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Finite Element Analysis of Ground Response due to Tunneling in Cohesionless Soil

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ABSTRACT

Tunneling in cohesionless soil leads to ground movement. In urban environment, the soil movement due to tunneling may affect surface or subsurface constructions. The ground movement is considered a major geotechnical challenge. The ground movements due to tunneling are predicted.

In the present study, the prediction of the ground movement under the impact of the tunnel construction is highlighted and a model is proposed to study the soil structure interaction using a 2-D finite element analysis. The ground movement due to tunneling is also calculated using surface displacement equation proposed by Peck and Schmidt (1969). The surface displacement computed by the proposed model and the surface displacement equation is studied at different sandy soil types due to tunneling so as to examine the computed results. The study presents a case history along the Greater Cairo Metro tunnel Line 2 to assess the accuracy of the proposed finite element model. Based on this case history, extensive study using the finite element model and the surface displacement equation is conducted to predict the ground movement due to tunneling. 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.

For the case study, this paper presents a comparison between the field measurements and those obtained by the finite element analysis and the surface displacement equation. There is a good agreement between computed and measured values. The tunnel system performance is expressed in terms of surface settlement due to the tunnel construction. The study presents the prediction of the surface settlement profile using the proposed model and the surface displacement equation at different sand soil types. The study also examines the results obtained by the surface displacement equation with those obtained by the finite element analysis. The results show that the surface settlement profiles using the surface displacement equation have a good agreement with those

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obtained by finite element analysis in loose to medium sandy soil. In addition, the surface settlement profiles computed by the surface displacement equation do not agree well with those obtained by the 2-D finite element model in dense to very dense sand soil. However, the surface displacement equation does not include the impact of different geotechnical parameters used to classify the different sandy soil types.

Keywords: Tunnels, settlement, numerical modeling and analysis, nonlinear displacement, surface displacement equation, deformations.

1. INTRODUCTION

Geotechnical problems were expected during the construction of the tunnel running in cohesionless soil. The constructed tunnel passes through the sand soil, as shown in Fig. 1. The tunnels lining are built of pre-cast reinforced concrete. The tunnel system performance under the impact of the tunnel construction is studied to calculate the ground surface displacement using the finite element analysis and the surface displacement equation (Peck and Schmidt, 1969).

This study is performed to understand the performance of the tunnel system due to tunneling so as to predict the ground movement. The tunnel system performance is expressed in terms of surface settlement under the tunnel construction. The study presents the prediction of the surface displacement profile using the finite element analysis and the surface displacement equation at different sandy soil types. The results obtained by the surface displacement equation are also compared with those obtained by the finite element analysis. Modeling of such problem should include the details of tunnel construction phases and the associated changes of stresses around the tunnels. To assess and predict the behavior of the tunnels due to tunneling, 2-D finite element model is used. The study presents a case study along the Greater Cairo Metro tunnel Line 2 to assess the accuracy of the finite element model, as shown in Fig. 1. A nonlinear stress-strain constitutive model is adopted for the soil surrounding the Greater Cairo metro tunnel Line 2 at central Cairo City. A yield function of the Mohr-Coulomb type and a plastic potential function of the Drucker-Prager type are employed. In addition, linear elastic behavior is assumed for the tunnel linings.

The 2-D effects on the performance of the tunnel system are examined. The effects are expressed in terms of the ground surface displacement and the vertical displacement at different locations.

2. FINITE ELEMENT MODEL

The finite element computer program (COSMOS/M) is used in this study. The finite element model takes into account the effects of the vertical overburden pressure, the lateral earth pressure, the nonlinear properties of the soils, and the linear properties of the tunnel lining. Figure 1 shows the configuration of the tunnels running in cohesionless soil. The soil, the tunnel lining, and the interface medium are simulated using appropriate finite elements. Numerical modeling of the tunnels reflects the ground continuum and the constructed tunnel. In addition, the compatibility and equilibrium condition at the interface between soil and the tunnel system are idealized in the numerical model. 2-D plane strain elements are used for modeling the soil media and 2-D beam elements for modeling the tunnel lining. Three-node triangle plane strain elements are adopted to simulate behavior of the soil media, as shown in Fig. 2. The high order plain strain elements are also adopted around tunnel excavation to study high stress change in soil due to tunneling.

