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PREDICTION OF SURFACE SETTLEMENT DUE TO TWIN TUNNEL CONSTRUCTION IN SOFT GROUND OF HANOI METRO LINE 03

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ABSTRACT: Construction of tunnels in the soft ground causes ground surface settlement in the urban conditions, especially for tunnels near the surface. The prediction of ground surface settlement caused by a single tunnel is well established in many documents. However, the ground surface settlement induced by the construction of twin tunnels is not well understood, and methods of predicting ground surface settlement in such projects are currently limited. This paper presents the three-dimensional numerical results using the finite element software (Abaqus) for the prediction of surface settlements caused by twin horizontal tunnels of the Hanoi Metro Line 03 excavated in soft ground. One of the aims of the study is to estimate the effect of the distance between tunnels on the magnitude and shape of the surface settlement trough. The results show that the center-to-center spacing of the tunnels has a significant influence on both the magnitude and the shape of the transverse surface settlement trough. The maximum surface settlement developed over twin tunnels will be reduced with an increase in the tunnels' center-to-center spacing.

Keywords: Twin tunnels, Side-by-side tunnels, Finite element method, Ground settlements

1. INTRODUCTION

Twin tunneling in urban areas is growing in response to the increased need for an improved transportation system. Many urban twin tunnels are constructed in the soft ground at shallow depths. Urban tunnels are usually constructed as twin-parallel tunnels. Twin tunnels construction in the soft ground may cause ground movements [1]. These ground movements, both horizontal and vertical, have been reported by many authors [2-17, 25-27]. These authors have shown several methods to evaluate the settlement of the surface, such as analytical, empirical, and finite element methods for the prediction of ground movements above twin tunnels. However, the settlements of the surface are dependent on many factors, including soil parameters, tunnel geometry, and types of construction methods.

Terzaghi [4] reported that the result of ground movements above twin tunnels is larger than above the first line tunnel. Peck [5] suggested the result of monitoring data for ground movements above twin tunnels driven in dense sand. The result of ground movements by twin tunnels was greater than that for the first-line tunnel. Moretto [6] also reported a larger settlement for the second tunnel when twin tunnels were constructed in dense silty sand, overlying firm clay. Cording and Hansmire [7] showed that the surface displacements above twin 6m diameter tunnels at 9m centers constructed at a depth of 15m in silty sand and clay. The surface settlements were received an increased surface settlement for the second tunnel. Hanya [18] studied surface settlements due to twin tunneling in Japan at various depths, diameters of tunnels, and soil types. For most cases, the increased settlement found above a second tunnel, when the second tunnel was constructed, is relatively close to the first tunnel. Akins and Abramson [19] recorded ground settlement above twin tunnels with a diameter of 6.1m at a center-to-center spacing of 6m constructed at a depth of 15m in residual soil. The results showed that an increase in volume loss was found for the second tunnel.

Numerical modeling of twin tunnels has been conducted by many authors. Addenbrooke [12] reported ground movements above twin tunnels when conducting non-linear finite element analysis of twin tunnels at 4.8m diameter, a depth of 34m, and various spacing. The results showed that the center-to-center spacing of the tunnels has a significant effect on the ground surface settlement trough. A study of ground movements by non-linear finite element analysis of twin tunnels at various depths and center-to-center spacing in stiff clay showed that an increase in volume loss was found for the second tunnel [20]. Kim et al. provided ground movements above twin tunnels when conducting finite element analyses of a second parallel tunnel at a center-to-center spacing of 0.4D and 1.0D. The most significant ground movements were caused by the construction of a nearer tunnel at a spacing of 0.4D. The results showed good agreement with ground movements found in the laboratory when conducting tests under gravity in Kaolin clay.

This study presented the results of the finite element analyses using the Abaqus/Standard three-dimensional finite element software to predict ground surface settlements above twin tunnels due to the construction of Hanoi metro line 03. These twin 6.3 m diameter tunnels for side-by-side tunnels at a center-to-center spacing of 15m to 30m and the tunnel crown depth of 20 m [22].

One of the aims of the study is to ascertain the effect of changes to the center-to-center spacing on the magnitude and the shape of the ground surface settlement trough.

