TWIN TUNNELS CRITICAL UNDERPASS DURING SOFIA METRO LINE 3 EXTENSION

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Abstract. Within Project Extension of Sofia metro, Line 3, phase I; 9.4 m EPB Machine challenged the underpass of two existing 5.2 m inner diameter tunnels with tight overburden of 1.4 m; few meters prior TBM breakthrough into MS 8. It was concluded to calibrate EPB parameters based on a vast analysis of the already excavated stretch. Determined TBM drive parameters and adjusted pressures were controlled by an extensive monitoring plan, to determine volume loss and confirm expected ground displacements induced by TBM underpass. Finally, boring below L1 tunnels and MS8's breakthrough was successfully performed through an unexpected uniform ground behavior.

Keywords: TBM, Tunnel boring, ground elevation monitoring, deep levelling pins, Sofia Metro extension.

INTRODUCTION

"Extension of the Sofia metro, Line 3, phase I, Boulevard Vladimir Vazov-Centre-Zhitnitsa Street" consists of 7.8 km of a new line, including seven new stations linking several residential districts with the Sofia city centre.

A consortium of Doğuş Construction, Via Construct and Ultrastroy is the lead contractor for tunnelling works. TunnelConsult Engineering has been in charge of both, detailed design related to underground works (permanent and temporary structures) and technical assistance during construction.

The analysis case hereunder reported is based on EPB underpass below pre-existing Metro Line 1 tunnels given narrow overburden of only 1.4 m from the top of the tunnelling machine up to the closest tunnel section. Metro Line 1 consists of single track-twin tunnels of 5.17 m inner diameter and 25 cm thick segments. Both tubes are crossed by Line 3 designed tunnel alignment under Knyazheska Garden, right before Metro Station 8 (MS8).

A case study has been tailored to investigate affectations to Metro Line 1 existing tunnels after TBM underpass and TBM breakthrough into MS8. The

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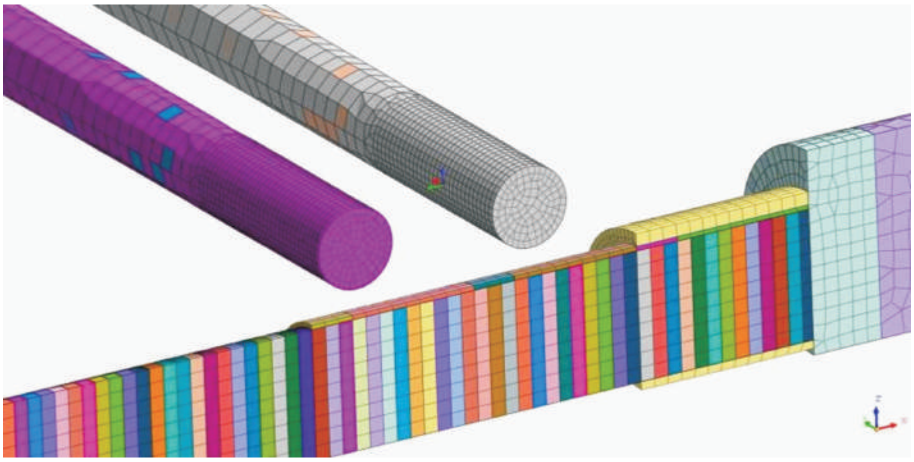

Fig. 1. MIDAS model. Line 1 Underpass. 3D view

analysis is complemented by comparison of on-site measurements to foreseen values defined at the preliminary stage.

2. WORKS PLAN

2.1. Preventive works

Due to the complexity of the single-track twin tunnels underpass, preventive measures were considered in order to minimize affectations to the existing infrastructure. However, the alternatives' spectrum was tightened due to distinct constructive constraints such as alignment rigidity or protected trees felling prohibition. Also, other actions were dismissed due to the uncertainty of its feasibility or effectiveness as opposed to its execution impact.

Given this juncture, a case study was designed to calibrate TBM main parameters prior Line 1 bi-tube underpass by paying especial attention to the little clearance between the edge of the EPB excavation section and the existing structures (1.4 m).

2.2. TBM calibration

The adopted solution is based on a preliminary settlements study beside an EPB pressures approach, all accompanied by the subsequent follow-up of the tunnel excavation works on-site. Hence, a special monitoring area was defined at Knyazheska Garden in order to determine ground response towards tunnelling to later set optimal TBM drive parameters which minimize any possible affectation to the existing tunnels.

TBM pressures were defined considering available geotechnical data and current hydrogeological conditions. According to the available geotechnical data, mainly sandy silt and silty sand shall be encountered whilst excavating this area. EPB pressures working range was adjusted by defining a lower limit for face stability (plus a suitable safety factor) and a higher limit to avoid surface heave.

