EPB pressure control and volume loss resulting in tunnelling Sofia Metro Extension (Metro Diameter 2: “Road junction Nadezhda-Central Railway Station-Sveta Nedelya Sq.-Patriarch Evtimiy Blvd.”)

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Summary

This paper deals with the EPB tunnelling methodology in terms of EPB face control and the resulting volume loss analysis concerning Lot 1 of Line 2 within the context of “Sofia Metro Extension Project”. First a brief description of the project is given and later the monitoring results in terms of recorded volume losses along the alignment during TBM drive are showed and discussed. Special attention is focused on the EPB pressure kept into the excavation chamber and on the importance of a proper ground conditioning. Both these aspects are fundamental in order to guarantee the face stability, thus reduced volume loss values.

Keywords: TBM tunnelling, EPB pressure, settlement control, critical sections

1. Introduction

At the present time just one Metro Line is in operation in the city of Sofia. To improve the underground public transport network, the General City Plan approved the project of two additional metro lines and the extension of the existing line, for a total length of 65km, 63 metro stations. It is foreseen that the new metro scheme will have a daily capacity of 1.2 million passengers. The second line (i.e. Diameter) “Lozenets RD- Centre – Ilientsi quarter” is 17km long and includes 17 metro stations. This line has been divided in lots to be entrusted to several construction groups, whereof Doğuş İnşaat that awarded the “Diameter 2 – Lot 1” construction in August 2008. Diameter 2 is foreseen to be opened in late 2012.

In this paper the most relevant aspects concerning the tunnelling works of Lot 1 of Diameter 2 are presented. Tunnel excavation has been executed by using a Tunnel Boring Machine (TBM) equipped with Earth Pressure Balance (EPB) technology. This methodology is widely used in urban area, since it minimize the effects of the excavation at the surface, avoiding dangerous settlements that compromise buildings and utilities, and it reduce traffic deviation in very dense urban area.

Doğuş İnşaat entrusted Tunnelconsult the segmental lining ring geometrical design, the definition of EPB working pressure together with the settlement analysis and ground treatment design at sensitive locations. This paper shows the results of the joint work between contractor and designer, which has resulted in a smooth tunnelling performance preventing and avoiding any surface disturbance.

The technical work presented in this paper is predominantly based on the experience gained by Tunnelconsult during years of tunnelling specialist services. Most of the aspects treated in this paper are deeply described in some technical references like for example [1], [2], [3] and [4]. The graphics, figures and tables included in this work have been extracted by the reports redacted by Tunnelconsult within the context of the Assistance Contract with Doğuş İnşaat.
2. Project main features

2.1 General outline

Lot 1 of Line 2 will serve the north-eastern sector of Sofia city center. It starts from Nadejda Junction in the Northern part of the city of Sofia and runs with a South-East direction to Patriarch Evtimiy Boulevard, running below main central streets like Knyaginya Maria Luiza Boulevard and Vitosha Boulevard. The alignment is 3770m long and includes 4 stations whose length is variable between 140m and 172m (MC-5, MC-6, MC-7 and MC-8). The first three stations have been constructed by Cut & Cover method before the TBM passage, thus the total tunnel length to be excavated by TBM has been 3300meters approximately.

Some sensitive structures have been under crossed during the TBM advance. Among the others, we mention the under pass of the Lion Bridge, a historical bridge constructed at the end of 19th century, whose foundations are located at less than 1m above the tunnel crown, and the passage below the Sveta Nedelya Cathedral dated from 10th century corresponding to the maximum overburden and piezometric load along the alignment. More details are contained in chapter 5.

The alignment minimum horizontal radius is 250m, while the tunnel slope ranges between 0.3% and 2.61%. Typical cross section of the TBM driven tunnel is illustrated in the next figure.

The lining of the excavated tunnels consist of pre-cast segments installed at the end of every excavation cycle inside the rear shield of EPB-TBM. The pre-cast concrete segments are 1.5m long and 320mm thick. Each ring will be formed by 6 universal segments plus one key-segment. The outer and inner diameters are 9070mm and 8430mm respectively.

