SOIL STABILISATION PRIOR TO THE DRIVING OF THE TUNNEL BORING MACHINE UNDER BUILDINGS AND FACILITIES DURING THE CONSTRUCTION OF THE SOFIA METROPOLITAN

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Abstract. Studies on the conditions in the area of Lion's Bridge were conducted regarding the work of the Tunnel Boring Machine (TBM) with back pressure when implementing the 2^{nd} metro diameter of the Sofia Metro. The expected subsidence is modelled and two calculation models in the conditions of preliminary injection and strengthening of the soil foundation are adopted. The stressed state of the soils in the area of the bridge is defined and the expected subsidence is estimated.

Keywords: measure settlement, shield method, soil strengthening.

1. INTRODUCTION

The technology for building tunnels with the Tunnel Boring Machine (TBM), also called the "Shield" has established itself as the safest. It achieves rapid progress of 10–20 m per day with a high degree of security. The application of the technology in urbanized areas is imperative to guarantee minimal deformations of the earth's foundation and ensure the safety of buildings and facilities on the earth's surface. In most cases, it is necessary to apply additional measures to limit the influence of the change in the stressed state of the massif, as a result of the construction of the tunnel. The technology is also applicable in conditions of high groundwater. Such high waters are characteristic of the central city parts of the city of Sofia. Due to the relatively weak soils and their high level in the central urban areas, shield technology with the so-called counter pressure is most suitable (TBM – EPB – Earth Pressure Balance) – Fig. 1. Water lowering is prevented by not allowing the soil to subside over the tunnel [1, 2]. For a better result when applying shield technology, it is also recommended to strengthen the soil in advance [3]. Due to the relatively low technological costs, injection with cement solution is most often applied [4].

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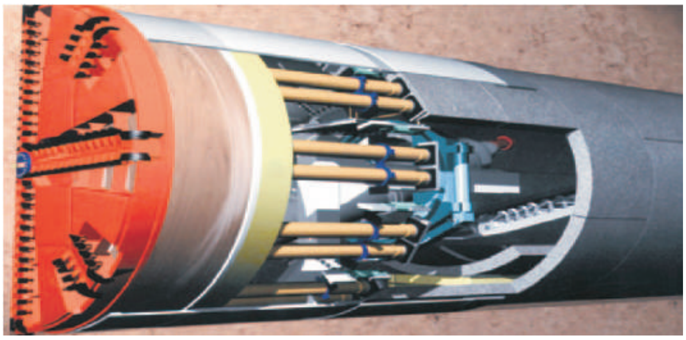

Fig. 1. Technological diagram of a mechanized shield with counter-pressure in the face chamber [2]

2. MODELING AND EXPECTED DEFORMATIONS

There are a number of sections along the route of the Sofia Metro that are a challenge for the application of TBM – ERV technology. One of these sections is the tunneling of the second metro line tunnel from km 4+140 to km 7+910 and specifically the section between km 6+130 and km 6+170, where the tunnel boring machine passes under the Lion Bridge. In this section, the machine passes less than 2 meters away from the bottom of Vladaiska River and literally centimeters from the foundations of the bridge. At the same time, the bridge, built in the period 1889–1891, is a historical landmark of the city of Sofia, and deformations and damage to the construction of the facility would be unacceptable. For this reason, the tunneling is done with a shield, with counter-pressure in the face chamber, which is able to pass safely near the foundations of the bridge and, at the same time, is the basis for the construction of a tunnel facility under the Vladaiska River [5].

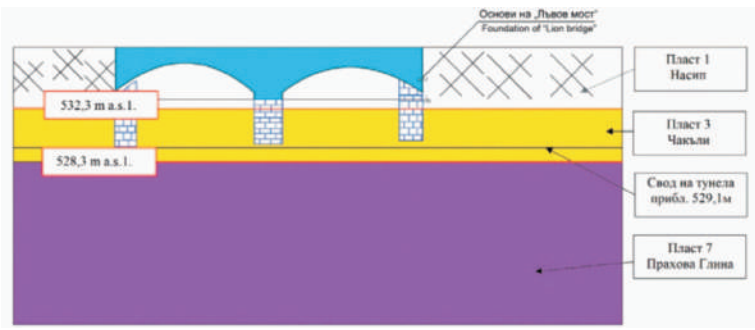

Fig. 2. Geological section of Lion Bridge and earth foundation [6]

