Tunnelling and Underground Space Technology 42 (2014) 40–51

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Three-dimensional numerical simulation of a mechanized twin tunnels in soft ground

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ARTICLE INFO

Article history:
Received 8 April 2013
Received in revised form 15 January 2014
Accepted 2 February 2014
Available online 25 February 2014

Keywords:
Numerical modelling
Twin tunnel
Segmental lining
Lining response
Settlement

ABSTRACT

The increase in transportation in large cities makes it necessary to construct of twin tunnels at shallow depths. Thus, the prediction of the influence of a new tunnel construction on an already existing one plays a key role in the optimal design and construction of close parallel shield tunnels in order to avoid any damage to the existing tunnel during and after excavation of the new tunnel.

Most of the reported cases in the literature on parallel mechanized excavation of twin tunnels have focused on the effects of the ground condition, tunnel size, tunnel depth, surface loads, and relative position between the two tunnels on tunnel behaviour. The numerical investigation performed in this study, using the FLAC^{3D} finite difference element programme, has made it possible to include the influence of the construction process between the two tunnels. The structural forces induced in both tunnels and the development of the displacement field in the surrounding ground have been highlighted.

The results of the numerical analysis have indicated a great impact of a new tunnel construction on an existing tunnel. The influence of the lagged distance between the two tunnels faces has also been highlighted. Generally, the simultaneous excavation of twin tunnels causes smaller structural forces and lining displacements than those induced in the case of twin tunnels excavated at a large lagged distance. However, the simultaneous excavation of twin tunnels could result in a higher settlement above the two tunnels.

1. Introduction

In recent years, many tunnels have been built in urban environments; this often involves the construction of twin tunnels in close proximity to each other. In addition, in many cases, the new tunnel is often excavated adjacent to an already existing one. Thus, the prediction of the influence of new shield tunnel construction on the existing tunnel plays a key role in the optimal design and construction of close parallel shield tunnels in order to avoid any damage to the existing tunnel during and after excavation of the new tunnel.

Interactions between closely-spaced tunnels were studied in the past using a variety of approaches: physical model testing, field observations, empirical/analytical methods and finite element modelling.

Kim et al. (1996, 1998) performed physical tests to investigate the response of the first tunnel lining on the approaching of the second shield. The results of their model tests showed that the interaction effects are greater in the spring line and crown of the existing tunnel. Chapman et al. (2007) described results from a series of small-scale (1/50) laboratory model tests carried out in a kaolin clay which focused on studying the short-term ground movements associated with closely spaced multiple tunnels. The influence of tunnel distance, tunnel depth and tunnel number were highlighted. The results showed asymmetrical settlement troughs, greater settlement above the second of the twin tunnels constructed. Their study also demonstrated that the commonly used semi-empirical method to predict the short-term settlement above twin tunnels, using the summation of Gaussian curves, can give inaccurate results. In the study by Choi and Lee (2010), the influence of the size of an existing tunnel, the distance between tunnel centres and the lateral earth pressure factor on mechanical behaviour of the existing and new tunnels was investigated by quantifying the displacement and crack propagation during the excavation

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http://dx.doi.org/10.1016/j.tust.2014.02.001
0886-7798/

of a new tunnel constructed near an existing tunnel. A series of experimental model tests was performed and analysed. It was found that the displacements decreased and stabilized as the distance between the tunnel centres increased, depending on the size of the existing tunnel.

Suwansawat and Einstein (2007) introduced interesting field measurement results on ground movements induced by parallel EPB tunnels excavated in soft ground in Bangkok. They showed that the operational parameters, such as face pressure, penetration rate, grouting pressure and filling, have significant effects on the maximum settlement and extent of the settlement trough. They also showed that the maximum settlement for twin tunnels is not usually located over the midpoint between the two tunnels and that the settlement trough is often asymmetric.

Chen et al. (2011) presented field measurements conducted on parallel tunnels using EPB shields in silty soil. Their results showed a great dependence of the ground movements on the distance between the second tunnel face and the monitored section. They also indicated that the two settlement troughs caused by the construction of the first and the second tunnel had similar shapes. However, the second tunnel trough was shallower and wider than that of the first tunnel. The first tunnel made the symmetric axis of the final trough of the parallel tunnels incline towards the first tunnel. In the study by Ocak (2012), thirty longitudinal monitoring sections, obtained through EPB tunnelling, were used to determine the interactions of the longitudinal surface settlement profiles in shallow twin tunnels. He et al. (2012) carried out field and model tests, based on Chengdu Metro Line 1 in China, to study the surface settlement caused by twin parallel shield tunnelling in sandy cobble strata. The surface settlement mechanism and the effect of tunnel distance on the surface settlement were also studied using the discrete element method (DEM). They showed that when the spacing between two tunnels is higher than twice the tunnel diameter, an independent collapsed arch can form. However, in any of the above studies, the resulting structural forces induced in the tunnel lining were not mentioned.

