Investigation of Footing Settlements Adjacent to Circular Tunnels

Ahmed Elzoghby Elsaied
Assistant Professor, Construction Research Institute
Cairo, Egypt

Abstract*-Urbanization developments with limited available area for construction, have led transportation to go underground areas. Unexpected damages due to wrong predictions for the tunnel lining behavior, the surrounding soil, and footing settlements on/or adjacent to the tunnel emphasized the importance of the current study. A 2-D finite element model using Plaxis V 8.6 program was developed to simulate the tunnel system performance based on Cairo, Egypt, metro tunnel-Line 3 measurements as a case study. An elasto-plastic constitutive model was adopted to represent the soil behavior surrounding the tunnel. Studying the rate of a footing settlement within the vicinity of tunnel was therefore of great importance. The effects were expressed in terms of surface displacement and soil stress change caused by tunneling. The horizontal and the vertical distances between the tunnel and the footing subjected to various loads, and the diameter of the tunnel at different depths were carefully considered. Also, rotation of the footing adjacent to tunnel was taken into account. Results indicated that the volume loss in soil due to tunneling is an important parameter in soil-tunnel numerical models to predict the ground settlements. The influence of the tunnel becomes negligible on the adjacent footing settlements beyond a horizontal distance of about 2.5 times the tunnel diameter or a vertical depth equal to twice the footing width. Correlation was achieved between measured and numerical results and predictions have been made on probable advance values to occur in the future.

