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INFLUENCE OF THE LAGGING DISTANCE BETWEEN TWIN STACKED TUNNEL FACES - 3D NUMERICAL ANALYSES

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ABSTRACT

During the excavation of parallel tunnels in urban area, twin tunnels can be stacked over each other in some cases to avoid pile foundations of existing buildings at the ground surface. Beside the distance between tunnels, a large impact of lagging distance between tunnel faces on the tunnel behavior and on the surrounding ground is expected due to the change of external loads along a mechanized tunneling machine. In this study, a three-dimensional (3D) numerical investigation, using the FLAC^{3D} finite difference software, was carried out in order to highlight the interaction between twins stacked mechanized tunnels considering the change in lagging distance. The critical situation of the lining stability occurs when the two tunnels were simultaneously excavated. The following lower tunnel should be excavated at an enough distance behind the preceding upper tunnel. The appropriate distance in this case study is about of three times of the shield length.

Keywords: Numerical modelling; tunnel lining; settlement; lagging distance; twin stacked tunnel.

1. INTRODUCTION

During the mechanized excavation of twin tunnels in cities and at shallow depth, tunnels can be stacked over each other to exclude the effect of tunnel excavation to the foundations of existing buildings. Distance between stacked tunnels should be as small as possible to reduce the length of tunnels. Interaction between tunnels cannot therefore be neglected.

A review of interaction between mechanized twin tunnels was given in recent works by the authors of the present work (Do et al. 2014a; Do et al. 2014b; Do et al. 2016). Accordingly, most researches have focused on the interaction between horizontally driven tunnels, using physical tests (Chapman et al. 2007; Ng and Lu 2014), field measurements (Suwansawat and Einstein 2007;), empirical/analytical methods (Yang and Wang 2011), and numerical analyses (Zheng et al. 2017). Unfortunately, less work has been devoted to the interactions between twin stacked tunnels (Do et al. 2014b; Senthilnath and Velu 2016). The works focused on the influence of lagging distance between tunnel faces on their behavior are even rarer (Do et al. 2016). Both researches are however focused on the case of two tunnels parallel excavated in horizontal direction.

Along the axis of a mechanized tunnel during excavation process, some temporary loads such as slurry/mud pressures on the tunnel face, jacking forces and compensation grouting pressures at the shield tail have great impact on the tunnel behavior, not only in terms of structural forces and lining deformation, but also on the displacement of the ground surrounding the tunnel (Do et al. 2014a; Do et al. 2016). Each of above loading components has only a certain impact range in the transverse section and also along the tunnelling direction. In addition, these construction loads are not permanently applied on the tunnel but depend on the advancement of the tunnel faces. The interaction between two tunnels therefore depends on both their distance from center to center of tunnel and the lagging distance between the two tunnel faces along the tunnelling direction.

In this paper, a 3D numerical investigation of the interaction between twin mechanized tunnels (with varying lagging distance of tunnel faces), using the FLAC^{3D} finite difference code is presented. Numerical results indicate that the critical situation of the lining stability is observed when the two tunnels are simultaneously excavated. The following lower tunnel should be excavated at a distance behind the preceding upper tunnel. The appropriate distance in this case study is about of three times the shield length.

2. NUMERICAL MODEL

Figures 1 and 2 show a longitudinal view and a cross section of the 3D model used in this study. The same 3D numerical model developed in the finite difference program FLAC^{3D} was used by the same authors (Do et al. 2016). All the parameters used in the numerical model are similar to those used in previous works by Do et al. (2014a). Therefore, only a short description is given here.

2.1. Constitutive model of the ground

The ground was modelled using the Cap-Yield (CYsoil) constitutive model, which is a strain-hardening constitutive model characterized by a frictional Mohr-Coulomb shear envelope (zero cohesion) and an elliptic volumetric cap in the (p', q) plane (Do et al. 2014a). Parameters of the ground are summarized in Table 1 (Do et al. 2014a). It should be mentioned that gravity stress field has been adopted in this study.