In order to control the surface settlements, guarantee the correct installation of the segments and allow an uniform transfer of ground loads to the lining, the annular gap created at the end of the shield has been filled by injecting pressurized cement grout.
2.2 TBM S-525

The TBM shield employed for the tunnel excavation is an Earth Pressure Balance shield (EPB machine) with an excavation diameter of 9.43 meters. It has been manufactured by Herrenknecht with serial number S-525. Herein we detail the main features of the S-525 TBM.

- The shield is 9.2m long approximately, and, taking into account the backup gantries, the length reaches 84m.

- The weight of the shield is 875t approx., considering also the backup gantries the TBM weight increases to 1250t.

- Cutterhead is equipped with soft ground tools (approx.172 scrapers, 16 buckets, 1 double arm centre cutter and 13 ripper tooth inserts).

- Cutterhead is also equipped with 21 twin cutter discs of 17” to cross shafts slurry walls and 1 over copy cutter with soft ground tool.

- Shield front diameter is 9360mm.

- 13 double thrust cylinders are installed at the front of TBM.

- The maximum design earth pressure is 3.0bar and 7 earth pressures sensors are situated in the excavation chamber on the bulk head to control the applied EPB pressure.

- Foam has been injected by 8 ports through cutterhead and 4 through bulkhead.

- Grout injections have been performed through 6 double injection lines DN50.

- Screw conveyor type is spiral coil with shaft in pipe and it is 14.7m long. It has a maximum discharge capacity equal to 700m$^3$/h. Also the screw conveyor is equipped of 2x4 foam injections points to facilitate the muck removal.

- Conveyor system consists of 1m width belt having maximum speed of 2m/s and a resulting capacity of 600m$^3$/h.
2.3 Geology and Hydrogeology

The project is situated on the border of Sofia Pliocene basin. The tunnel alignment crosses an alternation of clays, sandy clays, silts, sands and gravels that compose Lozenets Formation (Pliocene age). Two main geological units can be distinguished within this lithology: Clay with alluvial and fluvio-lacustrine origins composed by an alternation of multi-colored and laminated clayey, silty-sandy layers; Sand with heterogeneous grain size distributions, varying from silty fine sand to well-graded medium-coarse sand. At the surface, below an artificial filling layer, Quaternary deposits formed by brown sandy clays are present with a variable thickness between 1.0-6.0m.

For the geomechanical characterization of the lithologies present at the project area, a geological campaign consisting in drilling 27 boreholes has been performed during 2009. The soil investigations program included laboratory tests and in situ activities which have allowed the geotechnical parameters definition of the different soil layers.

With regard to the hydro-geological characterization, the Quaternary and Pliocene aged deposits are formed by lithologies with variable hydraulic features: the granular materials including coarse to fine sand, silty sand and sands with gravel represent a water bearing layer, i.e. an aquifer ($K_{a\text{QUIFER}}\cong 1E-5m/s$); the materials with the characteristics intermediate between cohesive and granular, like clayey sands, silty-clayey sands, clays with sand pocket, form an aquitard ($K_{a\text{QUITARDE}}\cong 1E-6m/s$); impervious lithologies represented by clays, silty-sandy clays constitute an aquiclude ($K_{a\text{QUICLUDE}}<1E-7m/s$). Because of the uneven presence of impermeable strata between aquiferous formations, it can be stated that at the project area it is present a common water bearing horizon, i.e. a low pressure aquifer. By means of piezometric measurements performed during the geotechnical field investigations, it has been possible to situate the ground water level at depths between 1-14m from surface.