Keywords- Tunnel, Soil, Footing settlements, Numerical model

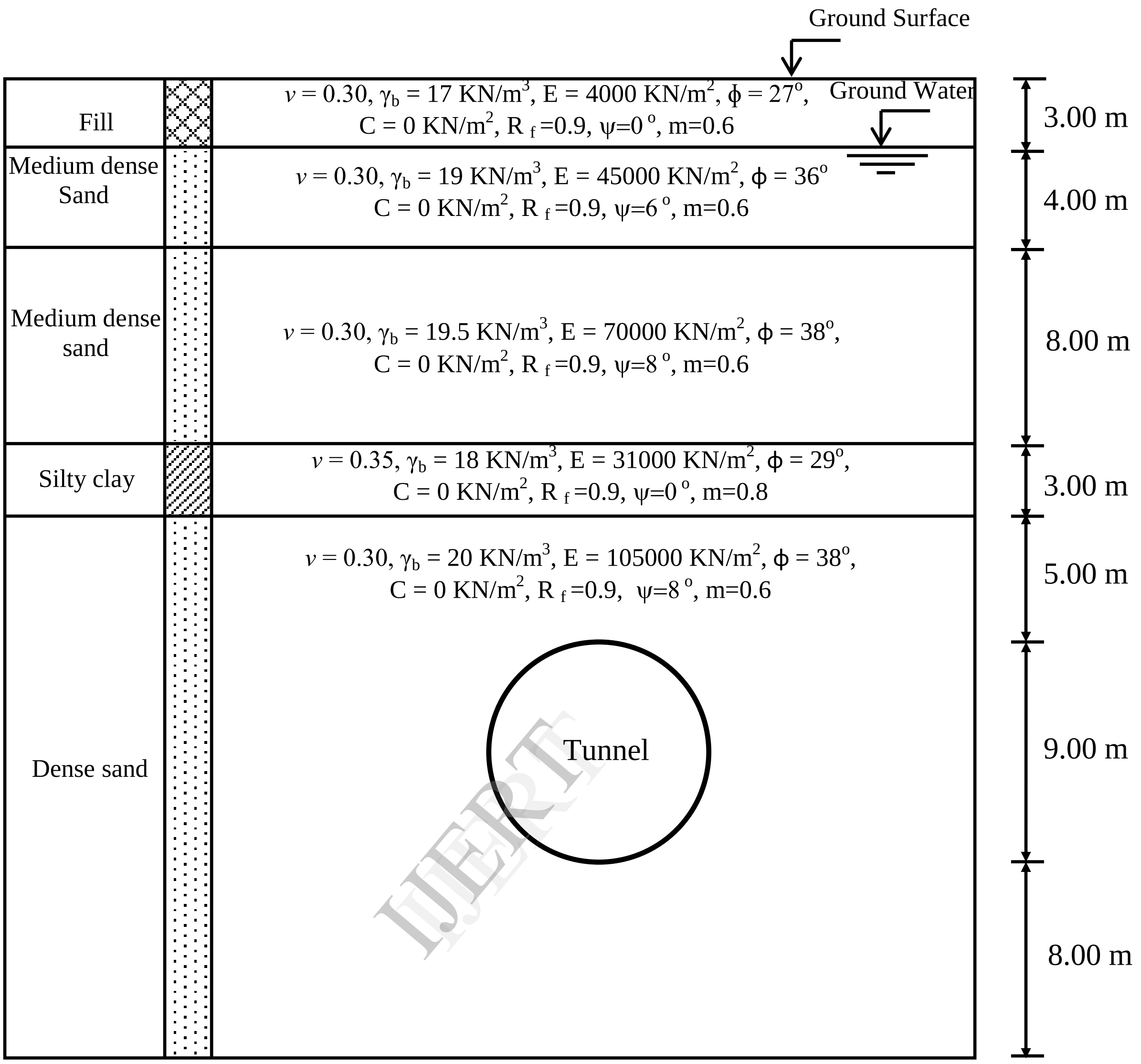
I. INTRODUCTION

A shield tunnel is constructed by excavating the soil at the front of the Tunnel Boring Machine (TBM) and installing a tunnel lining behind it. In this procedure the soil is generally over-excavated, which means that the cross section area occupied by the final tunnel lining is always less than the excavated soil area. As a result of the tunnel construction process, measures are taken to fill up this gap to avoid damage to the existing structure above the tunnel. However, there are no enough studies to develop a method that can accurately predict of ground deformations according to the tunneling effects on the surroundings. Most problems are related to damage of the surrounding buildings due to surface and subsurface ground subsidence [1 - 3]. Finite element method as an analytical technique to solve tunneling geotechnical problems were used [4 - 7]. An appropriate model to predict the behavior of the tunnel in Tehran No. 3 subway line was carried out [8]. They determined the variation of radial displacements along the longitudinal direction of the tunnel by an empirical method. Also, the tunnel deformations were defined. The ground movement properties caused by shield tunneling and expanding construction were numerically discussed [9]. Wang et al. [10] used finite element analysis to predict surface settlement above tunnel in clayey soil. The influence of drainage condition on surface settlement was also investigated.

In the present study, a finite element model was used to model the greater Cairo metro-Line-3 tunnel system performance as a case study. The Greater Cairo metro tunnel-Line 3 was constructed in 2011. A numerical analysis of the interaction between adjacent strip footing and circular tunneling was carried out. Various simulations were done using a finite element technique which takes into consideration the presence of the footing during tunneling. The numerous models for adjacent footing and the tunnel are assumed and the results are estimated and analyzed. Numerical analysis was conducted using a commercial finite element program PLAXIS V8, 6 [11] to examine configurations which have not been measured experimentally. The study explained the direct effect of the variation of the tunnel diameter and the horizontal and vertical distance between the tunnel and the footing on the footing settlement behavior. The constitutive model for this analysis utilizes elasto-plastic materials. The hardening soil models were employed for soil and a linear constitutive model was representing the tunnel liner. Model boundaries and volume losses (VL) were discussed to elaborate the performance of the metro tunnel. The associated stress changes in soil were studied and presented based on the tunnel construction process. The results obtained are compared with those obtained by the field measurement to verify the accuracy of the finite element model.

II. CASE STUDY PARAMETERS

The analyzed metro tunnel area lies within the Nile valley in Cairo vicinity. The soil layers and their parameters required to model the performance of the tunnel were indicated in Figure 1. The distinct soil layers encountered through the case study was analyzed by the author based on the National Authority for Tunnels report (after NAT, 2009) [12]. Duncan and Chang [13] material model was used to simulate soil as it assumes a hyperbolic stress-strain relation.



Where: ν= Poisson's ratio, γ_b =Bulk density, E=Modulus of Elasticity, ϕ=Angle of internal friction of soil, C=Cohesion of soil, R_f =Failure ratio, m= Power for stress-level dependency of stiffness, ψ(degree) =Angle of dilatancy

Figure 1 Cross section of soil layer including their parameters along the Greater Cairo metro-line 3 tunnel.

