Determination and validation of Longitudinal Displacement Profile by in situ measurements at the M85 motorway tunnel

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ABSTRACT: Tunnelling is an obviously three-dimensional process. Tunnelling in yielding ground also generates a 3D, bullet shaped zone of plasticity in soft rock, but also generates a bullet shaped fracture zones in the brittle rock masses. Longitudinal displacement profiles (LDP) characterize and describe the displacement history during tunnel excavation, including that occurring ahead of the tunnel face. Experimentally determined LDP provide a valuable database for validation of the tunnelling approaches. This study is presenting the in-situ measurements of two geotechnical instrumentation sections which includes MPBX extensometers and NATM pressure cells from the shallow depth M85 motorway tunnel which is excavated in soft ground and is situated beside Sopron city (Hungary).

The measurement results give us opportunity to validate the LDP and to verify the tunnel support interaction with the tunnel excavation. The results show good qualitative and quantitative agreement ahead of the tunnel face.

Keywords: Longitudinal Displacement Profile, MPBX extensometer, NATM pressure cell, deformation, excavation.

1 INTRODUCTION

Due to the tunnelling one of the technical factors that controls the choice of which tunnelling method and support to be used is the stability of the tunnel face. When the stresses in the rock mass surrounding a tunnel exceed the strength of the rock mass a zone of failure or a “plastic” zone (in hard rock tunnel a fractured zone, mainly EDZs) is formed around the tunnel. When the radius of the “plastic” zone around a tunnel exceeds twice the radius of the tunnel, the zone of failure around the tunnel interacts with the failed rock ahead of the tunnel face to form a continuous bullet shaped “plastic” zone. This three-dimensional plastic zone becomes increasingly difficult to stabilize as the ratio of stress to available rock mass strength increases (Hoek et al. 2008).

For investigation of the mentioned Longitudinal Displacement Profiles (LDP) with convergence-confinement analysis (Duncan-Fama 1993, Panet 1995, Carranza Torres and Fairhurst 2000, Hoek

1999, Vlachopoulos and Diederichs 2009 and others) is a widely used tool for preliminary assessment of squeezing potential and support requirements for circular tunnels in a variety of geological conditions and stress states. An analytical plasticity solution such as that developed by Carranza-Torres and Fairhurst (2000) is applied to a circular opening in an isotropic stress field. An internal pressure, initially equal to the in-situ stress is applied on the inside of the excavation boundary. The pressure is incrementally relaxed until the excavation boundary condition is that of zero normal stress. The extent of plastic yielding (or fracturing) and thereby, the boundary deformation is calculated at each stage of the process. This developing plasticity or yielding zone (or fractured zone in brittle rock mass), combined with the elastic closure of the surrounding rock mass creates a wall displacement profile that is non-linear, develops partially before the advancing face and continues for a number of tunnel diameters before equilibrium conditions are achieved. This profile, known as the LDP is a function of tunnel radius and the extent of the ultimate plastic radius (tunnel radius plus thickness of yielded ground).

The investigated pair of tunnels is part of the M85 motorway between the Fertőrákos village (near to Sopron city) junction and the Hungarian-Austrian border at km 90. The tunnel with 780 m length is being built using mining technology, using tunnel excavators and 24 hours a day in two shifts. The tunnelling was carried out by using sequential excavation method (SEM, is also known as the New Austrian Tunnelling Method - NATM) which is characterized by the sequential removal of ground material followed by the installation of support. The essential component of the SEM approach is to take advantage of the natural capacity and strength of surrounding geology to support the tunnel with minimum cost and time required. The SEM process includes a thorough investigation of the ground and adjacent structures to create functional classifications for support and advance lengths (maximum unsupported excavation length). The tunnels were excavated in 3 steps, using crown, bench and invert.

In the tunnels, two geotechnical monitoring sections were installed in the South Tunnel, as this tunnel was the first to be built, so that some of the deformations could be measured during the excavation of this tunnel, but the main objective was to study the approaching, arrival and passing during the construction of the adjacent North Tunnel. This allowed a complete deformation image to be captured and the behaviour of the pillar, the applied support and the LDP to be investigated.

