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# M5 Metro Line Tunnelling Works and their Effect on the Hydraulic Structures of the Dambovita River

# M5 Metro Line Tunnelling Works and their Effect on the Hydraulic Structures of the Dambovita River

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**Abstract**. In order to carry out the M5 Metro line in Bucharest, the undercrossing of the hydraulic works related to the Dâmboviţa River was required. The common technology for the metro tunnels is the earth pressure balanced excavation (EPB – TBM), precasted segment lining and back-fill grouting to minimize the surface settlements. The Dâmboviţa 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). To evaluate the structural effects of the undercrossing on the existing hydraulic structures, a 3D finite element model was created, to simulate the sequence of construction works. The model was calibrated based on the measured settlements, during the execution works of the metro tunnels before reaching the undercrossing section (a region with similar geotechnical properties). The calibrated parameters were the elastic modulus of the back-fill grout at early hardening stages and the length of the grout, still being in "gel phase" (with no stiffness). The paper presents a brief description of the existing and the designed structures, as well as the steps followed to create and calibrate the mathematical model. Concerning the results, the undercrossing area of influence is revealed, by longitudinal and transversal effects expressed in induced displacements and stresses. Several considerations and recommendations regarding the tunnelling works are made in order to avoid any damages to the existing facilities.

## 1. Introduction

Cities' urban development and population growth is unprecedented, with a continuous estimated trend, making traffic more and more difficult. The major consequences are the depreciation of air quality, the increase of the time spent in traffic and transportation costs, but also the population' anxiety. One forthcoming solution is the development of the existing metro lines. The execution of these new facilities, tunnels and stations, are regularly constrained by the existing surface and underground structures.

There is a variety of methods for performing tunnelling works, one of the most common is the use of TBMs and filling the space between the segmental lining and the overcut section with grout. There are many examples where this method was successfully used: the high-speed railway between Leon and Oviedo in Spain [1], Metro Line C in Rome (Italy) [2,3], Orakimain sewer Hobson diversion in Auckland (New Zealand) [2], Metro line 2 in Prague (Czech Republic) [2], Metro line in Sofia (Bulgaria) [4] and others.

A frequent subject of interest for researchers is the analysis (on physical or mathematical models) of the interaction between new structures and the existing ones, or the surrounding ground mass. 3D mathematical models based on the finite element method are the most common procedures used for settlement analysis or new tunnel-existing structure-foundation interaction. The existing literature is

filled with examples, some of them being: the analysis of the construction of a new tunnel which underpasses Marina Bay Station and two existing metro tunnels [5], the settlement analysis of 2 new metro tunnels of the Otogar and Kirazh-1 track in Istanbul [6], the analysis of the interaction between 2 tunnels regarding their relative position and execution phase [7] etc.

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.
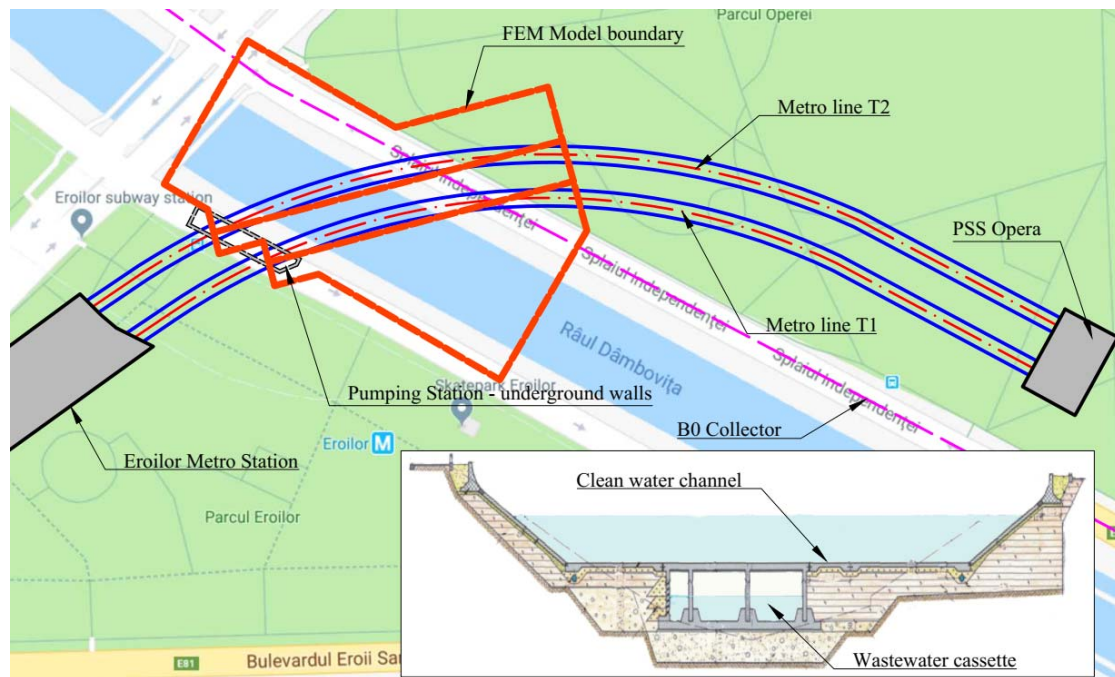
## 2. Project overview

