FULL FACE TUNNEL EXCAVATION IN SOILS

Corner T.[1], Marolt Cebasek T.[1]
[1]School of Civil Engineering and Built Environment,
Liverpool John Moores University, UK
T.MaroltCebasek@ljmu.ac.uk

Abstract

In this paper the different methods and implications of full-face tunnel excavation in soils are analysed through numerical FEA (Finite Element Analysis) software and compared with construction monitoring data, empirical predictions and previous analysis from studied literature. A 2D plane strain analysis of a section of the Milan metro-line 5 was conducted under free field conditions using PLAXIS software to display its impact on ground settlements and deformation around the tunnel face. The results found that the FEA model produced an accurate prediction of the settlement troughs, impact of the grouting pressure, and construction of the second tunnel tube on the final induced settlements. Empirical prediction equations were also used to fit Gaussian curves against the numerical curves which produced an accurate alignment of trough width to the numerical prediction.

Keywords: Finite Element Analysis, Full-Face Excavation, Settlements.

Introduction

With the ever-expanding urban landscapes within our cities the demand for sustainable infrastructure is growing constantly, and with the need to reduce carbon emissions from congested highways transport innovation is a necessity. Thus, increasing the need for underground construction to accommodate new infrastructure from expanding rail networks or highway tunnels. Due to this extensive research into the analysis and prediction of ground movements have developed over the years through empirical and numerical methods (Nikumbh, 2017, Elmanan et al, 2015). Through Finite Element Analysis (FEA), 2D and 3D models of the construction can be analysed in varying ground conditions. This paper aims to use and compare these prediction techniques with comparison to monitoring data collected from a chosen case study to evaluate the ground settlements induced by Tunnel Boring Machines (TBM). The most common forms of TBM'd tunnels in recent times are metro tunnels to provide infrastructure for major cities (Chapman et al, 2018). As typical metro tunnels consist of a network of tunnels, it is also necessary for the analysis of the impact of the excavation on the ground conditions when multiple tunnels are constructed (Maidl et al, 2012). Therefore, the following objectives for this research were drawn:

- To conduct a case study on the Milan metro-line 5, assessing the impacts of full-face tunnel excavation of singular and twin-tunnels in soils.
- Produce a 2D plane-strain analysis of a section of the Milan-metro 5 of the initial singular tunnel excavation and then of the second twin-tunnel excavation under free field conditions using FEA software PLAXIS.
- Evaluate the induced settlements, effective stresses and impact of the second tunnel excavation on the overall settlements and compare results to monitoring data fitted with empirical prediction techniques and 3D FEA models from the relevant literature.

Methodology

The section of tunnel for the model was selected on a stretch of roughly 1km between San Siro and Segesta stations. In which the tunnel axis remained at a depth of 15m, and the observed ground conditions stayed consistent as a gravelly sand soil, with a water table depth of 15m throughout. This provided the basis of a relationship between predicted ground settlement of the 2D FEA model against the average monitored settlement. The results of the FEA model were compared with the monitoring data fitted with Gaussian curves through Equation 1 (Peck, 1969) and 3 (O'Reilly & New, 1982). The first tunnel construction was first analysed singularly before the second tunnel was then modelled to be sequentially constructed after the first tunnel. As the section of tunnel modelled also carries several of the assumptions made for Equation (3), a Superposition of the Gaussian curves was fitted to analyse the impact of the second excavation on the maximum settlements.

$$S_v(x) = S_{vmax}\exp\left(-\frac{x^2}{2i_x^2}\right) \qquad (1)$$

In which S_{vmax} is the maximum settlement given above the tunnel centreline, x is the lateral distance from tunnel centre line, $S_v(x)$ the settlement at a given lateral distance from the centre line, and i_x the point of inflection on the curve given by:

$$i_x = Kz_o \qquad (2)$$

$$S_v(x) = \left[S_{vmax}\exp\left(-\frac{x^2}{2i_x^2}\right)\right] + \left[S_{vmax}\exp\left(-\frac{\mathrm{x}-\mathrm{d}^2}{2i_x^2}\right)\right] \qquad (3)$$

In which K is a constant depending on the nature of the ground, given generally as between 0.2-0.45 for sand and gravels (Mair and Taylor, 1997; Bloodworth, 2002). z_o is the depth of the tunnel axis.

