GROUND SURFACE SETTLEMENT INDUCED BY TWIN TUNNELLING

Elefterija Zlatanović[4]
Dragan Lukić[5]

UDK: 624.191.1
DOI: 10.14415/konferencijaGFS2014.123

Summary: *Ever increasing population of large cities, density of transportation, and need for storage capacity have led, inevitably, to an increased use of underground facilities. Tunnels in urban environment are often located at small depths underneath densely populated areas, in a soil or soft rock, and their construction may affect existing structures at the surface. Therefore, a reliable prediction and control of ground surface settlements are important tasks when designing an urban tunnel (in particular two closely spaced tunnels). This paper presents the analysis of ground settlements induced by a construction of twin tunnels and is based mainly on the work of Divall (2013) [4].*

Keywords: *Twin tunnels, soil, settlements, important aspects of analysis*

1. INTRODUCTION

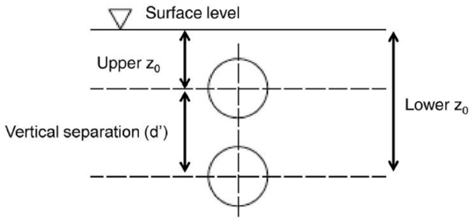
The rising population in urban areas comes with an associated demand for increased public transportation. Due to the lack of surface space, an often utilised solution is to construct rapid transit systems with tunnels. Any subsurface construction will generate ground movements, such as ground settlements and latteral movements, which have the potential to cause damage to existing surface and underground structures. An urbanisation and congested cities have imposed the need for accurate predictions of tunnelling-induced ground settlements, and have produced many publications (e.g., Peck, 1969; Cording & Hansmire, 1975; Clough & Schmidt, 1981; O'Reilly & New, 1982; Attewell & Yates, 1984; Cording, 1991; Mair *et al.*, 1993, and Mair & Taylor, 1997) [4, 9]. However, these empirical-based prediction methods are limited to the case of a single tunnel. Gauss curve is typical for surface settlement profile induced by a single tunnel. Yet, this curve cannot give either subsurface movement or stress distribution. Generally, rapid transport systems comprise of a pair of tunnels constructed in a close proximity, also known as twin-tunnel structures. A number of case studies has shown a significant difference in ground settlements due to a construction of twin tunnels (e.g., Cooper *et al.*, 2002; Cording & Hansmire, 1975, and Nyren, 1998) [3, 4]. Furthermore, a series of plane strain centrifuge tests was carried out in order to

[1] Assistant Elefterija Zlatanović, grad. Civ. Eng., University of Niš, Faculty of Civil Engineering and Architecture, Aleksandra Medvedeva 14, Niš, Serbia, tel: +381 18 588 200, e-mail: elefterija2006@yahoo.com
[2] Prof. dr Dragan Lukić, grad. Civ. Eng., University of Novi Sad, Faculty of Civil Engineering of Subotica, Kozaračka 2a, Subotica, Serbia, tel: +381 24 554 300, e-mail: drlukic.lukic@gmail.com

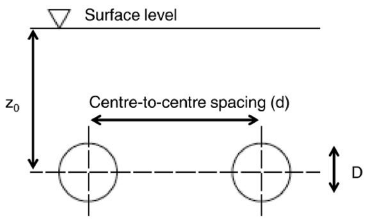
investigate twin-tunnelling-induced ground settlements in overconsolidated clay. The results of these tests are related to the prediction of ground movements in the plane perpendicular to advancing tunnels, and the significant remarks of the researches are as follows [4]:

1. Single-tunnelling-induced surface and subsurface settlement troughs are well represented by Gaussian distributions, however, the twin-tunnelling predictions can be improved by modifying the settlements solely due to the second tunnel construction.
2. The magnitude of volume loss induced by the newly-built tunnel structure is increased due to the presence of the first tunnel. This effect could be decreased by larger spacings between the tunnels.
3. Ground settlements induced by a construction of the second tunnel can be predicted using equations by Peck (1969) [10], O'Reilly & New (1982), and Mair et al. (1993), but with some modifications [9]. The surface and subsurface settlement distributions towards the existing tunnel were observed to be wider than that for the case of a single tunnel.