The tunnelling technology used to carry out of the new metro line in Bucharest (between Râul Doamnei and Eroilor /PSS Opera) is based on 2 EPB-TBMs. The new line will have 10 stations and a length of 6,9 km, divided in 2 sections delimited by TBM insertion/extraction pits (abbreviated as PSS). One of these sections is of interest for our paper, because, in order to connect Eroilor station with PSS Opera, the undercrossing of Dâmbovița River and its hydraulic structures is required (figure 1).

The development of Dâmbovița River (completed in 1988 [8]) 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):

- The clean water channel (the geometrized river bed) is protected and sealed using concrete revetment and its purpose is to give a safely pass of the river flow downtown Bucharest. Its length is approximatively 17 km and it is provided with 10 flat-gated dams, used for controlling the water level;
- The sewage/drainage cassette is situated immediately beneath 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.
- Parallel but close to these hydraulic structures there are also 2 main collectors – A0 and B0 (one on each side of the river). The A0 collector wasn't included in the analysis because it was recently rehabilitated (using GRP tubes), being placed near the diaphragm walls of a new pumping station (an area with an increased stiffness). On the left river bank, the B0 collector is an old structure with uncertain technical condition, thus it was included into the analysis. The collector has an ovoid shape (w/h – 1,10/1,65 m) made of plain concrete, padded with bricks in the lower part.

The 2 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 Dâmbovița 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.

The execution technology for the metro tunnels is the earth pressure balanced excavation (EPB), concrete segment lining and back-fill grouting to minimise the surface settlements. 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.
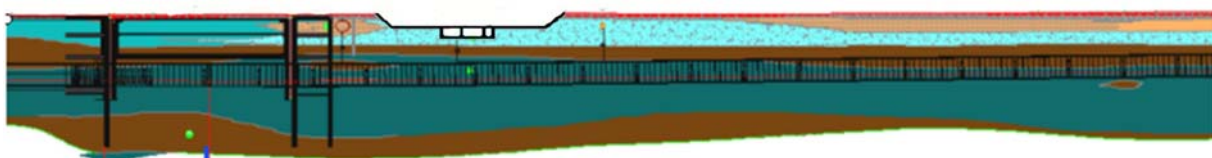
**Figure 1**. Plan view of the undercrossing area and the Dâmboviţa hydraulic structures (cross section)

The main steps considered in the modelling process, are:
- Step 1 – excavation works and TBM advance by 1.5 m (the length of one ring/the piston's maximum extension). In this phase the pressure applied on the excavation front ensures the settlement control and its stability.
- Step 2 – assembly of the precast ring, made at the end of the TBM, under the protection of TBM's tail skin.
- Step 3 – the advance of the TBM by another ring length and the gap grouting. The grouting step is a key factor for minimizing surface settlements [2-4].

## 3.  Geological, geotechnical and hydrogeological characteristics of the undercrossing area
Tunnelling works are located in Dâmboviţa's floodplain area which is characterized by the following geological profile (figure 2): 1. fillings; 2. silty clay complex (0 – 20 m thickness) made of loessial deposit with sandy seams; 3. granular complex made of gravel and sand with loessial seams (5-20 m thickness); 4. clay complex made of clay, silty clay and sandy - clayey silt; 5. Mostiştea sand complex made of fine and medium sand. The geotechnical characteristics for layers met by the undercrossing works are presented in table 1.



