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Appraisal of Surface Displacement Equation due to Tunneling in Sand Soil

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Abstract. : Tunnels are major projects of infrastructure for civil purposes. Surface settlements can occur by tunneling processes. This settlement can be predicted by different techniques like empirical methods and finite element methods which represent a simulation for real field measurement results. Most empirical solutions don't take into account the influence of changed soil densities upon ground deformation during tunneling excavations. The finite element analysis (FEA) reflects the parameters of strength and stress of the variant of densities of sandy soil. The tunneling process requires the study of great soil-structure interaction problems. In this paper, FEA is utilized to predict the ground displacements that happened by the tunneling process. For judging the reliability of the numerical analysis, a case history along the Greater Cairo Metro tunnel is studied. The ground displacements obtained by the surface displacement equation (SDE) produced by Peck and Schmidt (1969) are represented and discussed. Field measurements are compared with settlements obtained by both FEA and SDE. The ground displacements obtained by SDE are compared by those obtained by FEA at variant densities of sandy soil. The main target is to estimate a suitable formulation that represents the changed cases in sand densities in SDE compared with FEA. The results showed that the changed soil densities in the sand which are disregarded in SDE take an important signify canceup on the surface displacements that occurred by the tunneling in sand soil.

Keywords: Surface Settlement; Surface displacement equation; Sand; Tunnel.

1. INTRODUCTION

Construction of tunnels is a great project aim to ease fast transits, sewerage, water supply and other destinations. In general, these tunnels are constructed in inhabited cities and excavated in rock ground or soft soil. The construction of these underground infrastructures is complex in nature. Surface displacement is caused by tunneling through soft ground due to the associated stress change due to tunnel advancing. Surface displacement is to be considered a significant issue during study the phase and choice of a suitable way of the construction of tunnels. Predicting of surface displacement relies on multiple parameters such as geometry of tunnel, technique of the construction, depth of tunnel, properties of subsoil type. The excavation of tunnels can be modeled by FEM under variant conditions of soil, variant geometries of tunnel, and variant procedures of construction as presented by Ahmed [3], El-Nahhass [14], El-Nahhass [15], Mazek and El-Tehawy [21] and Ezzeldine [16]. Tunneling in sand soil is a complicated procedure tending to make a movement of ground and subsurface structures as presented by Mazek andEl-Tehawy [21] and Mroueh and Shahrour [24]. Abu-Farsakh and Tumay[2], Mazek et al.[19] and Vermeer andMoller[32] concluded that the finite element method is considered the most suitable numerical technique to find solutions for geotechnical problems.

Empirical methods are based on data obtained from field measurements and observation during tunnel processing. Empirical methods provide the greatest simple calculations and thus generally used in applicable uses. The most general and frequently used empirical method presented by Peck [29] for predicting settlement encouraged by tunnel. Peck observed that measured displacement of the ground surface above a tunnel along profiles perpendicular to the axis of the tunnel can be forecasted using a Gaussian curve that depends only on the maximum surface settlement above the tunnel centerline, S_{max}, and the inflection point of the settlement curve, i. Later, many authors have published an assortment of methods for estimating values of S_{max} and i for different cases of tunneling operations. It has been shown that Peck's method provides less than agreeable results, especially in granular media as presented by O'Reilly and New[28] and Mazek and El Ghamrawy[22]. Also, many researches like Atkinson and Potts[5], O'Reilly and New[28], Attewell [6], Herzog [17], Arioglu [4] and Mazek[19] suggests numerous good solutions to handle this shortage in Peck's method for instance. A good suggestion for representing the effect of sand soil densities on surface displacement in SDE presented by Mazek [23]. In this paper, the ground displacements obtained by SDE proposed by Peck and Schmidt[30] are represented and discussed. A 2-D FEM is used to forecast the ground movement due to tunneling.

The ground displacement is calculated by both FEA and SDE developed by Peck and Schmidt [30]. For judging the reliability of FEA, a case study on the Greater Cairo Metro tunnel Line 2 is considered to examine the precision of FEA as shown in Fig. 1.A good agreement in the results of comparing the calculated surface settlements with the field measurements.

The 2-D FEMconsiders parameters of changed densities in sandy soil. However, the SDE does not consider the influence of this difference on surface settlement caused by the tunneling process. Also, the field measurements are compared with both of the ground deformations obtained by the FEA and the proposed SDE. The main aim of this study is to present a proposed formula to represent the varying densities in sandy soil in the SDE. The results showed that the changed soil densities in the sand which ignored in SDE take an important significance upon the surface displacements that occurred by tunneling in cohesion less soil.