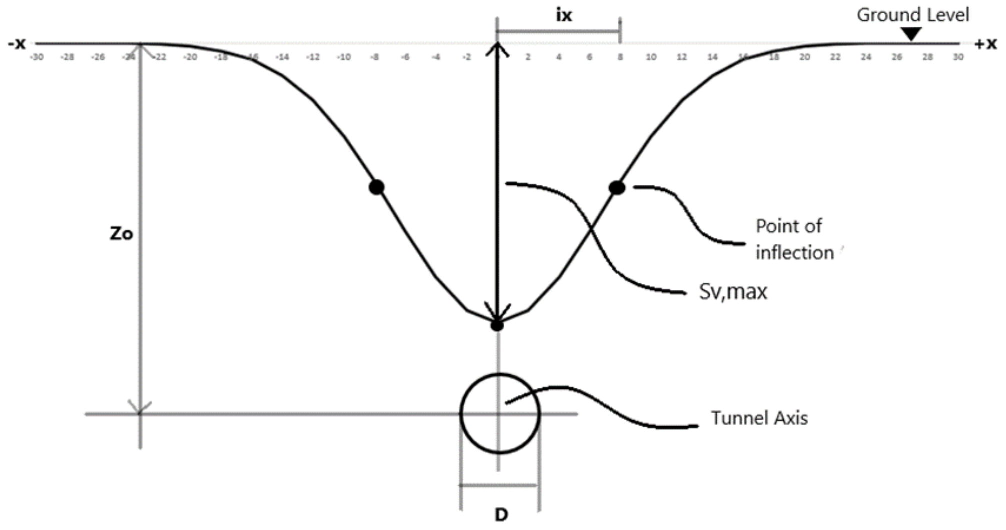

Fig. 1. Gaussian fitted transverse settlement trough above a tunnel axis.

Data Collection

The monitored maximum settlements (Sv,max) above both tunnel axis were collected and average values for maximum settlement along this section were calculated. An average value for point of inflection (ix) was obtained through the estimated ix values along the first tunnel axis. An average ix for the section was taken as 5.8m between S1-S25, and by rearranging Equation (2), an average value of K could be calculated as 0.39.

Table 1. Average values of Sv,max and Volume Loss above Tunnel 1 and 2 axis after first (a) and second (b) excavation and values of ix for first tunnel excavation.

	Sv,max (1a) (mm)	Sv,max (1b) (mm)	Sv,max (2b) (mm)	Volume Loss % (1a)	Volume Loss % (2b)	ix (1a) (m)
Average	11.54	13.84	11.88	0.5%	0.5%	5.80

Finite Element Model

A 2D plane-strain model was constructed of the tunnel construction. The soil and tunnel parameters were collected based on the site investigations from previous research (Fargnoli et al. (2013, 2015) and were based on the entire section of tunnel between monitoring stations S1-S25. The volume loss (V_L) which is caused by tunnel construction using TBM's was simulated through the software using the contraction method (Plaxis, 2018), in which a contraction is applied to the tunnel lining to simulate the volume loss experienced in the tunnel construction. Typically for an earth pressure balance machine in non-cohesive soil volume losses at 0.5% can be attained, therefore this value was selected as the design value for contraction (C_{ref}). The tunnel lining is constructed completely at once and is considered homogeneous and the grouting process for the tunnels were simulated by applying an equally distributed pressure on the surrounding soil of 150kN/m^2 for Tunnel 1 and 170kN/m^2 for Tunnel 2.