3. TBM Performance

The following graphic shows the evolution of the performance of TBM drive during the tunnel excavation. The initial stretch (200m approximately) represents the so called full erection of TBM and “learning curve”, i.e. the period during which the TBM crew gains skills with the machine, becoming confident in the TBM parameters interpretation and able to face eventual unexpected difficulties. In Metro Line 2 excavation, the learning curve included the initial stretch from the entry shaft to MC-5 Station and lasted about 1 month (average TBM advance = 7.5m/day). After this “training period”, the TBM speed incremented considerably, with an average progress of about 20m/day, i.e. 13ring/day approx. Along the final tunnel stretch, from MC-8 Station to the TBM Extraction Shaft, the maximum sustained average TBM advance has been recorded (26.4m/day ≅ 17 rings/day). We remark that along the last stretch TBM advance showed utmost impressive performance, reaching 43.5m/day (≅ 29rings/24hours).
4. EPB Pressure Study

The urban context, the minimum tunnel overburden and the presence of water-bearing unstable soil made necessary the continuous application of face pressure in order to maintain an active support of the excavation face. Tunnelling by using a proper EPB pressure at the front allows the tunnel construction with as little disturbance to the ground as possible. Generally in shallow tunnel like in "Diameter 2" case, the required face pressure corresponds to the full hydrostatic plus effective ground pressure.

In order to define the proper pressure to be applied, the alignment has been divided in stretches having homogenous geological-geotechnical behavior. Upon an accurate analysis of the available geological-geotechnical data, we came up with the following parameters, where cohesion has conservatively been considered nil in some stretches.

The main geometrical features corresponding at each considered section, like the overburden and the water table height respect to tunnel crown, have been identified. Average overburden ranges between 10 and 15 meters, while the maximum overburden is 23m at the passage below the Sveta Nedelya Cathedral. At this section it also corresponds the maximum hydrostatic pressure acting at tunnel crown, i.e. 1.4bar (14m·10kN/m3). A part from the entry and exit shaft areas where O.B. is even less than one tunnel radius, minimum overburden are encountered at some critical sections, like the under pass of the underground shopping area located before MC-6 Station or the Metro Line 1 just passed the MC-8 Station. At the critical sections, dedicated 2D and 3D FEM analyses have been performed to verify that the recommended EPB pressure was proper to avoid impacts on the sensitive structures. In the next chapter we will show some of them with more details.

Recommended EPB pressure has been computed averaging the results obtained from three different methods which estimate the working face pressure to avoid extrusion. These models have been inferred analytically and/or empirically on the basis of a given failure mechanism. Herein the main features of the adopted computation methods are indicated.

**Table 1** Properties of soil along tunnel alignment

<table>
<thead>
<tr>
<th>Stretch</th>
<th>Lithology</th>
<th>Unit weight [kN/m³]</th>
<th>Friction angle [°]</th>
<th>Undrained cohesion [kPa]</th>
<th>Permeability [m/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>From the Launch Shaft to MC-5 Station</td>
<td>Clayey sand</td>
<td>19.7</td>
<td>29.0</td>
<td>0</td>
<td>5.8E-6 / 1.1E-5</td>
</tr>
<tr>
<td>From MC-5 St. to MC-6 St.</td>
<td>Gravelly sand / gravel with silty-sandy filling</td>
<td>20.2</td>
<td>30.0</td>
<td>0</td>
<td>5.8E-6/ 1.1E-5</td>
</tr>
<tr>
<td>From MC-6 St. to MC-7 St.</td>
<td>Clayey sand, clayey sand with gravel, sandy clay</td>
<td>20.0</td>
<td>32.8</td>
<td>0</td>
<td>4.57E-07</td>
</tr>
<tr>
<td>From MC-7 St. to MC-8 St.</td>
<td>Silty clays</td>
<td>16.5</td>
<td>19.4</td>
<td>27.0</td>
<td>2.31E-08</td>
</tr>
<tr>
<td>From MC-8 Station to the Extraction Shaft</td>
<td>Clayey sand, at places sandy clay</td>
<td>19.9</td>
<td>31.0</td>
<td>0</td>
<td>4.57E-07</td>
</tr>
<tr>
<td></td>
<td>Silty sandy clay</td>
<td>20.4</td>
<td>26</td>
<td>74.9</td>
<td>&lt;1.00E-07</td>
</tr>
<tr>
<td></td>
<td>Clayey sand</td>
<td>19.8</td>
<td>32</td>
<td>0</td>
<td>1.15E-05</td>
</tr>
<tr>
<td></td>
<td>Silty clay</td>
<td>19.3</td>
<td>22</td>
<td>77.8</td>
<td>&lt;1.00E-07</td>
</tr>
</tbody>
</table>

