3-D Nonlinear Numerical Analysis to study the Performance of Twin Tunnel System

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ABSTRACT

Tunneling in loose soil is a sophisticate process leading to unexpected collapse for surface and subsurface structures. However, it is necessary to investigate the geotechnical problems related to tunnelling. Tunnelling process needs to more engineering insight analysis. Several numerical analyses have been conducted to model soil-structure interaction behavior. However, this study presents a case history along El-Azhar road tunnels.

In the present study, the finite element model (FEM) is proposed to predict performance of tunnel system based on the twin tunnel construction. The case history presented and discussed in this study gives a rare opportunity to understand the performance of the twin tunnel system. The constitutive model for this analysis utilizes elasto-plastic materials. A yielding function of the Mohr-Coulomb type and a plastic potential function of the Drucker-Prager type are employed. A linear constitutive model is employed to represent the tunnel liner.

The response of El-Azhar road tunnels system is described and presented to investigate the ground movement caused by tunnelling. The ground movement is calculated using 3-D finite element analysis (FEA). The results obtained by the 3-D nonlinear numerical model are compared with those obtained by the field measurement to assess the accuracy of the proposed 3-D FEM. A good agreement between the results obtained by the 3-D FEA and those by the field measurements is obtained.

RÉSUMÉ

Tunneling dans un sol meuble est un processus sophistiqué et provoquent l'effondrement inattendu des structures de surface et souterraines. Toutefois, il est nécessaire d'enquêter sur les problèmes géotechniques liés à effet tunnel. Tunneling processus besoins d'une analyse technique plus de perspicacité. Plusieurs analyses numériques ont été menées pour modéliser le comportement d'interaction sol-structure. Cependant, cette étude présente une histoire de cas le long des tunnels routiers Azhar El-. Dans la présente étude, le modèle éléments finis (FEM) est proposé pour prédire la performance du système de tunnel sous la construction du tunnel jumeaux. L'histoire de cas présentées et discutées dans cette étude offre une rare opportunité de comprendre la performance du système de tunnels. Le modèle constitutif pour cette analyse utilise-plastique des matériaux élasto. Une fonction de rendement de l'Mohr-Coulomb type et une fonction de potentiel plastique du type Drucker-Prager sont employés. Un modèle linéaire est constitutive employés pour représenter le revêtement de tunnel. La réponse du système de tunnels routiers El-Azhar est présentée et décrite pour enquêter sur les mouvements de terrain causés par effet tunnel. Le mouvement du sol est calculée en utilisant 3-D d'analyse par éléments finis (FEA). Les résultats obtenus par le modèle 3-D numériques non linéaires sont comparés avec ceux obtenus par la mesure sur le terrain pour évaluer l'exactitude de la proposition de FEM 3-D. Un bon accord entre les résultats obtenus par la FEA 3-D et celles de mesures sur le terrain a été obtenu.

KEYWORDS: twin tunnels, numerical model, finite element analysis, deformations.

1. INTRODUCTION

El-Azhar road tunnels have been constructed by tunnel boring machine (TBM) in a densely populated historical area in Cairo city. The twin road tunnels extend from Salah Salem street to Opera square at downtown. Each tunnel is 2.7 km long. Only one-km span of the twin road tunnels were constructed using cut-and-cover technique.

Tunnelling leads to ground movement due to the associated soil stress changes. The numerical techniques have been widely used to predict the ground movements (Abdel Meduid et al., 2002; Abu- Farsakh et al., 1999; Berant and Cambou, 1998; El-Nahhas, 1986; Galli et al., 2004; Mazek et al., 2004; Mazek et al., 2009; Mroueh and Shahrour, 2008). Finite element method is considered the most appropriate analytical technique to solve geotechnical problems (Addenbrooke and Potts, 2001; Karakus and Fowell, 2005; Mazek, 2004; Mazek et al., 2006; Migliazza et al., 2009; Oettl and Hofsetter, 1998). Modelling of geotechnical properties and tunnelling procedure are a sophisticated problem (Contini et al., 2007; El-Nahhas, 1999; Mazek and Tehawy, 2008). In this study, El- Azhar road tunnels in central Cairo city are considered. The twin tunnel system performance is studied. The tunnel system is modelled using 3-D nonlinear finite element analysis (FEA) under the shadow of the case history so as to understand the performance of the twin tunnels system.

