

Assessment of Empirical Method Used to Study Tunnel System Performance

Évaluation de la méthode empirique utilisée pour étudier la performance du système de tunnel

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ABSTRACT: Tunnels are major projects of buried structures in civil purposes. The Greater Cairo metro and El-Azhar road tunnels have been constructed as major projects of buried structures in Cairo City. Tunneling causes movements in surrounding soil. Tunnel construction in cohesionless soil is a sophisticated process leading to cause potential damage to exist surface and subsurface structures. The finite element analysis (FEA) is used to predict surface displacement due to tunnelling. Surface displacement equation (SDE) proposed by Peck and Schmidt (1969) is also used to calculate surface displacement due to tunnelling.

For assessing the reliability of the FEA, a case history along the Greater Cairo Metro tunnel is considered. A comparison between the field measurements and those obtained by the FEA and the SDE is made. The surface settlements obtained by the SDE are examined with those obtained by the FEA at different sand soil densities. However, the SDE does not consider impact of different sand soil types. The surface settlement profile computed by the SDE is in poor agreement with those obtained by the FEA in loose to medium sandy soil. The surface settlement profiles computed by the SDE agree well with those calculated by the FEA in dense and very dense sandy soil.

RÉSUMÉ : Tunnels et ouvrages souterrains sont grands projets de structures enterrées dans des fins civiles et militaires. Le Grand métro du Caire et El-Azhar tunnels routiers ont été construits comme des grands projets de structures enterrées au Caire City. Construction souterraine profonde provoque des mouvements dans le sol environnant. Mouvement du sol est un facteur important lors de la construction de tunnels. La construction de tunnels dans le sol sans cohésion est un processus complexe conduisant à potentiel de causer des dommages à l'existence des structures superficielles et souterraines. Les mouvements de terrain dépendent des propriétés du sol, la profondeur du tunnel, le diamètre du tunnel, et la méthode de construction.

Dans la présente étude, l'analyse par éléments finis (FEA) est utilisé pour prédire le déplacement de surface en raison de processus de tunneling basé sur l'étude de cas. Équation de déplacement en surface (SDE) proposé par Peck et Schmidt (1969) est également utilisé pour calculer le déplacement de surface en raison de processus de la structure de la construction enterrée. Pour évaluer la fiabilité de l'analyse par éléments finis, une histoire de cas le long de la ligne Grand Caire tunnel de métro 2 est envisagée.

KEYWORDS: Tunneling, settlement, numerical modeling and analysis, displacement, empirical method.

1 INTRODUCTION

Tunnel construction causes movements in surrounding soil. Ground movement is an important factor during design phase and selection of appropriate method of tunnel construction. The state of stress and the soil displacement around a tunnel system are affected by construction process of tunnel (Ahmed, 1994; El-Nahhass, 1986; Mazek and El-Tehawy, 2008). The influence zone due to tunneling depends on many parameters such as type of subsoil properties, tunnel depth, tunnel geometry, and tunneling method. The tunnel excavation can be modeled by finite element method under different soil conditions, different tunnel geometries, and different construction procedures (Ahmed, 1994; El-Nahhass, 1986; El-Nahhass, 1999; Mazek and El-Tehawy, 2008; Ezzeldine, 1999).

In this paper, a 2-D finite element model (FEM) is proposed to predict surface displacement due to tunneling. The modeling of such a problem should include details of tunnel construction phases and associated changes of stresses around the tunnels. A nonlinear stress-strain constitutive model is adopted for soil media surrounding the tunnel. A case study on the Greater Cairo Metro tunnel Line 2 (Fig. 1) is conducted to assess the accuracy of the finite element analysis (FEA). The computed surface settlements are compared with the field measurements. A good agreement is found. The main objective of this paper is to examine surface displacement obtained by both the FEA and the surface displacement equation (SDE) developed by Peck and Schmidt (1969). The 2-D finite element analysis considers parameters of different sand soil densities. However, the SDE does not consider influence of different sand soil types on surface settlement due to tunneling.

