ENGINEERING RESEARCH JOURNAL (ERJ)

Vol. 1, No. 43 Jan. 2020, pp. 77-86

Journal Homepage: http://erj.bu.edu.eg

Studying of Settlement Trough for Different Empirical Methods due to Tunneling in Cohesionless Soil

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Abstract. : Tunneling operation exposes the adjacent buildings to extra stresses by causing vibrations, ground displacements, and heaves which make these structures in a critical mode. For this reason, researchers dedicate to studying settlement trough due to the tunneling process. Many methods were being proposed to estimate ground surface deformations due to tunneling such as empirical methods, analytical methods, and numerical methods. Most of empirical methodsdon'ttake into consideration the effect of varying densities in cohesionless soil on the surface settlement due to tunneling. A few studies cure this shortage such as Mazek (2014). A proposed equation for assessment of the settlement trough width (i) is to be suggested to calculate the ground surface displacement due to tunneling in different densities of cohesionless soil .The purpose of this paper is to present a comparison between different empirical methods based on surface displacement equation (SDE) due to tunneling. Toensurereliability, a case history along the Greater Cairo Metro tunnel is considered. A comparison between the field measurements, the proposed equation and those obtained by different SDEsis presented. The results show the more appropriate method which approaches the field measurements. Another comparison between the surface displacements calculated by the proposed equation and calculated by Mazek (2014) in different cases in sand soil densities to assessment the proposed equation. The comparison shows a good agreement in results to favor the use of the proposed equation to predict the trough width (i) for variant cohesionless soil conditions.

Keywords: Surface displacement equation; Empirical method; Cohesionless soil; Tunnel

1. INTRODUCTION

Tunnel construction usually leads to some surface ground deformation. Often this deformation is of the little significance to green field sites (i.e., those without surface structures), but may cause appreciable damage where surface structures are existing. The evaluation of the max surface settlement (S_{max}) is important to tunnel designers, practitioners, associated engineers with tunneling and policymakers. Over the years, researchers and tunnel engineers have agreed that restraining the ground loss is ineffective because of ground cloudiness and filed circumstances. Hence the only solution is to restraint the deformation effects rather than to stop it. Over the last 50 years, empirical methods have been developed to estimate the surface deformation caused by tunneling in soft soil during numerous experiences and many of field studies by researchers, such as Peck [17], Atkinson and Potts [2], Clough and Schimdt [5], Attewell et al. [4], O'Reilly and New [16]. Peck [17] presents an empirical relationship which has become the most famous frequently familiar method to determine surface deformations upon tunnels, especially in soft soil. Also, when obtaining field data to deduce empirical relationships of ground deformation, a significant problem is the in homogeneity of the soil condition and suitability of the empirical methods to variant soil types. For example, most of the empirical formulas don't take into consideration the variation in sand soil densities in surface settlement calculation due to the tunneling process. After Peck, many researchers have presented a diversity of methods for predicting the 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, O'Reilly and New[16], Mazek and El Ghamrawy[9].A good suggestion for representing the effect of sand soil densities on surface displacement in the SDE presented by Mazek[10].

Based on experimental results, Meyerhof [11]can estimate the cohesionless soil density from standard penetration test (SPT) N-values. Also, relationships to get the angle of internal friction (φ) of sand soils are to be predicted by Meyerhof [11]. The angle of internal friction (φ) of sandy soils and SPT N-values for each sand soil density can be presented in table 1.

Table 1. Prediction of Cohesionless soil density from SPT N-values by Meyerhof [11]

Cohesionless soil density	SPT N-values	Friction angle φ (degree)
Loose	4-10	27-30
Medium	10-30	30-35
Dense	30-50	35-40
Very dense	>50	38-43

In this paper, a proposed equation for estimation of the trough width (i) is being presented to calculate the ground deformation due to tunneling in different cohesionless soil conditions. To ensure the trustiness of this study, a case history along the Greater Cairo Metro tunnel is considered. A comparison between the field measurements, the proposed equation and those obtained by different SDEs is presented for the case study. The results show that the more appropriate method which approaches the field measurements. Another comparison between the surface displacements calculated by the proposed equation and calculated by Mazek[10]in different cases in sand soil densities depending on Meyerhof [11] division to assessment the proposed equation. The discussed results show that the different sand soil densities neglected in the SDE have an important influence on the surface displacement due to tunneling in cohesionless soil. Also, the results show a good agreement to favor the use of the proposed equation to predict the trough width (i) for different cohesionless soil conditions.