III. NUMERICAL ANALYSIS

The FEM can be particularly useful for identifying the patterns of deformations and stress distribution in the soil, at all various loading stages. A plane strain elasto-plastic finite element analysis was carried out. The boundary conditions were chosen such that the right and the left vertical boundary were constrained horizontally. The bottom horizontal boundary was constrained in both the horizontal and vertical directions. The finite element model (FEM) takes into account the effects of the vertical overburden pressure, the lateral earth pressure, the non-linear properties of the soil, and the linear properties of the tunnel. Moreover, the interface between the soil media and the tunnel liner was considered in the numerical model. The soil was modeled using hardening soil model, which is elasto-plastic hyperbolic model. This model has the following basic characteristics: a-stress dependent stiffness according to a power law, b-hyperbolic relationship between strain and deviatoric stress, c- distinction between primary deviatoric loading and unloading/reloading, d- failure behavior according to the Mohr-Coulomb model, and e-an elasto-plastic Duncan-Chang model. The hardening soil model parameters that used in the finite element calculation were derived from a series of laboratory tests carried by the National Authority for Tunnels.

A tunnel lining consists of curved beams. The lining properties can be specified in the material for beams. Similarly, a tunnel interface is modeled as a curved interface. The contraction parameter was used to simulate the volume loss in the soil due to the tunnel construction. This procedure can be activated in a plastic calculation. The tunnel construction was under initial insitu stress condition. The excavation of the metro tunnel causes the soil around the excavated tunnel to respond in an unloading manner. Under the unload-reload condition, the ratio of unload and reload modulus (E_{ur}) to the vertical drained modulus (E_v) was used and considered equal 2 for sand [14, 15]. The 6-nodes element is used as the basic element type to create the fine mesh. The mesh should be refined in this area of stress concentrations occur around the tunnel. The tunnel composed of 50-cm thick segments. The characteristic of the tunnel and the adjacent footing are shown in Table 1.

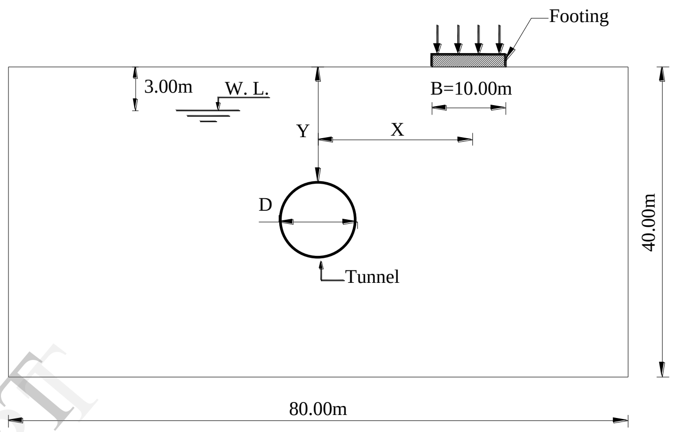
TABLE 1: Mechanical properties of the metro tunnel and the footing

Mechanical Properties	**Type of behavior**	**Modulus of Elasticity (KN/m^2)**	**Poisson's ratio**	**Thickness (m)**	**Density (KN/m^3)**
Tunnel	Elastic	$2.1x10^7$	0.20	0.50	25
Footing	Elastic	$2.1x10^7$	0.20	1.20	25

The stress changes in the surrounding soil due to tunneling were investigated to study the detailed soil behavior around the tunnel. In order to simulate the construction of the tunnel it is clear that a staged construction calculation is needed. The stresses in the subsoil have undergone three phases of change. At these phases, the loading steps of the tunnel construction were simulated using the finite element analysis. First, the initial principal stresses were computed with the absence of the tunnel. Second, the excavation of the tunnel was modeled by means of the finite element method. The excavation simulated by the removal of those elements inside the boundary of the external 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. Third, the volume loss in soil due tunneling was considered. The calculated changes in stresses were then added to the initial principal stresses computed from the first phase to determine the final principal stresses resulting from the tunnel construction. It is significant to note that the position changes ought to be set at zero in the earlier phase. The analysis of this model is for the purpose of evaluating the position change in the footing during the drilling process of the tunnel. Furthermore, it is assumed that while drilling the tunnel, there has passed a lot of time when the establishment of the structure thus it has come to its final position modification limit before the drilling time. In the final part, the analysis is completed by assuming the performance of final lining.

IV. GEOMETRY

The tunnel designer was used to generate the tunnel model, which is a special tool within PLAXIS that enables the use of circle segments to model the geometry of a tunnel. In modeled cases done by finite element software, a particular geometry used in such modeling selected optimally to prevent possible undesired effects that might emerge when there is a wrong or unsuitable selection of model dimensions. The parametric study was conducted to determine the suitable dimensions beyond which no changes, in both soil stress and vertical displacement, were occurred. In this study, the model width and height are 80 m and 40m respectively. The geometry of the problem to be analyzed is shown in Figure 2.