2. CHARACTERISTICS OF SOFT GROUND

Soft ground often consists of two materials cohesive soil and/or cohesion less soil. Case histories in fields are classified as one of these two materials, although in reality, no site ever fits this definition exactly. Most academics have known a divergence in ground movements caused by tunneling in these two materials, with movements in cohesion less ground seeming to be constrained to a limited region above the tunnel than in cohesive soils. For cohesion less soil, most of the previous researchers didn't take into consideration the effect of varying densities of cohesion less soil for assessment of ground surface deformation in empirical methods in contrast to FEM. Thus, in this paper, this shortage will be cured by deducing a proximately form to simulate field measurements and the other method of finite element. The subsurface soil profile along the Greater Cairo Metro is shown in Fig. 1, Compo and Richards[10], El-Nahhass et al.[13], ELNahhass[15],Mazek and El Ghamrawy[22], NAT[25], [26], [27]. The Geotechnical properties of soil in central Cairo city are presented in Table 1, Abdel-Salam[1], EL-Nahhass[15],Mazek and El Ghamrawy[22],NAT [25], [26], [27].

2. GEOLOGICAL AND GEOTECHNICAL CONDITION

The current studied area is part of line two of the Greater Cairo Metro Tunnel that mainly consists of dense alluvium structure of different particle sizes, i.e. silty clay and silty sand and sandy soil. The geological constitutions along this line are representative Cairo Nile Alluvial deposits, NAT [25], [26], [27]. The sequence of layers established the identity from these boreholes is shown in Fig.1.

Generally, the ground profile consists of a fill layer ranges three meters from the ground surface. The fill layer involved broken red bricks, stones and small pieces of asphalt. The next layer is a stiff silty clay layer varied from 4 m to 10 m. This deposit contains silt partings and occasional sand. The silty clay layer followed by a thin layer of silty sandy which extends from 0.25 m to 1.0 m overlying the sandy layer extends down to the bedrock. The parameters of soil were deducted from laboratory and in-situ tests. Table 1 shows the foremost geotechnical parameters of the soil layers used in the 2-D FEA. The tunnel was mostly excavated in the sandy layer. The tunnel lining has a circular shape and consists of 7 segments and one key. The segment has 1.5 m long and400 mm thickness. The characteristics of the lining material of the tunnel are tabulated in Table 2, NAT [25], [26], [27]. The water table was found approximately between 2 m to 4 m from the ground surface.

Table 1. Geotechnical Properties of soil Central Cairo City

Parameter	Fill	Silty clay	Silty Sand	Sand
Bulk Density(γ_b)t/m^3	1.8	1.9	1.85	2.0
Drained Poisson's ratio(ν)	0.4	0.35	0.35	0.3
Internal Friction angle(φ) °	20	26	30	37
Cohesion(C) kpa	0	10	0	0
Standard Penetration (blows/0.3)(N)	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
Young's 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_o)	1.00	0.80	0.50	0.39

Table 2. Characteristics of the tunnel lining

Type	Normal stiffness (EA) kN/m	Flexural rigidity (EI) kNm^2/m	Thickness (d) m	Concrete Density (γ_c)kN/m^3	Poisson's ratio (ν)
Tunnel Lining	8.40E+05	1.12E+04	0.40	25	0.20

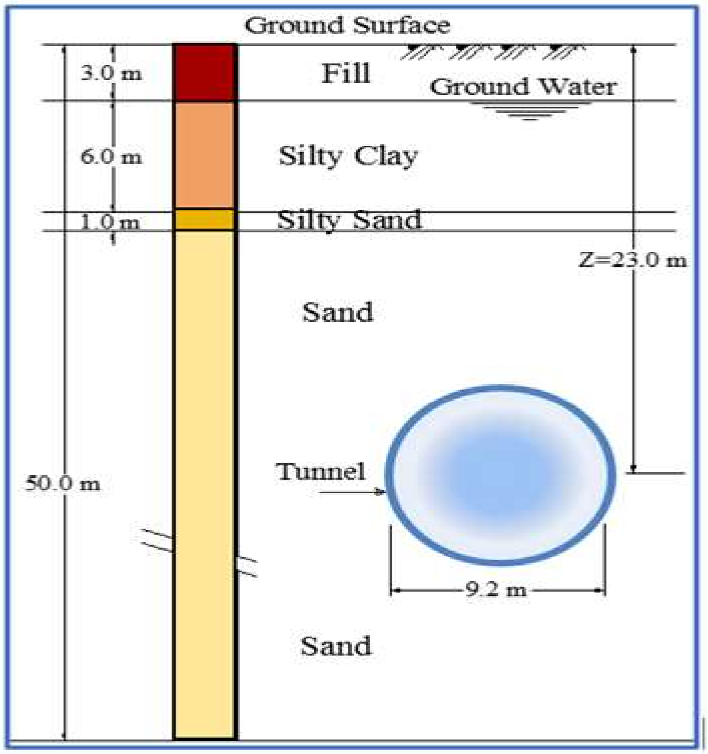

Fig 1. Cross section along the Greater Cairo Metro

4. FINITE ELEMENT MODEL

The finite element computer program Plaxis-V8.2 is used to model the performance of the tunnel system in this study. Analyses of stress and displacement near by the tunnel system are carried out using a 2-D plane strain.FEM takes into consideration the effects of the soil non-linearity properties, the vertical stresses, the lateral earth pressure and the linearity properties of the tunnel lining. Numerical modeling of the tunnel structure simulates the ground continuous sequence of the elements and the tunnel lining. In addition, the equilibrium and compatibility condition at the interface between the tunnel body and the surrounding soil are perfected in the numerical model.

