# Tunnel System Performance Based on Different Case Histories

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ABSTRACT

Development of tunneling is an effective tool to overcome high-density population challenges such as transportation and utilities activities. Tunnels are used for several purposes such as construction of sewers, railway, and roadway tunnels. The Greater Cairo Metro tunnel, El-Azhar road tunnels, and the sewage tunnel in the Greater Cairo city are considered as major projects to solve transportation and environmental problems. There are technologies to assist in excavation such as tunnel boring machine (TBM) and cut and cover method. To better understand the performance of the tunnel system, it is necessary to investigate the geotechnical problems related to tunneling.

In the present study, the finite element model (FEM) is proposed to predict performance of tunnel system under shadow of three case histories. The three case studies presented and discussed in this study give good and rare opportunity to understand the performance of the 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 the tunnel system is described by the ground movement caused by tunneling. The ground movement is presented and calculated using the proposed 3-D FEM. The recorded measurements are also presented for the three case histories. The results obtained by the 3-D numerical model are compared with those obtained by the field measurement to assess the accuracy of the proposed 3-D numerical model. There is a good agreement between the results obtained by the 3-D FEM and those obtained by the field recording.

RÉSUMÉ

Développement de tunnel est un outil efficace pour relever les défis forte densité de population telles que les activités de transport et les services publics. Les tunnels sont utilisés à plusieurs fins, comme la construction des égouts, des chemins de fer, tunnels et routes. Le Grand Caire Metro tunnel, tunnels routiers El-Azhar, et le tunnel des eaux usées dans la ville du Grand Caire sont considérés comme de grands projets pour résoudre les problèmes de transport et l'environnement. Il existe des technologies pour aider à l'excavation comme tunnelier (TBM) et la méthode en tranchée couverte. Pour mieux comprendre la performance du système de tunnel, il est nécessaire d'enquêter sur les problèmes géotechniques liés à effet tunnel.

Dans la présente étude, le modèle éléments finis (FEM) est proposé pour prédire la performance du système de tunnel sous l'ombre des trois histoires de cas. Les trois études de cas présentés et discutés dans cette étude donne l'occasion bonne et rare pour comprendre la performance du système de tunnels. Le modèle constitutif pour cette analyse utilise des matériaux élasto-plastique. Une fonction de rendement de type Mohr-Coulomb et une fonction 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 est décrite par le mouvement du sol causé par effet tunnel. Le mouvement de terrain est présenté et calculé en utilisant la proposition 3-D FEM. Les mesures enregistrées sont également présentés pour les trois histoires de cas. Les résultats obtenus par le modèle 3-D numériques sont comparés avec ceux obtenus par la mesure sur le terrain pour évaluer la précision du modèle numérique proposé en 3-D. Il ya un bon accord entre les résultats obtenus par le FEM 3-D et ceux obtenus par l'enregistrement sur le terrain.

**KEYWORDS**: tunnels, numerical modelling and analysis, finite element analysis, deformations.

## 1. INTRODUCTION

Tunneling leads to ground movement due to the associated stress change around an advancing tunnel. The numerical techniques are widely used to predict the ground movements (Berant and cambou, 1998). Finite element method is considered the most appropriate analytical technique to solve geotechnical problems (Addenbrooke and Potts, 2001; El- Nahhas, 1986; El-Nahhas et al., 1990; Karakus and Fowell, 2005; Karakus, 2007; Mazek, 2004; Mazek et al., 2006; Oettl and Hofstetter, 1998). Modeling of geotechnical properties and tunneling process is the sophisticated problem (El-Nahhas, 1986; Mazek et al., 2004). In this study, the Greater Cairo Metro tunnel, El- Azhar road tunnels, and the Greater Cairo Wastewater tunnel in central Cairo city are considered as three case studies. The tunnel system performance is studied. The tunnel system model is proposed by 3-D nonlinear finite element analysis (FEA) under the shadow of the three case histories. The aim of this study is to understand performance of the tunnel systems. In the 3-D nonlinear finite element modeling, tunneling process and interaction effects between tunnel and soil around tunnel are investigated. The 3-D nonlinear finite element analysis is used to estimate vertical displacements at ground surface due to tunneling.