**Figure 2**. Longitudinal profile via metro tunnels axis with geology

**Table 1.** Geotechnical characteristics

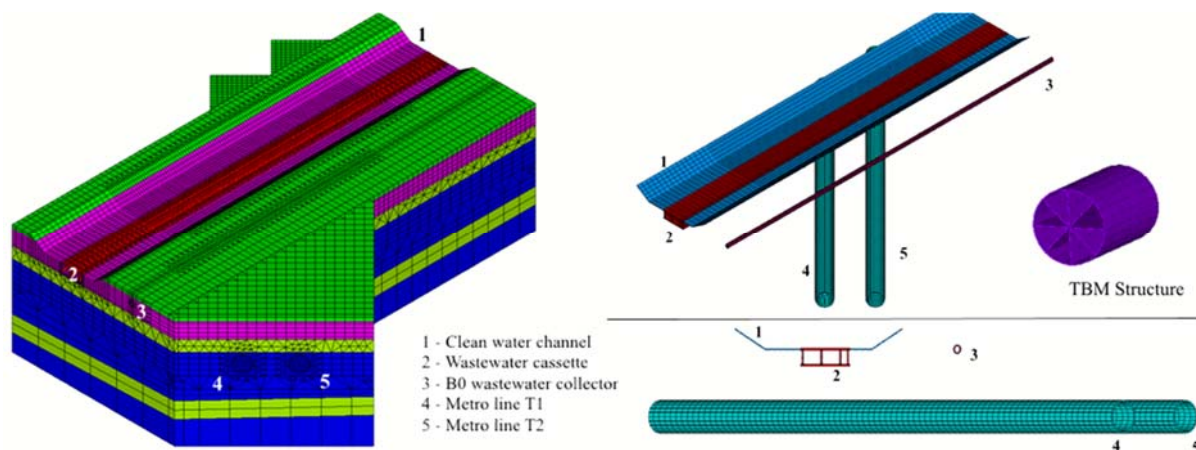| | Elevation | Layer[a] | Colour[a] | $\gamma$ [kN/m³] | $k_0$ [-] | $\Phi'$ [°] | $c'$ [kPa] | $cu$ [kPa] |
|---|---|---|---|---|---|---|---|---|
| **1** | 0.00 – 6.00 | 2 | | 20.0 | 0.645 | 25 | 10 | 100 |
| **2** | 6.00 – 9.00 | 3 | | 19.5 | 0.540 | 32 | 0 | 0 |
| **3** | 9.00 – 13.00 | 4 | | 20.0 | 0.660 | 24 | 20 | 0 |
| **4** | 13.00 – 14.50 | 5 | | 20.0 | 0.496 | 35 | 0 | 0 |
| **5** | 14.50 – 16.50 | 4 | | 20.0 | 0.660 | 24 | 20 | 0 |
| **6** | 16.50 – 18.50 | 5 | | 20.0 | 0.496 | 35 | 0 | 0 |
| **7** | 18.50 – 22.00 | 4 | | 20.0 | 0.660 | 24 | 20 | 0 |
| **8** | 22.00 – 28.00 | 4-5 | | 20.0 | 0.481 | 36 | 0 | 0 |

[a] Layer number and colour according to figure 2

The hydrogeological conditions of the site are characterized by the presence of 2 aquifers: the Colentina aquifer (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.

## 4. Mathematical Modelling

### 4.1. The mathematical model

In order to analyse the undercrossing effect of the metro tunnels a 3D linear-elastic model was built. 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 Dâmbovița 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 (figure 1 – orange thick line). Vertically, the model extends up to 45 m below the surface. The stratification was adopted in accordance with geotechnical studies.



1 - Clean water channel
2 - Wastewater cassette
3 - B0 wastewater collector
4 - Metro line T1
5 - Metro line T2

**Figure 3.** Mathematical model (view from downstream), shell elements in model (axonometric and front view from downstream) and TBM modelled structure

Two simplifying assumptions were considered: 1. a linear route of the metro tunnels oriented at 45° 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 entire model is shown in figure 3 and assigned material properties are presented in table 2.

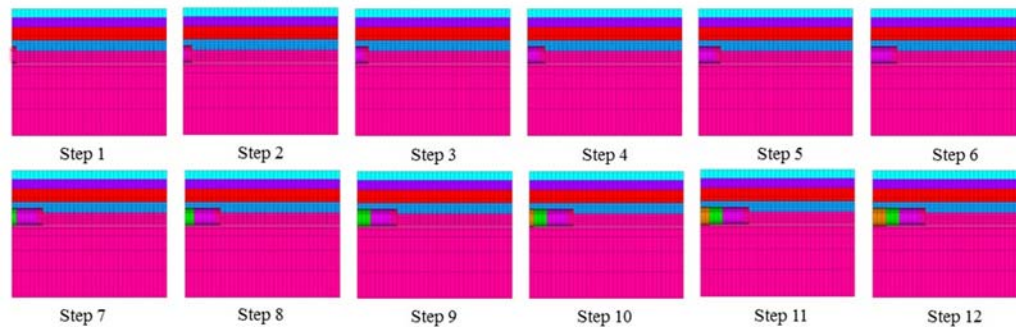**Table 2.** Material properties used in FEM model