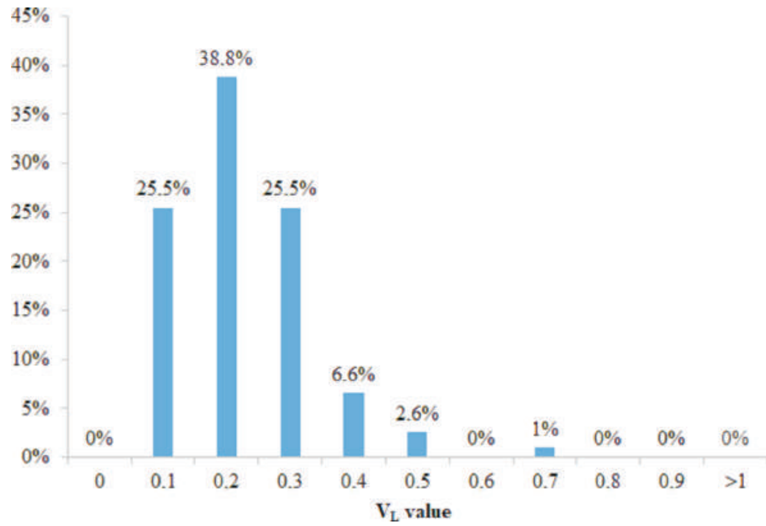

Fig. 2. Histogram of the V_L obtained values

Obtained results from previous excavation in-between MS14 and MS10 were used to determine Volume Loss (V_L) and k parameter on-site. Following is the histogram of the V_L obtained values from maximum settlements registered in survey points during MS14 – MS10 excavation.

Based on the presented histogram, a volume loss range of 0.2%–0.3% was considered for the settlement analysis at Knyazheska Garden area. The other main parameter (K) used to describe features of the site geology was set to $k = 0.5$; based on the back analysis of the collected data from the TBM advance at MS14 – MS10 stretch.

Once on site, all estimated parameters (both settlement analysis and EPB pressures estimation) needed to be compared to the measured values in situ during L3 tunnel works follow-up. The obtained results were used for the calibration of main TBM parameters.

3. MONITORING PLAN

An extensive monitoring plan was tailored to investigate ground movements due to TBM advance before, during and after its pass below existing Metro Line 1 tunnels and breakthrough into MS8.

3.1. Instrumentation at Surface

Prior TBM excavation along Knyazheska Garden, several cross-sections were installed following the new tunnel alignment. Likewise, additional measure points were also individually set in-between sections. Since different types of instrumentation were placed, settlements could be presented not only at ground level but also at existing tunnels' sections levels. Hence, whilst vertical displacements at surface could be measured with deep levelling pins (1.5 m length), the deeper measurements were obtained by means of 3-rod extensometers.

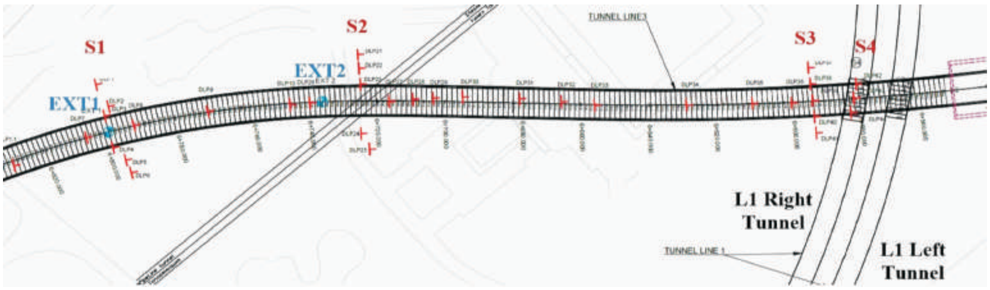

Fig. 3. Monitoring Layout at Knyazheska Garden

Readings of all instruments comprised inside tunnelling work's influence area were taken (at least) every 12 h. This allowed the collection of large amounts of data and consequent elaboration of an accurate and meaningful analysis.

3.1.1. Deep Levelling Pins

Five to seven deep levelling pins conformed the typical orthogonal section distributed such that closest pins to the middle instrument would be located about one tunnel radius to the axis. Moreover, an equidistant positioning of the pins would enhance to approach and compare on-site k parameter to the initial considered value ($k = 0.5$).

Four typical cross-sections were installed along the park:

- S1 at ca. 220 m from L1 right tunnel axis.

• S2 at ca. 150 m from L1 right tunnel axis.
• S3 at ca. 13 m from L1 right tunnel axis.
• S4 right above L1 right tunnel axis.

Besides, additional deep levelling pins (DLP) were also distributed at every ca. 20 m (or even less). Such instrumentation spread pretended to determine a more accurate picture of ground response to TBM advance. It should be noted that at the preliminary settlement analysis carried out before TBM launching, a volume loss of 0.65 % had been considered to estimate ground behaviour at TBM's pass along the park.

Afterwards, when studying ground behaviour after TBM drives between MS14 f – MS10, a back analysis concluded that a volume loss of 0.3% could be reached.

3.1.2. Extensometers

Due to a minimum clearance of only 1.4 m between existing tunnels and the new tube, 3-rod extensometers were also installed in some monitoring arrays, aligned with the new tunnel axis. Since 3-rod extensometers can measure ground vertical displacements at three different elevations, it was bent to define representative control points such as to simulate existing L1 tunnels' sections. Hence, measuring points would coincide with the existing tunnel's invert, centre and crown levels (as shown in Fig. 4).