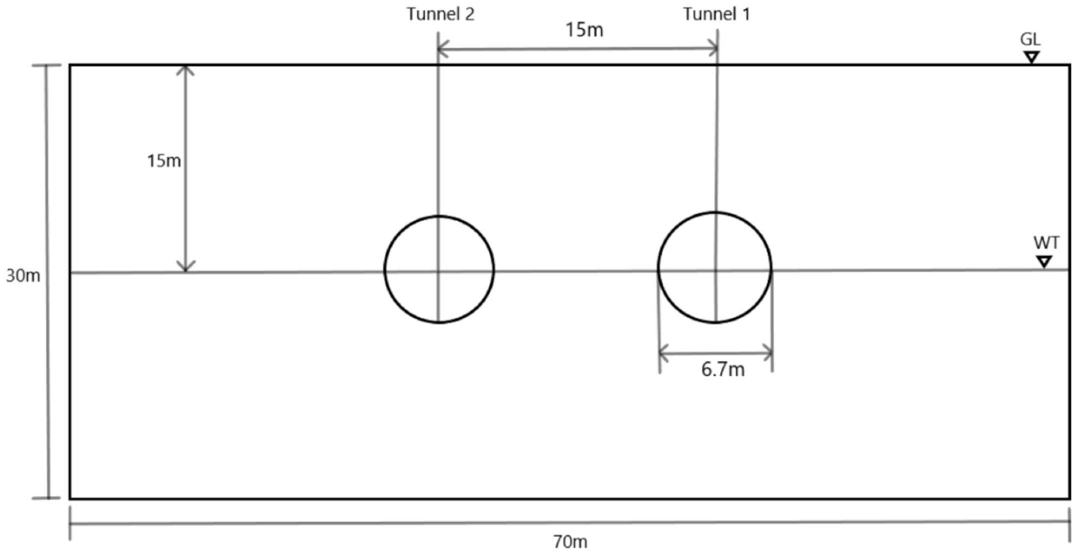

Fig. 2. Dimensional diagram for the 2D FEA model (PLAXIS).

Results and Discussion

The first stage of the construction consisted of the excavation of the first tunnel tube and the second stage consisted of the sequential excavation of the second tunnel tube. As displayed in Table 2, the settlements record above both tunnel axis were recorded and compared to the average monitoring data values. It can be seen that the FEA model correctly predicted the settlements induced by both stages of construction above both tunnel tubes. To show the effects of the construction of both tunnels on the surrounding ground the total displacements are displayed in Fig. 3. As can be clearly seen the FEA model correctly predicted the expected settlement trough of the singular tunnel construction with a Sv,max of 14.14mm. Upon completion of the second tunnel the FEA also correctly predicted an increase in the Sv,max above Tunnel 1 to 15mm and the settlements above the 2nd tunnel axis being smaller than the settlements above the 1st tunnel axis at 13mm. However all settlements were slightly overestimated in comparison to monitoring data as displayed in Table 2. Through analysing the settlements before and after the grouting process it was also shown that this simulation correctly predicted a reduction in maximum settlement as a result of grouting.

Table 2. Maximum Settlements recorded in finite element analysis compared with monitored data.

	Construction Stage	
	First	**Second**
Tunnel 1 FEA Model	14.14mm	15mm
Tunnel 2 FEA Model	-	13mm
Tunnel 1 Monitoring Data (Average)	11.54mm	13.84mm
Tunnel 2 Monitoring Data (Average)	-	11.88mm