In case of each geotechnical monitoring sections, 1 Geosense® GEO-XB2 borehole rod type extensometer ("MPBX" or "Multi-point Borehole Extensometer" - with 3 groutable anchors with depths of 3 m, 6 m and 9 m from the multipoint reference head) (see Figure 1) and 6 NATM pressure cells (3 radial and 3 tangential cells) were installed. This study is showing only the MPBX extensometer results from the geotechnical arrays due to the limited publication volume.

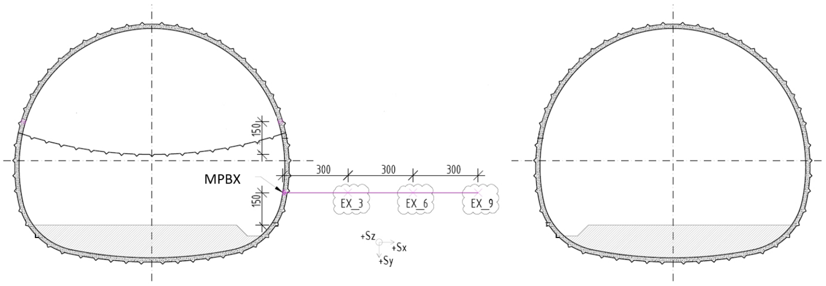

Figure 1. Schematic view of the MPBX extensometer.

2 CHARACTERISTICS OF THE INVESTIGATED TUNNEL

2.1 *Geology*

The tunnel system is situated beside Sopron city, under the Bécsi (Vienna) hill. Eisenstadt–Sopron (ES) sub-basin presents the eastern margin of the main Vienna Basin. The ES mini-basin is characterized by numerous surface lineaments (Spahic & Rundic 2015), representing the along-strike traces of intrabasinal fault structures. A near-surface large-scale normal fault (Master fault) is defined by the N–S trending extensional Rust–Fertőrákos system (Grachev & Mukhamediev 2010). The tunnel crossed the mentioned normal fault system, there was needed careful excavation. Most of the excavation was in soil-like material (calcareous clay, calcareous sand with low cohesion), but a major challenge to the tunnelling without blasting technology was the appearance of calcareous cemented conglomerate benches with decomposed calcareous sand in between, and the appearance of sound conglomerate rock mass. These features slowed down the tunnelling considerably.

3 THEORETICAL BACKGROUND

3.1 Longitudinal Displacement Profile (LDP)

Determination of the tunnel wall displacement that has occurred before the support is installed is not a trivial problem, since it involves a consideration of the three-dimensional stress distribution, and propagation of failure surrounding the advancing face. Chern et al (1998) published a set of results obtained from three-dimensional numerical analyses and also from measurements in an advancing tunnel where instruments had been installed from a parallel tunnel before excavation. Hoek (1999) derived the curve by averaging the results presented by these authors.

Hoek's relation is presented below (in Equation 1, y is the wall displacement/maximum displacement and x is the distance form face/tunnel diameter):

$$y = 1/\left[1 + e^{-(x/0.55)}\right]^{1.7} \qquad (1)$$

There are several empirical curves fitting the measured underground deformations. When processing numerous extensometer measurements from other projects we observed that in many cases the Hoek's empirical curve approximated the best to our results. The Panet's curve was adequate in case of good rock mass qualities (with no in situ stress disturbance). Despite this fact, the designer just based on the Panet curve during the determination of stress relaxation.

The development of radial deformation, however, is directly linked to the development of the plastic zone as the tunnel advances. Studies have shown that the longitudinal displacement profile function proposed by Panet (1995) and by Unlu & Gercek (2003) is reasonable for plastic analysis provided that the radius of the plastic zone does not exceed 2 tunnel radii and provided that the yielding zone in the tunnel face does not interact with the developing yield zone around the tunnel walls.

The advancing front of plastic yielding is bullet shaped in three dimensions. For large plastic zones (radius of plastic zone $R_p >> 2$) the shape of this developing yield zone is geometrically similar for increasing maximum plastic radii. Based on this no single longitudinal displacement profile will suffice for these conditions. In order to account for the influence of increased overall yielding on the shape of the normalized longitudinal displacement profile, the most logical index to relate to the longitudinal displacement profile function is the ultimate radius of the normalized plastic zone radius, R_p/R_t or r_o.

A more detailed investigation was developed by Vlachopoulos & Diederichs (2009). The Longitudinal Displacement Profile depends upon the properties of the rock mass and the in-situ stresses which, in turn, define the size of the plastic zone. These curves are important for determining the displacements at the tunnel face and at the time of support installation (Deák et al. 2022).