In this Study, the Greater Cairo Metro tunnel, El Azhar road tunnels, and the Greater Cairo wastewater tunnel are discussed through a comparison between the results calculated by the 3-D nonlinear finite element analysis and the results recorded by field measurements to assess the accuracy of the proposed 3-D finite element analysis (FEA). The typical geotechnical and soil properties used in this study are presented in Table 1. However, the results calculated by the finite element analysis agree well with those obtained by the field measurements.

## 2. FINITE ELEMENT MODEL

The finite element computer program (COSMOS/M, 2003) is used in this study. The finite element model takes into account effects of vertical overburden pressure, lateral earth pressure, and ground water table. The soil media, the tunnel lining, and the interface surface are simulated using appropriate finite elements. The numerical modeling of the soil tunnel system must reflect the characteristic of the ground continuum and the tunnel. In addition, the interface between the soil and the tunnel system should be idealized in the numerical model. Solid elements are used for modeling the soil media and the thick shell elements for modeling the tunnel liner. The thick shell element models both membrane (in plane) and bending (out plane) behavior of the tunnel structure. The solid element is chosen since it posses in-plane and out-of-plane stiffness. The solid element allows for both in-plane and out-of-plane loads. The solid element is prismatic in shape. The prismatic solid element and the triangular shell element interface are used between the soil media and the tunnel liner to ensure the compatibility conditions at the interface between them as well as the associated stress and strains along the interface surface.

The vertical boundaries of the 3-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 represented 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, as shown in Fig. 1. In the finite element analysis, the loading attributed to the construction process is considered.

## 3. PROPERTIES OF TUNNEL LINING AND SOIL

The three case studies discussed in this study were constructed at central Cairo city. 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 (El-Nahhas, 1994; Mazek et al., 2001; Mazek et al., 2004; NAT, 1993, 1999, 2009). 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 lies under the fill layer. This deposit includes occasional sand and silt partings of thickness from four to ten meters. Beneath the silty clay layers the sandy layer surrounding the entire excavation profile extends down to the bedrock. The main soil parameters required to model the performance of different tunnel systems are presented in Table1. The constitutive relationship adopted in the analysis is an elasto-plastic model. The Mohr-Coulomb criterion is adopted. The friction angles ($\phi$) 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 as presented in Eq. 1 (Janbu, 1963).

$$E_v = mp_a(\frac{\sigma_3}{p_a})^n \qquad [1]$$

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. The nonlinear soil parameters used for elasto-plastic finite element analysis for different types of the soil are presented in Table 1 (NAT, 1993, 1999, 2009).

The ground water table varies between two meters to four meters from the ground surface. Figure 2 shows the soil profile along the Greater Cairo City. The ground surface displacement due to the construction of the tunnel is calculated in this study. The final diameter (D) for the metro tunnel is 9.06 m and the excavation diameter of the metro tunnel is 9.56 m. The final diameter (D) for the road tunnel is also 9.06 m and the excavation diameter of the metro tunnel is 9.56 m. The final diameter (D) for the sewage tunnel is 4.65 m and the excavation diameter of the sewage tunnel is 5.15 m.

The tunnel lining is assumed to behave in a linear manner in the 3-D nonlinear finite element analysis. The characteristic of the tunnel lining is tabulated in Table 2.

## 4. GEOMETRIC BOUNDARIES OF 3-D MODEL

### 4.1 Dimensions of Model

The 3-D finite element mesh models a soil block with width, height, and depth in x, y, and z directions respectively, as shown in Fig. 1. The metro tunnel as the first case study is located at 18 meters from the ground surface, as shown in Fig. 2. Drain analysis is adopted in the numerical model as the metro tunnel passes through the sand layer.

The suitable geometric boundaries (model width and model height) are studied to reflect the performance of the metro tunnel 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 metro tunnel with different model widths is also presented in Fig. 4. The calculated invert heave of the metro tunnel with different model widths are also presented in Fig 5. The results also show that the model width is 100 meters beyond which there is no change in soil stresses occurred due to tunnelling. Hence, the one-hundred-meter model width is chosen to reflect the performance of the metro tunnel system.