The vertical boundaries of the 2-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 represented a rigid bedrock layer and the movement at this plane is restrained in all directions. The movement at the upper horizontal plane is free to simulate a free ground surface.

The lining is composed of 40 cm thickness segments. The stiffness at the joint may be appreciable less than elsewhere. The segments joints are never aligned along the tunnel and the thickness reduction is not as local 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 segments.

The construction of the tunnel caused the soil around the tunnel system to respond to unload manner. The nonlinear properties of soils, the different sandy soil types, and the confining pressure are included to study their effects on the ground surface displacement. In addition, the case study has been made with the metro tunnel, as it exists in the field at central Cairo city. Different nonlinear properties of soil have been chosen to realistically simulate the behavior of the different soils along the metro tunnel (Ezzeldin, 1999; Mazek, 2003; Mazek et al., 2006; National Authority for Tunnels, 1993). Moreover, the soil-tunnel excavation and the construction of the tunnel have been idealized using the yielding function of the Mohr-Coulomb type and the plastic potential function of the Drucker-Prager type.

3. PROPERTIES OF TUNNEL LINING AND SOIL

Displacements would be induced in the urban environment due to tunneling. The ground surface displacement due to the construction of the tunnel has been calculated in this study.

The final diameter (D) for the metro tunnel is 9.48 m and the excavation diameter of the metro tunnel is 10.28 m. The circular tunnel lining consists of seven segments and one key. The length of the ring is 1.5 m. The characteristics of the tunnels are tabulated in Table 1.

The 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 (Campo and Richards, 1998; El-Nahhass et al., 1994; Mazek et al., 2001; National Authority for Tunnels, 1993, 1999). Site investigations along the project alignment have indicated 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 a thick alluvial sand that extends down to bedrock, which is well below the metro tunnel. The watertable varies between two meters to four meters from the ground surface. The upper few metres of this alluvial sand are parts of a transition layer of highly interbedded clay silt and fine sand. Below the transition layer, the alluvial sand layer is more uniform with coarse to fine sand, which occasionally contains layers of silt to clayey silt that varies in thickness from a few centimetres to several decimetres. Lenses of gravel and cobbles, up to several metres thick, may also be present at depths of 25 to 80 metres. Soil parameters are presented in Table 2.

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 tunnels has been 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 empirical equation (Janbu, 1963), which is given by Eq. 1

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

In which, the modulus number (m) and the exponent number (n) are both pure number and (p_a) is the value of the atmospheric pressure expressed in appropriate units.

Geotechnical parameters have been presented in National Authority for Tunnels (NAT) documents (National Authority for Tunnels, 1993). The soil parameters used for elasto-plastic finite element analysis for different types of the soil are presented in Table 3 (Mazek et al., 2006; National Authority for Tunnels, 1993 and 1999).

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

4. STRESS IN SOIL

The stresses in the soil have undergone four phases of change. These phases correspond to the construction of the metro tunnel. At these phases, the loading steps of the tunnel construction have been simulated using the 2-D finite element analysis. First, the initial principal stresses are computed with the absence of the metro tunnel. Second, the excavation of the metro tunnel is modeled by means of the finite element method. The excavation has been simulated by the removal of those elements inside the boundary of the metro tunnel surface to be exposed by the excavation. The volume loss is considered in this study. The volume loss is the ratio of the difference between volume of excavated soil and tunnel volume over the excavate soil volume. The volume loss ranged from 1.5 % to 4.5 % and reached to 6 % at some location (El-Nahhass, 1999). The volume loss of 1.5 % is adopted in this study. Third, the movement and stress changes induced in soil media are calculated. Fourth, the calculated changes in stresses are then added to the initial principal stresses computed from the first phase to determine the final principal stresses resulting from the metro tunnel construction.