Where; D=Tunnel diameter, B=footing width, X=Horizontal distance between centers of the footing and the tunnel, Y=Vertical depth between the ground surface and the tunnel crown, Z= ground water depth

Figure 2 A schematic diagrams model verification used in the analyzed study

V. VOLUME LOSS

The volume loss (VL) is the ratio of the difference between the excavated soil volume and tunnel volume over excavated soil volume. In the present study, the volume loss was studied and varied from 1.0 to 5.0%. The surface settlement due to construction of the metro tunnel was measured. Calculated surface settlements against various volume losses were studied. The FEM gets more powerful as its results are verified with experimental results. Results indicated that there is a good agreement between readings obtained by both the FEM at VL=3.2% and the field data measurements as indicated in Figure 3. However, this comparison is used to assess the accuracy of the proposed 2-D finite element model. Results indicated that the surface settlements due to tunneling increased with the increased of the volume loss value. The volume loss is an important parameter on the numerically calculated ground surfaces settlements over tunnels. The volume loss value of 3.2% was chosen to reflect the performance of the metro tunnel line-3. It is used in all the numerical models in this study.

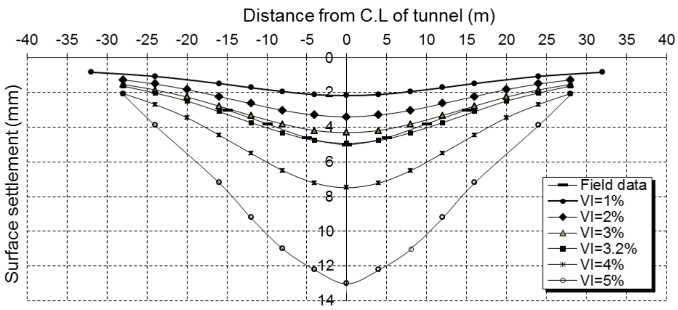


Figure 3 Comparison between measured and calculated settlements for different VL values

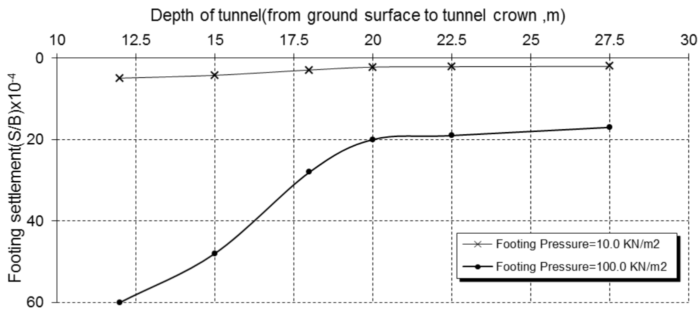


Figure 4 Footing settlements versus vertical tunnel depth (Y) for different footing pressure, (D=9.0)

VI. NUMERICAL MODEL RESULTS

The model results obtained were discussed to study the effect of different parameters on the settlement of the adjacent footing to the tunnel. These different parameters were the vertical and the horizontal distance between the footing and the tunnel. Also, the effect of changing the tunnel diameter was studied.

A. *Vertical Depth between Footing and Tunnel*

Variations in the depth of the tunnel located vertically underneath the footing have been considered. Demonstration of the settlement changes as a result of increasing the depth of the tunnel has diameter (D=9.0m) are plotted in Figure 4. Footing settlement was expressed in a dimensionless parameters (S/B) where S= average footing settlement and B=footing width. As expected, with decreasing the tunnel depth (Y) the footing settlement was increased. This is due to the tunneling effect which loss the soil around the tunnel. Increasing the tunnel depth near or equal to twice the footing width the footing settlements reduced dramatically. This is due to the vertical stress beneath the footing rapidly reduced with increasing the depth. Results also show that the soil above the crown of the tunnel moves down due to the final vertical stress moved downward. But the soil under the invert of the tunnel heaves as a result of the soil stress reduction which pushes the soil to move upward. There are fully agreed with the soil movements and vertical stress change, with their directions and magnitudes, after tunneling (D=9.0m and Y=23.0 m) underneath a footing subjected to 100 KN/m2 as shown in Figures 5 and 6 respectively. The vertical stress, shown in Fig. 6, was calculated as an average stress along the tunnel width. Also, the effective stress as principal stresses, with an indication of their direction and relative magnitude after tunneling for the same case is shown in Figure 7. The plot of the effective stresses shows that an arching phenomenon occurs around the tunnel which reduces the stresses acting on the tunnel lining, also minims the effect of the loosed soil around the tunnel on the footing settlements.