| | Material description in FEM model | $E$ [kPa] | $\mu$ [-] | $\rho$ [t/m³] |
|---|---|---|---|---|
| 1[a] | Tunnel structure | 2.50 e +07 | 0.20 | 2.50 |
| 2[a] | TBM structure | 2.10 e +08 | 0.30 | 9.50 |
| 3[a] | Wastewater cassette | 2.00 e +07 | 0.20 | 2.50 |
| 4[a] | Clean water channel | 1.50 e +07 | 0.20 | 2.50 |
| 5[a] | Collector B0 | 1.50 e +07 | 0.20 | 2.40 |
| 6[a] | Soil layer 1 | 8000 | 0.348 | 1.75 |
| 7[a] | Soil layer 2 | 20000 | 0.328 | 2.00 |
| 8[a] | Soil layers 3 and 5 | 10000 | 0.30 | 2.00 |
| 9[a] | Soil layers 4 and 6 | 25000 | 0.328 | 2.00 |
| 10[b] | Anulus filling material (gel phase) | 250 | 0.40 | 2.20 |
| 11[b] | Anulus filling material (rigid phase) | 1.00 e +07 | 0.20 | 2.20 |

[a]Colour used in main FEM model (figure 3); [b]Colour used in calibration models (figure 4)

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 4:

- Step 0 – initial stress state simulation – items modelled: terrain and Dâmboviţa'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 $6 \times 1.5$ 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.
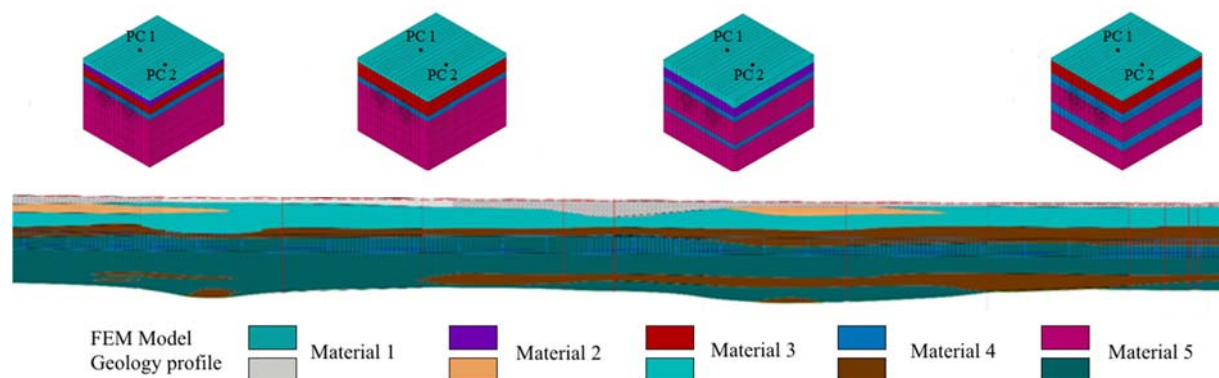
**Figure 4**. Steps used in FEM analysis
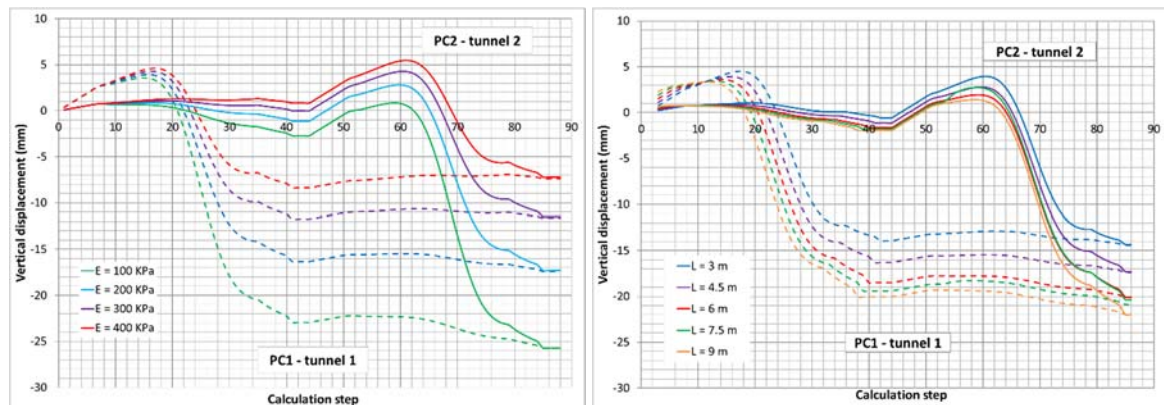
### 4.2. Mathematical model calibration