**Singapore’s method**

This formulation is based on the methodology developed for the Singapore Metro construction ([5], [6] and [7]). For not cohesive materials, this formulation considers that the minimum value of EPB...
pressure has to counteract the earth pressure at rest plus the acting water pressure. In case of cohesive material, the active earth pressure has been taken into account instead of the earth pressure at rest.

**Empirical formulation**

This method consists in an empirically based formulation that is indicated to obtain an order of magnitude of the required pressures. This formulation considers that the minimum value of EPB pressure has to be 0.2 bar higher than the active earth pressure and the water pressure acting at a determinate level.

**COB method (Dutch Centre Ondergron Bowen)**

This formulation is similar to the previous one except that it takes into account a possible surface load and, in case of cohesive material, the positive contribution of cohesion. In the considered case, a surface load equal to 0.1 bar has been applied to take into account the road traffic. In case of cohesive material, cohesion contribution makes that lower values of EPB pressure are obtained with COB method with respect to the ones computed by the empirical formulation.

The working EPB pressure has been estimated as the average value resulting by the three mentioned methods. Since maintaining an exact and constant EPB pressure value represents a difficult task for the TBM operator, a working range has been indicated: the minimum EPB pressure that should never be underpassed corresponds to the pressure that should guarantee face stability and restrain any soil displacements; the maximum EPB pressure corresponds to the pressure value that should not be surpassed to avoid ground breaking and surface heave. As further verification, Jancesz method has been applied confirming that the upper EPB pressure limit (pmax) never overpasses the maximum pressure corresponding to soil uplift [8].

The pressure values indicated in Figure 8 are referred to the upper pressure cell (P1) located 0.7 m below the cutterhead crown (see Figure 5).

Some low points correspond to cutting wheel inspections and tool changes, which have always been performed at atmospheric pressure due to good soil behavior.

**5. Critical sections**

As commented in the previous paragraph, at some critical locations, special and detailed 2D or 3D FEM analyses have been performed in order to verify the influence of the tunnel excavation on sensitive structures. Herein we briefly describe the most critical sections through which TBM has excavated without that any inconvenient occurred thanks to the cooperation between designer and construction team and the TBM operators’ ability.

The main railway tracks of Sofia Central Station were located at 30 m approximately from the TBM entry shaft and tunnel alignment crossed under them for a 50 m long stretch with a curve of 273 m radius. The overburden at tunnel crown was limited to 9 m at this section. Along this critical tunnel stretch, due to the difficult geological context and the sensitive structures present at the surface, Tunnelconsult has recommended to Dogus the EPB shield working parameters to be adopted, with
the corresponding alert & alarm levels. These values have been defined by means of an accurate analysis of the data recorded during the excavation of the first 164 rings. By defining the range within which TBM parameters can vary it has been possible to have a rapid detection of complications and consequently reduce the “reaction” time of the TBM team; furthermore the suggested TBM working parameters aimed to the cutting tools preservation. Herein we show the analysis performed on TBM data during the excavation of the first tunnel stretch comparing them with the TBM parameters ranges we recommended.

The total TBM thrust (Fig.9) represents the total force necessary to balance the earth pressure in the chamber, to give enough force to the cutting wheel tools to penetrate into the ground and excavate it, to win the friction forces along the shield and to drag the back-up.

This parameter is strictly correlated to the cutting wheel torque (Fig.10) that is the torque necessary to win the viscosity of the material into the chamber and drag force of the cutting wheel and tools against the face.

The cutting wheel thrust, or contact force, is that part of the total thrust that is directly transmitted to the cutting wheel. From there it is then transmitted to the face or though the cutting tools or by mechanical contact between the cutting wheel front plates and the faces.