In the 3-D nonlinear FEA, tunnelling process and interaction effects between twin tunnels and soil around the tunnels are investigated. The 3-D nonlinear FEA is used to estimate the vertical displacement at ground surface due to tunnelling. A comparison between the results calculated by the 3-D nonlinear FEA and the results recorded by field measurements is conducted to assess the accuracy of the proposed 3-D nonlinear FEA. The typical geotechnical properties used in this study are presented. However, the results calculated by the 3-D nonlinear finite element analysis agree well with those obtained by the field measurements.

2. EL-AZHAR ROAD TUNNELS MODELLING

The finite element computer program (COSMOS/M, 2003) is used in this study. The finite element model takes into account the effects of the vertical overburden pressure, the lateral earth pressure, the soil parameters, the twin tunnel liners, and the ground loss.

The soil media, the road tunnels liners, and the interface are simulated using the appropriate finite elements. Solid elements are used for modelling the soil media and thick shell elements for modelling the twin tunnel liners. A 3-node triangular thick shell element is used with each node having 6 degrees of freedom (three translations and three rotations). As shown in Fig. 1, the solid element is prismatic in shape and has 6 nodes with each node having 3 degrees of freedom (three translations). The prismatic solid element and the triangular shell element interface are used between the soil media and the twin tunnel liners to ensure compatibility conditions at the interface between them. Figure 2 shows the configuration of El-Azhar road tunnels.

The 3-D finite element mesh models a soil block with width, height, and length in x, y, and z directions, respectively, as shown in Fig. 1. The vertical boundaries of the 3-D finite element model are restrained by roller supports to prevent a movement normal to the boundaries. The horizontal plane at the bottom of the mesh represents a rigid bedrock layer and the movement at this plane is restrained in all three directions. The movement at the upper horizontal plane is free to simulate a free ground surface.

Due to the construction of El-Azhar road tunnels, the ground surface is subjected to settlement. The twin tunnel liners are composed of 40-cm thick segments. The segments joints are never aligned along the tunnel and the thickness reduction is not as local construction as it is simulated in the model, which is conservative. The computed normal forces and bending moment values must comply with the strength of the 40-cm thick reinforced segments and the 24-cm thick joints between the segments.

3. PROJECT DESCRIPTION

El-Azhar road tunnels project area under analysis lies within the alluvial plain, which covers the major area of the low land portion of the Nile valley in Cairo vicinity (El-Nahhas, 1994; Mazek et al., 2001; NAT, 1993, 1999, 1993, 2009). Site investigations along the project alignment indicate that the soil profile consists of a relatively thin surficial fill layer ranging from two to four metres in thickness. A natural deposit of stiff, overconsolidated silty clay underlies the fill. This deposit includes occasional sand and silt partings of thickness from four to ten metres. Beneath the clay layer, there is thick alluvial sand that extends down to bedrock, which is well below El-Azhar road tunnels. The watertable varies between two meters to four meters from the ground surface. The geotechnical parameters are presented in Table 1.

Since soil behavior is generally inelastic, the constitutive relationship adopted in the analysis is an elasto-plastic model. The Mohr-Coulomb criterion is adopted. Excavation of the twin tunnels are simulated by removing elements from the excavated boundary. The friction angles (ϕ) adopted for the layers have been obtained using laboratory test results from reconstituted samples. The vertical initial drained modulus (E_v) is related to the effective pressure based on Janbu's empirical equation (Janbu, 1963) as given by Eq. 1.

$$E_v = mp_a(\frac{\sigma_3}{p_a})^n \tag{1}$$

Where; the modulus number (m) and the exponent number (n) are both pure numbers and p_a is the value of the atmospheric pressure expressed in appropriate units.

The diameter of twin tunnel liners (D), the characteristic of the tunnel liners, and the excavation diameter of the twin tunnels (D_0) are presented in Table 2. The twin tunnel liners are assumed to behave in a linear manner in the 3-D nonlinear finite element analysis. The ground surface displacement due to the construction of the tunnel is calculated in this study.

4. 3-D MODEL ANALYSIS

The twin road tunnels are located at 20 meters from the ground surface, as shown in Fig. 2. Drain analysis is adopted in the numerical model as El-Azhar road tunnels pass through the sand layer.