2. GROUND MOVEMENTS DUE TO TWIN TUNNELING

2.1 Superposition Method

New and O'Reilly proposed a method of calculating ground surface settlement due to the construction of twin tunnels. The method sums together the settlement trough above each tunnel [10], as shown in Eq. (1):

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

where: d is the horizontal distance between tunnel centers (m); x_A is the lateral distance of the center-line of the first bored tunnel (m); i is the distance from the tunnel centreline to the inflection point.

The subsequent longitudinal displacements horizontal displacements can also be found by summation and have been reported by New and O'Reilly [10].

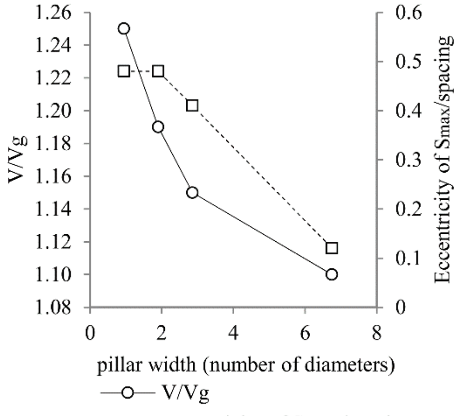

Fig.1 Effect of pillar width on the eccentricity of maximum settlement (S_{max}) and an increase in volume loss of the second tunnel, where V is the volume loss from the second tunnel construction; V_g is the volume loss of the first (greenfield) tunnel construction [13].

2.2 Addenbrooke & Potts Method

Addenbrooke and Potts [13] introduced numerical results of twin tunnels. The authors proposed a method for adjusting the predicted settlement twin tunnels. The volume loss of the second tunnel is greater than that of the first. The position of maximum settlement (S_{max}) above the second tunnel is offset from the tunnel axis. Figure1 can be used to evaluate the eccentricity of maximum settlement (S_{max}) and an increase in volume loss of the second tunnel [13].

2.3 Modification Method

Hunt [1] provided a different method for predicting ground movements above twin tunnels. The influence of the changes to soil stiffness on the displacement profile above the second tunnel is directly related to the amount of modification applied [1].

The equation of the modified settlement above a second tunnel is shown in Eq. (2):

$$S_{\text{mod}} = F.S_v \qquad (2)$$

where S_{mod} is the modified settlement (m); S_v is the unmodified settlement above the second tunnel competed by semi-empirical method (m); F is the modification function (m), which can be determined using Eq. (3), [1].

$$F = \left\{1+\left[M\left(1-\frac{|d+x_A|}{A.K_A.Z^*}\right)\right]\right\} \qquad (3)$$

Where $Z^* = Z_0 - Z$ (m), Z_0 is the depth from the surface to tunnel axis, Z is the depth from the surface to the horizon analysis; A is the multiple of i (m); K_A is the value of K in the region of the first tunnel bored; d is the center-to-center spacing of the twin tunnels (m); M is the maximum modification.

3. NUMERICAL MODELING

3.1. Input Parameters and Numerical Computation Scenarios

Hanoi Metro line 03 starts from "Nhon" station, located in the west of the Hanoi city, passes through "Cau Giay" and then run towards the east, "Kim Ma" and "Cat Linh", until the "Hanoi" terminal station as shown in Fig.2. Project metro line 03 of Hanoi Metro Rail System is the first metro of Hanoi city, Vietnam. The length of line 03 from "Nhon" station to "Hanoi" station is 12.5 km long with a mixed path passing from surface to underground. The elevated part is 8.5 km long from the "Nhon" station to the "Kim Ma" station using the cut and cover method. The underground part is 4 km long from the "Kim Ma" station to the "Hanoi" station using the mechanized tunneling method [22], [23].