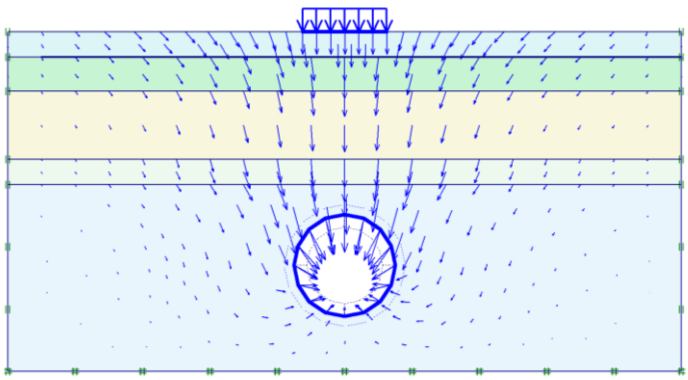


Figure 5 Soil movements after tunneling

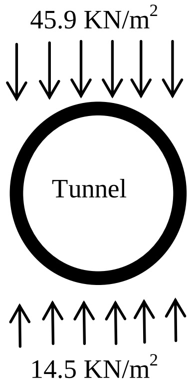


Figure 6 Vertical stress changes after tunneling

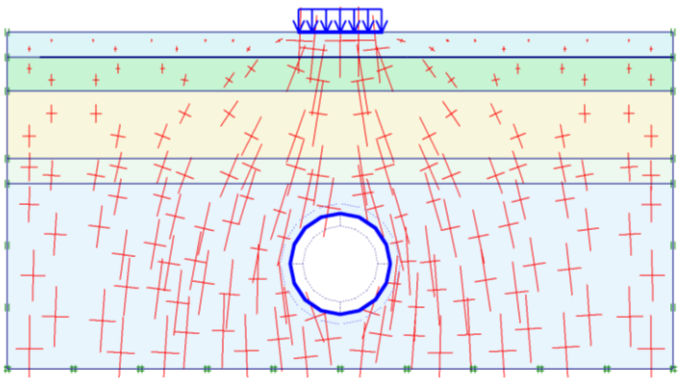
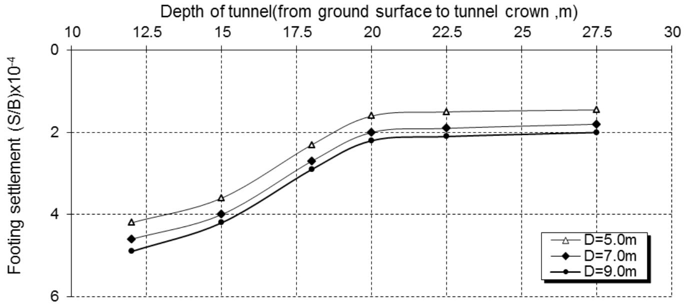


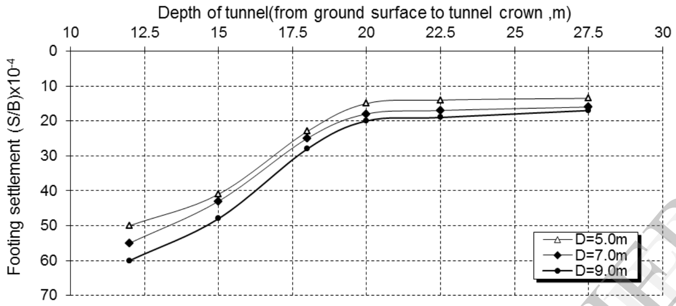
Figure 7 Effective stress changes after tunneling

B. tunnel diameter

Figures 8,a and b illustrate the provided models for the settlements of footing subjected to different pressure and underneath by a tunnel with various diameters. It is clear that increasing the tunnel diameter leads to increasing the footing settlement as a result of increasing the volume loss in soil due to tunneling. The increase in footing settlements in case of tunnel (D=9.0m) reached to 1.2 times than that of (D=5.0m).