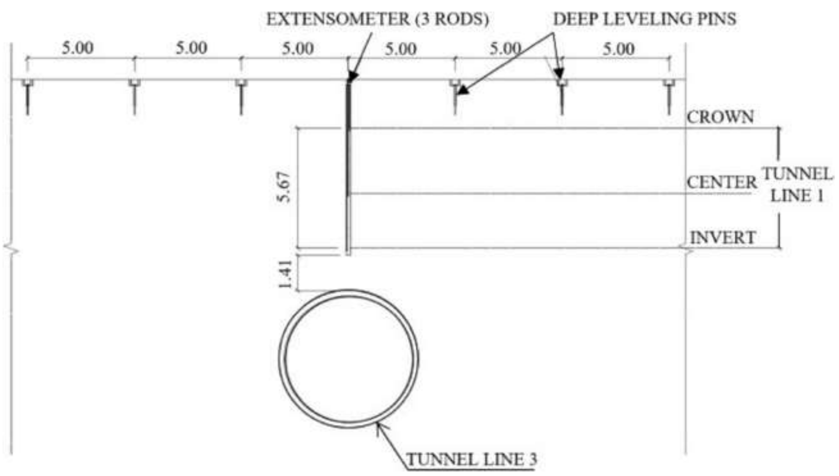

Fig. 4. Surfaces monitoring. Typical cross section

Two 3-rod extensometers were finally installed (see Fig. 3):
- S1 at ca. 220 m from L1 right tunnel axis.
- S2 at ca. 150 m from L1 right tunnel axis.

3.2. Instrumentation inside existing tunnels

The special monitoring plan was completed by installation of additional instrumentation inside existing L1 tunnels. Therefore, in order to evaluate settlements and convergences within Metro Line 1 existing tunnels, convergence prisms at both L1 tunnels were installed.

3.2.1. Convergence Prisms

Convergence prisms were a very useful tool for the follow up of L1 tunnels response towards TBM excavation in order to determine real TBM affectation to these tunnels. Five convergence prisms sections were equidistantly set out within the Zone of Influence (ZOI) (center, midpoints and limits of the ZOI).

Convergence prisms distribution was analogous per both Metro Line 1 tunnels.

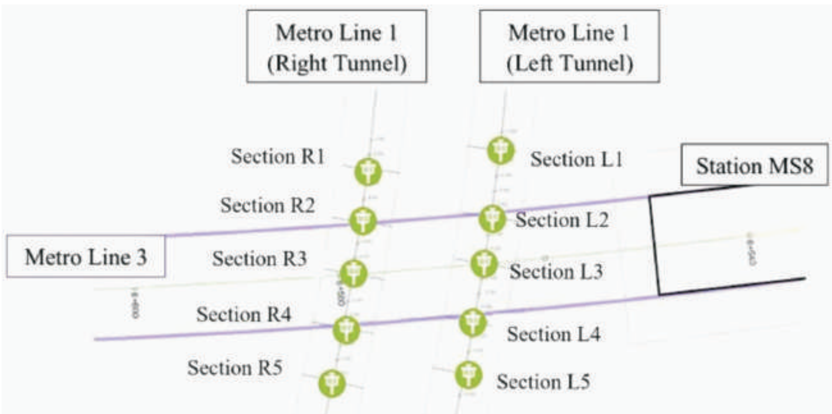

Fig. 5. Prisms sections distribution. Plan view

For convergence measurements, 5 reflective prisms were set at each of the 5 sections installed at both right and left tunnels. As per general distribution, the positioning of prisms at every section has been the following: one prism at the tunnel crown, two prisms at 2/3 of the tunnel height on the sidewalls and two prisms on the lower sidewalls at a minimum vertical distance of 0.5 m from the invert slab.

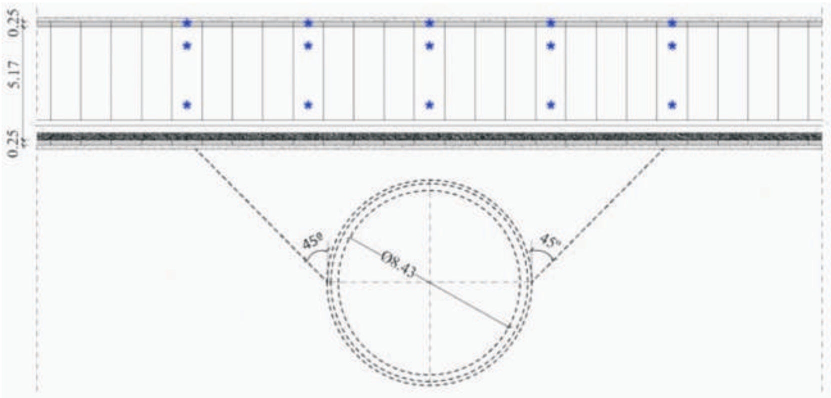

Fig. 6. Prisms sections distribution. L3 cross section

Since all prisms were automatically read every 10 min, live displacements charts could be constantly updated.

4. TBM FOLLOW-UP (ON-SITE)

On the first stage, TBM follow-up at Knyazheska Garden area was performed up to Ch. 6+600 (right before S3); where EPB stoppage was programmed prior Metro Line 1 existing tunnels underpass. At this point, study of all TBM drives up to ca. 15 m before TBM reached existing L1 tunnels included the analysis of on-site monitoring readings prior, during and after TBM advance as well as of main TBM excavation parameters. Likewise, a comparison of these results to the initially estimated values at preliminary stage was also performed.