The model calibration consisted in the management of the material properties for the gel-phase back-fill grout. In this regard the recorded settlements were used, obtained from the monitoring program carried out for the section executed before the undercrossing section (with comparable geotechnical stratification and terrain properties). The recorded settlements at the ground surface were approx. 5 – 7 mm. In order to obtain the same values for surface settlements 4 different cross sections from the longitudinal profile were selected, with different distributions of the stratification. The depth of the metro tunnels is between 15.4 and 15.6 m.

For each of these sections a 3D model was built (figure 5) with the same components as the main model: terrain, TBM machine, segmental lining, back-fill grout region and the same mesh density – 1.5 m along the axis, which corresponds to TBM advancement for 1 ring of segmental lining. All the material characteristics and load steps are similar to those from the main model. The only difference between the 4 models is the stratification, in accordance with the geotechnical profile. The entire length of the models is 52.5 m corresponding to 35 rings of segmental lining and the two lines are executed subsequently.



**Figure 5.** Models realized for calibration and longitudinal profile of the calibration area with geology

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 5). The results obtained for 2 simulations are presented in figure 6: a) variable stiffness for gel state of the grout, length L = 4.5 m and b) variable gel state length, gel stiffness E = 200 kPa.

**Figure 6.** Results obtained on calibration models (displacements of PC1 and PC2) – (a) variable stiffness for gel injection, injection length L = 4.5 m; (b) variable injection length, gel injection stiffness E = 200 kPa;

The results on the calibration models indicated a reduced influence of the geotechnical stratification, the settlements having similar values in all 4 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 should be between 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).
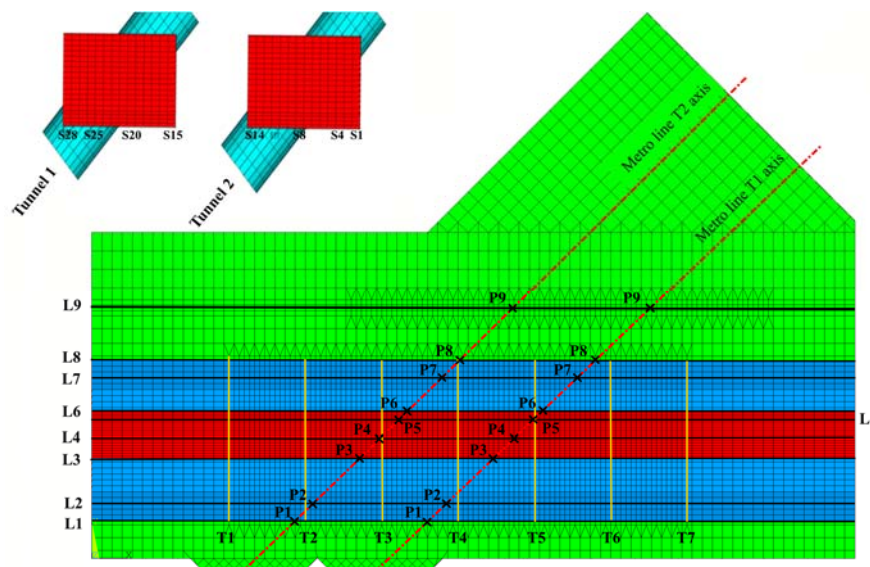
## 5. Results and discussions

### 5.1. Chosen section for results interpretation

Results were chosen for different length of the gel-phase grout, to highlight the effects of the tunnelling works on the existing hydraulic structures. In this regard, figure 7 presents the position of all bench-marks chosen for results interpretation: 9 longitudinal profiles (L1 ÷ L9 for the hydraulic structures and the collector B0), 7 cross sections (T1 ÷ T7) and 18 points situated at the surface along the tunnels axis (P1 ÷ P9 for each tunnel). For the bending moment and shear forces additionally occurring in the wastewater cassette, 28 cross sections placed above the tunnels were chosen (S1 ÷ S28).