Table 1. Soil parameters (Do et al. 2014a)

CYsoil model	Value
Reference elastic tangent shear modulus G^e_{ref} (MPa)	58
Elastic tangent shear modulus G^e (MPa)	98
Elastic tangent bulk modulus K^e (MPa)	213
Reference effective pressure p^{ref} (kPa)	100
Failure ratio R_f	0.9
Ultimate friction angle ϕ_f (degrees)	37
Calibration factor β	2.35
Lateral earth pressure factor K_0	0.5

2.2. Shield machine simulation

The external diameter of tunnels is equal to 9.4 m and the upper tunnel was excavated at a depth of 20 m below the ground surface. The twin stacked tunnels are excavated at a vertical distance of 11.75 m from center to center.The tunnel construction process was modelled using a step-by-step approach (Do et al. 2014a). The advance length after each excavation step is of 1.5 m. This length is equal to the width of a lining ring.

In this 3D numerical model, most components of a shield machine have been simulated: tunnel face pressure, distributed pressures acting in the cylindrical void just behind the tunnel face, the conicity of steel shield and its self-weight, the jacking force applied on the last lining ring at the shield tail, the grouting pressure in the liquid state and the hardened grout, the tunnel linings with the joints and the back-up train. A detailed description of the numerical simulation of each of the above components is given in work of the same authors (Do et al. 2014a). It should be noted that the presence of the joints in the tunnel lining, including the longitudinal joints and the circumferential joints, was taken into consideration in this model due to their important influence (Liu et al. 2016).

In order to highlight the influence of the lagging distance L_F on the behavior of twin tunnels, the excavation process of the twin stacked tunnels was simulated as follows: (i) excavation of the preceding upper tunnel; (ii) excavation of the following lower tunnel at a certain lagging distance L_F. Five scenarios of the lagging distance L_F were simulated: $0L_S$, $1L_S$, $2L_S$, $3L_S$ and $6L_S$, in which L_S is the length of the shield machine (L_S = 12 m). The case $L_F = 0\ L_S$means that the two tunnels are simultaneously excavated, while the value $L_F = 1\ L_S$ corresponds to the situation that the face of the following lower tunnel is at the same transverse section as the shield tail of the preceding upper tunnel. The case $L_F = 6\ L_S$ implies that the following lower tunnel is excavated when the preceding tunnel lining reached asteady state.

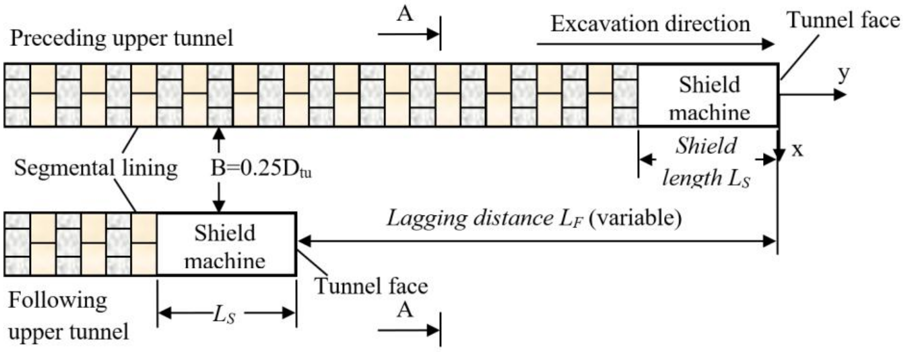

Figure 1. Longitudinal view of the twin stacked tunnels (not scaled).