The subsurface soil profile along the Greater Cairo Metro is shown in Fig. 1 (Compo and Richards, 1998; El-Nahhass et al., 1994; El-Nahhass, 1999; NAT, 1993, 1999, 2010). The Geotechnical

properties of soil in central Cairo city are presented in Table 1 (Abdel-Salam, 1998; EL-Nahhass, 1999; NAT, 1993, 1999, 2010).

2 FINITE ELEMENT MODEL

The finite element code Plaxis-V8.2 is used to model tunnel system performance. Analyses of displacement and stress around tunnel system are carried out using a 2-D plane strain finite element taking into account behavior of tunnel lining and soil media. The soil, the tunnel lining, and the interface medium are simulated using appropriate finite elements model as shown in Fig. 2. Numerical modeling of tunnel system reflects the ground continuum and the tunnel lining. In addition, the compatibility and equilibrium condition at the interface between the soil and the tunnel system are idealized in the numerical model. Six nodes triangular 2-D plane strain element is used to model soil media. 2-D beam element is used to model the tunnel lining.

A nonlinear stress-strain constitutive model is adopted for soil around tunnel system. A yield function of the Mohr-Coulomb and a plastic potential function of the Drucker-Prager are employed. Linear elastic behavior is assumed for the tunnel liner.

Boundary conditions are defined to provide stability of tunnel system. The vertical boundaries of the 2-D finite elements 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 two directions. The movement at upper horizontal plane is free to simulate a free ground surface.

3 PROPERTIES OF MODEL MATERIALS

The geological formations along Greater Cairo Metro line 2 projects are typical Cairo Nile Alluvial deposits (NAT, 1993, 1999; 2010). The tunnel was mostly bored in slightly sand. The ground water table varies between 2 m and 4 m from ground surface.

Three distinct soil layers were encountered. A fill layer extends three meters from ground surface. The fill layer consisted of asphalt, broken red bricks, and stones. A natural deposit of stiff overconsolidated silty clay layer under the fill layer is varied from 4 m to 10 m. This deposit includes occasional sand and silt partings. Beneath the silty clay layers, the silty sandy layer extends from 0.25 m to 1.0 m. Beneath the silty sand layers, the sandy layer extends down to the bedrock.

Soil parameters were derived from in-situ and laboratory tests. The main Geotechnical parameters used in the 2-D FEA are presented in Table 1. The circular tunnel lining consists of seven segments and one key. The length of the ring is 1.5 m long. The thickness of tunnel lining is 400 mm. The characteristics of the tunnel lining are tabulated in Table 2 (NAT, 1993, 1999, 2010).

4 TUNNEL PERFORMANCE UNDER VARIOUS PARAMETERS

The stress and the strength parameters of loose, medium, dense, and very dense sand are considered in the FEA (Duncan et al., 1980). The soil parameters required to model performance of tunnel system are presented in Table 3 (Duncan et al., 1980).

Diameter of tunnel is varied from 5 m, 7.5 m, 10 m, and 12.5 m. The tunnel is located at different types of cohesionless soils (loose sand, medium sand, dense sand, and very dense sand). The numerical analysis is carried out using the drain analysis as the tunnel passes through sand layer. The variation of soil modulus (E_s) with confining pressure is related to effective pressure based on Janbu's empirical equation (Janbu, 1963) as presented in Eq. (1). The different soil parameters (m , n) are selected to simulate the behavior of different soil types (Duncan et al., 1980).

$$E_s = mP_a \left(\frac{\sigma_3}{P_a} \right)^n \quad (1)$$

Where; the modulus number (m) and the exponent number (n) are both pure numbers, P_a is the atmospheric pressure expressed in appropriate units, and σ_3 is effective confining pressure.