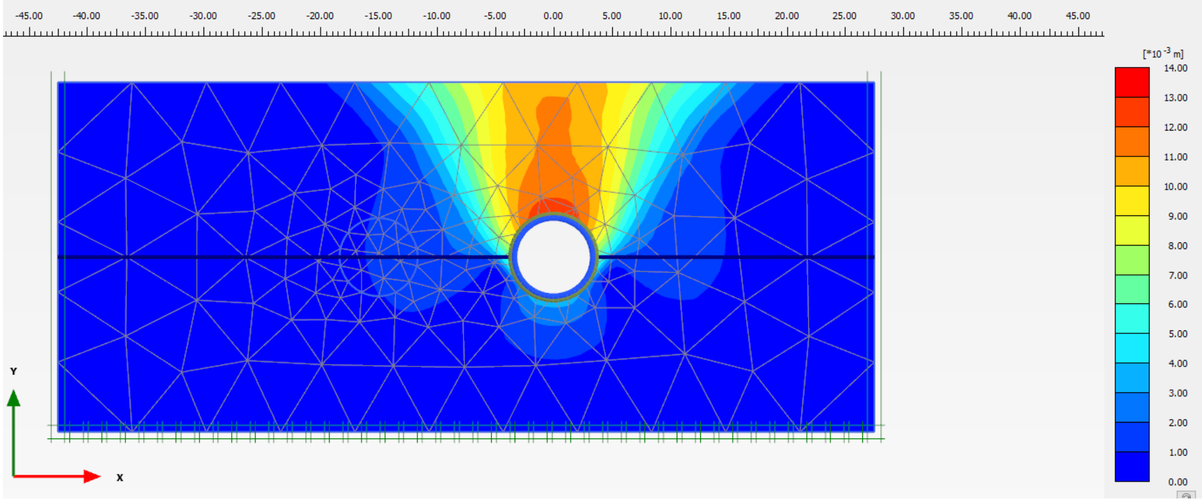

Fig. 3. Total displacements upon completion of the first tunnel.

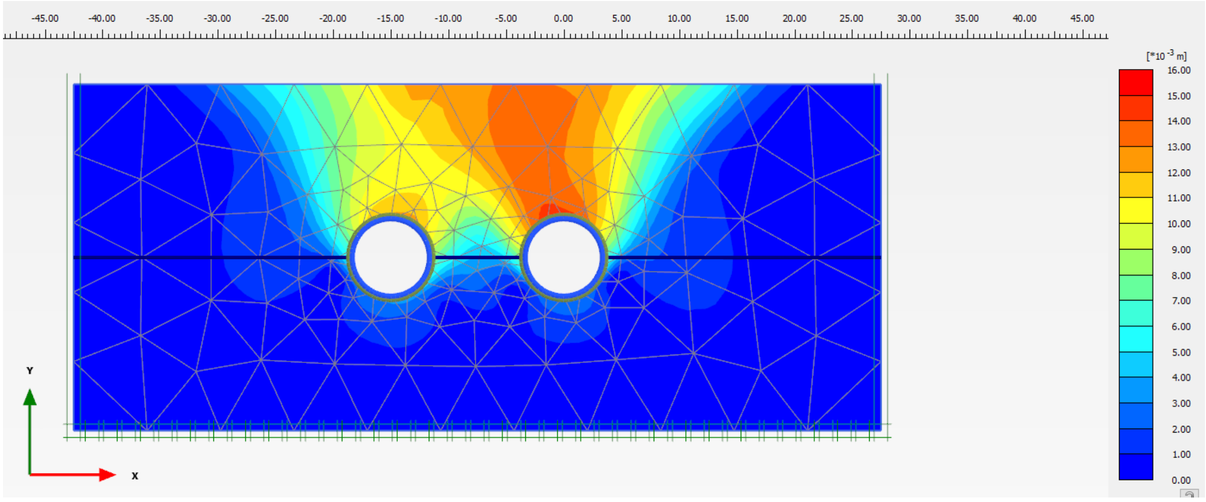

Fig. 4. Total displacements upon completion of the second tunnel.

The effective stresses in the y direction in the model are also displayed to show a concentration of compressive stresses in the site of Tunnel 2 before its construction. This can be said to be the cause of the reduced settlement above the 2nd axis and in other sequential twin-tunnel excavations.