To exemplify, some results corresponding to the longest gel-phase of the grout – 9 m (6 rings) are presented. They comply with the highest advancing speed, i.e. 36 m/day, considering that the final stiffness of the grout is achieved in approximately 6 hours. These hypotheses led to the most significant settlements and thus, in the most detrimental situation.
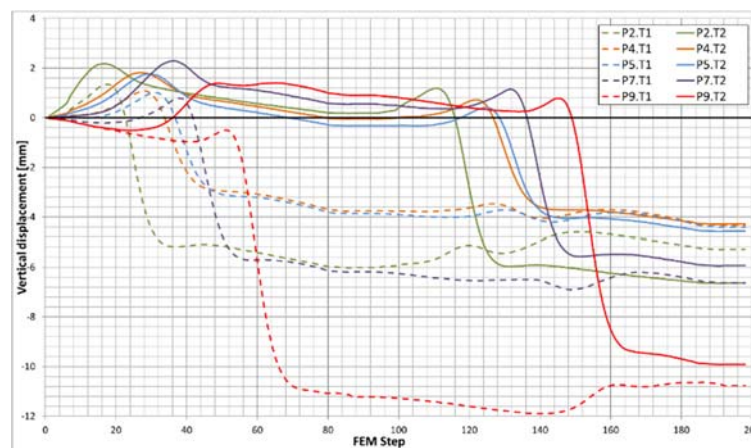
**Figure 7** - Profiles and points for results interpretation. a) for displacements; b) for moment diagrams

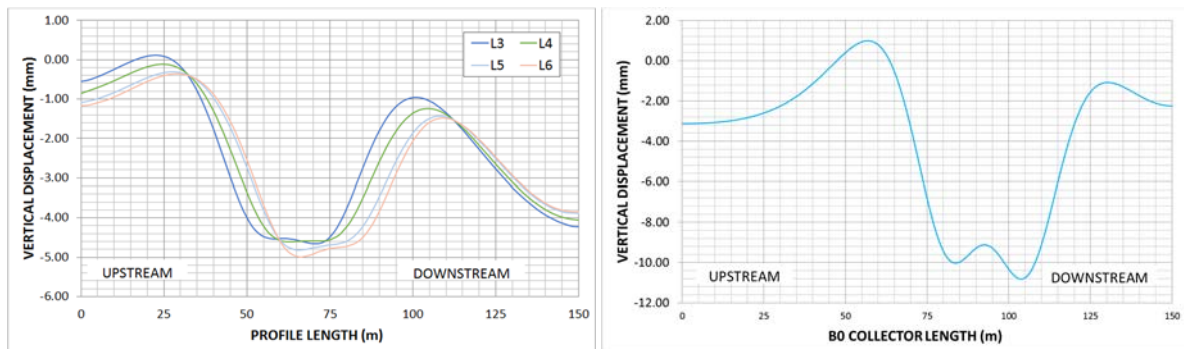## 5.2. Settlement evolution over time

To highlight the evolution in time (in load steps) of the vertical displacements along the 2 tunnels, the results for points P2, P4, P5, P7 and P9 are presented in figure 8. A rising trend of the terrain in the excavation front can be observed, followed by settlement, but also the mutual influence of the 2 TBMs' crossings. The maximum settlements occur for the last calculation step (for tunnel 2) and the maximum values are noticed at point P9 – the point situated at the keystone of collector B0 (round 10 – 10.50 mm). For points related to tunnel 1, a rising trend can be observed when tunnel 2 is executed in the proximity. The effect is caused by a relaxation of the soil mass when the TBM excavates the second tunnel.



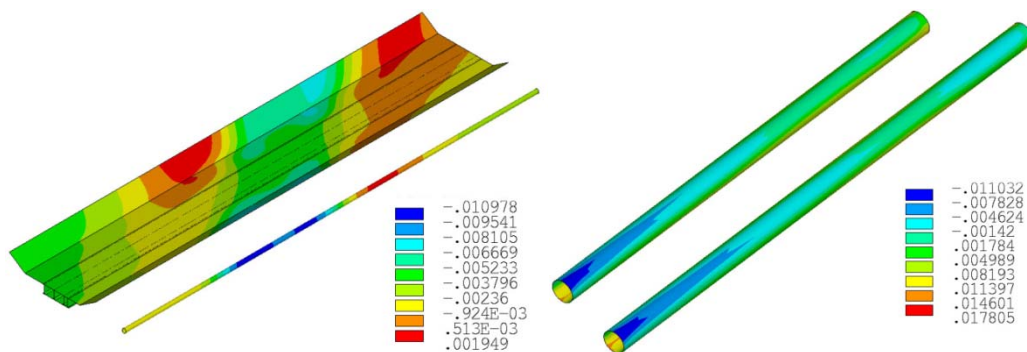**Figure 8**. Vertical displacements for 10 points situated at the top of the model