At the detailed modelling the 3D tunnelling in 2D plane were simulated using RS^2 code's (from Rocscience) core replacement technique. The tunnel wall displacements were exported from the model. The longitudinal displacement profiles have been analysed using the empirical curves. Where these curves did not fit on the modelled line, then parameters in the equations were adjusted to get better fitting (Figure 3).

4 RESULTS

In this study two main approaches were introduced, namely the analytical calculations and numerical modelling. For using the analytical and axisymmetric numerical modelling approaches there is needed circular tunnel shape for the calculations. The investigated tunnels have noncircular shape. There is a right way to approach more precisely the transformation of non-circular tunnel shape into the circular one.

The area of an arbitrarily shaped cross-section can be calculated either using analytical equations for its different sub-areas, or using a numerical algorithm. One such simple algorithm is based on a discrete version of Green's theorem that relates the double integral over a closed region to a line integral over its boundary (Curran et al. 2003).

Also, a basic approximation is possible if it is measured the circumference of the noncircular tunnel which result could be used for the circular tunnel's circumference too. Using the above explained opportunity in this study has been transformed the original shape of the tunnel into circular one.

4.1 MPBX measurement results

The MPBX-1 extensometer array was installed at 352.7 tunnel meter in the Southern tunnel (in grey slightly cemented silty fine sand). As a first step, the displacement of about 1 mm caused by the South Tunnel itself moving away from the section during the arriving tunnel was subtracted. The Geotechnical Monitoring System nr. 1, according to the material excavated during the tunnel excavation, was classified by design in the following excavation and support category: B02a.

For the processing, a summary table was provided by the Contracting Party with the SEM excavation (Crown, Bench and Invert), with the corresponding dates and several comments.

This table was used to identify the spatial and temporal events of tunnel driving in our measurement datasets. The event log and maximum displacements, also fitted to the MPBX-1 extensometer measurement dataset, are shown in the figure below (see Figure 2). The MPBX-2 extensometer array was installed at 535.8 tunnel meter (in reddish slightly cemented silty fine sand). As a first step, the displacement of about 1.5 mm caused by the South Tunnel itself moving away from the section during the coming tunnel was subtracted (see the results in Figure 2). The Geotechnical Monitoring System nr. 2, according to the material excavated during the tunnel excavation, was classified by design in the following excavation and tunnel safety category: B02av.

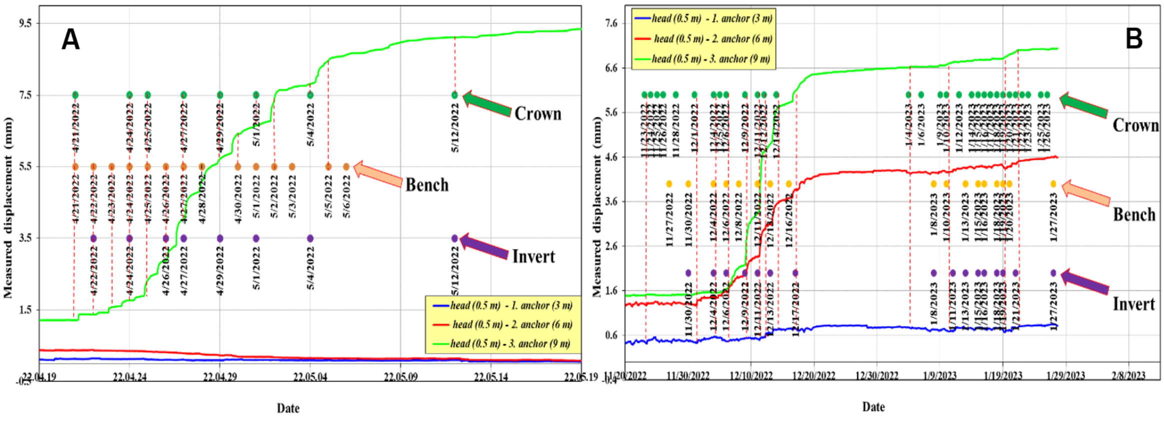

Figure 2. MPBX extensometer measurements which shows the deformation effect of the adjacent tunnel due to the tunnelling (A is MPBX-1, B is MPBX-2).