2. GEOTECHNICAL PROPERTIES USED IN CASE STUDY

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 [13], [14], [15]. The sequence of layers established the identity from these boreholes is shown in Fig. 1. Generally, the ground profile consists of a fill layer extends to 3 meters from the ground surface. The fill layer consisted of asphalt, broken red bricks, and stones. A natural deposit of stiff over consolidated silty clay layer under the fill layer is varied from 4-10 m. This deposit includes occasional sand and silt partings. The silty clay layer followed by a thin layer of silty sandy which extends from 0.25-1.0 m overlying the sandy layer extends down to the bedrock. Soil parameters were derived from in-situ and laboratory tests. Table 2 shows the main geotechnical parameters of the soil layers. The tunnel was mostly excavated in the sandy layer. The water table was found approximately between 2 m and 4 m from the ground surface. The volume loss is considered in this study varies from 0.25% to 2.0%.

Table 2. 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) ^{o}	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

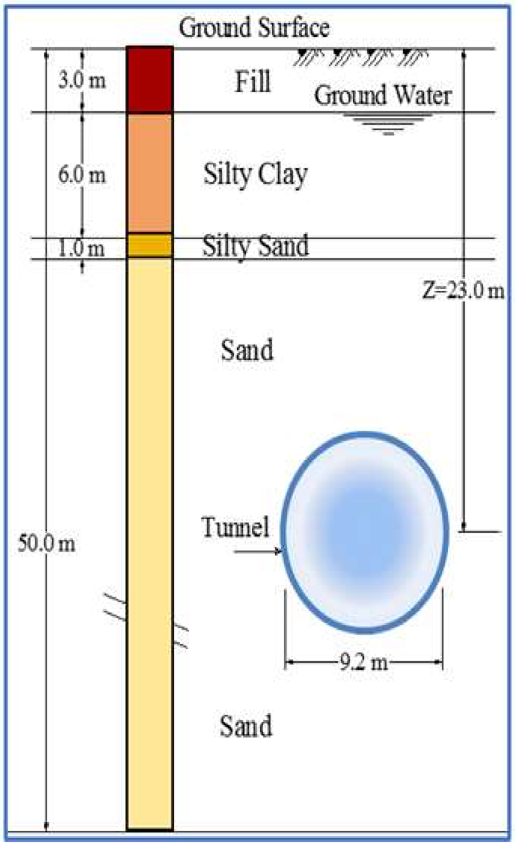

Fig 1. Cross section along the Greater Cairo Metro

3. A REVIEW OF EVOLUTION OF EMPIRICAL METHODS

Prediction of ground deformations during tunnel operation is an important matter for most researchers and tunnel engineers. Over the last 50 years, many researchers have tried to develop methods for estimating the deformations of the ground. This part aims to introduce a review of these methods which are used to predict S_{max} and i for the tunneling process. The most famous used approach is the supposal of a point origin leading to a settlement trough contiguity to a Gaussian distribution. It is noticed that the shape of the surface settlement trough upon the tunnel excavation can usually be represented by a Gaussian curve, this observation is supervised firstly by Martos[8]. Later, Peck and Schmidt [18]studiedthe surface settlement data in the fields from a numerous of tunnels' sites and suggested that the Gaussian function as shown in equation (1) can be implemented for depicting the surface settlement trough. This deductive was based on a statistical assessment of the field observed data over twenty case histories. Thus, the empirical relationship presented by Peck [17]has become the most famous frequently accepted method to estimate surface settlements upon tunnels, especially in soft soil. The formula is as follows:

$$S= S_{max} exp\left(\frac{-x^2}{2i^2}\right) \qquad (1)$$

Where; S is the vertical surface displacement of a point moves awayfrom a horizontal distance x from the vertical plan beginning of C.L. of the tunnel as shown in Fig. 2, S_{max} is the maximum surface displacement directly upon the tunnel axis, and i is a parameter that defines the width of the settlement trough's and is determined by the conditions of the ground.