First stage completion gave way to the second follow-up stage; consisting of final check and calibration of the main TBM parameters to overcome the most challenging stretch, in which TBM had to underpass L1 existing tunnels and later break-into MS8.

4.1. On-site monitoring

4.1.1. Deep Levelling Pins

In order to know new tunnel affectations at different levels sections S1 and S2 were set perpendicular to tunnel alignment. Both orthogonal sections consisted of several deep levelling pins separately placed so that k parameter

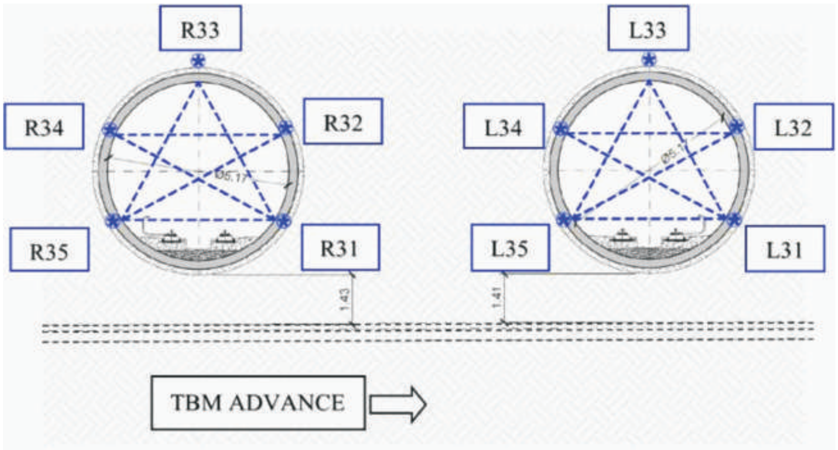

Fig. 7. Prisms sections inside L1 existing tunnels

could be also approached and compared to the initial considered value $k = 0.5$, obtained from the previous back analysis.

Hereunder are the on-site maximum settlement values compared to initially expected displacements obtained from the settlement analysis carried out in advance (by considering volume loss range of 0.2%–0.3% and $k = 0.5$).

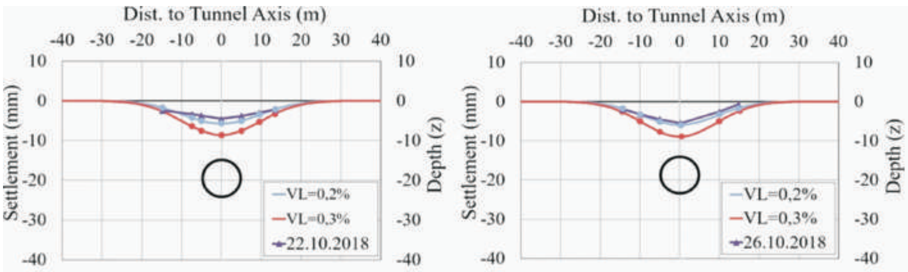

Fig. 8. Settlement troughs S1 at Ch. 6+800 (Left) & S2 at Ch. 6+725 (Right)

4.1.2. 3-Rod Extensometers

Two 3-rod extensometers were installed at the existing tunnels elevation along Knyazheska Garden, prior Metro Line 1 tunnels underpass.

After continuously readings of both instruments, none of the extensometers presented any relevant vertical displacement. The following charts show expected vertical displacements at each rod elevation against real settlements read on-site during a total period of 20 days. In both cases, very little settlement gradient was obtained when comparing measurements on surface and at the deepest rod of the extensometer.