The suitable geometric boundaries (model width and model height) are studied to reflect the performance of the road tunnels system. The 3-D finite element analysis (FEA) is used to choose the suitable model width. The model width is varied from 40 meters to 120 meters.

The calculated surface settlements due to tunnelling with different model widths are shown in Fig. 3. The calculated crown settlement of the twin tunnels with different model widths is also presented in Fig. 4. The calculated invert heave of the twin tunnels with different model widths are also presented in Fig 5. The results show that the model width is 120 meters beyond which there is no change in soil stresses occurred due to tunnelling. Hence, the 120-meter model width is chosen to reflect the performance of the road tunnels system.

The soil depth beneath the invert of the twin tunnels is 2.5 times diameter of the twin tunnels (Mazek et al., 2004; Mazek et al., 2006). The 120-meter model width and the fifty-meter model height are used in the FEA to compare the results obtained by both the 3-D FEA and the field measurement.

In addition, the model mesh size is studied to reflect the performance of the road tunnels system based on the FEA. The element size is varied from 2 m, 3 m, 4 m, up to 5 m along the outer boundary of the soil model block. The element size is also varied from 1 m, 1.5 m, 2 m, 2.5 m, up to 3 m along the twin road tunnel liners. The calculated surface settlement based on different element sizes is presented in Table 3. The results reveal that as the element size along the outer boundary of the soil model block is smaller than three meters there is no change in calculated surface settlement due to tunnelling. The results also show that as the element size along the twin tunnel liners is smaller than one meter there is no change in calculated surface settlement due to tunnelling.

5. GROUND LOSS IMPACT

The ground loss is considered in this study. The ground loss is the ratio of the difference between the excavated soil volume and the tunnel volume over the excavate soil volume. The ground loss ranged from 1.5 % to 4.5 % and reached 6 % at some locations (El-Nahhass, 1999). The ground loss of 3 % is adopted in this study using the 3-D finite element analysis, as shown in Fig. 6.

6. SOIL PERFORMANCE

The stress changes in soil around the twin road tunnel system due to tunnelling are investigated to study the detailed soil behavior. The stresses in the soil have undergone two stages of change. The first stage corresponds to the construction of the first tunnel (northern tunnel) and the second stage to the construction of the second tunnel (southern tunnel).

The loading steps are simulated using the 3-D nonlinear finite element analysis. First, the initial principal stresses are computed with the absence of the first tunnel. Second, the excavation of the first tunnel is modelled by means of the finite element method. The excavation is simulated by the removal of those elements inside the boundary of the first tunnel surface to be exposed by the excavation. Third, the movements and stress changes induced in the soil media are calculated. Fourth, the calculated changes in stresses are then added to the initial principal stresses computed from the first step to determine the combined stresses resulting from the first tunnel construction. Fifth, the final stresses due to the construction of the second tunnel are computed using the combined stresses obtained in the fourth step as the initial stresses.

The friction angles (ϕ) adopted for the layers are obtained using laboratory test results from reconstituted samples. The friction angles for sand are 37^{o}. The coefficient of lateral earth pressure at rest $\mathbf{k_o}$ of theses layers is given by $\mathbf{k_o}$ = 1- sin (ϕ).

The excavation of the twin tunnels causes the soil around the tunnel system to respond in an unloading manner. The unload moduli are appropriate during this stage. Under unload-reload condition, unload and reload moduli (E_{ur}) are similar and are 1.2-3 times the vertical drained modulus (E_v) (Duncan et al., 1980). Byrne et al. (1987) based on tests on granular soils found that E_{ur} / E_v was in the range of 2-4 times. A shear modulus (G_{vh}) is used in the finite element analysis. The ratio of the shear modulus to the vertical modulus G_{vh} / E_v is about 0.35 in initial loading condition for sand layer. In unloading condition, the G_{vh} / E_v ratio is about 0.25 for sand layer. Effective stress is used in the finite element analysis, as the twin tunnels are located in sand

The initial in-situ stresses of the excavated tunnel boundary before tunneling are calculated and plotted in Fig. 7a. The vertical stress change after tunnelling is calculated and presented in Fig 7b. The final vertical stress change after tunnelling is calculated and compared with the initial in-situ vertical stress before tunnelling, as shown in Fig 7. The results show that the soil above the crown of the road tunnels settles downward and the soil under the invert of the road tunnels excavation heaves based on the soil stress change around the tunnel system. The soil stress change above the crown of the tunnel liners moves downward at which the soil stress change pushes soil downward. The soil stress change beneath the invert of the tunnel liners moves upward at which the soil stress change pushes soil upward.