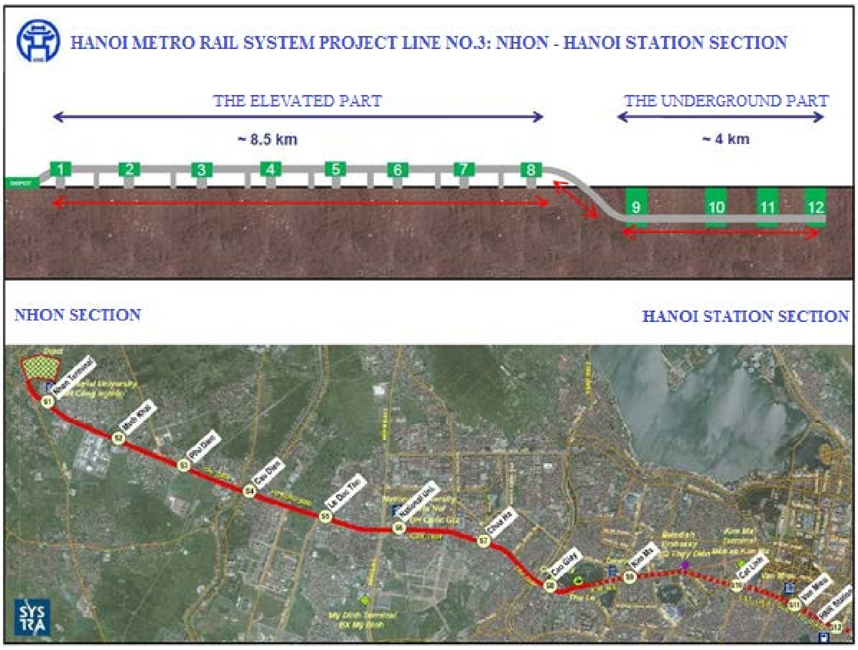

Fig.2 Hanoi metro line 03 "Nhon - Hanoi" station

Profile of Hanoi metro line 03 with twin 6.3 m diameter tunnels excavated side-by-side and at a center-to-center spacing of 15 m to 30 m, the tunnel crown depth of 20 m is shown in Fig.3.

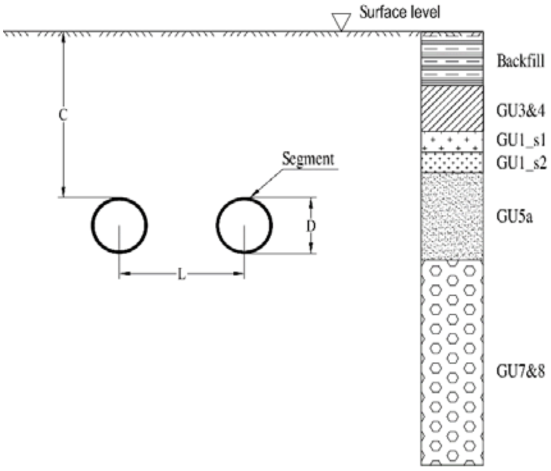

Fig.3 Cross-section profile of the twin tunnels and different soil layers

According to the investigated geological conditions, the twin tunnels located in the stratum, mainly stiffer clay, sand, or silty sand. The upper soil layers over the twin tunnels are organic, backfill and soft to firm leam clay [24]. The tunnel on the left is excavated first and then followed by the tunnel on the right. Parameters of the soil layers are determined as shown in Table 1.

3.2. Establish the Numerical Model

The analyses were performed using the Abaqus software version 6.12-3. While the Mohr-Coulomb failure criterion is applied for the soil, the concrete lining is assumed to be elastic.

The case of twin tunnels with 6.3 m diameter, 15.0 m center-to-center spacing (L=15.0 m), and the tunnel crown depth of C=20.0 m is adopted. A length of 50 m twin tunnels excavation stages was considered in this study. The 3D model was set up with dimensions of 120 m length and 100 m width in the X and Z-direction, respectively, and a height of 100 m in the Y-direction, as shown in Fig.4. The upper model boundary (y = 0.0 m) was set to be free, whereas the vertical and horizontal displacements at the bottom boundary (y = -100.0 m) were fixed.