A 2-D FEA was conducted to model the tunnel behavior using isoparametric triangular elements. During the mesh generation of the model, clusters are parted into triangular elements. These lection between 6-nodes elements and 15-nodes elements can be made. The influential 15-nodes elements supply a precise calculation of stresses to model soil medium. The tunnel lining can be modeled in the program by using a2-D beam element. A nonlinear stress-strain constitutive model is accepted for the soil around the tunnel system. A Drucker-Prager and Mohr-Coulomb yield condition is used to model the soil behavior. Linear elastic conduct is supposed to simulate the tunnel lining behavior.

Boundary conditions are defined to supply stability of the tunnel system. The vertical borders of the 2-D FEM are restrained by roller supports to prevent a movement normal to the borders. The horizontal border at the mesh bottom is represented by an inflexible bedrock layer and any displacement at this plane is forbidden in all directions. The movement at the above horizontal border is free to emulate a free ground surface. The tunnel lining, the surrounded soil, and the interface media are emulated using suitable finite elements as shown in Fig. 2.

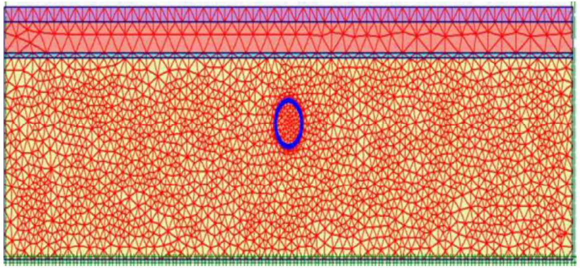

Fig 2. 2-D finite element model of the Greater Cairo Metro

5. BOUNDARY CONDITION IN FEM

In this study, the elastoplastic material model can be utilized in the analysis as a fundamental model. A Drucker-Prager and Mohr-Coulomb yield condition is used to model the soil behavior, Chen and Mizuno [8]. A linear elastic constitutive model is supposed to simulate the tunnel lining behavior. The materials properties of the tunnel lining are arranged in Table 2. The soil depth underneath the tunnel invert is set to be 3 times the diameter of the tunnel, Mazek[20].The nonlinear parameters of different sand soil types are given in Table 3. When the numerical model width exceeds 100 meters there is no change in the estimated surface settlement, Mazek [20].Thus, the choice of a suitable geometric boundary of the 2-D numerical model in this paper taken (200m x 50m) as shown in Fig. 2. Effective vertical stress is calculated before the tunneling process as shown in Fig. 3.The volume loss (VL) is the fraction of the change between the volume of the excavated soil due to tunneling and the tunnel volume over the same excavated soil volume. Both of the ground conditions and the construction method determine the value of volume losses induced by tunneling. The volume loss is considered in this study varies from 0.25% to 2.0%.

The strength and the stress parameters of different densities of sandy soil (loose, medium, dense, and very dense sand) are considered in the FEA,Duncan et al. [12]. The parameters of soil required to model the execution of the tunnel process are presented in Table 3, Duncan et al. [12],Mazek [23]. The 2-D numerical model should reflect the conduct of the tunnel in the field. The tunnel diameter is 9.2m. The tunnel is excavated in different sand soil conditions (loose, medium, dense, and very dense sand). The performed numerical analysis uses the drained behavior to represent the excavated tunnel in the sandy soil. The changing of the modulus of soil (E_s) with the confining pressure belongs to effective pressure depend on Janbu's empirical equation as given in Eq. (1),Janbu[18]. The soil parameters (m, n) are chosen to imitate the conduct of different types of soils, Duncan et al. [12].

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

Where; m, n are constant numbers where m is the modulus number and n is the exponent number, σ_3 is effective confining pressure, and P_a is the atmospheric pressure.

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

Parameter	Fill	Silty clay	Silty Sand	Loose Sand	Medium Sand	Dense Sand	Very Dense Sand
Bulk Density($\gamma_{b)}$ t/m^3	1.8	1.9	1.85	1.80	1.85	1.90	2.0
Drained Poisson's ratio(ν)	0.4	0.35	0.35	0.35	0.32	0.3	0.25
Internal Friction angle(φ) °	20	26	30	27	32	38	43
Cohesion(C) kpa	0	10	0	0	0	0	0
Modulus Number(m)	300	325	400	300	500	800	1000
Exponent Number(n)	0.74	0.6	0.6	0.6	0.51	0.5	0.4
Coefficient of Lateral Earth Pressure(K_o)	1.00	0.80	0.50	0.55	0.47	0.38	0.32