7. EL-AZHAR ROAD TUNNELS PERFORMANCE

In this study, El-Azhar road tunnels are studied through a comparison between the results calculated by the 3-D nonlinear FEA and the results recorded by field measurements.

The computed surface settlements are compared with those obtained by the field measurements so as to understand the behavior of the twin road tunnels, as shown in Fig. 8.

This comparison is used to assess the accuracy of the proposed numerical model. The comparison shows that there is a good agreement between the computed and measured readings.

Generally, the calculated surface settlement due to the tunnel construction underestimates by up to 10% with respect to the field measurement for this case study. This discrepancy between calculated and measured readings may be caused by the accuracy of soil strength parameters, soil stress parameters, soil modelling, or instrumentation.

The final vertical displacement along the centreline of the twin tunnels at different levels is also presented in Fig. 9. The results show that the soil above the crown of the road tunnels excavation moves down and the soil under the invert of the road tunnels excavation heaves due to soil stress change as discussed in section 6.

8. CONCLUSIONS

A 3-D nonlinear finite element analysis is used to study the performance of the twin tunnel system based on El-Azhar road tunnels project. The analysis considered the changes in soil stress, the non-linear behavior of the soil, and the construction progress. The following conclusions can be drawn.

- The 3-D nonlinear numerical model is applicable to analyze and predict the detailed performance of the twin tunnel system for the case study.

- The results calculated by the proposed 3-D nonlinear finite element analysis have a good agreement with the field data. The predicted surface settlements underestimate by up to 10% for the case history with respect to the field measurement.
- Ground loss is an important parameter effect on the performance of the twin tunnel system. An increase of ground loss from 1% to 6% increases the estimated surface settlements due to tunnelling by up to 50%. A smaller ground loss due to tunnelling a smaller calculated surface settlement.
- The minimum width of the 3-D nonlinear model is set to be ten times the tunnel diameter in the 3-D numerical model.

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Table 1: Geotechnical properties

Soil parameters	Type of soil			
	Fill	Clay	Silty sand	Sand
Modulus number (m)	300	325	350	500
Exponent number (n)	0.74	0.60	0.60	0.53
Effective cohesion (c) (t/m^2)	1	0	0	0
Effective angle of internal friction (ϕ)	25	26	32	37
Poisson's ratio (ν)	0.40	0.35	0.30	0.30
Soil bulk density γ_b (t/m^3)	1.80	1.90	1.85	2.0

In Table 1, γ_b is bulk density, k_o is coefficient of lateral earth pressure, υ_s is Poisson's ratio, ϕ is the angle of internal friction for the soil, and C is cohesion.

Table 2: Characteristics of the twin road tunnels

Tunnel	E_b (t/m^2)	ν	f_c (t/m^2)	(t) cm	Diameter of tunnel liner (D) m	Excavation diameter (D_0) m
Road	2.1×10^6	0.18	4000	25	9.06	9.56

Table (3): Estimated settlement of ground surface considering different elements sizes (El-Azhar road tunnels)

Mesh Size (m)	Element size along outer boundary of soil block mesh	5 m					4 m				3m**		
	Element size along tunnel Liner model	1 m	1.5 m	2m	2.5 m	3 m	1 m	1.5 m	2 m	2.5 m	1 m**	1.5 m	2 m
Surface Settlement (mm)		8.7	8.4	8.1	7.5	7.1	9.3	8.9	8.5	8.0	9.7**	9.3	8.9