The soil depth beneath the invert of the metro tunnel is 2.5 times diameter of the tunnel (Mazek and Tehawy, 2008). The one-hundred-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.

For El-Azhar road tunnels (second case study), similar analysis is also carried out to choose the appropriate geometric boundaries. The results also show that when the model width exceeds 120 meters there is hardly any change in the soil stresses occurred due to tunnelling. 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.

For the sewage tunnel (third case study), similar analysis is again conducted to choose the appropriate geometric boundaries. The model width varies from 40 meters to 100 meters. When the model width exceeds 80 meters there is no change in soil stresses occurred due to tunnelling. The eighty-meter model width is adopted in the 3-D FEA to compare the results obtained by both the FEA and the field measurement.

### 4.2 Mesh Size

The model mesh size is studied to reflect the performance of the metro tunnel 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 metro tunnel liner. 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 tunneling. The results also show that as the element size along the metro tunnel liner is smaller than one meter there is no change in calculated surface settlement due to tunnelling.

Similar analysis is also conducted for both El-Azhar road tunnels and the sewage tunnel to choose suitable element mesh size. A three-meter element size along the outer boundary of the soil model block and the one-meter element size along the tunnel liner are chosen for the rest of the 3-D FEA.

### 4.3 Ground Loss

The construction of a tunnel leads to a subsurface movement due to move soil towards excavated tunnel. The ground loss ($V_L$) is the ratio of the difference between excavated soil volume and tunnel volume to the excavate soil volume. The ground loss ranged from 1.5 % to 4.5 % and reached to 6 % at some location along the Greater Cairo metro project (El-Nahhas, 1999). The impact of the ground loss on behavior of the tunnel system is investigated to assess the accuracy of the 3-D nonlinear FEA. Surface settlement due to construction of the metro tunnel is calculated.

In the parametric study, the ground loss is varied from 2% to 6% due to tunnelling. The calculated surface settlements against different ground losses due to the metro tunnel construction are analyzed and presented in Fig. 6. Based on the FEA, the ground loss of 4% is chosen to reflect the performance of the metro tunnel system. The results show that an increase of the ground loss due to tunneling leads to an increase of the surface settlements.

For El-Azhar road tunnel, similar analysis is also carried out to choose the suitable ground loss. The ground loss of 3% is also chosen to reflect the performance of the road tunnels system.

For the third case study (sewage tunnel), the ground loss of 6% is used in the 3-D FEA to reflect the performance of the tunnel system.

## 5. SOIL BEHAVIOR

The stress changes in surrounding soils due to tunneling are investigated to study the detailed soil behavior around the tunnel systems. The stresses in the subsoil have undergone three phases of change. At these phases, the loading steps of the tunnel construction are simulated using the 3-D finite element analysis. First, the initial principal stresses are computed with the absence of the tunnel. Second, the excavation of the tunnel is modeled by means of the finite element method. The excavation is simulated by the removal of those elements inside the boundary of the metro tunnel surface to be exposed by the excavation. The excavated tunnel boundary is free to move until the soil comes into contact with the tunnel liner resulting from ground loss. The ground loss is considered in this study. The ground loss of 4 % is adopted in this study. Third, 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 tunnel construction. The initial in-situ stresses of the excavated tunnel boundary before tunneling are calculated and plotted in Fig. 7. The final vertical stress change after tunneling is calculated and compared with the initial in-situ vertical stress before tunneling, as shown in Fig. 7. The results show that the soil above the crown of the metro tunnel settles downward and the soil under the invert of the metro tunnel excavation heaves based on the soil stress change due to tunneling process.

## 6. 3-D FINITE ELEMENTS MODEL VERIFICATION (CASE HISTORIES)

The performance of the three case studies is modeled using the 3-D nonlinear finite element elements analysis (FEA). In this study, the Greater Cairo Metro tunnel, El-Azhar road tunnel, and the Greater Cairo wastewater tunnel are studied through a comparison between the results calculated by the 3-D nonlinear model and the results recorded by field measurements.

### 6.1 Greater Cairo Metro Tunnel Line 2 (First case history)

This case study is located along the Greater Cairo Metro Line *2,* as shown in Figure 2. The nonlinear 3-D finite element model is used to predict the performance of the metro tunnel. The computed surface settlement is compared with those obtained by the field measurements so as to understand the behavior of the metro tunnel, as shown in Fig. 8. This comparison is used to assess the accuracy of the proposed numerical model. The comparison shows that there is good agreement between the computed and the measured readings.