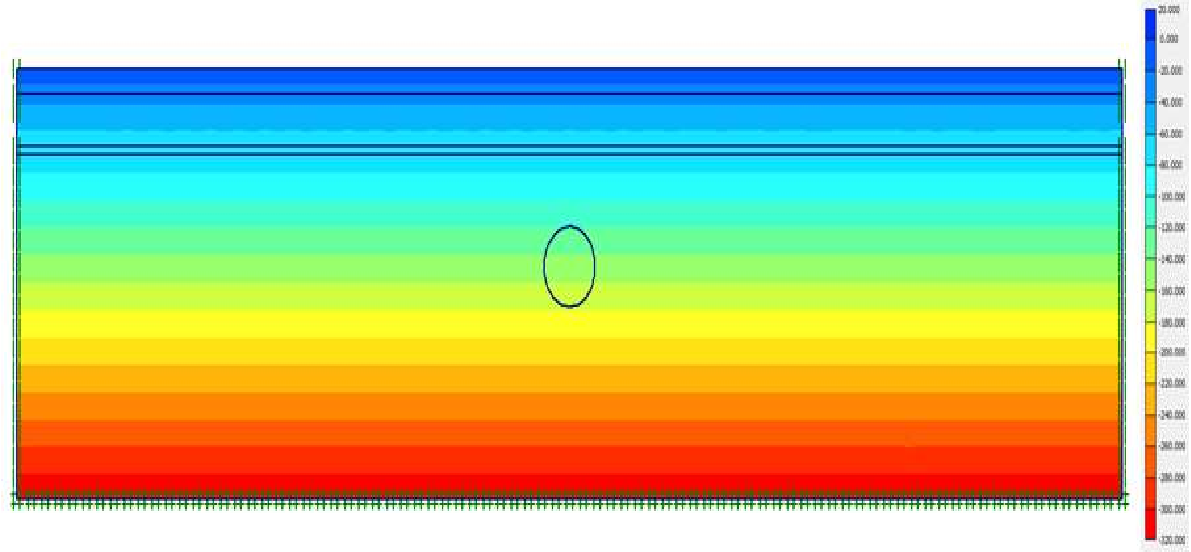

Figure 3.Vertical effective stress before tunneling (318.26 kN/m^2)

6. TUNNEL PERFORMANCE UNDER NUMERICAL ANALYSIS

The results of the numerical analysis are used at the design stage to evaluate the safety of the excavation procedure. However, conflict often exists between the predicted behavior and actual behavior. It is only possible during the construction to reassess the input data and to refine the numerical model using field measurements and back analysis.In the tunnel designing, it is fundamentally important to estimate initial stresses and material constants of the ground. But the tunnel movements are affected not only by these factors, but also by joints, non-homogeneity, and nonlinearity of the ground. Therefore, it is very difficult to estimate the tunnel movements with results obtained before the tunnel is being excavated. It is useful to evaluate the amount of volume loss which is used to emulate tunnel behavior. As the exact parameter values of the model are not known, criteria do not exist to check back analysis results. The only way to check back analysis results is by using the field measurements. In this check, the obtained parameters from the back analysis are adopted to perform the forward finite element analysis using the same model of the back analysis and only the calculated displacements are compared with the field measurements.

The current studied area is part of line two of the Greater Cairo Metro Tunnel, as shown in Fig. 1.The tunnel diameter is 9.2 m. The resulted final displacements along tunnel axis at 23.00 m below the ground surface are calculated according to taking the value of 0.45% as a contraction value, and the ratio of (Z/D) equals 2.5. The numerical analysis is accomplished using the drained soil modulus (E_s) calculated by Janbu [18]as the metro tunnel passes through the sandy soil. The maximum vertical displacement is 29.89mm at the tunnel bed can be illustrated in the deformed mesh as shown in Fig. 4.The calculated vertical effective stress around the metro tunnel is also illustrated in Fig. 5. The vertical surface displacement value is-10.33 mm and the vertical displacement values along the tunnel depth can be clarified in Table 4and Fig. 7. The computed values of surface displacement are compared with those from the in-situ measurements to be aware of the performance of the tunneling process. This comparison is a benefit for evaluating the numerical model accuracy, Fig. 6. The comparison shows that there is good compatibility between the computed results and the measured data.

Based on the good agreement between the computed results and the measured data, one can proceed to use the 2-D numerical analysis to investigate other perspective of the tunnel system performance under the tunnel construction. The proposed model can help to predict the surface displacement at the different sandy soils.

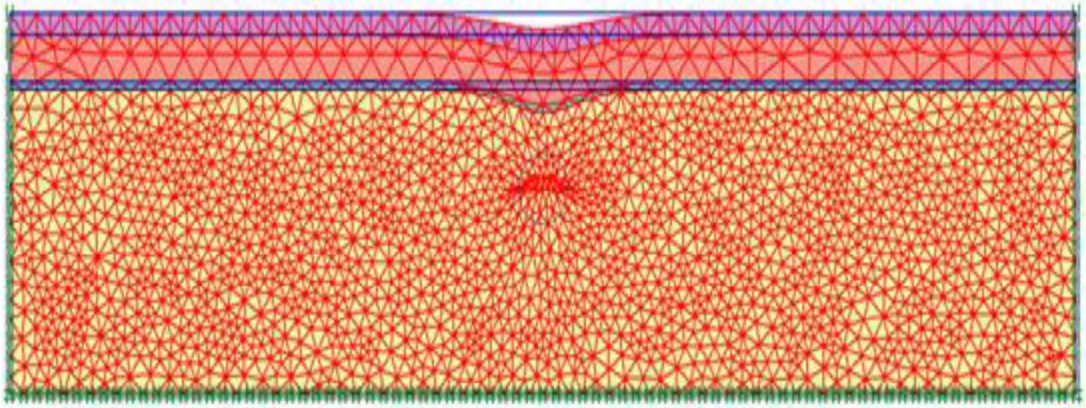

Fig4. Deformed mesh (max. vertical displacement is (29.89mm))