5. 2-D FINITE ELEMENT MODEL VERFICATION (CASE HISTORY)

This case study is located along the Greater Cairo Metro Line 2, as shown in Fig. 1. The 2-D finite element model is proposed to predict the performance of the metro tunnel. The computed surface settlement obtained by the finite element analysis is compared with those obtained by the field measurements so as to understand the behavior of the metro tunnel. This comparison is used to assess the accuracy of the proposed numerical model, as shown in Fig. 3. The comparison shows that there is good agreement between the computed and measured readings.

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

6. SURFACE DISPLACEMENT DUE TO TUNNELING

The ground surface displacement due to tunneling is calculated using the surface displacement equation proposed by Peck and Schmidt (1969). The surface displacement computed by the proposed finite element model and the surface displacement equation is studied at different sandy soil types due to tunneling so as to examine the computed results. The calculated results using the proposed model and the surface displacement equation are also compared with those obtained by the field measurements.

The surface displacement trough can be approximated by the normal probability curve as written in Equation (2). The surface displacement profile above a tunnel with diameter 9.48 meters are calculated and plotted in Fig. 4 to Fig. 7 using the surface displacement equation.

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

In which, S is the surface displacement; S_{max} is the maximum surface settlement at the point above the tunnel centerline; x is the distance from the tunnel centerline in transverse direction.

The width parameter (i) is the horizontal distance from the tunnel centerline inflexion point of the curve. O'Reilly and New (1982) proposed the empirical relationship as presented in Equations (3) and (4)

$i = 0.43\ Z + 1.1$ for cohesive soils (3)

$i = 0.28\ Z + 0.1$ for cohesionless soils (4)

In which, Z is the depth of the tunnel axis below ground level, as well I and Z are in meters.

The finite element analysis is also conducted so as to determine the surface displacement due to tunneling. The average values of different sand soil parameters adopted in the finite element analysis are summarized in Table 3 (Duncan et. al., 1980). The numerical analysis is carried out under the unload reload modulus (E_{urn}) for the soil based on Janbu's equation [Equation 1] applying different nonlinear soil parameters. The analysis is performed through main stages as follows. The loading of the metro tunnel construction using the finite element analysis includes: (1) initial soil condition before the construction of the metro tunnel; (2) removal of the soil inside the boundary of the metro tunnel surface; and (3) construction of the metro tunnel liners. Based on the finite element analysis, the surface displacements along centerline of the metro tunnel using different sandy soil types are presented in Fig. 4 to Fig. 7.

The surface displacement profiles obtained the finite element analysis are used to examine those obtained by the surface displacement equation. Fig. 4 shows a comparison between the results obtained by finite element analysis with those obtained by the surface displacement equation in loose sand soil. The results indicate that the surface displacement profile computed by finite element analysis has the same trends with surface displacement profile calculated by surface displacement equation. It is also observed that the surface displacements calculated by finite element analysis is more conservative than those calculated by surface displacement equation at the range from 5 m to 20 m measured from the centerline of the tunnel. Generally, the results obtained by finite element analysis agree well with those obtained by surface displacement equation.

The comparison among the calculated maximum surface settlements obtained by the finite element model, the surface displacement equation, and the field measurements in medium sand are shown in Fig. 5. The comparison among results shows that the surface displacement profiles calculated by the surface displacement equation and the finite element analysis are in a good agreement with those obtained by the field measurements around the centerline of tunnel. In the case of medium sand, the results observe that the surface displacement profile readings obtained by finite element analysis are higher than those calculated by surface displacement equation at the range from 5 m to 20 m measured from the centerline of the tunnel. Generally, the surface displacement profile calculated by finite element analysis has a good agreement with this calculated by surface displacement equation.

Fig. 6 shows a comparison between the results obtained by finite element model with those obtained by the surface displacement equation in dense sand soil. The surface settlement profile calculated by the finite element analysis is not the same trend as the surface settlement profile obtained by the surface displacement equation. Finally, the surface displacement profile readings obtained by the finite element analysis does not agree well with those obtained by the surface displacement equation in dense sand soil. Generally the surface displacement readings obtained by the finite element analysis is more conservative than those calculated by the surface displacement equation.

Fig. 7 shows a comparison between the surface displacement profiles obtained by the finite element analysis with those obtained by the surface displacement equation in very dense sand soil. The surface settlement profile calculated by the finite element analysis is not the same trend as the surface settlement profile obtained by the surface displacement equation. Finally, the surface displacement readings obtained by the finite element analysis is more conservative than those calculated by the surface displacement equation.