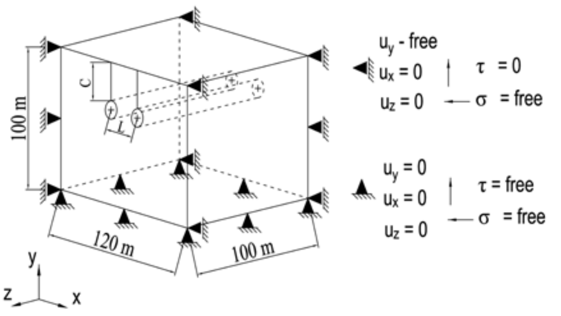

Fig.4 Boundary conditions of the 3D model

The tunnel lining consists of concrete cast-inplace rings characterized by a length (1.5 m), 300mm thick (Fig.5). The properties of concrete are unit weight (25 kN/m^3), Young's Modulus (25 GPa), and Poissons' ratio (0.2).

Table 1 Soil's parameters [24]

Soil layer	Thickness, H (m)	Density, ρ (kg/m^3)	Young's modulus, E (MPa)	Poisson's ratio, υ	Friction angle, φ (0)	Cohesion, c (kPa)	Horizontal pressure coefficient, K_0
Backfill	6.5	1900	-	0.3	32	-	0.47
GU3&4	5.5	2000	8	0.3	20	5	0.66
GU1_s1	2.5	1850	12	0.3	25	10	0.58
GU1_s2	2.5	1900	50	0.3	25	25	0.58
GU5a	10.5	2000	55	0.3	34	25	0.44
GU7&8	72.5	2100	75	0.25	38	25	0.36

Note: Layer GU3&4 - Organic fat and elastic clays; GU1_s1 - soft to firm lean clay; GU1_s2 - Stiffer clay; GU5a - Sand or silty sand; GU7&8 - Coarse sand or gravel [24].

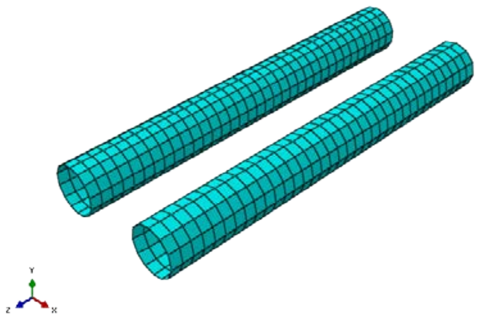

Fig.5 Segment lining twin tunnels

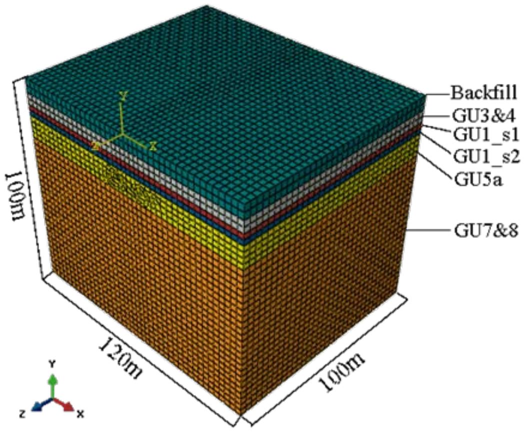

Fig.6 Segment lining twin tunnels 3D discretized block with soil layers and twin tunnels

The excavation of the twin tunnels was simulated in a step-by-step procedure. In the first step, boundary conditions and gravity stresses are applied, and the model is launched to reach the initial state. In the second step, the tunnel on the left is excavated by deactivating the zone elements inside the tunnel periphery. The concrete lining is then installed on the tunnel boundary. The model is launched to reach a new equilibrium state. After that, the same procedure of excavating the soil and installing the concrete lining is applied for the tunnel on the right before reaching the final equilibrium state (Fig. 6).

3.3. Results and Discussions

Figs.7 and 8, respectively, show the vertical displacements after the excavation of the tunnel on the left and the tunnel on the right.

The maximum ground surface settlement of 8.25 mm is observed after the excavation of the left tunnel. The position of maximum ground surface settlement is located over the center-line of the left tunnel. The shape of the transverse ground surface settlement trough is in good agreement with the Gaussian curve.