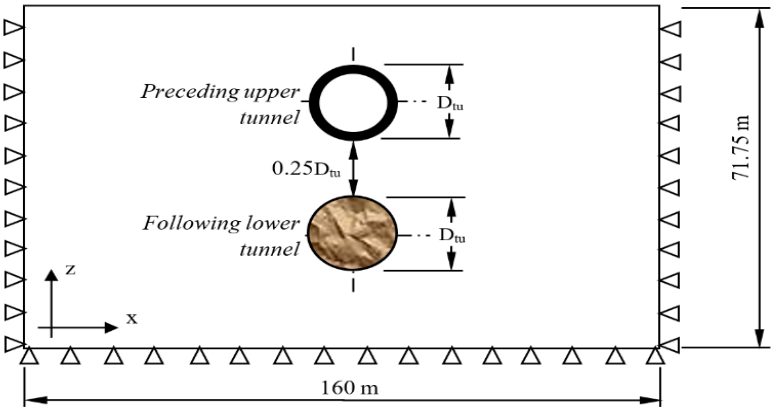

Figure 2. A–A: typical cross section view of the twin stacked tunnels (not scaled).

3. NUMERICAL RESULTS AND DISCUSSION

This section presents the variation of the ground displacements developed over the tunnels during the excavation of the twin stacked tunnels at different lagging distances of tunnels faces, L_F. The ground displacement were determined at the transverse section of the 30th ring of the following lower tunnel, counting from the model boundary (y = 0 m) in order to avoid the effect of the model boundary (Do et al. 2014a).

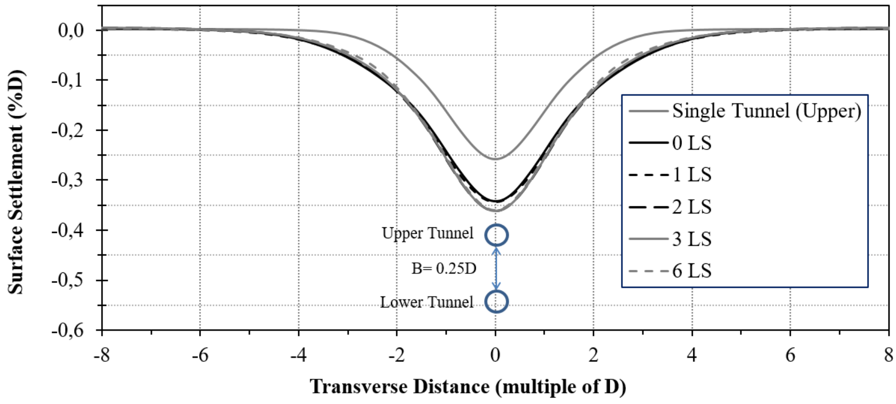

Figure 3.Comparison of the surface settlement troughs in the transverse section of the twin lagging stacked tunnels (L_S is the length of shield machine).

Figure 3 shows the surface settlement at the ground surface corresponding to different lagging distances between the faces of twin stacked tunnels. For comparison purpose, the settlement trough over the single upper tunnel is also presented. Obviously, excavation of twin tunnels causes a great increase in the settlement trough. However, it can be seen from Figure 4 that the lagging distance between tunnels face has an insignificant influence on the maximum settlement value. The maximum settlement in all considered cases of lagging distance changed from 32.2 mm to 34 mm. The shape of the settlement trough and of the total volume loss caused by the twin stacked tunnel is nearly similar (Figure 3). It is therefore possible to conclude that lagging distance between two stacked tunnel faces has an insignificant influence on the settlement trough in all considered cases.