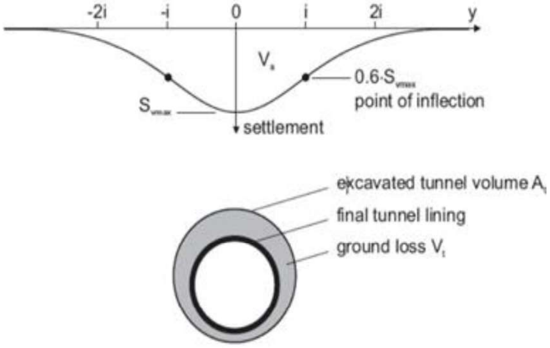

Fig2.Gaussian curve for trough width i, after Peck and Schmidt [18]

If displacement occurs without any change in the soil volume, then the volume of the soil (Vs) between the original ground surface and the settlement trough is gained by the integration of equation (2), that is,

$$Vs = \sqrt{(2\pi)} \cdot i \cdot S_{max} \qquad (2)$$

Peck established a relation between the point of inflection of transverse surface settlement trough and the relative depth of tunnel for different soil types in a dimensionless chart as shown in Fig.3.

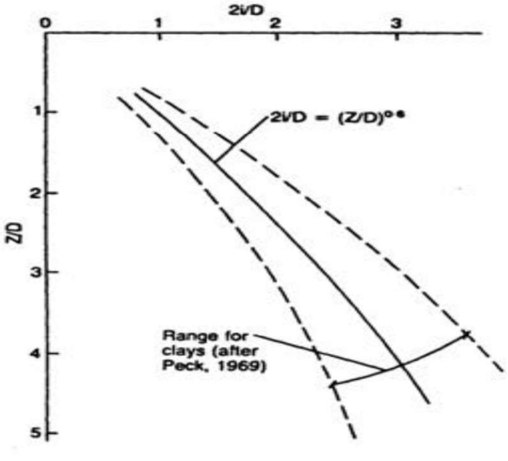

Fig3.Trough width i and tunnel depth relationship, Peck[17]

The relationship that can match the Peck's chart was presented by Peck and Schmidt [18] as follows:

$$\frac{2i}{D} = \left(\frac{Z}{D}\right)^{0.8-1.0} \qquad (3)$$

Where; D is the diameter of the tunnel, i is a parameter which means the width of the settlement trough, and Z is the depth of the tunnel from the ground surface to tunnel axis. Another expression has been suggested for evaluation of the width of trough (i) by Attwell [3]. He suggested the trough width (i) parameter included in the SDE as presented in equation(4).

$$\frac{i}{R} = \alpha\left(\frac{Z}{2R}\right)^{n} \qquad (4)$$

Where; R is the radius of the tunnel, and α and n are constant parameters, Attwell [3]suggested α =1, n=1 depending on field observations of tunnels in UK.Clough and Schimdt [5] proposed another values for α and n, where α =1, n=0.8 based on field observations of USA tunnels. Another relationship suggested by Rankin[19] is often used as:

$$i = k.Z \qquad (5)$$

Where; k is a dimensionless constant, depending on the type of soil: k = 0.25 for cohesionless soils; k = 0.5 for clay, Z is the measured depth from ground surface to axis of tunnel. Also, Mazek [10] presents a good solution for representing the effect of variation in sand soil densities on surface deformation in the SDE, where the range of α parameter varies from (0.82 to 0.95) depending on sand density and value of n=1 substitution in equation (4).