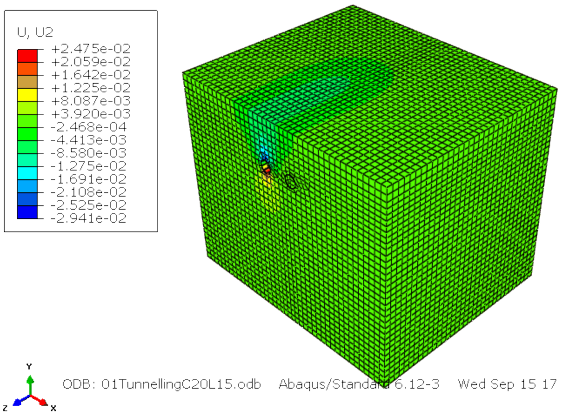

Fig.7 Vertical displacements after the left tunnel excavation

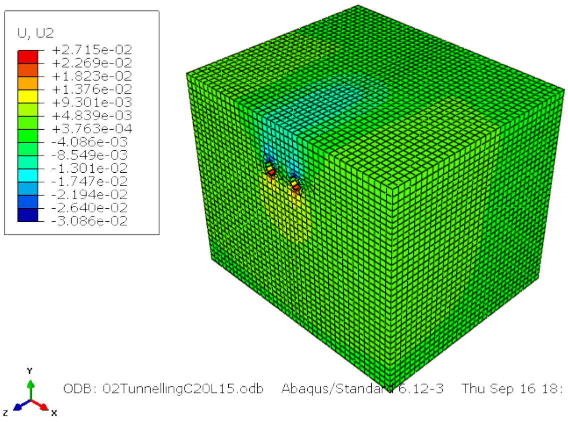

Fig.8 Vertical displacements after the right tunnel excavation

Fig.9 shows the ground surface settlement trough induced by the excavation of the first left tunnel and then the second right tunnel.

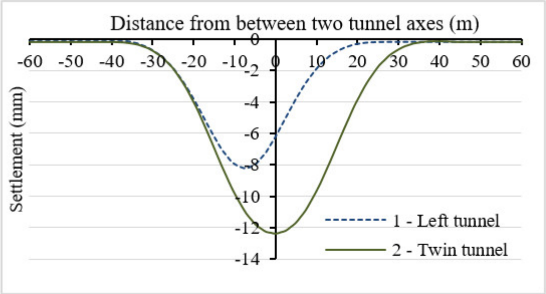

Fig.9 Surface settlement trough due to the construction of the left tunnel (1) and twin tunnels (2)

After the right tunnel excavation, the maximum ground surface settlement of 12.38 mm is reached. The position of maximum ground surface settlement is eccentrically displaced 7.5 m from the center-line of the left tunnel and towards the right tunnel. Fig.10 presents the longitudinal settlement on the ground surface determined after the excavation of the left tunnel and the right tunnel.

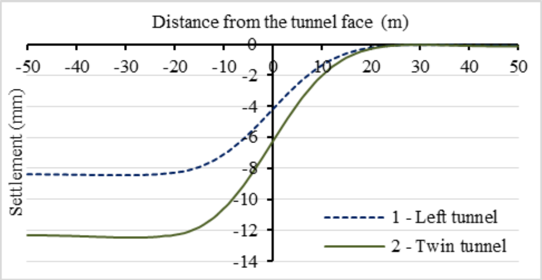

Fig.10 Longitudinal settlement trough on the ground surface due to the construction of the left tunnel (1) and twin tunnels (2)

A length of 50.0 m twin tunnels excavation was considered in this study. As shown in Fig.10, after the left tunnel excavation, the magnitude of ground surface settlement at the tunnel face section is 4.18 mm. It is approximate 50.67 % compared to the maximum ground surface settlement (8.25 mm). After the right tunnel excavation, the magnitude of ground surface settlement directly above the right tunnel face is 6.26 mm, coinciding with 50.56 % of the value of maximum ground surface settlement (12.38 mm).

The surface settlement will appear in front of the tunnel face at a distance of 3-5 times the tunnel diameter. The surface settlement reached the maximum value at a distance, behind the tunnel face, of 5-7 times the tunnel diameter.