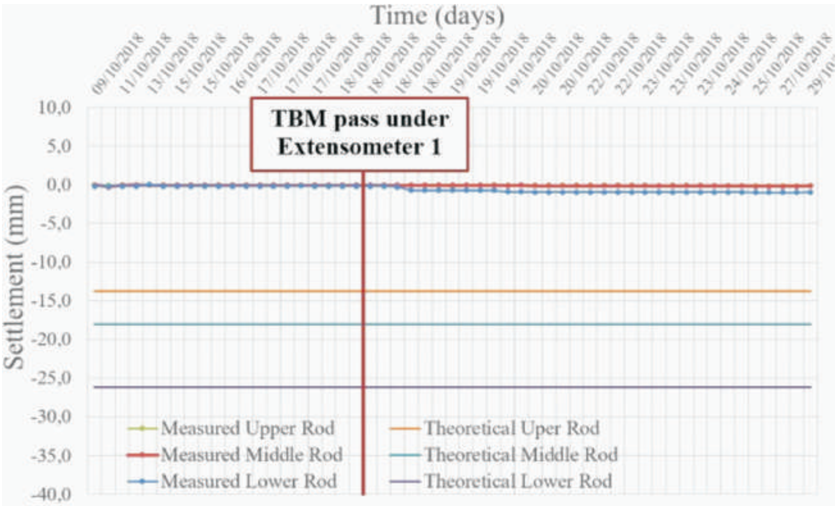

Fig. 9. Extensometer 1 readings at Ch. 6+800

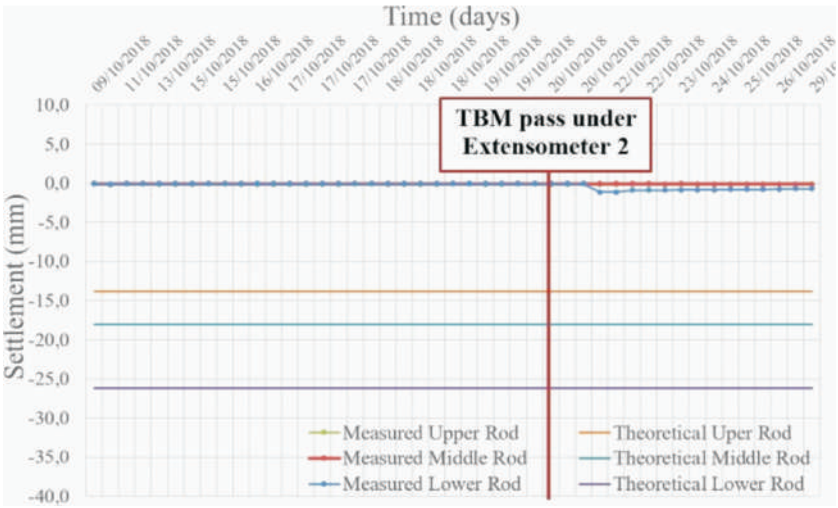

Fig. 10. Extensometer 2 readings at Ch. 6+735

To be noted that presented are relative displacements since the extensometer's top level also decreased in accordance with registered settlements at the surface.

4.2. EPB Pressures

During TBM advance along the entire stretch, average pressures on top of the excavation chamber were continuously measured, checked and compared to the initially estimated pressures as well as to defined pressure limits.

TBM excavation parameters recorded along the 270 m of TBM drive below Knyazheska Garden, prior reaching L1 tunnels (Ch. 6+880 up to Ch. 6+610) were deemed. This corresponds to 180 TBM excavation reports which were daily collected and studied in order to understand and analyse the TBM early drive.

Five pressure cells were encountered inside the excavation chamber:

- EPBS-1 and EPBS-5, located at 2.1 m from the top.
- EPBS-4 at 3.5 m from upper sensors. Hence, an overall of 5.6 m from the top.
- EPBS-2 and EPBS-3, the lower sensors, positioned 8 m down from the top.

EPB pressures inside the chamber were constantly checked in order to ensure the most suitable pressure gradient that may result on a proper TBM performance.

In order to keep pressure in the chamber at the designed level during the entire cycle, it was decided to use bentonite slurry injection system to the excavation chamber during any planned or sudden stoppage (even during ring erection or belt conveyor stop).

Tailskin grout injected volumes during TBM drives also became a relevant parameter, highly important to be traced to achieve even volumes and pressure distribution around the ring.

Additionally, soil conditioning control was carried out in order to ensure proper material distribution inside excavation chamber avoiding air accumulation on it. Achieving constant soil conditioning with an approximate range value of 14–15 kN/m^3 would ensure workability of material encountered inside the chamber as stabilizer for the excavation face.

5. CHALLENGE DAYS

After final check and calibration of main TBM parameters, tunnelling works could be resumed in order to overcome the most challenging stretch, in which TBM had to underpass Line 1 existing tunnels and later break-in MS 8.

5.1. Line 1 Tunnels Underpass

5.1.1. Deep Levelling Pins

Monitoring layout on the surface after Ch. 6+650 was formed by two main DLP sections (S3 and S4) respectively located a few rings ahead first L1 tunnel to be crossed (right tunnel) and right over the same L1 tunnel axis. Besides these two sections, several deep levelling pins (DLP34 -DLP36) were also positioned above the Line 3 tunnel axis.

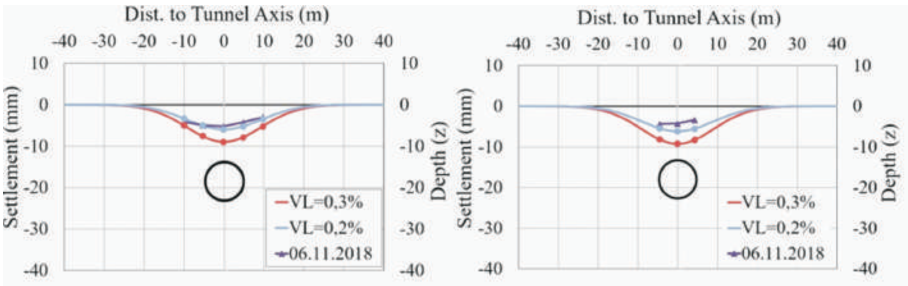

Fig. 11. Settlement troughs S3 at Ch. 6+592 (Left) & S4 at Ch. 6+580 (Right)

Five deep levelling pins constitute S3, separately placed so that the closest pins to the middle instrument are located at one radius distance to itself. An equidistant positioning of the pins enhances to approach and compares the k parameter to the initial considered value $k = 0.5$ obtained from the previous back analysis. For setting out of section S4, three deep levellings aligned to Line 1 right tunnel were installed. The middle one over L3 tunnel axis and the other two – at one tunnel radius each.