The width parameter equation (i) [Equations (3)] adopted at the surface displacement equation is computed for cohesionless soils. This width parameter equation is applied for different sandy soil types. This equation does not include the impact of different geotechnical parameters used to classify the different sandy soil types. The proposed finite elements model takes into account the effects of the nonlinear properties of the different sandy soil types. This discussion may lead to the discrepancy between the readings obtained by both the 2-D finite element model and the surface displacement equation at the case of dense to very dense sand soil.

7. CONCLUSIONS

A 2-D nonlinear finite element analysis has been used to study the ground surface displacement. The analysis takes into account the changes in stress, the non-linear behavior of the soil, and the construction progress, etc. The following conclusions can be drawn regarding the performance of the tunnel under the effects of different factors.

- The proposed 2-D numerical model is applicable to predict the performance of the tunnel system under the shadow of the case history.
- The 2-D finite element model can be adopted to analyze and predict the performance of the tunnel system under the tunnel construction effect.
- The surface settlement profile using the surface displacement equation has a good agreement with the surface settlement profile using finite element analysis in loose to medium sandy soil.
- The surface settlement profile using the surface displacement equation does not agree well with the surface settlement profile using the 2-D finite element model in dense to very dense sand soil.
- In different soil types, the surface settlement readings calculated by the finite element analysis are more conservation than those computed by the surface displacement equation.

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Table 1: Characteristics of the road tunnel lining

ν	E_b (t/m^2)	(t) cm	**f_c (t/m^2)**
0.2	2.1×10^6	40	4000

In Table 1, ν is Poisson's ratio of tunnel liner, E_b is the elastic modulus of the tunnel lining, t is the thickness of tunnel lining, and f_c is the compressive strength of concrete.

Table 2: Geotechnical properties

Soil parameter	Fill	Silty clay (drain condition)	Sand
γ_b (t/m^3)	1.8	1.9	2.0
k_o	0.58	0.8	0.37
υ_s	0.4	0.35	0.30
ϕ (Degree)	25	26	40
C (t/m^2)	1.0	0	0
Depth (m)	0.0 to 4.0	4.0 to 10.0	10.0 to end

In Table 2, 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 3: Soil parameters

Material	m	n	C_u (kPa)	C (kPa)	ϕ_u	ϕ	υ_u	υ
Fill	300	0.74	50	10	20	25	0.4	0.4
Silty Clay	350	0.60	75	0	0	26	0.45	0.35
Sand	400-600	0.5-0.6	0	0	-	40	-	0.3
Loose sand	350	0.5	0	0	-	31	-	0.3
Medium sand	500	0.5	0	0	-	35	-	0.3
Dense Sand	800	0.5	0	0	-	39	-	0.3
Very dense sand	1100	0.5	0	0	-	43	-	0.3

In Table 3, C_u is the undrained cohesion, C the effective cohesion (drained), ϕ_u is angle of internal friction in terms of total stress (for unsaturated fill $\phi_u = 20^{\circ}$), ϕ is the effective angle of internal friction (drained), υ_u is the undrained Poisson's ratio, and υ is the drained Poisson's ratio.