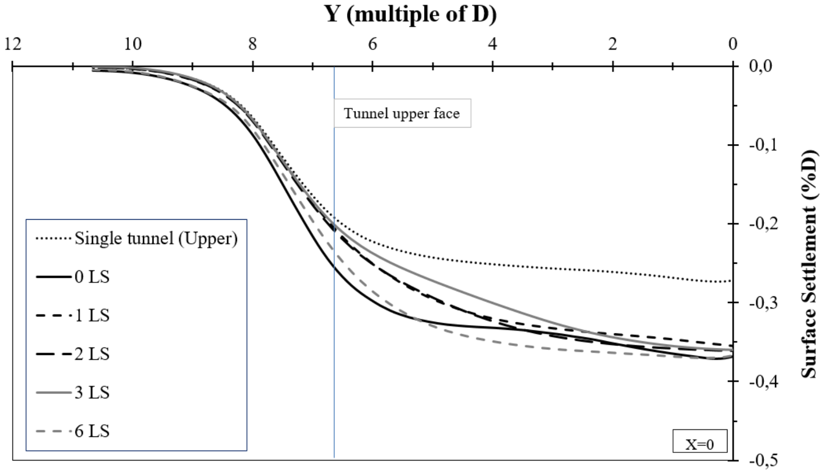

Figure 4. Comparison of the surface settlement troughs in the longitudinal section of the twin lagging stacked tunnels (L_S is the length of shield machine).

Figure 4 presents the longitudinal surface troughs in different lagging distances between tunnel faces. The maximum settlement value at the upper tunnel face section is observed in the case of simultaneous excavation of twin tunnels. These values in the cases of L_F = 1 LS, 2 LS and 3 LS are nearly similar to that in the case of the single upper tunnel. Nevertheless, in the case that the following lower tunnel is excavated when the ground mass surrounding the preceding upper tunnel has reached a steady state (i.e. the case of L_F = 6 LS), the settlement value at upper tunnel face section increases again. Figure 4 also indicates that unless the case of L_F = 6 LS, the greater the lagging distance between tunnel faces, the larger the length of longitudinal section of surface settlement trough which is affected by the twin tunnel excavation. In other words, the ground surface settlement trough in longitudinal section is steeper when the lagging distance is smaller.

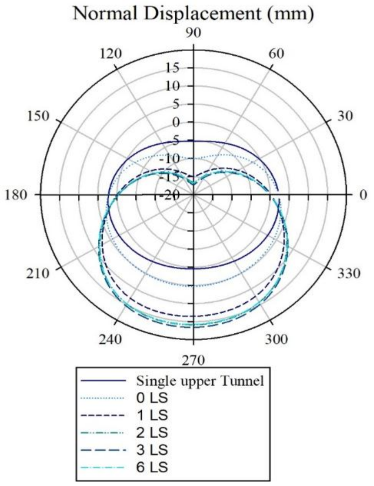

Figure 5. Normal displacement induced in the lining of the preceding (upper) tunnel.

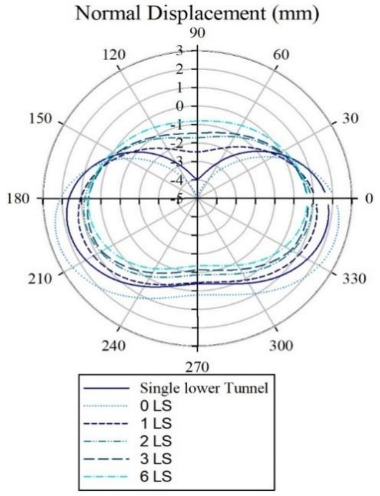

Figure 6. Normal displacement induced in the lining of the following (lower) tunnel.

The excavation of twin tunnels generally causes downward and outward movements of the upper tunnel lining. It is interesting to note that the greater the lagging distance between tunnel faces, the larger the downward/outward displacement at the tunnel bottom and the greater the ovalling deformation of the upper tunnel lining (Figure 5). It could be explained by the smaller effect of upward forces, i.e. face pressure, grouting pressure, acting from the following lower tunnel on the lining in the preceding upper tunnel when the lagging distance increase. It is necessary to mention that the ovalling deformation of the tunnel lining in this case with the small lateral earth pressure coefficient (K_0 = 0.5) means the inward movement along the vertical direction at the tunnel crown and bottom, and the outward movement along the horizontal direction at the two sides.

As for the lining deformation which is related to the movement of the soil surrounding the tunnels, the smallest affection of twin tunnel excavation on the normal deformation of the upper tunnel is observed in the case of simultaneous excavation (i.e., L_F = 0 LS) (Figure 5). This may be concerned to the effect of face pressure in both tunnels and the presence of the lower tunnel shield.