The surface displacements (surface settlement) are estimated using empirical equation developed by Peck and Schmidt (1969) as presented in Eq. (2). The surface displacement trough is calculated by the normal Gaussian probability curve as shown in Fig. 3.

$$S = S_{\max} \exp \left(\frac{-x^2}{2i^2} \right) \quad (2)$$

where; S is surface displacement, S_{\max} is maximum surface settlement at the point above tunnel centerline, x is distance from tunnel centerline in transverse direction, and i is horizontal distance from tunnel centerline to point of inflection of settlement trough.

Based on the case study involving medium sand, S_{\max} is recorded in the field. For loose sand, dense sand, and very dense sand, S_{\max} is estimated using the 2-D finite element analysis. Atwell et al. (1986) proposed (i) parameter included in the SDE as presented in Eq. 3.

$$\frac{i}{R} = \alpha \left(\frac{Z}{2R} \right)^n \quad \alpha = 1, n=1 \quad (3)$$

Where; Z is overburden depth from ground surface to C.L of tunnel, R is radius of tunnel, and α and n are constant parameters.

5 SOIL-TUNNEL PERFORMANCE

The case study is located along the Greater Cairo Metro Line 2, as shown in Fig. 1. The 2-D finite element model is used to predict the performance of the metro tunnel. The overburden depth from ground surface to crown of the metro tunnel is 18 m. The computed values are compared with the field measurements so as to understand the behavior of the metro tunnel system. This comparison is used to assess the accuracy of the numerical model, as shown in Fig. 4. The comparison shows that there is a good agreement between the computed and measured results.

The stress changes in soil around the metro tunnel system due to tunneling are also investigated to study detailed tunnel system behavior. For the metro tunnel, the soil stress analysis has been

undergone four steps of change. These steps correspond to the construction of the metro tunnel. The loading steps are simulated using the 2-D FEA. First, the initial principal stresses are computed with the absence of the metro tunnel. Second, the excavation of the tunnel is modeled by means of the finite element method. The metro tunnel excavation is simulated by the removal of those elements inside the boundary of the 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 stresses computed from the first step to determine the combined stresses resulting from the metro tunnel construction. The calculated vertical effective stress around the metro tunnel is also illustrated in Fig. 5.

Based on the good agreement between the computed and measured values, one can proceed to use the 2-D numerical model to explore other aspects of the tunnel system performance under the tunnel construction. In fact, the proposed model can help to predict the surface displacement at the different sandy soils.

6 SURFACE DISPLACEMENT DUE TO TUNNELING

The surface displacement profile above a tunnel with diameter 9.48 meters are calculated and plotted in Fig. 6 to Fig. 9 using the SDE. The FEA is also conducted to determine the surface displacements due to tunneling in different sandy soils (loose sand, medium sand, dense sand, and very dense sand) based on different ground losses (V_L). The average values of the different sandy soil parameters adopted in the finite element analysis are summarized in Table 3 (Duncan et al., 1980). The volume loss is considered in this study. The volume loss is the ratio of the difference between the excavated soil volume and the tunnel volume over the excavate soil volume. The volume loss of 3 % is adopted in this study (El-Nahhass, 1999). Based on the FEA, the surface displacements along the centerline of the metro tunnel for different sandy soil types are presented in Fig. 6 to Fig. 9. However, the results obtained by the SDE are examined with those obtained by the FEA.

In the case of loose sand, the surface displacement profiles obtained by both the FEA and the SDE are shown in Fig. 6. The comparison shows that the surface displacements obtained by the finite element analysis are higher than those calculated by the surface displacement equation. However beyond 20 m from the centerline of the tunnel, the surface displacement calculated by the FEA does not agree with this calculated by the SDE. The result reveals that the surface settlement profile obtained by the SDE does not agree well with those obtained the FEA.

In the case of medium sand, the surface displacement profiles obtained by both the FEA and the SDE are shown in Fig. 7. The comparison shows that the surface displacements obtained by the FEA are higher than those calculated by the SDE. However beyond 20 m from the centerline of the tunnel, the surface displacement calculated by the FEA has different shape than this calculated by the SDE. The result reveals that the surface settlement profile obtained by the SDE does not agree well with those obtained the FEA.