Many researches have been instructed insertion of field investigation and tests concerning assessing the parameter i, as mentioned in Table 3. Trough width i values can be evaluated by various researchers according to the empirical formulas can be abridged in Table 3 as follows:

Table 3. Different empirical solutions for assessment of trough width i

No.	Author	Value of (i)	Remarks
1	Peck [17]and Peck and Schmidt [18]	$\frac{2i}{D} = \left(\frac{Z}{D}\right)^{n}$ n=0.8 to 1.0	-Depend on field observation. -For all soil.
2	Cording& Hansmire [6]	$\frac{2i}{D} = \left(\frac{Z}{D}\right)^{n}$ n=0.8	- Depend on field observations of tunnels in UK. -For all soil.
3	Atkinson and Potts[2]	i = 0.25(Z + R) for loose sand i = 0.28(1.5Z + 0.5R) for dense sand and over consolidated clay	- Depend on field observations
4	Attewell[3]	$\frac{i}{R} = \alpha\left(\frac{Z}{2R}\right)^{n}$ α =1 and n=1	- Depend on field observations of tunnels in UK.
5	O'Reilly and New[16]	i = 0.43Z + 1.1 for cohesive soil i = 0.28Z - 0.1 for cohesion less soil	- Depend on field observations of tunnels in UK.
6	Herzog [7]	i=0.40Z+1.92	-For all soils
7	Arioglu [1]	i=0.386Z+2.84	-For all soils
8	Mazek [10]	$\frac{i}{R} = \alpha\left(\frac{Z}{2R}\right)^{n}$ α =0.82-0.95 and n=1	-For cohesionless soil

Note: Z is the tunnel depth below surface to C.L.of the tunnel and R is the tunnel radius and α and n are constant parameters.

4.PROPOSAL ANOTHER FORMULA TO ESTIMATE TROUGH WIDTH (i) IN COHESIONLESS SOIL

The excavated tunnels in soft ground result in the ground movement, Mroueh and Shahrour[12] .Predicting of the surface displacement by using the empirical methods is favorite although of the absence of comprehensiveness for all different soil conditions. Unfortunately, studying the influence of varying densities in sandy soil on the surface settlement caused by tunneling didn't take into consideration for most empirical solutions. A few studies cure this shortage such as Mazek [10]. Thus, it is be needed to suggest another expression to recover this shortening .In this study, a proposed formula is suggested to estimate the trough width (i) for calculation of the ground surface displacement caused by tunneling in varying densities in sandy soil. Many trials for suggestion an accepted form for the desired equation to be easy in used and accurate for predicting the surface settlements for different cases in sand soil. The proposed expression of i can be presented in equation (6) as follows:

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

Where; Z is overburden depth from the ground surface to C.L. of tunnel, D is the diameter of the tunnel and φ is the internal friction angle of sand soil.

5. CALCULATED SETTLEMENT BY DIFFERENT EMPIRICAL EQUATIONS FOR THE CASE STUDY

The case study area is part of line two of the Greater Cairo Metro Tunnel as it is being mentioned previously. The tunnel has a circular shape with a diameter of 9.2m. This tunnel was mostly excavated in the sand layer. The axis of the tunnel is located at 23.00 m below the ground surface. Thus the ratio (Z/D) is 2.5 which used in the calculation. The surface displacements are obtained by the various empirical method which mentioned previously in table 3. The computed displacements are compared with the measured reading of settlements gained from the field during excavation of tunnel and are calculated according to taking the value of 0.45% as a contraction value. The ground deformation trough for these methods can be illustrated as shown in Fig.4 compared with field readings. This comparison will help us to analyze the variation in the results of the settlements of these methods.

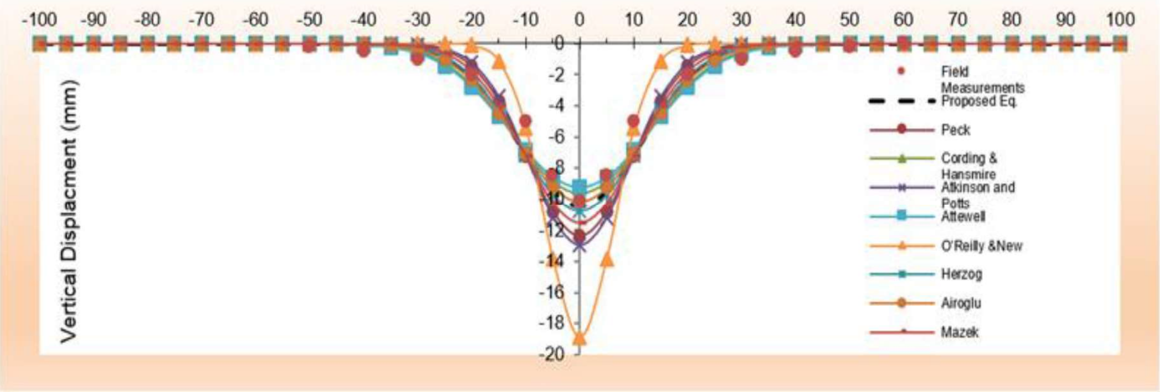

Fig4. Comparison between field measurements and calculated vertical surface displacements by different SDEs for case study