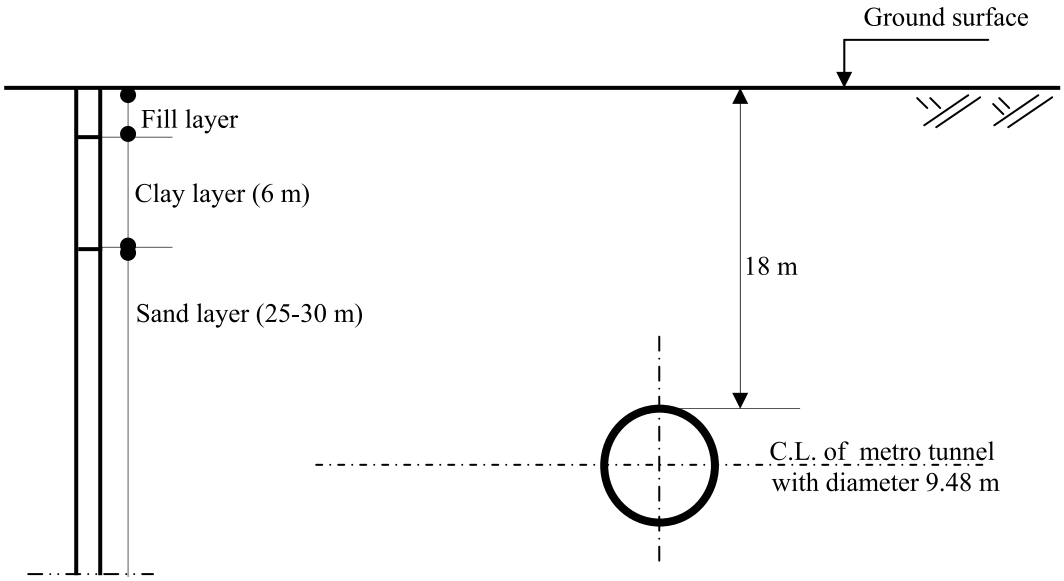

Fig. 1: Cross section along the Greater Cairo Metro tunnel Line 2 (Case study)

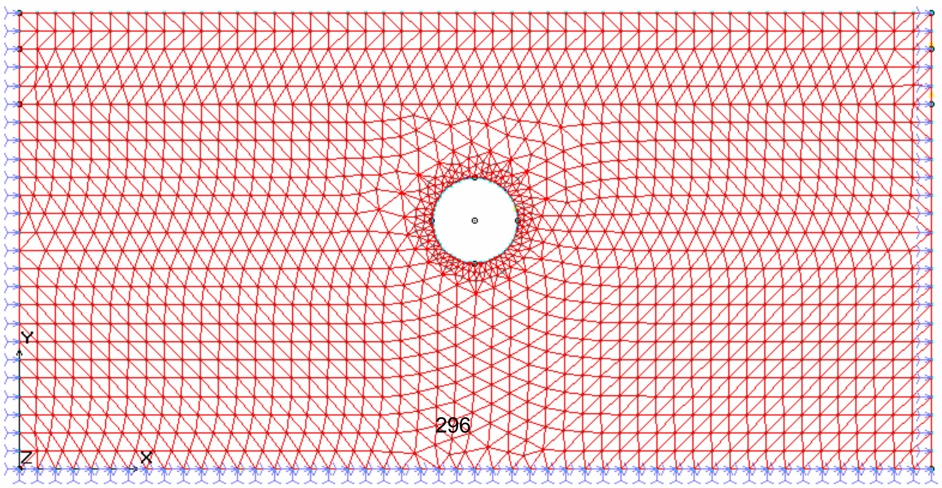

Fig. 2: 2-D finite element model of metro tunnel (case history)

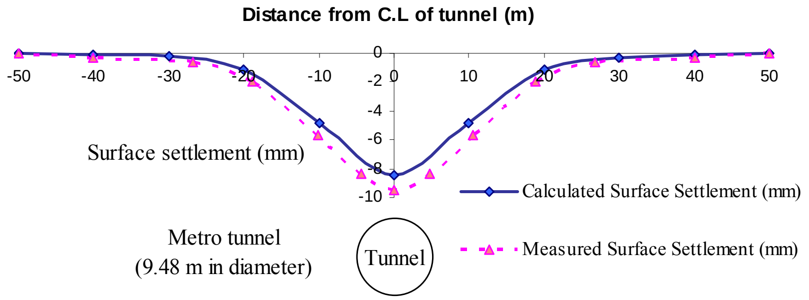

Fig. 3: Vertical displacement of soil at the ground surface after achievement of the Greater Cairo metro tunnel construction (Case history)