Fig. 8 shows the comparison between the results obtained by the FEA with those obtained by the SDE for dense sand. The comparison indicates that the surface displacement profile computed by the FEA has the same trend as the surface displacement profile calculated by the SDE. It is also observed that the surface displacements calculated by the FEA are larger than those calculated by the SDE in the region beyond 20 m from the centerline of the tunnel. In the region between the centerline of the tunnel and 20 m from centerline of the tunnel, the surface displacements calculated by the FEA is the same as those calculated by the SDE. Generally, the results obtained by the FEA agree well with those obtained by the SDE.

Fig. 9 also shows the comparison between the results obtained by the FEA with those obtained by the SDE for dense sand. The comparison again shows that the surface displacement profile computed by the FEA has the same trend as the surface displacement profile calculated by the SDE. It is also observed that the surface displacements calculated by the FEA are larger than those calculated by surface displacement equation in the region

beyond 20 m from the centerline of the tunnel. In the region between the centerline of the tunnel and 20 m from centerline of the tunnel, the surface displacements calculated by the FEA is the same as those calculated by the SDE. The results obtained by the FEA agree well with those obtained by the SDE.

Therefore, the finite element analysis gives a better estimation of surface settlement as demonstrated with the comparison between the calculated and the measured settlements in medium dense soils involved in the case study. For the loose and medium sandy soils, ignoring the appropriate soil characteristics in the surface displacement equation (Eq. 2) probably leads to larger error and further deviation from the actual values. The surface displacement readings obtained by the FEA is more conservative than those calculated by the SDE.

The difference between the two sets of computed settlements is noticed in loose sand and in medium sand. The difference between the two sets of computed settlements lies in the use of the width parameter (i) as presented in Eq. (3). This (i) parameter is used for cohesionless soils but it does not take into account the different geotechnical parameters associated with different densities of cohesionless soil. The proposed finite elements model takes into account the effects of the stress and strength parameters of the different sand soil densities. Therefore, the differences between surface displacement profiles obtained by the FEA with those obtained by the SDE may be due to the value of the shear strength and stress parameters for the soil media around tunnel system adopted in the 2-D nonlinear FEA.

7 CONCLUSIONS

Based on the proposed 2-D finite element model, the following conclusions are presented due to tunneling through different sand soil types.

- The 2-D nonlinear numerical model is applicable to analyze and predict detailed performance of tunnel systems.
- The results calculated by the proposed 2-D nonlinear finite element model have a good agreement with the field data.
- The predicated surface settlements due to tunneling underestimate by up to 10 % from the field measurements. The discrepancy between the calculated and the field readings may be due to the stress-strain soil parameters and the strength soil parameters.
- Surface settlement profile computed by the surface displacement equation (SDE) by Peck and Schmidt (1969) is in reasonable agreement with surface settlement profile computed by the 2-D finite element analysis in dense to very dense sand soil.
- Surface settlement profile calculated by the SDE does not agree well with surface settlement profile calculated the 2-D FEA in loose and medium sand soil.
- The surface displacement equation proposed by Peck and Schmidt (1969) does not consider the impact of different sandy densities soil types. However, the finite element analysis takes into account strength and stress parameters of different sand densities.
- The surface settlement profiles calculated by the finite element analysis are more conservative than those computed by the surface displacement equation at different sand densities.