From the geological section in the area of the bridge – Fig. 2, 3 main layers are defined as follows [6]:

- layer No. 1 – from the surface (approximate elevation 537.4 m) to approximate elevation 532.3 m. Modern embankment consisting of gravel with sand filler, dusty clays with gravel inclusions and old construction waste – concrete, bricks, etc.;
- layer No. 3 – from elevation 532.3 m to elevation 528.3 m. Quaternary gravels – fine to medium gravels, rock soils and brown to yellow-brown aggregates or sometimes silty sands aggregate. The lower boundary of layer 3 is located at a depth of 4.5 m from the bed of the Vladaiska River (average elevation 532.8 m), i.e. at elevation 528.3 m; between 528.8 m and 532.8 m, with the binding material of layer 3 becoming more clayey. This fact is indicative of zones in which quaternary gravels and lower-lying fine sedimentary pliocene formations are successively alternated.
- layer No. 7 – below the elevation 528.3 m. Pliocene sediments – dark green to oil green silty clays (average clay content between 35% and 40%), which are highly plastic with high water content (natural water content between 35.5% and 62.4%).

The laboratory indicators (geotechnical parameters) of the construction soil are indicated in Table No. 1 [6].

Table 1. Laboratory indicators of the construction soil

Final Parameters								
Layer No	1	2	3	4	5	6	7	8
Volume weight γ, kN/m^3	19.5	17.9	21.6	22.1	19.9	19.8	16.6	18.5
Parameters after drainage								
Cohesion in one-plane shear C, kN/m^2	–	26.1	–	–	–	60.8	54.0	56.03
Angle of internal friction in one-plane shear φ°	40.5	36.0	37.6	33.2	33.1	27.2	19.4	30.09
Parameters before drainage								
Cohesion C, kN/m^2	36.8	51.5	–	–	–	167.0	120	135
Angle of internal friction φ°	–	–	–	–	–	–	–	–
Deformation module, MPa	14.1	12.9	25.8	20.7	17.5	18.0	27.6	28.0

The level of the ground water is identical to the level of the Vladaiska River and is about 7 m from the elevation of the terrain. After studies in the Lion's Bridge area, very high water permeability values with a water permeability coefficient Kv reaching 7 m/d can be expected in the quaternary unbound coarse soil materials. Pliocene fine clay soil materials have low to very low water permeability values and Kv of 0.00001–0.02 m/d [7].

3. STRESSED CONDITION OF CONSTRUCTION SOILS AND EXPECTED SETTLEMENTS

Software and information about the models used

Settlement calculations were made using Plaxis 8.1. – a software product oriented towards solving problems in tunnel construction. The product is based on the Finite Element Method (FEM) [8]. In order to assess the effect of the tunnel boring machine passing under the bridge and to predict/calculate the expected settlements, 2 models have been prepared:

- Model A – shows the construction of the tunnel in the real geotechnical conditions, in the Lion Bridge area.
- Model B – the same geometry, but the characteristics of the construction soil have been improved, as a result of strengthening, specifically injecting a cement solution the layer of Quaternary gravels, in which fall the foundations of the bridge and the crown of the tunnel.

4. MODELING

The modeled situation – Fig. 3 meets the conditions at the northern foundation of the bridge. There, the TBM progress has the maximum eccentricity with respect to the fundaments, which is why the highest impacts are expected there.

The first 5 m is an embankment, followed by a 4 m thick layer of gravel, in which fall the foundation of the bridge and the tunnel key. From the elevation – 9 m in depth, dusty clays continue. The level of ground water is – 7 m. Most values of the geotechnical characteristics of the rock and the three layers used in the calculations are indicated in Table 1.

The parameters of the tunnel support structure (tunnel diameter 9.5 m and segment thickness 0.32 m) used in the calculations are as follows:

- Thickness of the segment/lining – 0.32 m.
- Modulus of elasticity – 35.000 MPa.
- Poisson's ratio – 0.2.
- Axial stiffness EA – 11.200 MN/m.
- Bending stiffness Kmm – 62.65 MN m^2/m.
- Weight – 8 KN/m.