### 6.2 El-Azhar Road Tunnels (Second case history)

For El-Azhar road tunnels project, similar analysis is also carried out to predict the performance of the road tunnels. The 3-D nonlinear numerical model is also used to predict soil-tunnel interaction of El-Azhar road tunnels to assess the accuracy for the numerical model. The comparison between the calculated results using the FEA and the measured values are presented in Fig. 9. The study shows that the results calculated by the numerical model have a good agreement with the field data.

### 6.3 Greater Cairo Wastewater Project (Third case history)

For the Greater Cairo wastewater tunnel project, the nonlinear 3-D finite element model is also used to predict the performance of the sewage 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 sewage tunnel, as shown in Fig. 10. The comparison shows that there is 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 the three case studies. This discrepancy between calculated and measured readings may be caused by the accuracy of soil strength parameters, soil stress parameters, soil modelling, or instrumentation.

## 7. CONCLUSIONS

A 3-D nonlinear finite element analysis is used to understand the performance of the tunnel system under shadow of three case studies. 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.

1- A 3-D nonlinear numerical model is applicable to analyze and predict the detailed performance of the tunnel systems under the shadow of the three case histories.

2- The results calculated by the proposed 3-D nonlinear finite element model have a good agreement with the field data. The predicted surface settlements underestimate by up 10 % for all case histories with respect to the field measurement.

3- The minimum width of the 3-D nonlinear model is set to be ten times the tunnel diameter in the 3-D numerical model.

4- Ground loss is an important parameter effect on the performance of the tunnel system.

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Table 1**:** Geotechnical properties

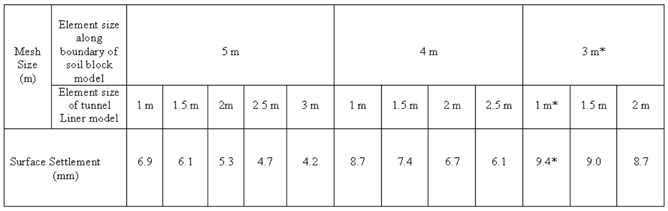
| Soil parameter | Fill | Silty clay | Sand |
|---|---|---|---|
| $\gamma_b$ (t/m$^3$) | 1.8 | 1.9 | 2.0 |
| $k_o$ | 0.58 | 0.8 | 0.37 |
| $\upsilon_s$ | 0.4 | 0.35 | 0.30 |
| $\phi$ (Degree) | 25 | 26 | 37 |
| C (t/m$^2$) | 1.0 | 0 | 0 |
| m | 300 | 350 | 400-600 |
| n | 0.74 | 0.6 | 0.5-0.6 |
| Depth of each layer | 0.0 to 4.0 | 4.0 to 10.0 | 10.0 to end |

In Table 1, $\gamma_b$ is bulk density, $k_o$ is coefficient of lateral earth pressure, $\upsilon_s$ is Poisson's ratio, $\phi$ is the angle of internal friction for the soil, and C is cohesion.

Table 2: Characteristics of the metro, sewage, and road tunnel

| Tunnel | $E_b$ (t/m$^2$) | $\nu$ | $f_c$ (t/m$^2$) | (t) cm |
|---|---|---|---|---|
| Sewage | $2.1\times10^6$ | 0.18 | 4000 | 25 |
| Metro | $2.1\times10^6$ | 0.18 | 4000 | 25 |
| Road | $2.1\times10^6$ | 0.18 | 4000 | 25 |

Table 3: Estimated settlement of ground surface considering different elements sizes (Greater Cairo Metro)



| Mesh Size (m) | Element size along boundary of soil block model | 5 m | | | | | 4 m | | | | 3 m* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Element size of 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) | | 6.9 | 6.1 | 5.3 | 4.7 | 4.2 | 8.7 | 7.4 | 6.7 | 6.1 | 9.4* | 9.0 | 8.7 |