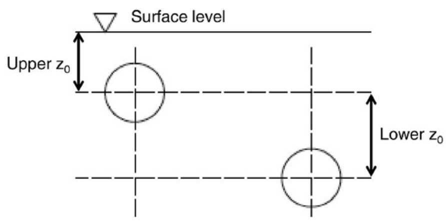
These were further investigated by numerical studies, which have confirmed the aforementioned observations (e.g., Addenbrooke & Potts, 2001, and Hunt, 2005) [1, 6]. Numerical analyses that used isotropic linear elastic – perfectly plastic soil models have resulted in somewhat wider surface settlement troughs than that observed by the Gaussian distribution (Mair et al., 1981) [7]. Predictions have been improved by using non-linear elastic – perfectly plastic models, which have resulted in deeper and wider settlement trough predictions that compare more favourably with field observations .
The layout of twin tunnels can have a number of different configurations such as horizontal, vertical, or inclined alignment (Figure 1) [4]. During the construction of each line, two tunnels can be constructed within a relatively short time and in a reasonably close proximity (up to 3D, where D stands for a tunnel diameter) [1, 5].



a) Tunnels with horizontal alignment (side-by-side)



b)Tunnels with vertical alignment (stacked or piggy back)



c) Tunnels with inclined alignment (offset)

Figure 1. Idealization of three possible twin-tunnel configurations in the y-z plane [4]

2. SINGLE-TUNNELLING-INDUCED GROUND MOVEMENTS

Many useful insights into bored tunnelling-induced ground movements in clayey soil deposits can be gained from investigations that are assumed to be “greenfield”, as illustrated in Figure 2 after Attewell & Yeates (1984) [2].

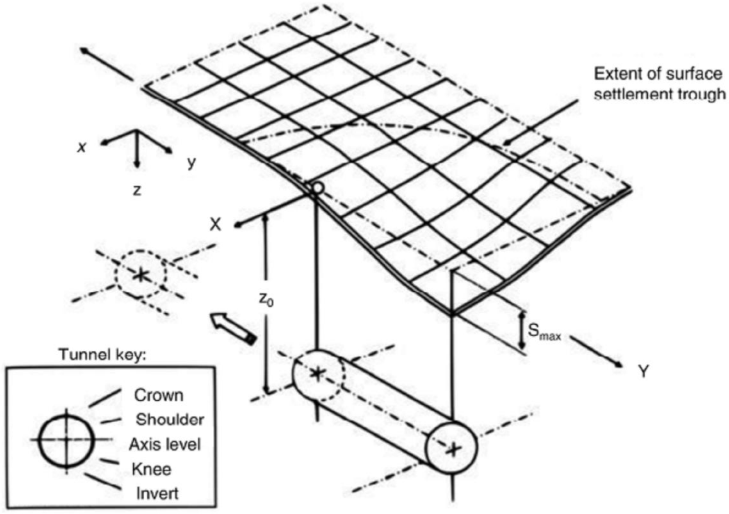


Figure 2. Settlement above an advancing tunnel heading (Attewell & Yeates, 1984) [2,4]

The knowledge on ground deformations bellow a ground surface is derived from surface settlement data. The Gaussian settlement trough shape can be observed throughout the overburden depth (Mair et al,. 1993). In the mentioned study, data from case studies and centrifuge experiments have been analysed, and the results have shown that settlement troughs tends to be narrower with depth, but similar in shape, as it could be seen in Figure 3 [6]. This figure essentially shows the distribution of i (the distance from the tunnel centre-line to the inflexion of the trough) throughout the overburden depth, and it could be observed that the distribution is linear. Consequently, the corresponding assumption is that the tangent of these settlements has a point of vector focus on the tunnel centre-line.

A tunnel construction in clay is often considered as an undrained event, and therefore, it is assumed that, per unit length of a settlement trough, the volume loss remains unchanged within subsurface regions [4]. Under this assumption, the ratio of surface to subsurface values of i with depth is inversely-proportional to the ratio of subsurface maximum settlement to surface maximum settlement (Figure 3). The maximum settlement at the tunnel crown should therefore be greater than the maximum settlement at the surface. However, the linear distribution of i throughout the depth is not appropriate at the distance of 0.5D from the tunnel crown. Lo et al. (1984) [6] reviewed several case studies and suggested a different linear distribution of i throughout the depth. In most cases, the value of 0.33 was the most suitable for the ratio of surface maximum settlement to subsurface maximum settlement.