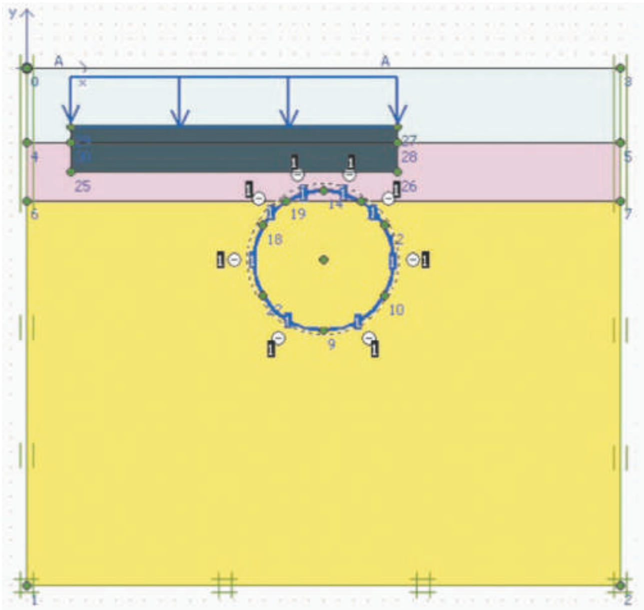

Fig. 3. Modeled situation at the northern foundation of Lion Bridge [6]

The foundations of the bridge are made of stone masonry with the following parameters:

- Modulus of elasticity, E – 1000 MPa.
- Poisson's ratio – 0.25.
- Weight – 19 KN/m^3.

The total weight of the Lion Bridge is 23,140 kN. In order to account for the weight on the foundations, a vertical load was applied.

5. CALCULATION STEPS

The calculation approaches are identical for both models adopted. In the first stage are taken into account the deactivation of the soil elements next to the river bed and the presence of the Vladaiska River. The second stage accounts the existing foundations of the Lion Bridge and the surface loads on the foundations are activated. In the third stage, the ground displacement is reset to zero, taking into account the first and second stages. The settlement that affects the tunnel is calculated with a combination of activation of the tunnel lining and deactivation of the earth layers along the contour of the tunnel [6, 9].

6. CALCULATION RESULTS

From the results obtained from Model A, the maximum settlement was reported to be 7.8 mm (Fig. 4). Although the value of the predicted deformations is not large, it is important to note that because the bridge was built in 1891 and because of the likely displacement of the strata below it, it is not possible to predict the value of the deformations that would affect its structure. For this reason, in order to avoid any future stressing of the bridge, settlements (subsequent angular deformations, etc.) caused by the counter-pressure tunnel excavation under the bridge, the deformations must be limited as much as possible by performing an improvement (strengthening) of the soil.

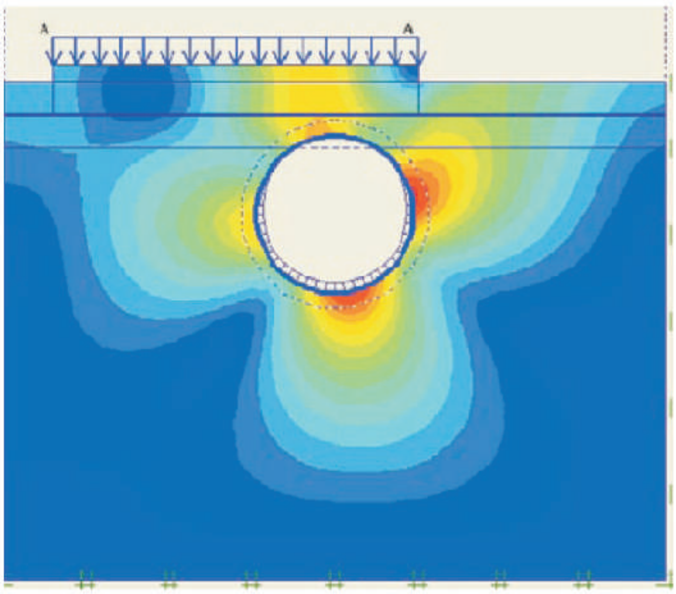

Fig. 4. Deformations according to Model A

According to Model B

Due to the above-mentioned reasons, Layer 3 (highly permeable Quaternary gravels) was injected with cement solution before passing the machine. Cement injection is intended to form a solid and reinforced gravel block (slab-like) beneath the foundations, which will reduce bridge settlements [10].