* Selected element size of 3-D numerical model

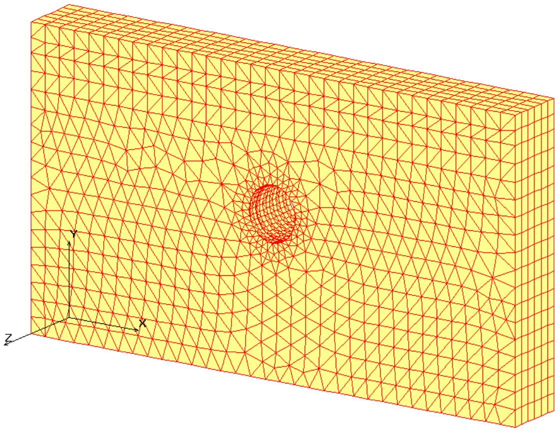


Fig. 1: 3-D finite element model of tunnel system

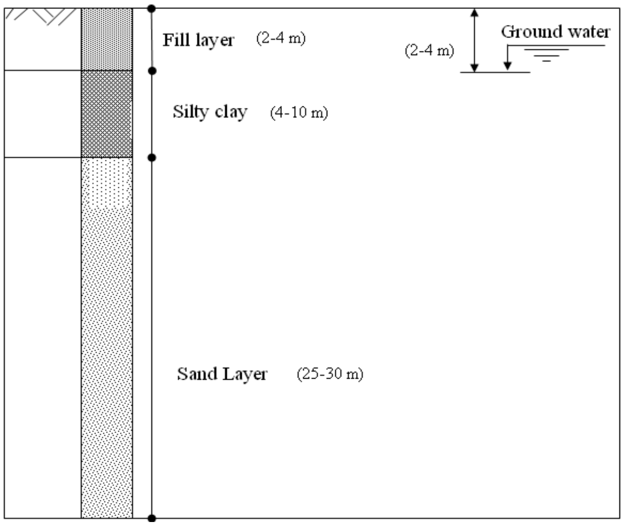


Fig. 2: Soil profile along the Greater Cairo City

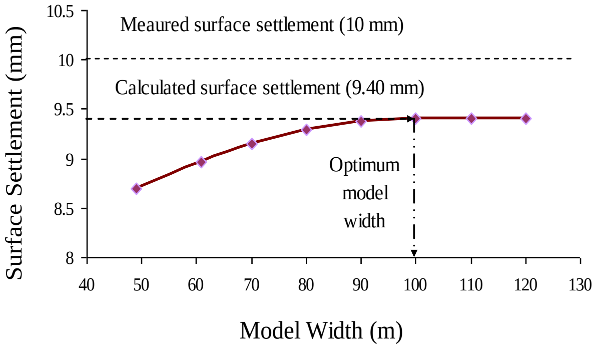


Fig. 3: Calculated surface settlement due to metro tunnel construction with different model widths

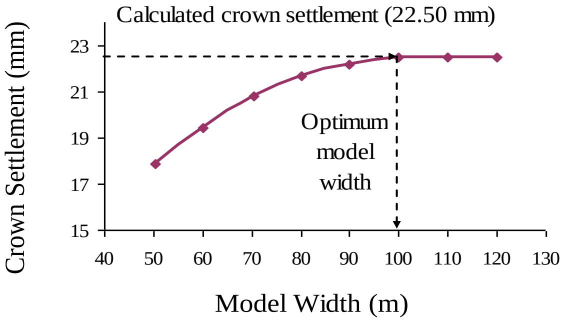


Fig. 4: Calculated crown displacements of the metro tunnel with different model widths

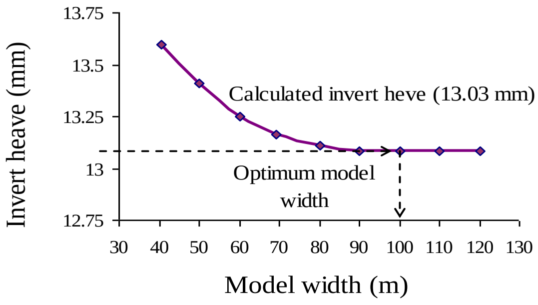


Fig. 5: Calculated invert displacements of the metro tunnel with different model widths