** Selected elements size of 3-D finite element model

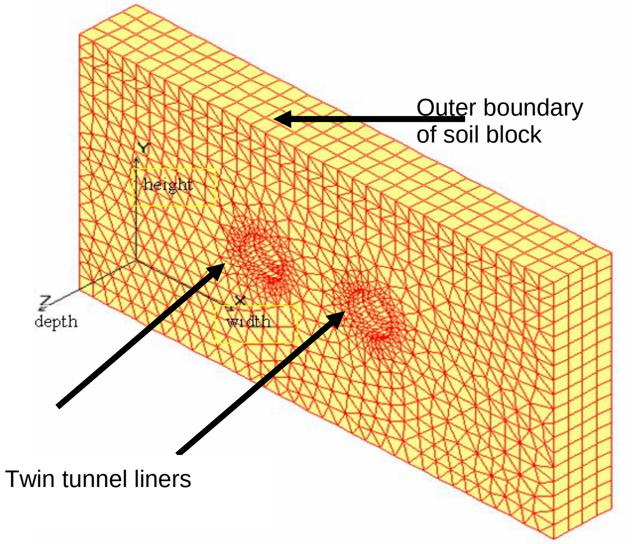


Fig. 1: 3-D finite element model of El-Azhar road tunnels

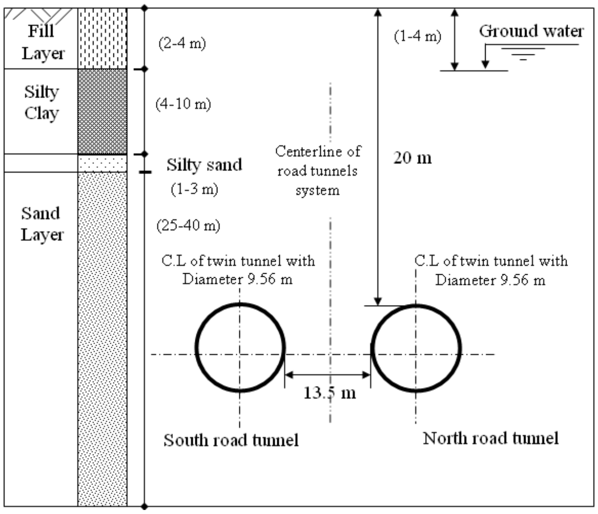


Fig. 2: Soil profile along El-Azhar road tunnels

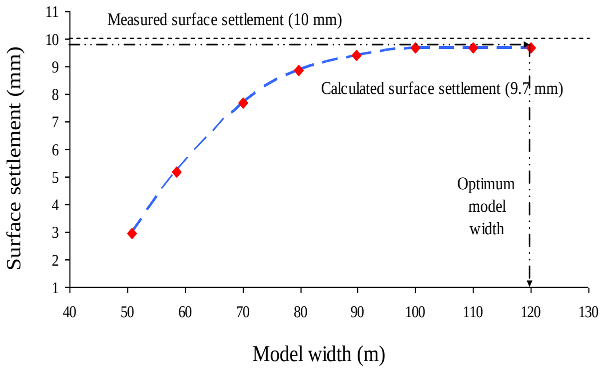


Fig. 3: Calculated surface settlement due to the road tunnels construction with different model widths

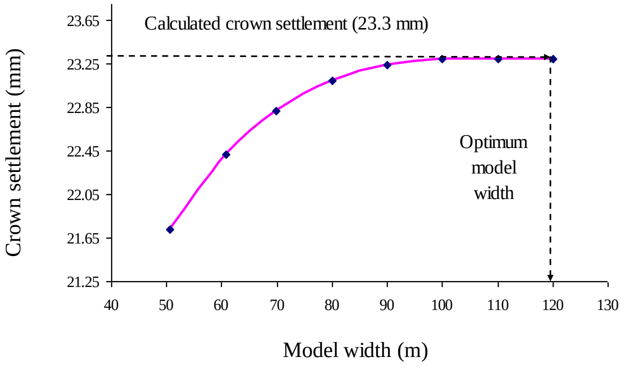


Fig. 4: Calculated crown settlement of the road tunnels with different model widths