## 5.3. Final settlements

To highlight the final distribution of the vertical displacements and the influence area of the tunnelling works, the results obtained for the last calculation step are presented in figures 9 and 10. At the extremities of the model, the final vertical displacements are almost zero. The highest settlements occurring at the ends of the profiles (figure 9-a) are explained by the bending stiffness of the cassette, whose ending nodes are constrained along the longitudinal direction.
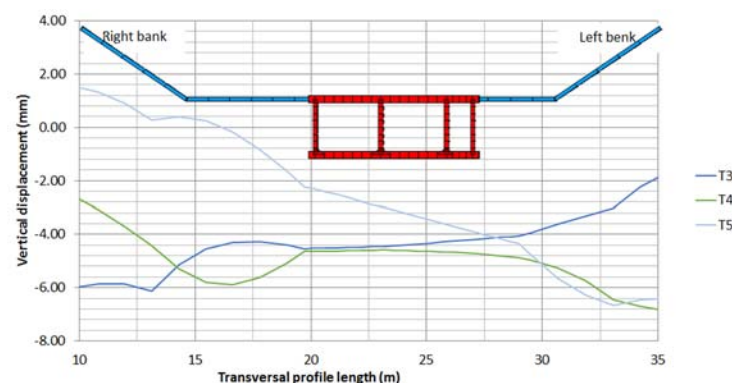
**Figure 9.** Final vertical displacements for 4 longitudinal profiles on the cassette (a) and on the B0 collector (b)

The displacements gotten for the P9 profile (nodes situated at the collector's keystone) are presented in figure 9-b. The maximum displacements for the collector are about 10 to 11 mm. Similar results are provided in figure 10-a, where the vertical displacements for both the hydraulic structures and the B0 collector are shown. In the same image, the influence area of the tunnelling works is emphasized. Figure 10-b represents the vertical displacements for the 2 tunnels for the last calculation step.



**Figure 10**. Vertical displacements for the hydraulic structures a) and for the metro tunnels b) [m]
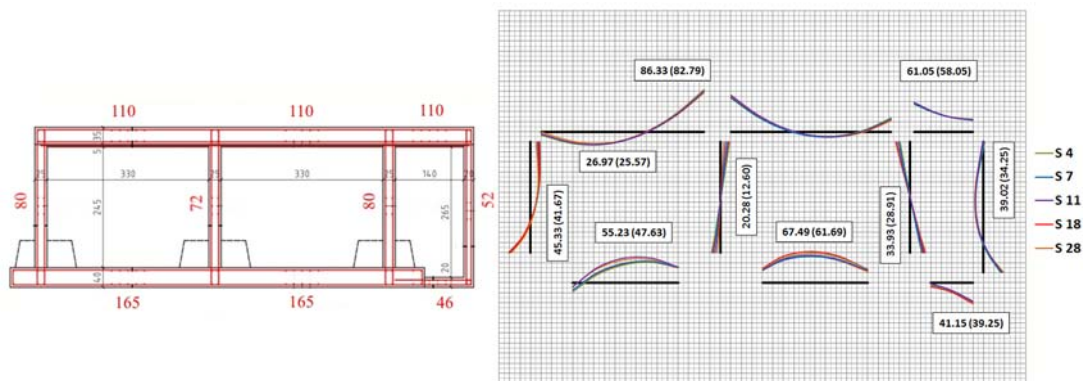
In figure 11, the final calculated displacement for the transversal direction (T3, T4, T5) are shown. The deformed shapes of the three subsequent sections indicate a torsion of the structure round it's longitudinal axis, over a length of about 30 m. The structure of the wastewater cassette has differences of about 1 mm on the left bank and 3 mm on the right. For the clean water channel, the differences are more significant: 4 - 8 mm (the points placed at the top and base of the slopes).
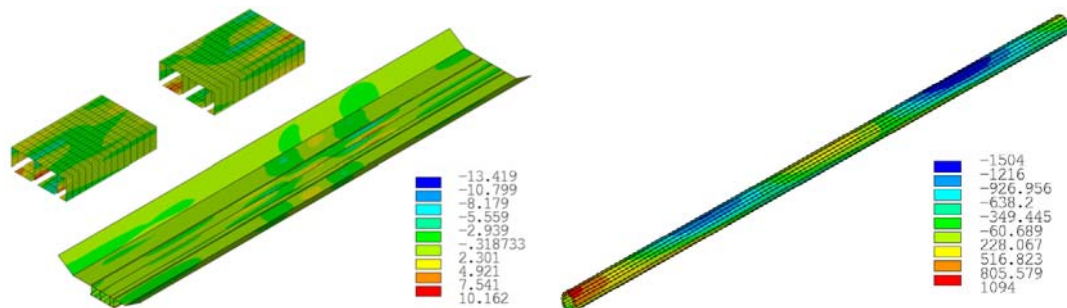