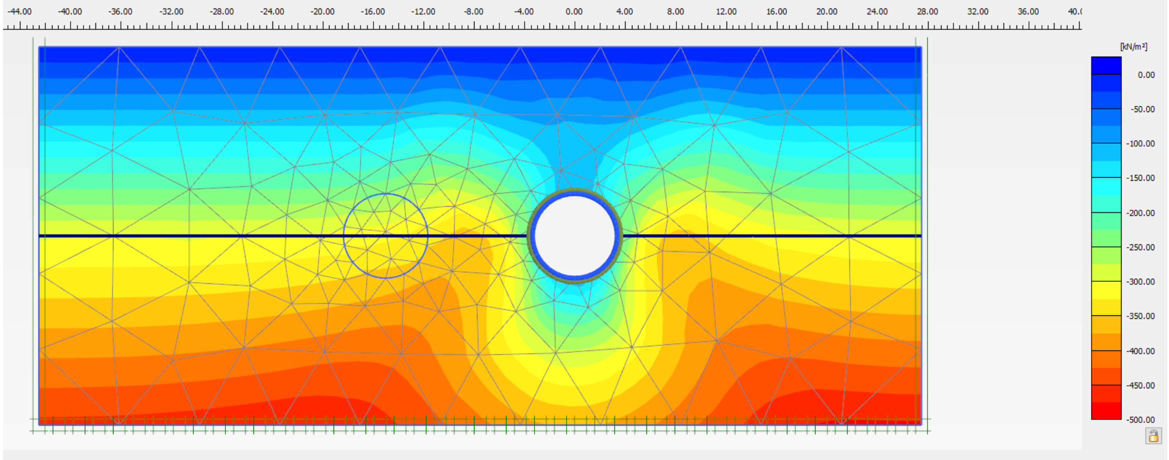

Fig. 5. Effective stresses in the y direction after first tunnel excavation.

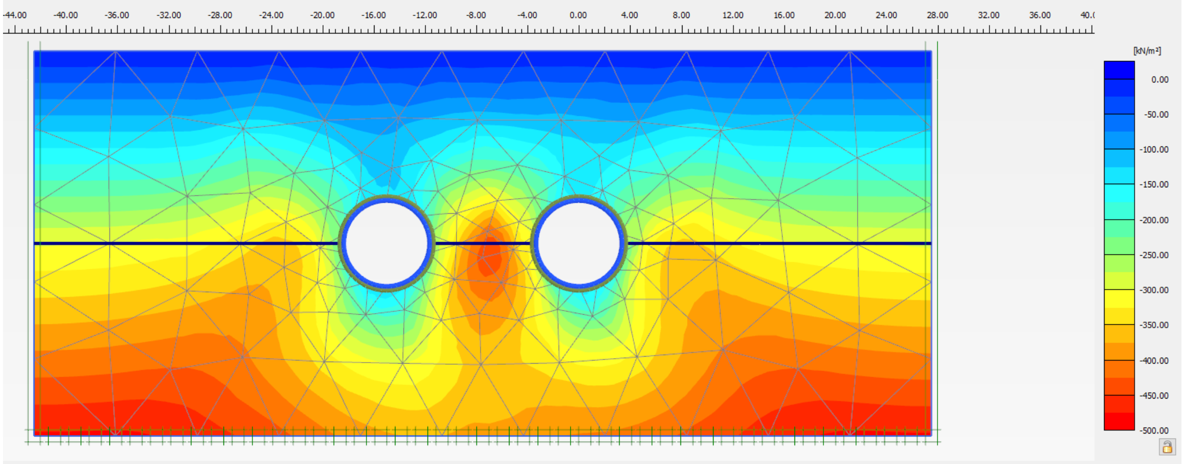

Fig. 6. Effective stresses in the y direction after second tunnel excavation.

As displayed in Fig.7 and 8, the FEA produced trough widths of roughly 20m laterally to the tunnel axis. An empirical curve was fitted using Equation 1 to the maximum settlement average from the monitoring data above the first tunnel, using an average value of ix = 5.8m. This produced an accurate comparison of trough width with predicted numerical curve displayed in Fig. 7, although showing the clear overestimation of settlement and resulting volume loss. This can again be seen in Fig. 8 for the prediction after the 2nd tunnel construction, producing similar curves and accurate trough widths, however slightly overestimating all settlements across the curve.