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Table 1: Geotechnical properties in Central Cairo City

Layer	Fill	Silty-clay	Silty sand	Sand
Bulk density $\gamma_b(t/m^3)$	1.8	1.9	1.85	2.0
Drained Poisson's Ratio V_s	0.4	0.35	0.35	0.30
Effective Angle of initial Friction (ϕ)°	20	26	30	37
Effective Cohesion C (KPa)	0	10	0	-
Standard penetration (blows/0.3m)	4-20	13-15	-	35
Modulus Number(m)	300	325	400	400-700
Exponent Number(n)	0.74	0.6	0.6	0.5-0.6
Drained Modulus of Elasticity $E_s(t/m^2)$	1000	1200	3000	7000
Over Consolidation Ratio (OCR)	1	1.5	-	-
Coefficient of Lateral Earth Pressure K_0	1	0.8	0.5	0.39

Table 2: Characteristics of the tunnel lining

Type	E_b (t/m^2)	(t) cm	F_c (t/m^2)	W (KN/m ²)	V
Tunnel liner	2.1×10^6	40	4000	10.0	0.20

Table 3: Geotechnical soil parameters (Different sand soil densities)

Soil Parameters	Fill	Silty-clay	Loose sand	Medium Sand	Dense sand	Very Dense Sand
Drained Poisson's Ratio V_s	0.4	0.35	0.35	0.30	0.30	0.25
Effective Angle of initial Friction(ϕ) ² (drained)	25	26	27	32	38	43
Modulus Number(m)	300	350	300	500	800	1000
Exponent Number(n)	0.74	0.6	0.6	0.51	0.5	0.4
Soil density (γ_b) t/m ³	1.8	1.9	1.8	1.85	1.9	2.0
Coefficient of Lateral Earth Pressure K_0	0.58	0.57	0.56	0.47	0.38	0.32

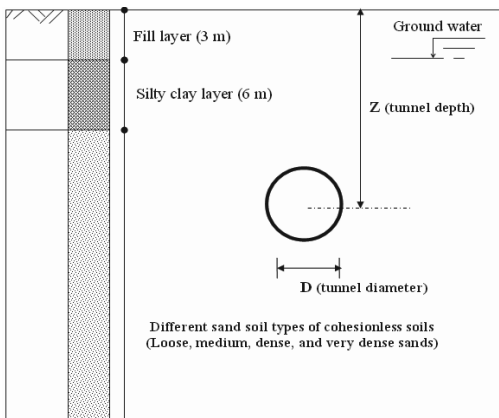


Fig. 1: Cross section along the Greater Cairo Metro tunnel Line 2

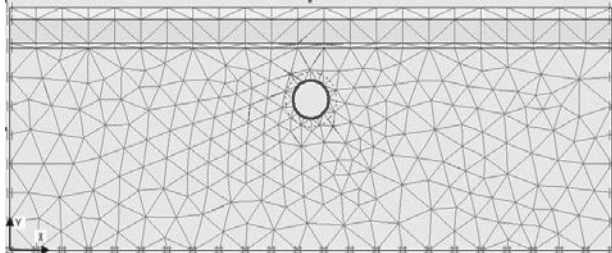


Fig. 2: 2-D finite element model of the Greater Cairo Metro

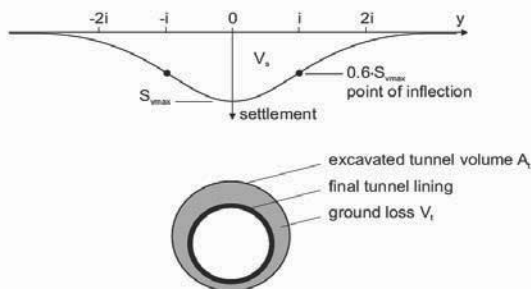


Fig. 3: Gaussian curve for transverse settlement trough and ground loss (After Peck and Schmidt, 1969)

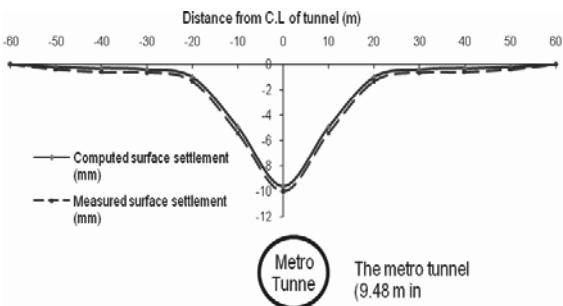


Fig.4: Comparison between measured and calculated surface settlements due to metro tunnel construction (case history)

