results the undercrossing area of influence is revealed.

The required construction phases (excavation, segmental lining, grouting) show increased displacements in the ground surrounding the tunnels (especially at top and bottom points), caused by the temporary deformability of the gel-phase grout. Those displacements are local and are transmitted to a small extent to the surface. The displacements of the existing hydraulic structures are small and do not endanger them: 6 - 8 mm for the cassette structure, roughly 9 mm for clean water channel and 12 mm for B0 collector.

For an increased advancing rate (6 or 9 m the length of the gel-phase grout), the capable bending moment of the collector is exceeded. This was the reason why the advancing speed of the TBMs was restricted at maximum 12 m/day, in order to avoid the risk of plain concrete cracking.

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