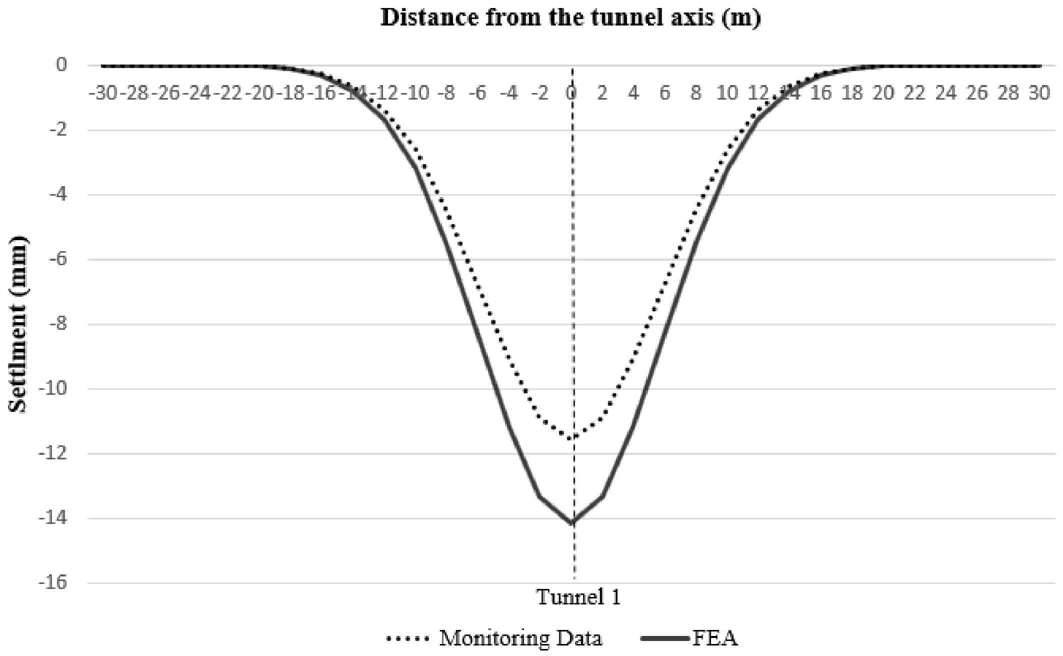

Fig. 7. Comparison of settlement trough given by monitoring data and FEA results for Tunnel 1.