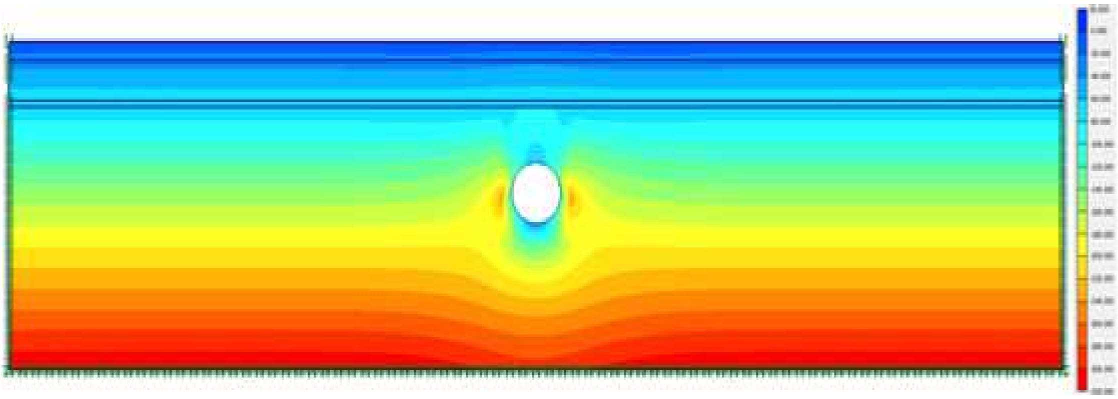

Fig5. Vertical effective stress after tunneling (290.8 kN/m^2)

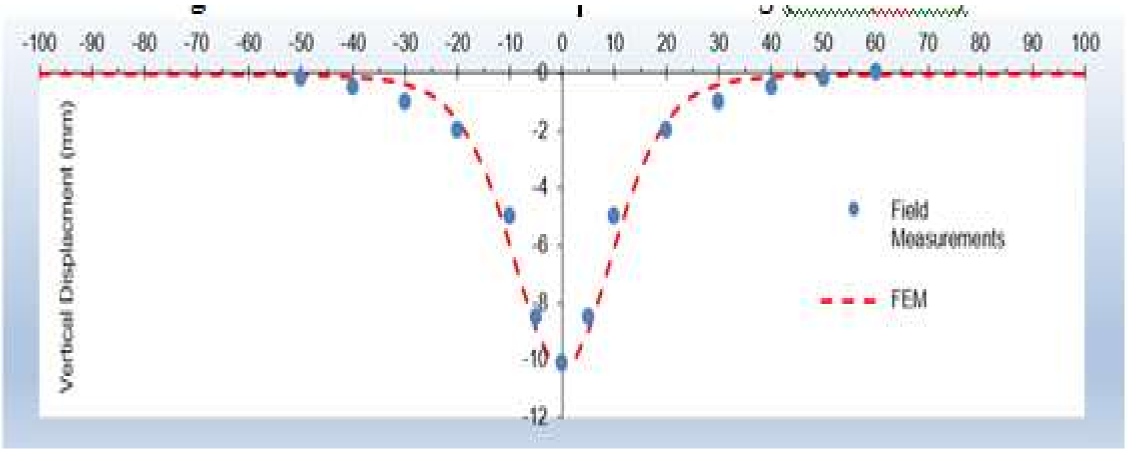

Fig6. Comparison between measured data and calculated vertical surface displacement by FEM

Table 4. Vertical displacement by FEM

Depth Z(m)	Vertical Displacement(mm)
0.0	-10.33
-2.5	-11.40
-4.0	-12.06
-7.8	-13.84
-10.0	-15.40
-12.4	-16.56
-13.5	-17.22
-14.3	-17.79
-15.4	-18.74
-16.1	-19.50
-17.1	-20.85
-17.4	-21.33
-18.4	-23.21
-27.6	29.89
-28.7	26.41
-29.0	25.49
-30.2	22.31
-30.9	20.55
-32.3	17.35
-32.9	16.14
-34.4	13.63
-34.9	12.93
-36.0	11.35
-37.0	10.09
-38.2	8.66
-38.8	8.02
-40.3	6.57
-41.0	5.96
-42.7	4.59
-42.9	4.44
-42.9	4.38
-44.5	3.20
-44.6	3.17
-44.6	3.16
-45.9	2.27
-46.8	1.70
-48.0	1.03
-50.0	0.00