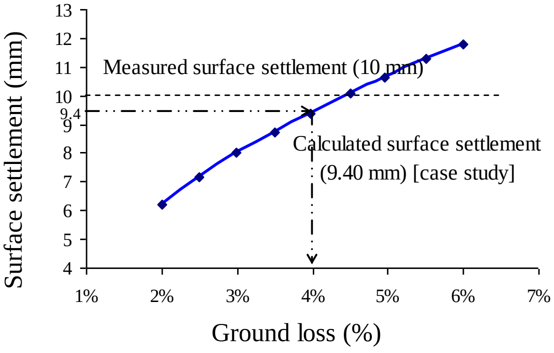


Fig. 6: Calculated surface settlement due to different ground losses (metro tunnel)

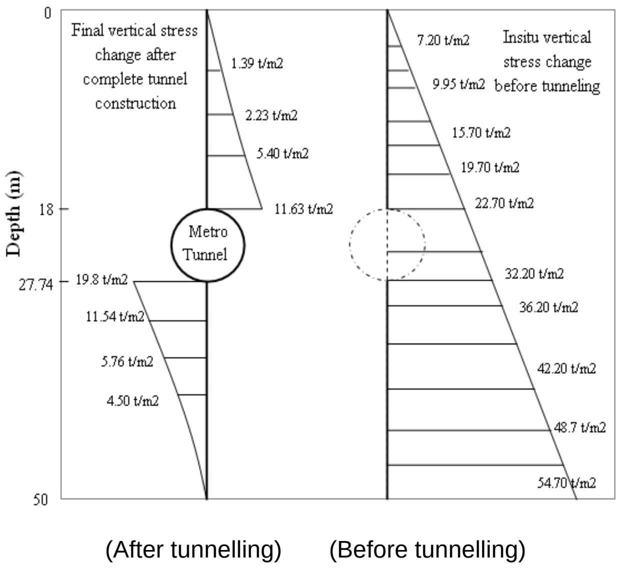


Fig. 7: Vertical stress before and after tunnelling (The Greater Cairo Metro tunnel)

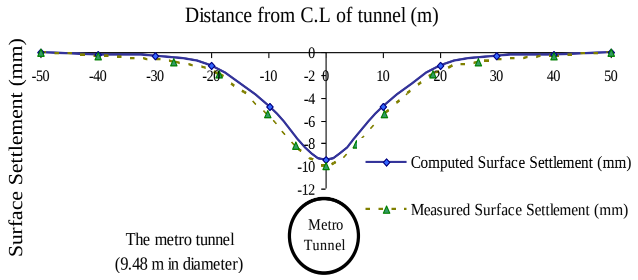


Fig. 8: Comparison between measured and calculated surface settlement due to the construction of the Greater Cairo metro tunnel

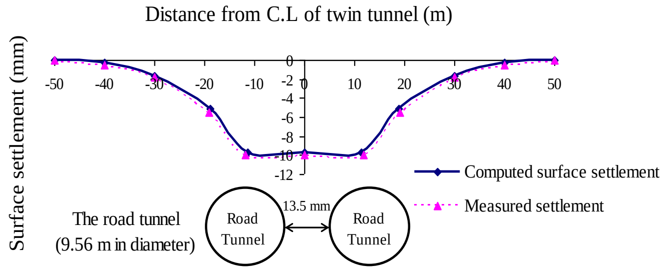


Fig. 9: Comparison between measured and calculated surface settlement due to the construction of El-Azhar road tunnels

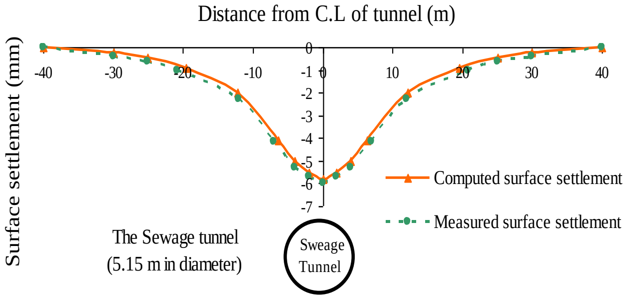


Fig. 10: Comparison between measured and calculated surface settlement due to the construction of the sewage tunnel