Unlike for the upper tunnel, Figure 6 indicates a reduction of inward displacements of the lower tunnel lining for most of cases of lagging distances between tunnel faces, except for the case of simultaneous excavation. The greater the lagging distance L_F, the smaller the inward displacements around the lining of the lower tunnel. It should be noted that inward displacements around the lower tunnel has originated from the redistribution of the stresses in ground surrounding the lower tunnel during the excavation, which depends on the low value of the earth pressure coefficient (K_0 = 0.5). When the lagging distance between the upper and lower tunnel faces increase, redistribution of stresses in the ground mass surrounding the preceding upper tunnel reaches closer to the steady state when the following lower tunnel pass through. At this state, stresses are more uniform from all sides of the lower tunnel. Consequently, the ovalling deformations of the lower tunnel lining decreases (see Figure 6).

4. CONCLUSIONS

A series of 3D numerical analyses of the mechanized twin stacked tunnelling process were conducted in order to highlight the effect of lagging distance between two tunnels faces on the structural forces induced in the lining of both tunnels and on the displacement of the ground surrounding the tunnels. Based on the numerical results obtained in this study, the following comments can be drawn:

The lagging distance between two stacked tunnel faces has an insignificant influence on the settlement trough on the ground surface. The shape of the settlement trough caused by the twin stacked tunnel is nearly similar.

The ground surface settlement trough in longitudinal section is steeper when the lagging distance is smaller.

The greater the lagging distance between tunnel faces, the larger the downward/outward displacement at the tunnel bottom and the greater the ovalling deformation of the upper tunnel lining. However, the ovalling deformations of the lower tunnel lining decreases.

It should be noted that the numerical investigation in this study is conducted in drained conditions and for a homogeneous ground medium. Experimental studies and on-site monitoring will also be necessary in the future to validate the numerical results obtained in this study.

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REFERENCES

[1]. Chapman DN, Ahn SK and Hunt DVL (2007). Investigating ground movements caused by the construction of multiple tunnels in soft ground using laboratory model tests. Canadian Geotechnical Journal 446, 631-643.

[2]. Do NA., Dias D., Oreste PP. and Djeran-Maigre I. (2014a). Three-dimensional numerical simulation of a mechanized twin tunnels in soft ground, *Tunnelling and Underground Space Technology*, 42, 40-51.

[3]. Do NA., Dias D., Oreste PP. (2014b). Three-dimensional numerical simulation of mechanized twin stacked tunnels in soft ground, *Journal of Zhejiang University SCIENCE A*, 15(11), 896-913.

[4]. Do NA., Dias D., Oreste PP. and Djeran-Maigre I (2016). 3D Numerical investigation of mechanized twin tunnels in soft ground - Influence of lagging distance between two tunnel faces, *Engineering Structures*, 109, 117-125.

[5]. Liu X., Bai Y., Yuan Y. and Mang HA. (2016). Experimental investigation of the ultimate bearing capacity of continuously jointed segmental tunnel linings, *Structure and Infrastructure Engineering*, 12(10), 1364-1379.

[6]. Ng CWW. and Lu H. (2014). Effects of the construction sequence of twin tunnels at different depths on an existing pile, *Canadian Geotechnical Journal*, 51, 173-183.

[7]. Senthilnath GT, and Velu D (2016). Stacked tunnelling induced surface settlements in soft soil - A case study from Singapore, *International Journal of Geoengineering Case histories*, 3(3), 162-175.

[8]. Suwansawat S and Einstein HH (2007). Describing settlement troughs over twin tunnels using a superposition technique, *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 445-468.

[9]. Yang XL and Wang JM (2011). Ground movement prediction for tunnels using simplified procedure, *Tunnelling and Underground Space Technology*, 26, 462-471.

[10]. Zheng G., Du Y., Cheng X., Diao Y., Deng X., Wang F. (2017). Characteristics and prediction methods for tunnel deformations induced by excavations, *Geomechanics and Engineering*, 12(3), 361-397.