As previously mentioned, from TBM drives experience between MS14 – MS10, it was concluded that $V_L = 0.3$ % could be reached. Also, during same previous back analysis $k = 0.5$ was set.

Considering all previous assumptions and given the fact that maximum settlement registered was not greater than 6 mm down, following are presented the volume loss values associated to on-site measured settlements. Following the previous trend and as shown on Fig. 12, TBM associated volume loss not only resulted in less than the estimated $V_L = 0.3$ % but equal or even lower than $V_L = 0.2$ % in all measured points.

Two additional charts are presented to provide complementary vision of ground behaviour prior to, during and after the TBM pass in-between Ch. 6+880 and 6+550. Fig. 13 shows ground vertical displacements according to

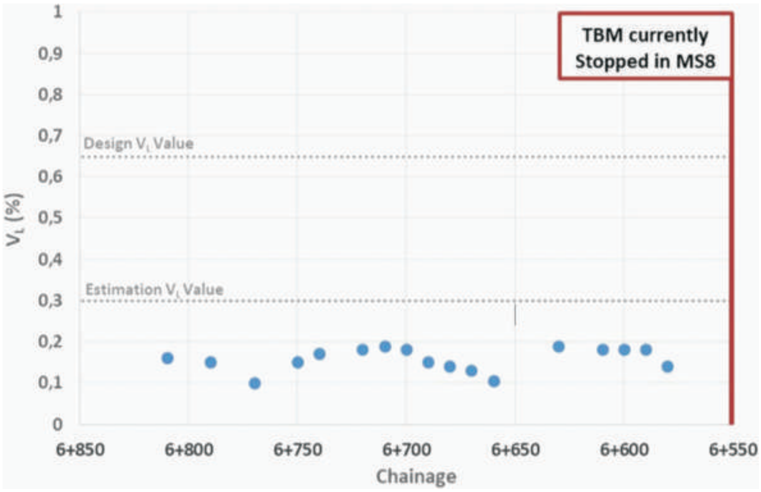

Fig. 12. Calculated V_L (Ch. 6+880 - 6+550)

TBM position; whilst Fig. 14 presents observed settlements according to time towards TBM crossing.

From Fig. 13 it can be observed that the greatest vertical displacements happened mainly during: a) the cutterhead approach and b) after ring installation and the entire TBM shield's length passing. Afterwards, settlements are smoothed. The effect of the TBM's passage can be clearly seen in the

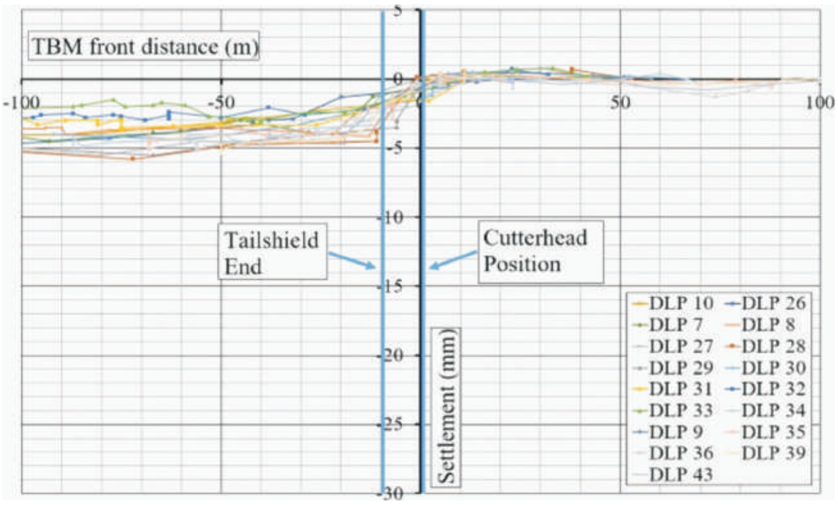

Fig. 13. Settlement Vs Distance to TBM front (Ch.6+880 – 6+550)

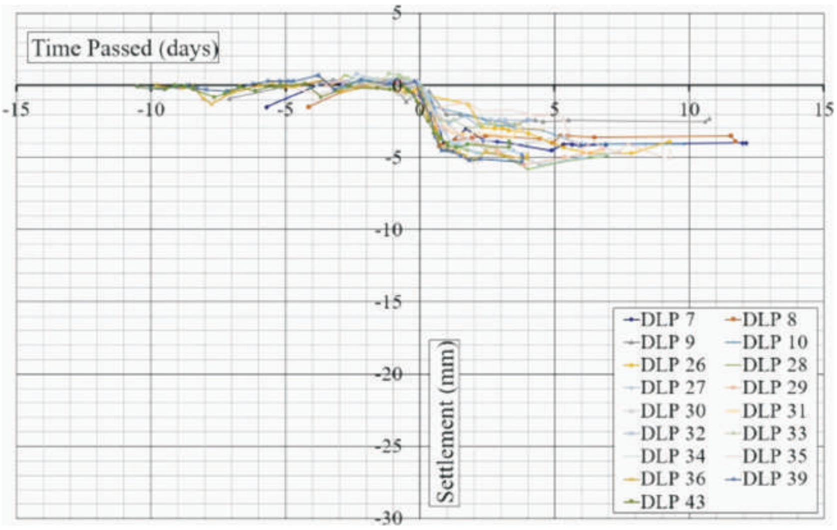

Fig. 14. Settlement Vs Time after TBM pass (Ch.6+880 – 6+550)