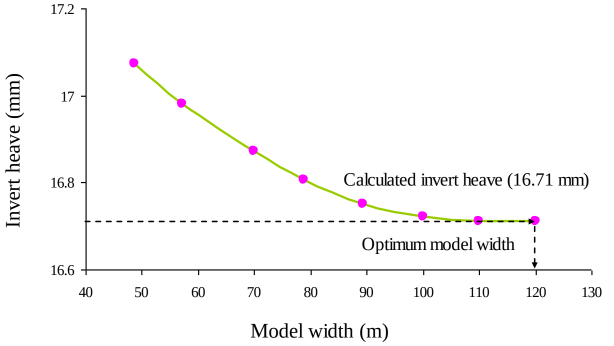


Fig. 5: Calculated invert heave of the road tunnels with different model widths

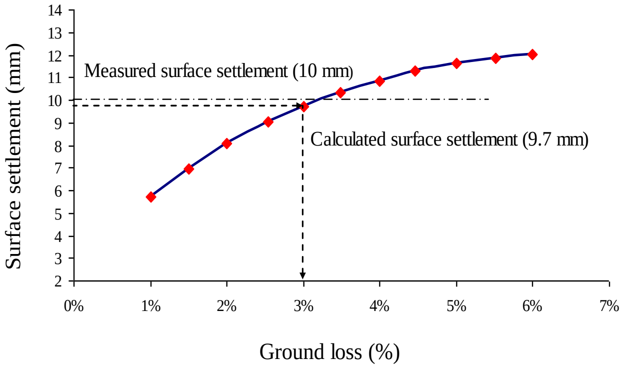
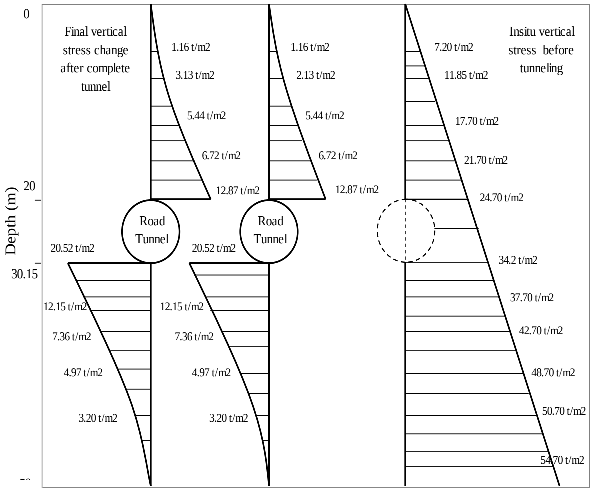


Fig. 6: Calculated surface settlement due to different ground losses during the construction of the road tunnels



(7b) Final vertical stress change after complete tunnelling

(7a) Insitu vertical stress before tunnelling

Fig. 7: Vertical stress before and after tunnelling (El-Azhar road tunnels)

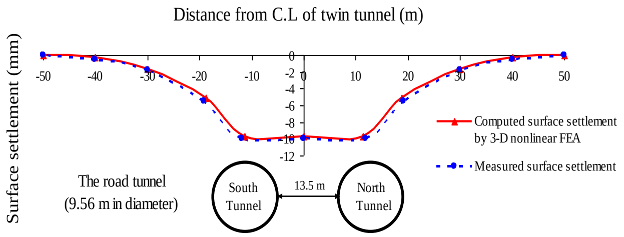


Fig. 8: Comparison between measured and calculated surface settlements due to construction of El-Azhar road tunnels

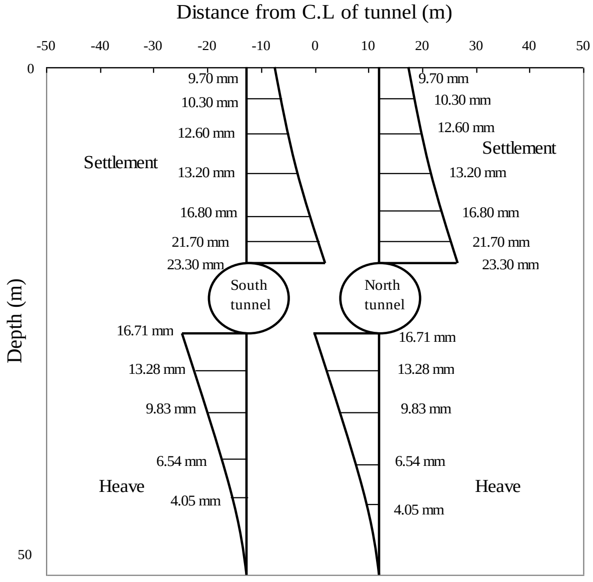


Fig. 9: Calculated vertical displacement at different levels along centreline of El-Azhar road tunnels