A settlement analysis has been especially developed using 2D and 3D FEM codes to study the influence of the tunnel construction on the underground structures located in the near proximity of MC-6 Station. The sensitive structures potentially affected by the tunnelling work were: an underground shopping center situated before MC-6 station (in TBM advance direction) between chainages 5+308 and 5+376, a pedestrian underpass located after...
MC.6 station between chainages 5+506 and 5+597 and a collector pipe that needed to be diverted since its original position would have intercepted by the tunnel alignment. The estimation on the possible settlements and angular distortions potentially induced by the tunnel excavation has been performed by means of FEM models, whilst the damage risk assessment has been based on Bjer- rum damage classification criterion (dated 1963).

Between chainages 6+130 and 6+170 approximately, S-525 shield has excavated underpassing Lion Bridge, a historical structure built at the end of 19th century to allow Vladaiska river crossing. Along the aforementioned tunnel stretch, overburden is minimal and the tunnel crown level is very close to the bridge’s foundations. It has been of primary importance estimate the possible settlements induced by tunnelling and define consequently the ground treatments to improve the safety of bridge foundations. Bridge foundations are formed by large stones filling wooden piles embedded in the river bed; the stone foundations total height is 2.8m and the wooden piles are 3.5m long.

In order to avoid any further stress on the bridge structure that is being already affected by an uncertain longitudina and transversal angular distortion, it was established that ground treat intervention was necessary. Thus grout cement injections were executed before the TBM underpass. A specific monitoring plan was proposed in order to detect any movement induced on the Lion Bridge by the grouting process and the TBM passage.

A further settlement analysis has been performed along the tunnel stretch included between sta- tions MC-7 and MC-8 in order to study the possible induced settlements on the "Banya Bashi" Mosque and the Central Old Market, located on the left and right side of the tunnel alignment respectively (with respect the TBM advance), just before entering MC-8 Station. We remark that the distance between the western column of the Mosque and the tunnel axis was reduced to 7.7m approx. (i.e. just 3.0m with respect to the tunnel wall), while the horizontal distance between the Old Market wall parallel to the tunnel alignment and the tunnel itself was about 15.5m.
Between chainages 6+963 and 6+983 approx., the Sofia Metro Line II TBM tunnel excavation will run below the existent Sofia Metro Line I with reduced cover. At the intersection area the lining of Metro Line I consists of a twin concrete boxes, which have been constructed with cut & cover method. The most important aspect to be considered has been that during the Line II TBM drive at the intersection area, Metro Line I shall be kept operative. Thus, the influence of Sofia Metro Line II tunnel excavation on the Line I twin tunnel has been studied by developing a 3D FEM numerical model, computing the expected settlements and to study the Line II TBM tunnel face stability in the considered area.

The results obtained from 3D simulation, have verified that both vertical settlements and the angular distortion related to the Line I structure are well below the acceptable operational limits. A constant monitoring of the Line I tracks movements has been carried out to check in real time the actual deformations and eventually intervene on the excavation parameters.

Along the final stretch of the tunnel alignment, just after having intersected with Metro Line I, a very critical point of the entire project has been represented by the underpass of Sveta Nedeleya Cathedral. The Church is situated at the surface exactly above the tunnel alignment between chainages 7+075 and 7+123 approximately (see the next figure).

The orthodox cathedral, originally built during 10th century, has suffered many damages during its life and has been rebuilt several times along the centuries. Due to its high historical-cultural importance, the underpass below this sensitive structure has represented a very critical point and several analyses have been performed to ensure that the church foundations would have not suffered any damage due to tunnelling. Surface settlements have been evaluated with a double approach: first they have been estimated by the empirical method proposed by Peck and then they have been verified developing numerical calculation by FEM code.
6. Settlement Control

The evaluation of the proper face support pressure is the most critical aspect in the design and construction phases of a TBM bored tunnel, but there are some other elements of relevant importance which must be managed to guarantee an outstanding TBM advance rates and minimum disturbance on the surface. As general concept, during excavation by EPB machine, the volume of the extracted material should be equal to the excavation section by the shove length. In order to achieve this equilibrium, a part from maintaining a proper working pressure, it is necessary to control other fundamental parameters, like the conditioning system of the material in the chamber. Furthermore, a crucial parameter for volume loss control is represented by a proper grout injection of tail void as TBM advances.