representation of the absolute settlements in millimetres and settlement face distance. In this type of graph, the influence of the TBM on settlements in front of the face can be clearly seen, and the same for the passage of the shield and shield tail. From Fig. 14 it can be concluded that the greatest seats occur during the two following days after TBM pass. If we consider that the stabilisation of the ground after the shield and tail have passed finishes once 95 % of the total settlement produced by the excavation is reached, most of the readings show how the ground is stabilized approx. 4-5 days after TBM has crossed.

5.1.2. Convergence Prisms

Convergence prisms were a very useful tool for follow-up of L1 tunnels response towards TBM excavation.

TBM impact to Metro Line 1 tunnels during machine advance was much lower than expected, resulting in maximum settlements not greater than 5 mm (ca. 25 mm were foreseen). Main displacements measured by the theodolite installed at Metro Line 1 right tunnel occurred during TBM cutterhead approach and whilst TBM shield crossing. Nevertheless, no relevant displacements were observed after shield end passing.

Notwithstanding, main vertical settlements in L1 left tunnel were measured only during TBM cutterhead approach. Afterwards, despite little additional

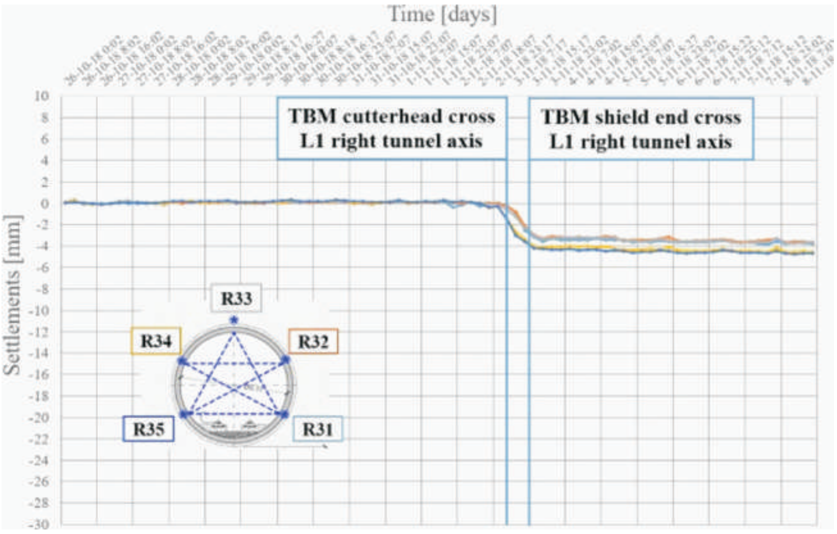

Fig. 15. Reflective prisms at L1 right tunnel (Section R3)

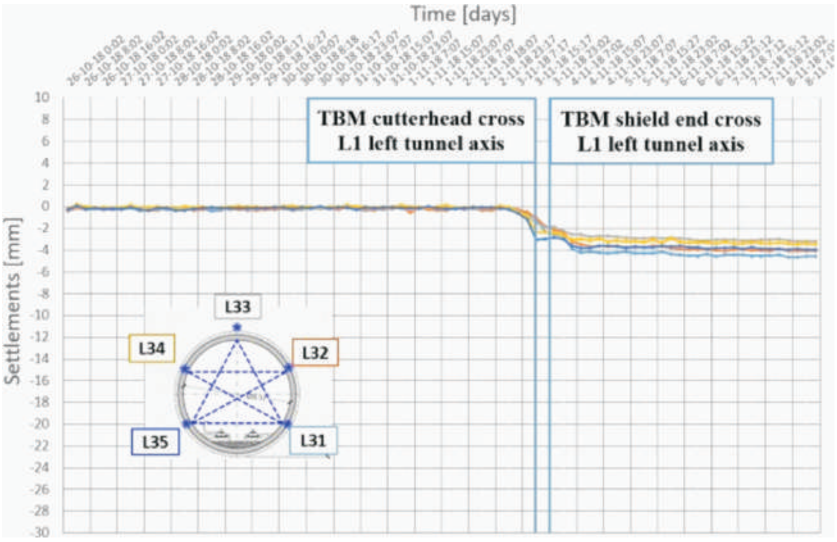

Fig. 16. Reflective prisms at L1 left tunnel (Section L3)

movements were registered after underpassing of the shield end, no relevant displacements were observed.