Fig.11 shows the lateral movements determined at the distance: x = L/2 = 15/2 = 7 m measured from the left tunnel axis (where L is the centre-to-centre spacing, L =15 m). After the left tunnel excavation, the maximum ground horizontal movements of 15.98 mm are seen (Fig.11). After the right tunnel excavation, it equals 4.52 mm.

The changes of center-to-center spacing between tunnels have a significant influence on the ground surface settlement. The surface settlement caused by the construction of twin tunnels at centre-to-centre spacings of 2.5D (L=15.75 m), 3.0D (L=18.9 m), 3.5D (L=22.05 m), 4.0D (L=25.2 m), 4.5D (L=28.35 m) are shown in Fig.12. The magnitude of the maximum ground surface settlement was found to be 12.2 mm, 10.37 mm, 9.1 mm, 8.47 mm, 8.16 mm, respectively (Fig. 12).

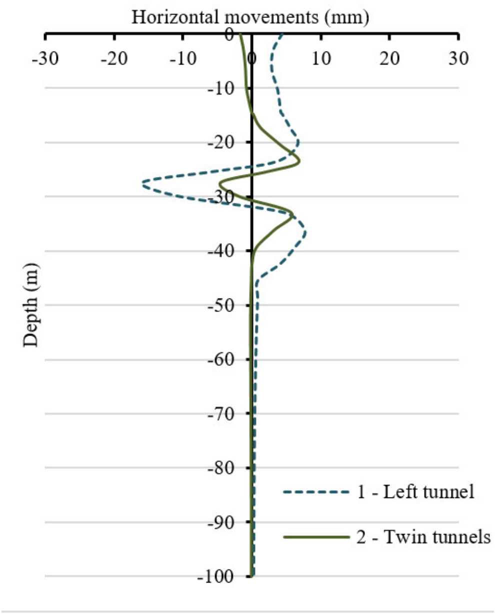

Fig.11 Horizontal movements along the vertical line between two tunnel axes due to the construction of left tunnel (1) and twin tunnels (2)

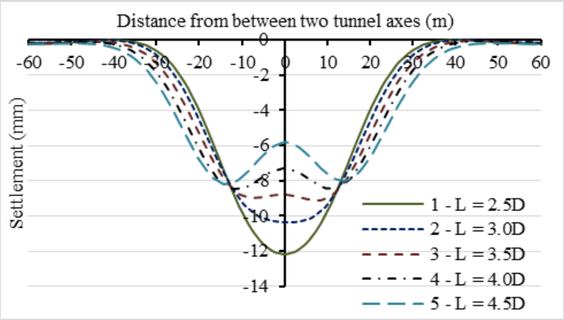

Fig.12 Maximum ground surface settlement trough due to the construction of twin tunnels in other cases 2.5D, 3.0D, 3.5D, 4.0D, and 4.5D m center-to-center spacing

The results are in agreement with the results of Addenbrooke & Potts [13], Divall et al. [15] in both terms of the transverse surface settlement trough and the position of maximum settlement.

At the small center-to-center spacing of 2.5D (L=15.75 m) and 3.0D (18.9 m), the position of maximum settlement is located at the axis between two tunnels when the center-to-center spacing increases, i.e., 3.5D (L=22.05 m), 4.0D (L=25.2 m) and 4.5D (L=28.35 m), the maximum settlement is observed on the left and right tunnels' axis.

4. CONCLUSION

Based on the case study of Hanoi Metro line 03, ground surface settlement due to the construction of Hanoi metro line 03 was presented and analyzed. From the numerical analysis, the following conclusions could be drawn:

After the twin tunnels excavation, the magnitude of ground surface settlement directly above the face of the tunnel equals 50.56 % of the maximum ground surface settlement.

Surface settlement began to appear in front of the face of the tunnel and at a distance of 3-5 times the diameter of the tunnel. The location where the maximum surface settlement is reached is behind the tunnel face and a distance of 5-7 times the diameter of the tunnel.

The center-to-center spacing of the tunnels affects both the magnitude and the shape of the transverse ground surface settlement trough. The maximum ground surface settlement due to the construction of twin tunnels reduces when increasing the center-to-center spacing.

5. ACKNOWLEDGMENTS

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