a) In the case of footing pressure = 10.0 KN/m^2



b) In the case of footing pressure = 100.0 KN/m^2

Figure 8 Settlements of footing versus tunnel depth (Y) for different tunnel diameters

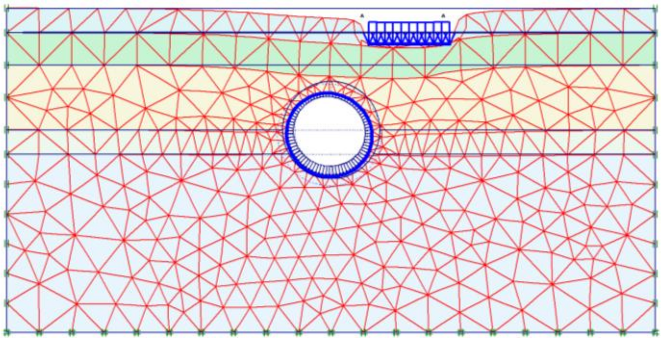


Figure 9 deformed mesh after tunneling adjacent to footing

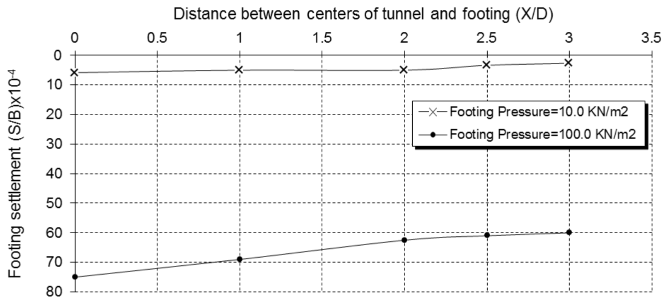


Figure 10 Footing settlements versus (X/D) for different footing pressure (D=9.0m and Y=9.0m)

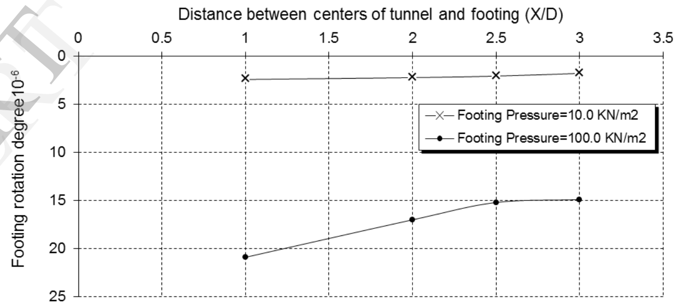


Figure 11 Footing rotation versus(X/D) for different footing pressure (D=9.0m and Y=9.0m)

C. Horizontal distance between footing and tunnel

The simultaneous influence of variation in the horizontal distance between centers of the footing and the tunnel was considered. The model tunnel is located at different horizontal distances from the adjacent footing (X/D =0.0, 1.0, 2.0, 2.5, and 3.0). Figure 9 shows the deformed mesh (scaled up) at the end of the calculated phases of constructing the tunnel (D=9.0m, Y=9.0m, and X/D=1.0) adjacent to footing subjected to 100 KN/m2. The deformed mesh indicates a settlement trough at the ground surface. Figure 10 demonstrates the effect of increasing the horizontal distance between centers of the tunnel and the footing versus footing settlements for different footing pressures. In addition, Figure 11 illustrates the footing rotation, for the same cases. It was observed that while the horizontal distance between the footing and the tunnel increased the footing settlements and rotation reduced. Beyond a distance of about 2.5 times the tunnel width, away from the tunnel center to footing center, the influence of the tunnel becomes negligible on the footing settlements.

CONCLUSION

Based on the above soil investigations and Cairo metro-Line-3 tunnel, the following conclusions were reached:

1- A 2-D numerical model with PLAXIS 8.6 program is a good tool for investigating the performance of the footing settlements adjacent to the tunnel.
2- The influence of the tunnel becomes negligible on the adjacent footing settlements beyond a horizontal distance of about 2.5 times the tunnel width or a vertical depth equal to twice the footing width.
3- The volume loss of soil due to tunneling is an important parameter in tunnel numerical models to predict the ground settlements. It is recommended a volume loss value equal 3.2 % for the Cairo metro-Line-3.
4- The footing settlements due to tunneling (D=9.0m) reached to 1.2 times than that of tunnel (D=5.0m).

5- The soil above the crown of the tunnel moves down however the soil under the invert of the tunnel moves upward.

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