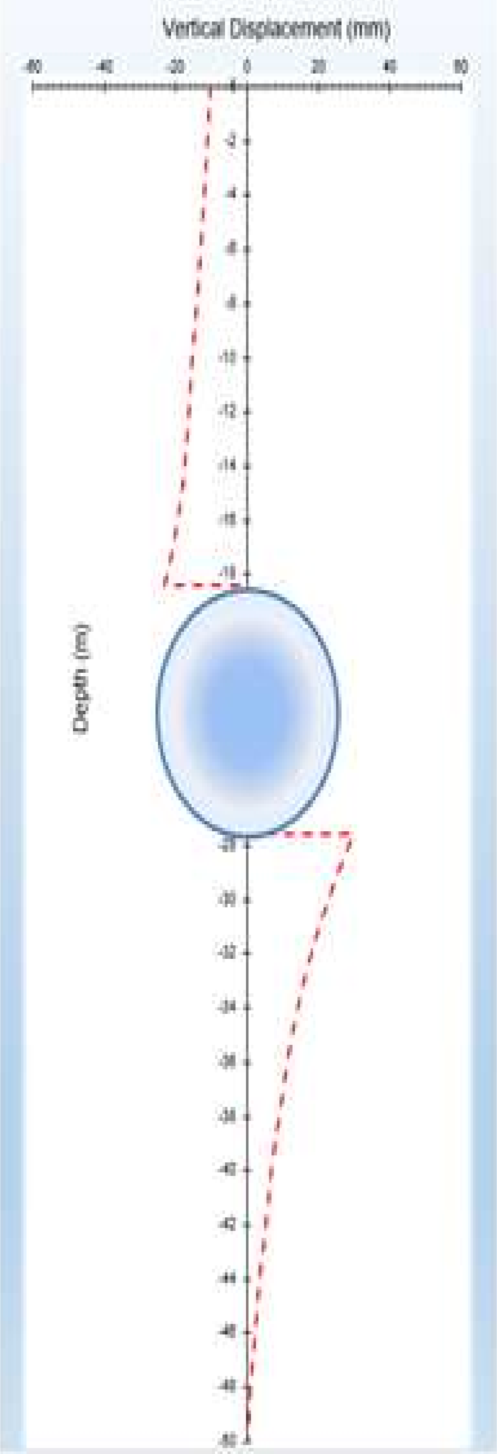

Fig7. Vertical displacement by FEM

7. GROUND DISPLACEMENT DUE TO EMPIRICAL METHODS

Empirical methods are based on data obtained from field measurements and observation during tunnel processing. Empirical methods provide the most simple calculations and thus generally used in practical applications. The Peck's formula is considered the most common and widely used empirical method for predicting settlement induced by tunnel, Peck[29], Eq. (2). Figure 8 shows that the computed settlement trough by the normal Gaussian probability curve. The traditional empirical method is beneficial for preliminary approximation and initial idea about surface settlement. The formula is given as follows:

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

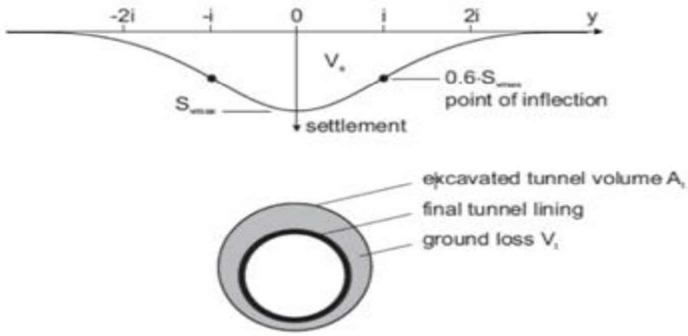

Fig8. Surface settlement, from Peck[29]

Where; S is the vertical surface displacement of a point which is at a horizontal distance x from the vertical plan beginning of tunnel centerline as shown in Fig. 8, S_{max} is the maximum surface displacement of the point directly above the tunnel axis, and i is a parameter that defines the width of the settlement trough's and is determined by the ground conditions. Later, variant expressions have been suggested for computation of the trough width (i). In practice, the following relationship suggested by Rankin [31] is often used:

$$i = k.Z \qquad (3)$$

Where; k is a dimensionless constant, depending on soil type: k = 0.5 for clay; k = 0.25 for cohesionless soils, Z is the depth from ground surface to the tunnel C.L.Peck established a correlation between the relative depth of tunnel and the point of inflection of transverse surface settlement trough for various soil types Cording and Hansmire [11] and Peck [29]presented anormalized relation of the width parameter, 2i/D, versusthe tunnel depth, Z/D for tunnels driven through different geological conditions i.e.

$$\frac{2i}{D} = \left(\frac{Z}{D}\right)^{0.8} \qquad (4)$$

Where;D is the diameter of the tunnel. Another expression has been suggested for computation of the trough width (i) by Attwell [6].He proposed the (i) parameter included in the SDE as presented in Eq. 5.

$$\frac{i}{R} = \alpha\left(\frac{Z}{2R}\right)^{n} \qquad (5)$$

Where; R is tunnel radius, α and n are constant parameters, Attwell and Farmer[7] proposed α =1, n=1 based on-site observations of UK tunnels. Clough and Schimdt[9]proposed another values for α and n, whereα =1, n=0.8 based on-site observations of USA tunnels. A very good suggestion for representing the effect of sand soil densities on surface displacement in the SDE presented by Mazek [23], where the range of α parameter varies from (0.82 to 0.95) depending on sand density and n=1using Eq. (5).