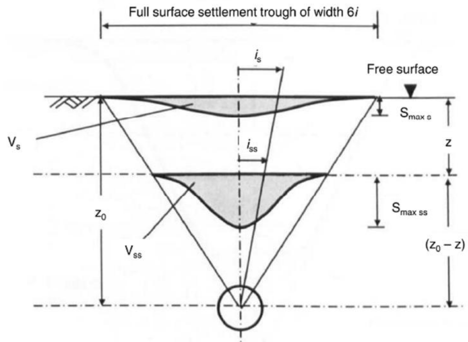


Figure 3. Distribution of settlement troughs throughout the depth [6]

3. TWIN-TUNNELLING-INDUCED GROUND MOVEMENTS

In this section a number of methods for the prediction of soil movements induced by twin bored tunnelling is outlined. A relative small body of the literature is dealing with the behaviour of twin tunnels and their interaction, and consequently, only few prediction methods have been developed. The complexity of any of these prediction methods is further increased by the almost infinite number of possible configurations of twin tunnels. Under the assumption that the tunnels are parallel, it could be stated that, generally, there are three possible twin tunnel configurations. Two-dimensional idealisations are shown in Figure 1. It could be seen that among these three variations, a side-by-side configuration (Figure 1(a)) refers to twin tunnels being constructed at the same horizontal axis depth. A stacked/piggy back configuration (Figure 1(b)) stands for the case of the second tunnel being constructed directly above or below the first one. An offset (Figure 1(c)) could be described as the middle case of the side-by-side and stacked configurations [4].

The Superposition Method is a simplified approach for predicting surface settlements above any twin-tunnel configuration. According to this simplified method, a tunnelling-induced ground settlement curve positioned over the centre-line of each tunnel is obtained, ignoring any influence from the other tunnel. The summation of these two overlapping curves describes the total settlement. This is illustrated in Figure 4 that shows the superposition of two individual tunnelling-induced ground settlement curves, with regard to the case of 4m-diameter twin-tunnel structures. The settlement troughs are calculated for tunnels with 3% volume loss in a clayey soil deposit with an overburden cover of 8m [4]. O'Reilly & New (1982) provided a formula for evaluation of twin-tunnelling-induced ground settlements by superposition:

$$S_v = S_{\max}\left[\exp\left(-\frac{{x_A}^2}{2i^2}\right)+\exp\left(\frac{(x_A-d)^2}{2i^2}\right)\right] \tag{1}$$

where d is the horizontal distance between two tunnels' centre-lines, and x_A is the lateral distance from the centre-line of the first bored tunnel.
The expression presented above assumes that the tunnels are parallel and they have the same tunnel diameter, volume loss, and settlement trough width. Moreover, it is possible to take into account different depths of twin tunnels and tunnelling-induced trough widths by expansion of the expression. However, this expression due to the priciple of superposition implicitly ignores any interaction between the tunnels.

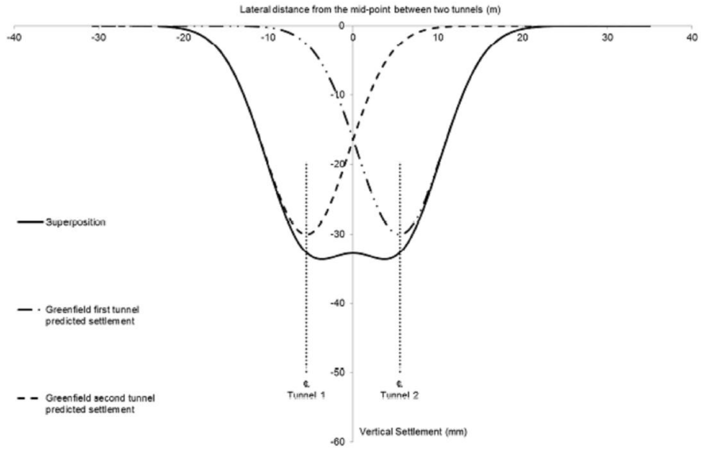


Figure 4. Example of the Superposition Method used to predict the surface settlement induced by 4m-diameter twin tunnels with an overburden cover of 8m [4]

Recently, with an aim to predict twin-tunnelling-induced ground movements, several numerical studies have been undertaken using the finite element based simulation platforms, under plane-strain (2D) conditions, considering an undrained clayey soil deposit [1, 5, 6].