**Figure 11.** Vertical displacements for 3 transversal profiles (last calculation step)

### 5.4. Structural effects on existing works

For the existing structures, the influences of the tunnel execution are expressed 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. The results are presented in figure 12: (a) the cross section of the cassette with the capable bending moments, according to the initial design drawings; (b) the calculated bending moments (absolute values) for 5 cross sections corresponding to the first and last calculation steps. One can notice that the final values augment with 4% to 60% compared with the ones in the first step, but a safety factor against structural failure is still provided. In figure 13 (a) the relative bending moments (last step – first step) for the entire hydraulic structure and the detailed ones for all the 28 selected sections are presented.
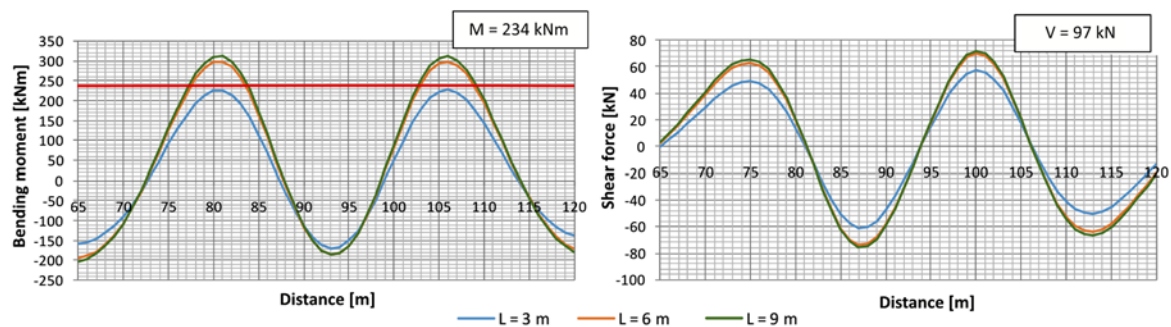


**Figure 12**. Cassette – capable bending moments and calculated ones [kNm]



**Figure 13**. Bending moment distribution– relative values (final step – initial step) [kNm] a);
B0 Collector – axial stresses distribution [kN/m$^2$] b)

In terms of the collector, the axial stresses on longitudinal direction caused by the vertical bending were checked. In figure 13 (b) the axial stresses distribution is presented (a detail from the undercrossing area). In figure 14 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). For an increased advancing speed (6 or 9 m), 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).

**Figure 14.** Results obtained for B0 Collector (Bending moment and shear force on longitudinal direction)

## 6. Conclusions

The paper presents the structural response of the hydraulic structures associated with the Dâmboviţa River due to the tunnelling works for the M5 metro line. The structural evaluation was made using a 3D finite element model which encloses the entire interaction area and simulates the execution steps by activating and deactivating different sets of elements.

The calibration process led to a series of conclusions: the applied front pressure and the stratification have a reduced influence on the final vertical displacements; the main parameters influencing the final results are the initial elasticity modulus for the gel-phase grout and the length of the grout in gel state (equivalent to the TBM's advance speed).

The results were analysed in order to assess the transversal and longitudinal effect of the tunnelling works on the existing structures: channel, cassette and B0 collector. In this regard, 9 longitudinal profiles, 7 cross sections, 18 characteristic points and 28 cross section through the cassette were defined. The calculated displacements, bending moments and shear forces for the Dâmboviţa hydraulic structures led to the conclusion that the influence of the tunnelling works is not significant. On the other hand, the results obtained for the B0 Collector led to a constrain regarding the tunnelling works – the advancing speed should not exceed 12m/day, because for a higher speed the plain concrete cracking may occur due to axial tensions.

Concerning the tunnels, the results of the execution 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.

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