8. PROPOSED FORMULA FOR ESTIMATION THE TROUGH WIDTH

(i) IN THE SANDY SOIL

The excavated tunnels in soft soil leads to ground movement by Mroueh and Shahrour[24]. In urban cities, this movement can affect surface and underground structures. Predicting of ground movement caused by tunneling is a significant engineering challenge. Unfortunately, most empirical solutions didn't consider the influence of different densities in sandy soil on the surface settlement due to tunneling. A few studies cure this shortage such as Mazek [23]. A proposed formula for predicting of the trough width (i) is suggested in this study to calculate the ground deformation due to tunneling in different densities of sandy soil. The proposed expression of i can be presented in Eq. (6) as follow:

$$i = 0.68\, D \left(\frac{Z}{D}\right)^{0.9} \cos\varphi \qquad (6)$$

Where; D is the tunnel diameter, Z is the depth from the ground surface to C.L. of the tunnel and φ is the internal angle of friction of sand soil. The computed values of surface displacement by the SDE are compared with the in-situ measurements. This comparison aims to evaluate the range of matching in results between the real measurements and the calculated displacements to clarify the accuracy of the assumed parameter in the proposed equation. The showed comparison in Fig. 9 illustrates that there is a good agreement between the computed results and measured data in the field.

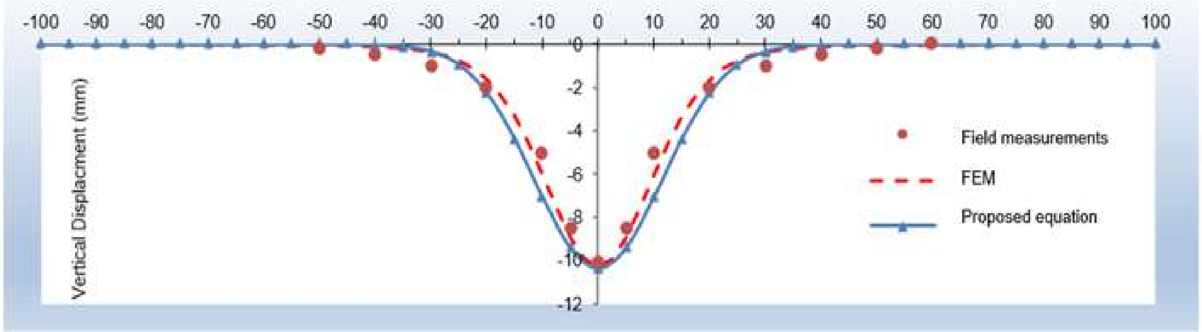

Fig9. Comparison between field measurements and calculated vertical surface displacement by FEM and by the proposed equation for case study

Based on the good consistency between the measured and the computed values, it is preferable to investigate other perspective of tunnel system behavior under the tunnel construction by using the 2-D numerical analysis. Based on the 2-D FEA, it can be trusted to predict the ground response due to tunneling for different densities in sandy soil. In this part, loose, medium, dense, and very dense and are considered around the tunnel instead of the sand layer in the previous case study to calculate the surface settlement due to tunneling in sand soil. Actually, the proposed formula is useful for estimating the surface displacement at different sandy soil cases, where the calculated displacements by using the proposed equation are compared with the calculated displacements by the FEM for each different case of sand, as shown in Figures 10 to 13.

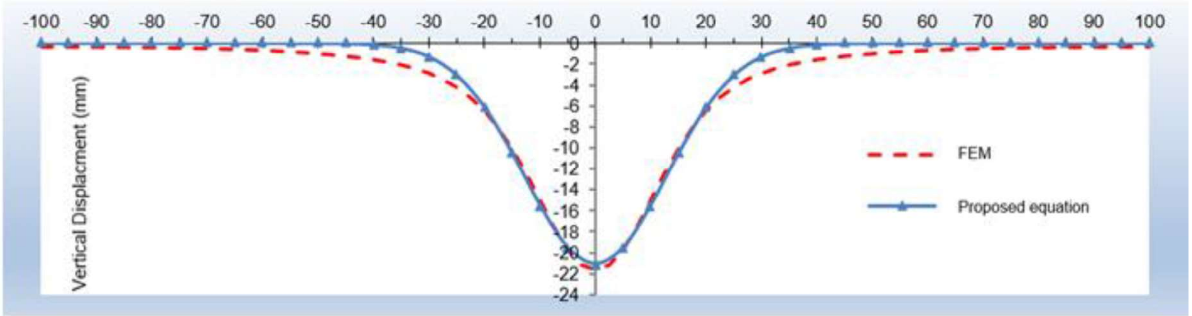

Fig10. Vertical surface displacement obtained by FEM and proposed eq.in loose sand