4.2 Numerical modelling

Due to the numerical modelling were used two material models, the Mohr-Coulomb (MC) and the Hoek-Brown (HB) and as constitutive model, the elastic perfectly plastic model was used.

From one model variation here are enumerated some material parameter: $UCS_{mass} = 5$ MPa; $c = 60$ kPa; $\varphi = 32°$; $E = 24$ MPa; $\mu = 0.3$; $K_0 = 0.4 – 0.6$ (Deák 2023).

The distribution of stresses around the advancing face of a tunnel is three-dimensional. At a section in a rock mass, which is at approximately distance of two and a half tunnel diameters ahead of the face, the stress state is undisturbed and equal to the in-situ stress conditions. At the tunnel face, the rock mass provides a support pressure that is approximately 25% of the in-situ stress. The apparent support pressure provided by the face allows excavated sections to stand up long enough for support to be installed. Support pressure gradually reduces to zero at a distance of about four and a half tunnel diameters behind the advancing face (Curran et al. 2003).

Due to the three-dimensional stress distribution at tunnel faces, straightforward application of two-dimensional numerical analysis to the design of tunnel support systems is inaccurate. Most two-dimensional numerical formulations for excavation analysis assume plane strain conditions. However, these conditions are only applicable to tunnel sections far from the advancing face (Hoek et al. 2008).

In the numerical simulation of a tunnel, if the tunnel is first excavated and a passive support system installed thereafter, the support system will carry no loads. This is because all deformations would have taken place before the support is installed. On the other hand, if the supported is installed in the model before the tunnel is excavated, the support system will be exposed to the entire induced loading, a scenario that would arise only if the support were to be installed before any displacements whatsoever of the excavation boundary occurred. This would lead to conservative design since in reality some degree of stress relief always occurs by the time support is installed.

In order to use two-dimensional numerical tools to realistically design tunnel support therefore, one needs to estimate displacements of the excavation boundary that occur before support is installed. There are a variety of different methods for simulating the deformation that takes place prior to support installation. A preferred method is the so called „material softening” approach.

In axisymmetric numerical modelling, the radius of the circular tunnel section is taken as the basis, this will represent half a slice of the tunnel and it can be drawn either in one step or in multiple steps.

A summary figure shows the results from the deepest anchors of the extensometers, together with the analytical approaches, and the numerical modelling curves that best approximated the measured results are also shown (Figure 3).

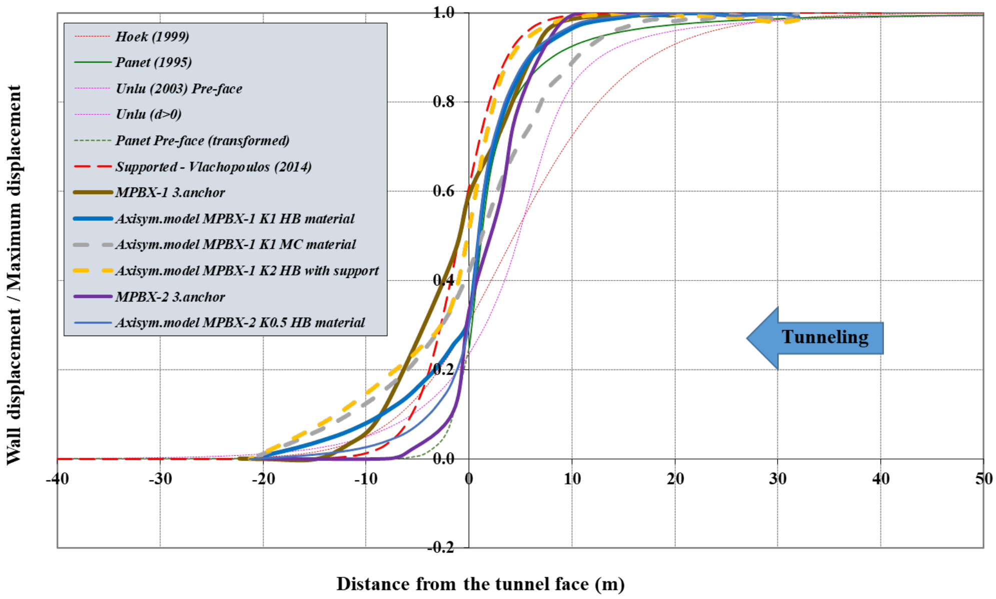

Figure 3. Longitudinal displacement profiles for the M85 tunnel showing MPBX-1 and MPBX-2 3rd anchor measurements together with the axisymmetric modelling results.