Field observations remain the key to understanding the interaction between adjacent tunnels. Unfortunately, however, field data are often incomplete. It is clear that model testing can only be used to study limited interaction behaviour. Empirical and analytical methods, using the superposition technique (e.g. Wang et al., 2003; Hunt, 2005; Suwansawat and Einstein, 2007; Yang and Wang, 2011), have been used on the basis of the prediction of each individual excavation in order to obtain the final accumulated settlement trough. Generally, superposition method cannot take into account rigorously the effect of an existing tunnel and the repeated unloading of the ground caused by the previous excavation of the first tunnel and, therefore, the settlement curves do not represent the final displacement very well (Divall et al., 2012). Furthermore, empirical and analytical methods also introduce drawbacks for those cases in which complex geological conditions (e.g. multilayer strata) are expected. The use of a finite element model seems to be a promising way of addressing this issue.

Leca (1989), Addenbrooke and Potts (1996), Yamaguchi et al. (1998), Sagaseta et al. (1999), Hefny et al. (2004), Ng et al. (2004), Karakus et al. (2007), Hage Chehade and Shahrour (2008), Afifipour et al. (2011), Chakeri et al. (2011), Ercelebi et al. (2011), Mirhabibi and Soroush (2012), Hasanpour et al. (2012) have all carried out numerical analysis of this interaction problem. Most of these studies focused on considering the effect of the ground condition, tunnel size, tunnel depth, surface loads, and relative position between two tunnels on the surface settlement. Their results were similar in that the influence of the second tunnel on the previously installed lining of the first one has been shown to depend on the relative position of the tunnel and on the spacing between the two tunnels.

The literature reviewed above clearly indicates that an extensive amount of research has been conducted on tunnel interactions between parallel tunnels. Most of this research has focused on the influence of twin tunnels on ground deformation. However, less work has been devoted to the influence of the interaction between tunnels on the structural forces induced in a tunnel lining.

Ng et al. (2004) performed a series of three dimensional (3D) numerical simulations to investigate the interactions between two parallel noncircular tunnels constructed using the new Austrian tunnelling method (NATM). Special attention was paid to the influence of the lagged distance between the excavated faces of the twin tunnels (L_F) and the load-transfer mechanism between the two tunnels. It was found that L_F has a greater influence on the horizontal movement than on the vertical movement of each tunnel and that the magnitude of the maximum settlement is independent of L_F. They showed that the distributions of the bending moment induced in the tunnel lining are similar in shape, but different in magnitude in the two tunnels.

In the study by Liu et al. (2008), the effect of tunnelling on the existing support system (i.e. shotcrete lining and rock bolts) of an adjacent tunnel was investigated through full 3D finite element calculations, coupled with an elasto-plastic material model. It was concluded that the driving of a new tunnel significantly affects the existing support system when the advancing tunnel face passes the existing support system and has less effect when the face is far from the system. It was also pointed out that the effects of tunnelling on the existing support system depend to a great extent on the relative position between the existing and new tunnels.

In order to investigate the influence of new shield tunnel excavation on the internal forces and deformations in the lining of an existing tunnel, Li et al. (2010) presented a series of 3D numerical simulations of the interaction between two parallel shield tunnels and parametric analyses. Unfortunately, the existence of the joints in the segmental lining, the construction loads induced during shield tunnelling, such as face pressure, jacking force, grouting pressure, were not simulated in this numerical model. The impact of the new tunnel excavation on the existing tunnel during the advancement of the new tunnel was not considered either.

The purpose of a numerical mechanized tunnelling (TBM) model is to take into consideration the large number of processes that take place during tunnel excavation. In order to conduct a rigorous analysis, a 3D numerical model should be used. Obviously, there is not a full 3D numerical simulation for mechanized twin tunnels in soft ground that allows both ground displacement and structural lining forces to be taken into consideration.

The main purpose of this study was to provide a full 3D model which would allow the behaviour of the interaction of mechanized twin tunnels to be evaluated, in terms of structural forces induced in the tunnel lining and ground displacement surrounding the two tunnels. Most of the main elements of a mechanized excavation can be simulated in this model: the conical geometry of the shield, the face pressure, the circumferential pressure acting on the cylindrical surface of the excavated ground in the working chamber behind the tunnel face, the circumferential pressure caused by the migration of the grout acting on the excavated ground at the shield tail, the grouting pressure acting simultaneously on the excavated ground and on the tunnel structure behind the shield tail, progressive hardening of the grout, the jacking force, the weight of the shield machine, the weight of the back-up train behind the shield machine and the lining joint pattern, including the segment joints, the ring joints and their connection condition. The CYsoil model, which is a strain hardening constitutive model, has been adopted. The Bologna–Florence high speed railway line has been adopted in this study as a reference case.