Actually, the gravel layer located above the tunnel vault is characterized by high permeability – $K_f = 0.12{-}0.012$ cm/sec [11]. Injection with cement solution reduces the permeability of the gravel and guarantees the applied pressure in the face of the boring machine. The geotechnical parameters applied for the elements of the injected gravel have been calculated experimentally and correspond to gravel-type materials injected with cement solution. They are assumed to have the characteristics of a weak rock.

To calculate the stress state of the massif in Model B, the characteristics of the middle layer of Quaternary gravels are replaced by new ones. The improved features are as follows:

- Bulk weight γ – 23.7 kN/m^3.
- Young's modulus E – 300 MPa.
- Poisson's ratio – 0.35.
- Cohesion C – 300 KPa.
- Angle of internal friction φ° – 40°.

The calculation approaches for Model B are the same as for Model A. From the obtained results it is evident that there are deformations. In this case they are lower than 5 mm, while in Model A they are 8 mm – Fig. 5.

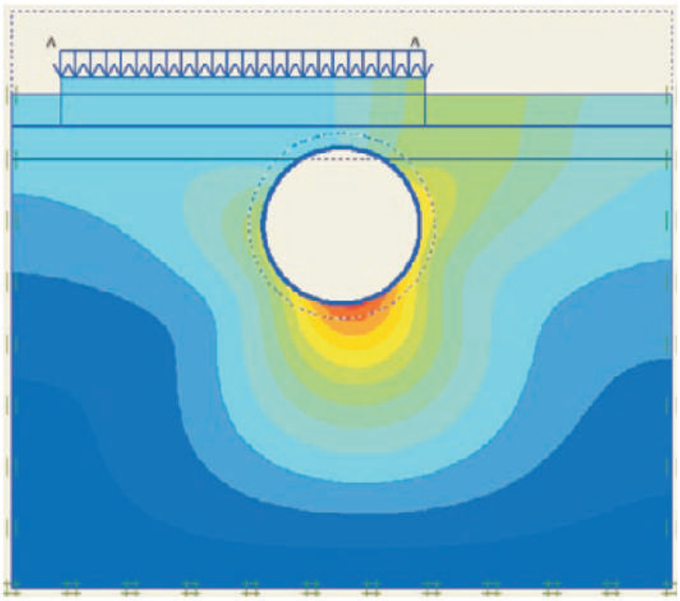

Fig. 5. Deformations according to Model B

The calculations made are extremely necessary to determine the settlements and deformations apart from the direct effects on the bridge structure. In the area of the bridge, the Lions Bridge metro station is being designed and built under the cut-and-cover method, which is located north of the bridge facility. The metro station has an extremely complex structure from an architectural and construction point of view. It is designed to four underground levels and as an underground facility it must be combined with the tunnel structure driven in pre-consolidated construction soils. Taking into account the expected subsidence in the reinforced areas along the tunnel route, the indirect and direct loads were taken into account when sizing the structure of the metro station. Load schemes are prepared – permanent, short-term and seismic load, which determine the type of the subsequent calculation scheme. The loads from a special combination with the inclusion of special effects are decisive [12].

7. CONCLUSIONS

The conducted research proves that when laying metro tunnels with a shallow foundation and in the vicinity of above-ground buildings and facilities, it is imperative to carry out strengthening activities in advance. From the obtained results it is clear that the strengthening of the massif must be in accordance with the geometrical parameters of the underground facility and the location of the buildings on the surface. In this way, the costs of the healing itself are optimized. After the implementation of the tunneling project in the area of Lions Bridge, the accepted models for predicting settlements have proven themselves in practice. The actual deformations of the soil base after injection did not exceed 3.5 mm, and virtually no displacements of the bridge structure were found.

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