6.1 Soil conditioning

When driving an EPB shield, the muck in the excavation chamber shall behave like a homogenous and plastic mass with pulpy to soft consistency, low inner friction and low water permeability. In order to obtain a suitable ground for EPB applications and enhance the tunneling performance, special additives are injected at the face in the excavation chamber in a process called soil conditioning.

Soil conditioning can be achieved by adding and weighing out special additives (agents), i.e. foam, into the excavation chamber. The foam consists of a mixture of air with a liquid solution which is composed by water, tensid agent (foaming soap) and polymer as stabilizing agent. High FIR values are needed to have good workability and flowability, as well as a homogenous face pressure application. For example, in the last stretch alignment (beyond MC-7 Station up to chainage 7+450) a higher average FER value has been used for “wetting” requirements in cohesive materials.

6.2 Grout injection

In TBM tunnelling backfill grouting is a crucial and critical process since only a perfectly filled gap guarantees the structural capacity of the lining ring and the control of secondary volume losses. In S-525 TBM the grouting system is included into the TBM tail shield and it can inject bi-component grout (mortar and accelerator) synchronized with the excavation. Within the context of Sofia Metro Extension Project the main functions of grout were:

- To ensure a uniform contact between the lining and the ground.
- To limit the volume losses due to excavation profile contraction.
- To hold the ring in place during shield advance.
- To improve the water-tightness of the tunnel lining.

S-525 TBM is provided of 8 double grout injection lines. Injection quality is controlled by two parameters, i.e. pressure injection and mortar volume.
7. Volume Losses

Volume loss represents, for a given tunnel section, the ratio between the loss of area due to the excavation profile displacement through inside the tunnel and the total bored area. In order to evaluate the performance of the TBM in terms of surface disturbance and based on the recorded vertical displacement, we have computed at several locations the apparent volume loss generated by the tunnel excavation. The apparent volume loss has been obtained by integrating the vertical displacements through the settlement basin and relating them to the excavation section (i.e. 69.8m²).

On the basis of monitoring data referred to many tunnelling experiences with EPB shield in metropolitan area, it can be stated that normal values of volume loss range between 0.5% and 2.0% (mostly between 0.5 - 1.0%). In Sofia Metro Extension, the estimated apparent volume loss values fall in a very acceptable range, being the average apparent volume loss equal to 0.21% a quite comforting value. Higher volume losses have been noticed at cutting wheel inspections. Anywhere, the maximum recorded volume loss is well within international practice and in any case it has over passed the expected performance. In some cases, when excavating under minimum overburden, negative volume loss has been recorded, indicating negligible soil uplift related the applied face pressure. The monitoring of the apparent volume loss has been constantly performed during tunnel excavation since it gives an indication on the performance of TBM drive.

8. Conclusions

Diameter 2 - Lot 1 of Sofia Metro Extension, consisting in 3300m of TBM bored tunnel, has been executed in 1 year and 4 months, without any relevant accidents. EPB shield has shown good performance with a maximum average advance of 26.4m/day in the last tunnel stretch. The difficult geology consisting in sand, sandy clays and gravel with high underground water level, and the urban context made the execution of Diameter 2 - Lot 1 of Sofia Metro Extension a challenging construction project. By applying the proper working EPB pressure at the excavation face, maintaining the TBM excavation parameters within the prescribed range and performing grout injections with particular attention to the injected grout volume and pressure, paired with the constant control on the monitoring data had assured a smooth boring which has not been even noticed on the surface.

9. Acknowledgements

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10. References

REFERENCES