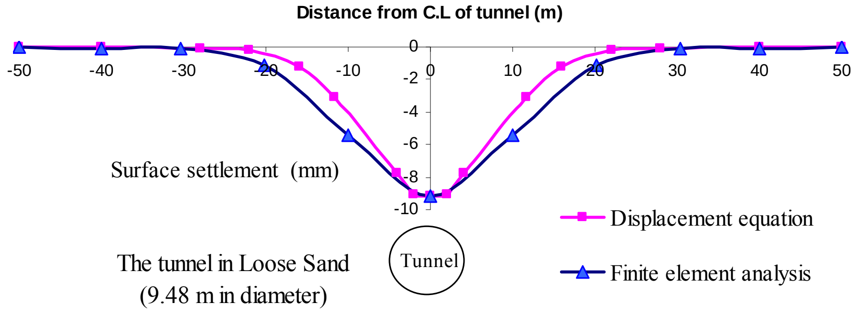

Fig. 4: Comparison between calculated surface settlements obtained by finite element model and surface displacement equation (tunnel located in loose sand)

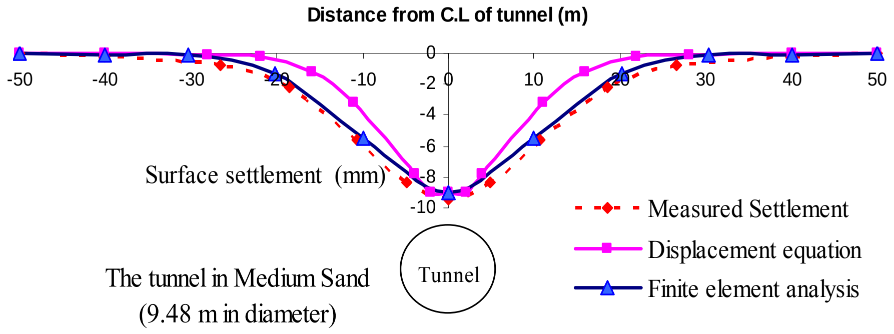

Fig. 5: Comparison among surface settlement obtained by finite element model, surface displacement equation, and field measurements (tunnel located in medium sand)

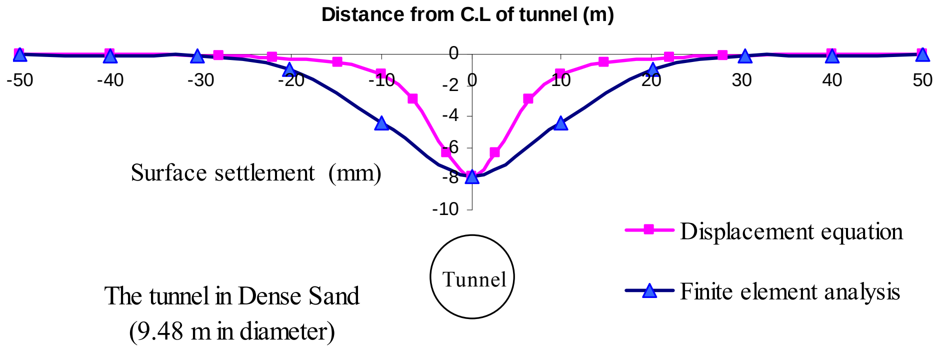

Fig. 6: Comparison between calculated surface settlements obtained by finite element model and surface displacement equation (tunnel located in dense sand)

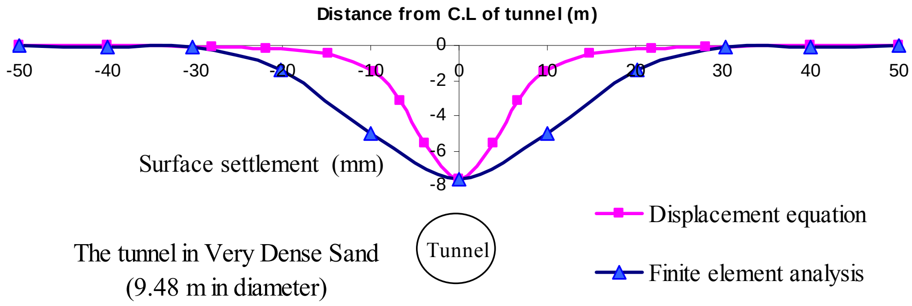

Fig. 7: Comparison between calculated surface settlements obtained by finite element model and surface displacement equation (tunnel located in very dense sand)