To be noted that although additional settlement sharp drop was expected after passing of the TBM shield end, it did not occur. One main responsible factor for the low values recorded was the accurate performance of grout injections at the tailskin during TBM drives under Line 1 existing tunnels. Same picture happened during underpass of both Line 1 tunnels. Considering maximum settlements registered at each prism of every section one settlement trough per tunnel can be displayed. Hence, below is Fig. 17 where the total number of 5 troughs is shown. Each one, represented by five points, refers to the measured settlement at the same prism position along the 5 convergence sections of the right tunnel. Therefore, since each section has 5 different prisms (e.g. R11/R12/R13/R14 & R15), these will be displayed as first point of each settle ment thrust. Maximum vertical displacement of 4.7 mm corresponding to $V_L = 0.16$ % and $k = 0.5$ was observed at prism R15.

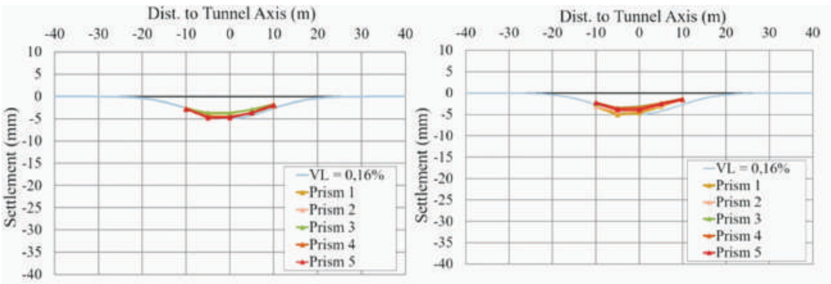

Fig. 17. Settlement trough at L1 right and left tunnels
(1st and 2nd tunnel crossed by TBM accordingly)

Similarly, to L1 right tunnel, left tunnel is composed by five settlement troughs. On this case, prisms L11/L12/L13/L14 & L15 conform the first point of each settlement thrust. Maximum vertical displacement on left tunnel is 4.8 mm, observed at prism L21. Likewise, vertical movements registered on left tunnel also correspond to $V_L = 0.16$ % and $k = 0.5$.

5.1.3. 3-Rod Extensometers

Back to 3-rod extensometers readings, given minimum deformations observed during the on-site analysis it was suggested to revise installed instruments due to possible issues during its installation or reading process. However, after Line 1 tunnels' underpass it was noticed that similar settlements were observed at both elevations: at surface (S4 deep levelling pins) and inside L1 western tunnel (convergence prisms).

Hence, it can be assumed that the expected settlements' gradient within ground surface and tunnel crown elevation was not performed due to a higher on-site soil cohesion coefficient than the one considered during the settlement analysis. In addition, a visual inspection of both existing tunnels was successfully carried out during and after TBM passing, without any type of incident or damage to highlight.

5.2. TBM Breakthrough into Metro Station 8

The complexity of the operations was higher due to the proximity of Metro Station 8. Difficulty of last TBM drives was mainly due to a simultaneous approach of the cutterhead to MS8 and the underpass of shield's tailskin end below the existing Line 1 (left) tunnel.

Therefore, tailskin grout injections during the final approach were relevant; highly important to be traced to achieve even volumes and pressure distribution around the ring. Proper injections performance was imperative to minimize settlements as well as any possible affectations to existing tunnels. Besides special monitoring plan set on surface and inside L1 existing tunnels, several reflectors were also installed at MS8 wall in order to monitor wall reaction during TBM approach.

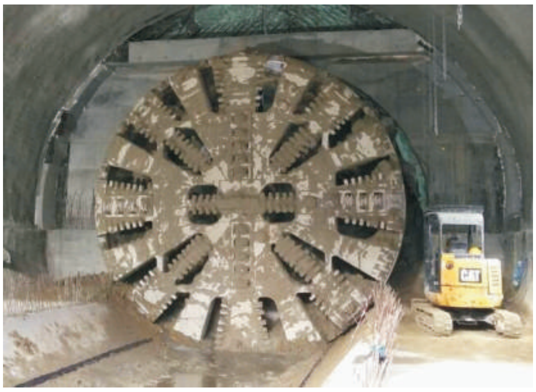

Fig. 18. TBM breakthrough at MS8

Since TBM under passed Line 1 left tunnel, MS8 wall was checked at every TBM advance. It was during last TBM drives when readings were constantly taken from a specific survey team bound on-site. This data was used as additional support for follow up of the TBM performance during the last advances up to the MS8 breakthrough.

6. CONCLUSIONS

After detailed analysis of all TBM advance reports and on-site monitoring readings along Knyazheska Garden, no relevant affection at surface was observed. Following the proper managing of the TBM registered during the previous TBM drives, main TBM excavation parameters related with settlement generation were well managed below the bi-tube without any major or remarkable issues, resulting in very low volume loss rates (lower than expected in preliminary studies).

Settlements range obtained from deep levelling pins' on-site readings confirmed that volume loss range of 0.2%–0.3% registered on the previous TBM drives was maintained along the entire stretch running under Knyazheska Garden up to Metro Station 8.

Moreover, TBM affectations to existing structures during Metro Line 1 tunnels' underpass were minimal since no relevant displacements were measured at the ground surface nor in any of the other two tubes. In addition, it should be also noted that the visual inspection of both existing tunnels was successfully carried out after TBM passing, without the presence of any type of incident or damage. The order of magnitude reached by the volume losses can be considered as inherent to the use of a mechanized shield tunnelling system in these ground conditions and this TBM performance.

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