CONCLUSIONS

With the analytical solutions for the longitudinal displacement profile (LDP), we observed that the empirical equations gave quite different results from the measured values. The main reason for this is that in the tunnels at the monitoring points the soil-like material was characteristic rather than a good rock mass (and these methods does not take into account the used tunnel support - only one curve, the shotcrete support – Vlachopoulos & Diederichs 2014). For the given tunnel diameter, we could see that 30% of the total deformations were redistributed at the tunnel face, for the same diameter, if there was applied tunnel support (up to 1.5 m from the face) 60% of the deformations were played out. Another important finding, the LDP calculated from the measured results gave similar fittings, for instance 60% of the deformations were played out at the tunnel face for the observed cross section MPBX-1, but the shape of the curve was slightly different. Similar results were obtained from the axisymmetric model when using the HB material parameters and setting K=2. The shape of the curves calculated from numerical modelling could be fitted well by adjusting the in situ primary stress boundary conditions and input parameters. At MPBX-2, 33% of the deformations occurred at the tunnel face. In this case, the best approximation by the numerical modelling was K=0.5.

REFERENCES

Carranza-Torres, C., Fairhurst, C. 2000. Application of the convergence–confinement method of tunnel design to rock masses that satisfy the Hoek–Brown failure criterion. Tunn. Undergr. Sp. Tech. 15(2): pp. 187–213.

Chern, J.C., Shiao, F.Y. & Yu, C.W. 1998. An empirical safety criterion for tunnel construction. Proc. Regional Symp. Sedimentary Rock Engng, Taipei, Taiwan, pp. 222–227.

Curran, J.H., Hammah, R.E. & Yacoub, T.E. 2003. A Two-Dimensional Approach for Designing Tunnel Support in Weak Rock Proc. 56th Canadian Geotechn. Conf. Winnepeg, Canada.

Deák F. 2023. Geotechnical measurement system and monitoring activity of the tunnel system belonging to the M85 motorway – II. Interpretative Report, manuscript in Hungarian, 53 p.

Deák, F., Salem, A., Török Á. & Vásárhelyi B. 2022. Tunnel design across the Zagros Main Fault – Iraq-Kurdistan Penjween Region. ISRM Fifth symposium of the Macedonian Association for Geotechnics, pp. 185-195.

Duncan Fama, M.E. 1993. Numerical Modeling of Yield Zones in Weak Rock. In: Hudson JA (ed) Comprehensive Rock Engineering, 2. Pergamon, Oxford, pp 49–75.

Grachev, F. & Mukhamediev, A. 2010. On the nature of the junction zone between the Vienna and Pannonian sedimentary basins. Izvestiya, Physics of the Solid Earth 46. pp. 849–861.

Hoek, E. 1999. Personal Communication.

Hoek, E., Carranza-Torres, C.T, Diederichs, M.S. & Corkum, B. 2008. Integration of geotechnical and structural design in tunnelling. Proc. Univ. of Minnesota 56th Annual Geotechnical Engineering Conference1. Minneapolis, 29 February 2008, pp. 1-53.

Panet, M. 1995. Calcul des Tunnels par la Méthode de Convergence–Confinement. Presses de l'Ecole Nationale des Ponts et Chaussées. Paris. 178p.

Spahic, D. & Rundic, L. 2015. Multi-phased normal faulting of the Eisenstadt-Sopron basin margins as a controlling factor over spatially confined coal mini-hydrocarbon play (East Austria). Carpathian Journal of Earth and Environmental Sciences, May 2015, Vol. 10, No. 2, pp. 45 – 58.

Unlu, T. & Gercek, H. (2003): Effect of Poisson's ratio on the normalized radial displacements occurring around the face of a circular tunnel. Tunnel. Underground Space Techn. 18. 547–553.

Vlachopoulos, N. & Diederichs, M.S. 2009. Improved linear tunnel displacement profiles for convergence confinement analysis. Rock Mech. Rock Engng. 42(2): pp. 131-146.

Vlachopoulos, N. & Diederichs, M.S. 2014. Appropriate Uses and Practical Limitations of 2D Numerical Analysis of Tunnels and Tunnel Support Response. Geotech Geol Eng 32, pp. 469–488.