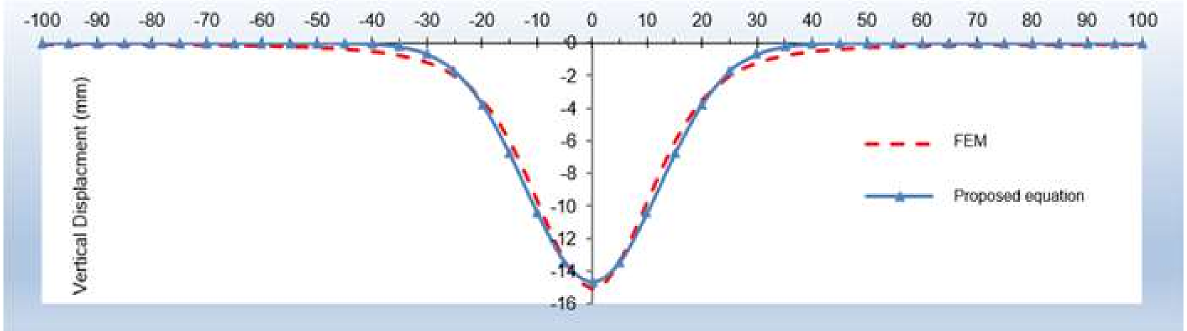

Fig11. Vertical surface displacement obtained by FEM and proposed eq. in medium sand

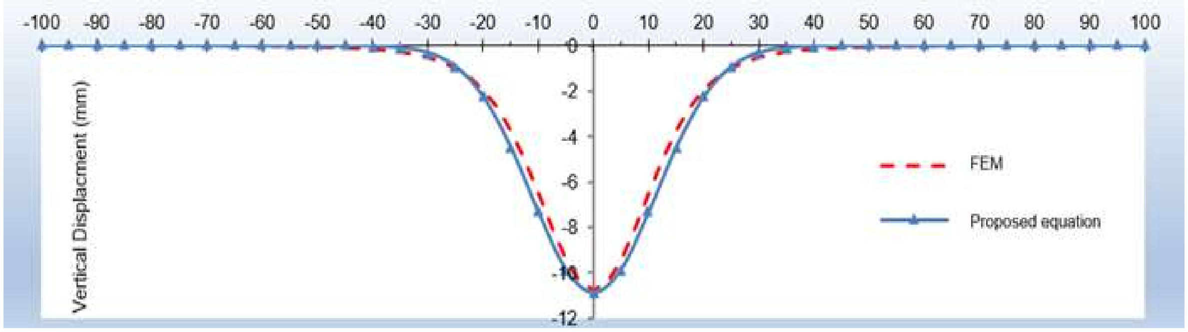

Fig12. Vertical surface displacement obtained by FEM and proposed eq. in dense sand

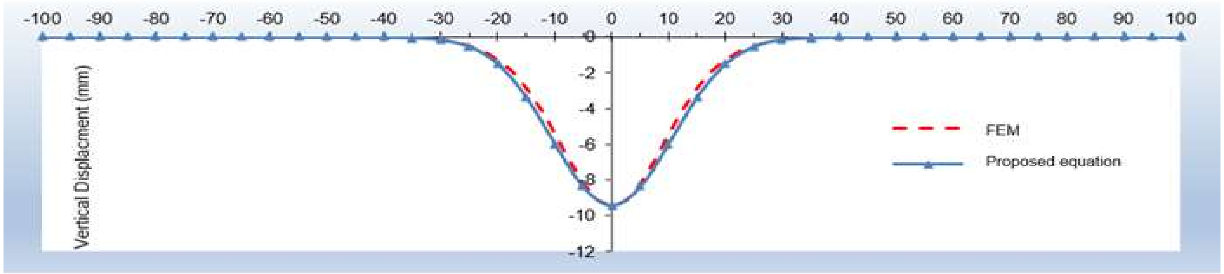

Fig13. Vertical surface displacement obtained by FEM and proposed eq. in very dense sand

9. CONCLUSIONS

In this study, the results of the empirical and numerical methods are compared with the measured data. Based on the suggested 2-D FEM for different cases of sandy soil. A proposed formula is presented for forecasting the trough width to get the maximum surface displacement due to tunneling in cohesionless soil. Main conclusions which could be deduced from this study are listed below:

- The 2-D FEM is agreeable to analyze and forecast the detailed performance of tunnel systems.
- The calculated results by the proposed 2-D finite element model have a good consistency with the field data.
- Considering numerical results, a suitable convergent formula for predicting the trough width (i) can be presented as:

$$i = 0.68\, D \left(\frac{z}{D}\right)^{0.9} \cos\varphi$$

- The results show that the maximum surface settlement obtained from the proposed equation has a better consistency with the actual measurements.
- The surface settlement profiles calculated by the FEA are more conservative than those computed by the surface displacement equation at different sand densities.

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