4. CONCLUSIONS

The prediction of tunnelling-induced ground movements during excavation of twin tunnels could be carried out using various methods, including empirical methods derived from field observations and centrifuge modelling, or numerical and analytical methods. Empirical method assumes a distribution of ground movements with some coefficients. These coefficients are determined through fitting field or centrifuge observations. Gauss curve is typical for surface settlement profile induced by a single tunnel; however, it cannot give either subsurface movement or stress distribution. Analytical expressions for twin-tunnelling-induced surface and subsurface settlements are based on simplified methodologies that use the principle of superposition of two individual tunnelling-induced ground settlement curves. This approach ignores any interaction between two closely spaced tuunels. Analytical solutions on tunnelling-induced movements are useful, however, they cannot accommodate all important factors such as complex soil stress–strain behaviour, construction details, and geological conditions. In recent years, numerical simulation of shallow tunnelling has made a great progress. Numerical methods can include as many factors as possible, and they could reflect both subsurface movements and the interaction effects between two closely spaced tunnels. In addition, they could be conducted for different values of the tunnel spacing ratios, for various tunnel configurations, as well as for different cases of twin tunnelling – simultaneous excavation of a pair of tunnels, or excavation of a new tunnel close to an existing one.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Ministry of Education, Science, and Technological Development of the Republic of Serbia in the scope of the scientific–research projects TR36028 (2011–2014) and TR36043 (2011–2014).

REFERENCES

[1] Addenbrooke, T. and Potts, D. M.: Twin tunnel interaction - surface and subsurface effects. International Journal of Geomechanics, 2001, Vol. 1, pp. 249-271.
[2] Attewell, P. B. and Yeates, J.: Ground movements and their effects on structures. Blackie and Son Ltd, Attewell, P. B. and Taylor, R. K., 1984.
[3] Cooper, M. L., Chapman, D. N. and Rogers, C. D. F.: Prediction of settlement in existing tunnel caused by the second of twin tunnels. Transportation Research Record 1814, 2002, Paper No. 2-2729, pp. 103-112.
[4] Divall, Sam: Ground movements associated with twin-tunnel construction in clay. (Unpublished Doctoral thesis, City University London), 2013. http://openaccess.city.ac.uk/2437/
[5] Hage Chehade, F. and Shahrour, I: Numerical analysis of the interaction between twin tunnels: Influence of the relative position and construction procedure. Tunneling and Underground Space Technology 23, 2008, pp. 210-214.
[6] Hunt, D. V. L.: Predicting the ground movements above twin tunnels constructed in London Clay. Ph.D. Thesis, University of Birmingham, 2005.
[7] Mair, R. J., Gunn, M. J. and O'Reilly, M. P.: Centrifugal testing of model tunnels in soft clay. Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, 1981, Vol. 1, pp. 323-328.
[8] Mair, R. J.: Centrifugal Modelling of Tunnel Construction in Soft Clay. Ph.D. Thesis, Cambridge University, 1979.
[9] Mair, R. J. and Taylor, R. N.: Bored tunnelling in the urban environment. Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, 1997, Vol. 4, pp. 2353-2385.
[10] Peck, R. B.: Deep excavation and tunnelling in soft ground. Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, 1969, Mexico City, Vol. 3, pp.225-290.

[11] Wu, B. R., Chiou, S. Y., Lee, C. J. and Chen, H. T.: Soil movements around parallel tunnels in soft ground. Proceedings of the International Conference Centrifuge '98, 1998, Vol. 1, pp. 739-744.

СЛЕГАЊЕ ПОВРШИНЕ ТЕРЕНА УСЛЕД ИЗГРАДЊЕ ДВОЈНИХ ТУНЕЛА

Резиме: *Тенденција сталног пораста популације великих градова, густина саобраћаја и потреба за складишним капацитетима довели су несумњиво до повећаног искоришћења подземног простора. У градовима се тунели најчешће налазе на малој дубини испод густо насељених зона, у тлу или мекој стени, и њихова изградња може имати веома неповољне ефекте на постојеће објекте. Због тога је од изузетног значаја да се при пројектовању тунела (посебно двојних тунела) адекватно предвиде и контролишу слегања која су резултат њихове изградње. У раду се приказује анализа слегања терена услед изградње два паралелна блиска тунела , која су у највећем делу базирана на истраживањима Divalla (2013) [4].*

Кључне речи: *Двојни тунели, тло, слегање, важни аспекти анализе*