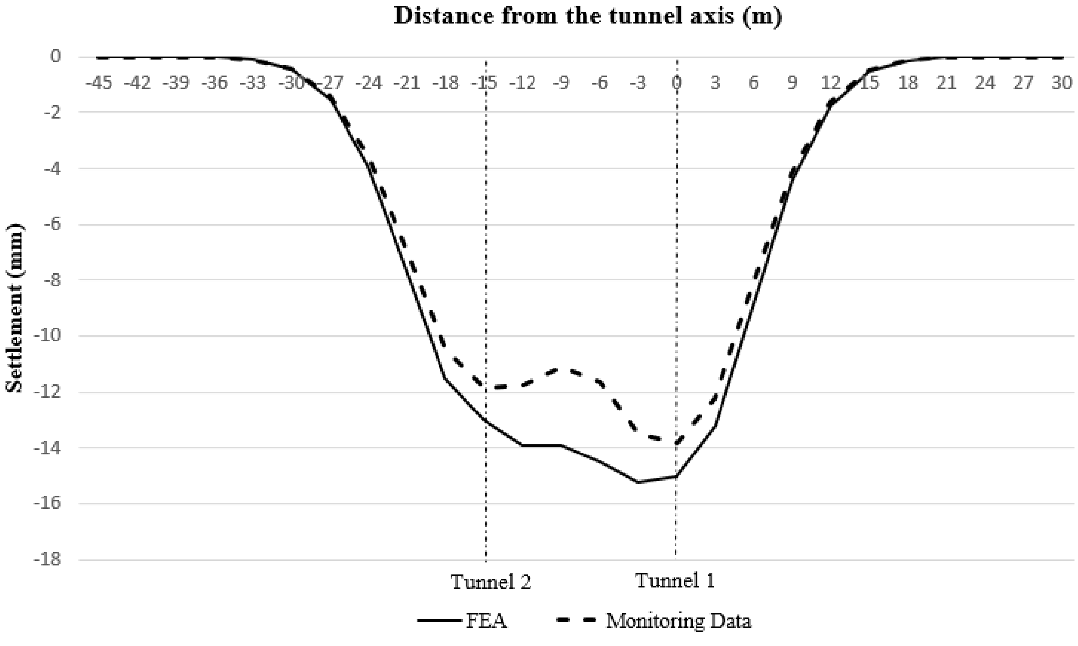

Fig. 8. Comparison of settlement trough given by monitoring data and FEA results for Tunnel 1 and 2.

Conclusions and Recommendations

All objectives of this research were achieved, and it can be concluded that the 2D FEA prediction model using the contraction method can produce accurate predictions for ground settlements in the construction of singular and twin TBM'd tunnels and provides a quick and easy prediction tool for engineers in the design process. These predictions could be further improved by using a finer mesh in the modelling of the soil. This research could be continued through analysing these prediction techniques in varying ground types in further case studies and also through obtaining more substantial amounts of monitoring data of the transverse settlement profile to further analyse the accuracy of the predictions between twin tunnels. Particularly in the area between the tunnel tubes in which the empirical prediction of the settlement troughs does not account for the impact of sequential excavation. In addition, the impact of twin tunnels at different depths in close proximity could also be explored.

References

Bloodworth A. G. (2002). Three-Dimensional Analysis of Tunnelling Effects On Structures To Develop Design Methods by Alan Graham Bloodworth Brasenose College Michaelmas Term 2002 A thesis submitted for the degree of Doctor of Philosophy at the University of Oxford.

Chapman. D, Metje N., Stark A. 2018 – Introduction to Tunnel construction – Second Edition

Elmanan et al. (2015) - Analysis of surface settlement due to tunnelling in soft ground by using empirical and numerical methods. The Fourth African Young Geotechnical Engineers Conference

Maidl et al. 2012 – Mechanised Shield Tunnelling – 2nd Edition

Mair, R. J., and R. N. Taylor. 1997. "Bored tunnelling in the urban environment. State-of-the-art report and theme lecture." In Vol. 4 of Proc., 14th Int. Conf. on Soil Mechanics and Foundation Engineering, 2353–2385. Hamburg, Germany: A.A. Balkema.

Nikumbh R. K. Karra R. C. 2017 - Analysis of stresses around a tunnel opening. 6th International Engineering Symposium - IES 2017

O'Reilly, M. P., and B. M. New. 1982. "Settlements above tunnels in the United Kingdom: Their magnitude and prediction." In Proceedings-Tunnelling '82, 173–181. Brighton, UK: Institution of Mining and Metallurgy.

Peck, R. B. (1969). "Deep excavations and tunnelling in soft ground." Proc., 7th Int. Conf. on Soil Mechanics and Foundation Engineering, Vol. 4, State of the Art Volume, Sociedad Mexicana de Mecanica de SueIos, Mexico City, 225–290.

Plaxis 2018, PLAXIS 2D CONNECT Edition V20 – Tutorial Manual – Settlements due to tunnel construction.

V. Fargnoli, D. Boldini, and A. Amorosi, "TBM tunnelling induced settlements in coarse-grained soils: the case of the new Milan underground line 5" Tunnelling and Underground Space Technology, vol. 38, pp. 336–347, 2013.

V. Fargnoli, D. Boldini, and A. Amorosi, "Twin tunnel excavation in coarse grained soils: Observations and numerical back-predictions under free field conditions and in presence of a surface structure, Tunnelling and Underground Space Technology, Volume 49, June 2015, Pages 454-469