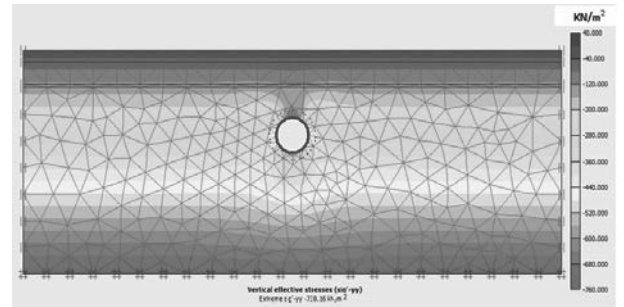


Fig. 5: Calculated vertical effective stress around the Greater Cairo metro tunnel after tunnel construction

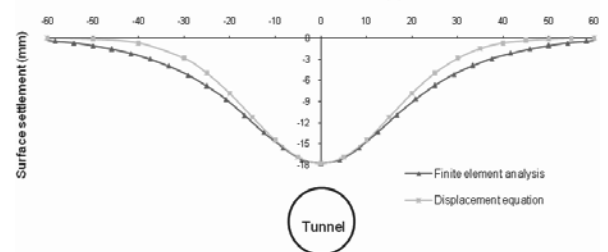


Fig. 6: Surface settlement profile obtained by both finite element analysis and surface displacement equation in loose sand (ground loss of 3%, D=12.5 m, Z/D=2.5)

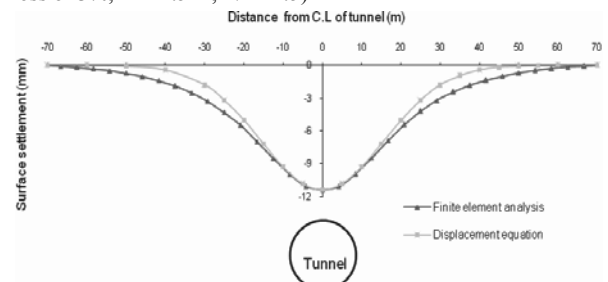


Fig. 7: Surface settlement profile obtained by finite element analysis and surface displacement equation in medium sand (ground loss of 3%, D=12.5 m, Z/D=2.5)

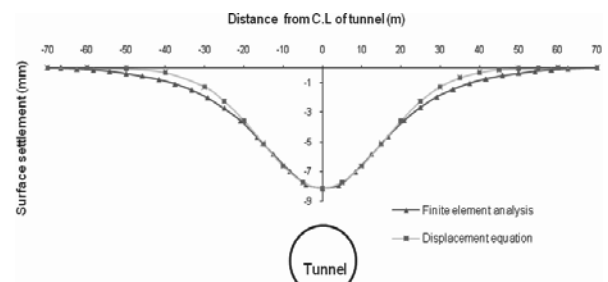


Fig. 8: Surface settlement profile obtained by both finite element analysis and surface displacement equation in dense sand (ground loss of 3%, D=12.5 m, Z/D=2.5)

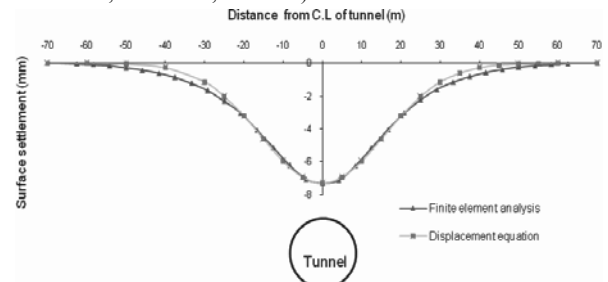


Fig. 9: Surface settlement profile obtained by both finite element analysis and surface displacement equation in very dense sand (ground loss of 3%, D=12.5 m, Z/D=2.5)