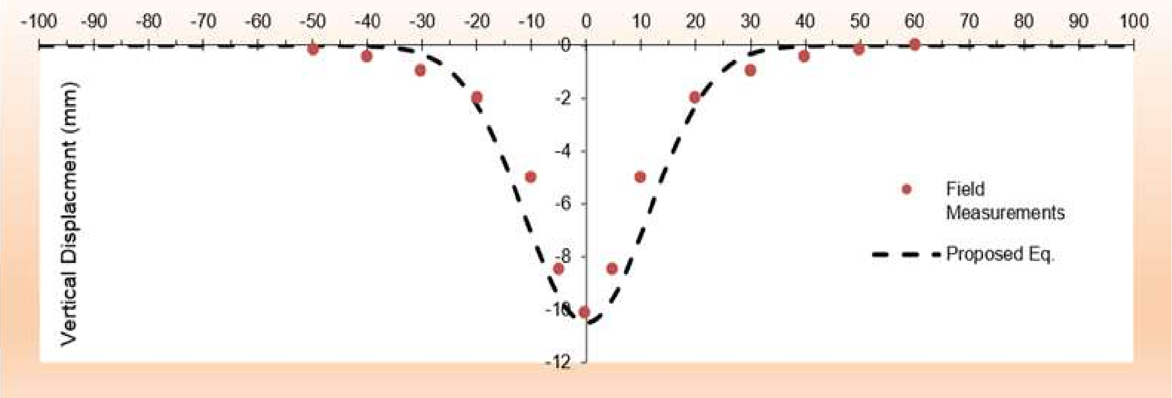

Fig5. Comparison between field measurements and vertical surface displacements calculated by the proposed equation for the case study

Unfortunately, the required comparison is unfeasible because of the large numbers of the compared curves. Thus, the main chart will be divided into several charts to facilitate this comparison. A comparison between field measurements and vertical surface displacements calculated by the proposed equation for the case study can be shown in Fig. 5. It shows a very good convergence in results for the proposed equation compared with the filed measurements. Figures6 to13 show the charts that illustrate a distinct comparison between the field measurements and the vertical displacement obtained by the proposed equation and each method of the empirical methods separately.

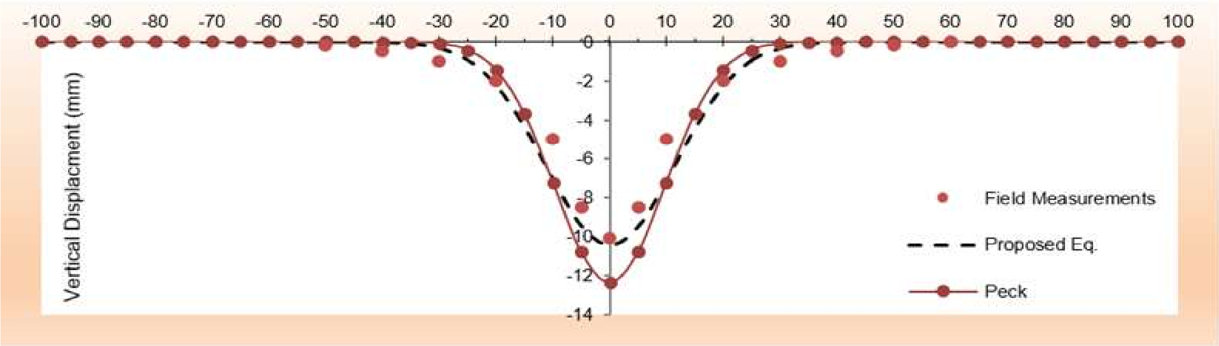

Fig6. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Peck for the case study

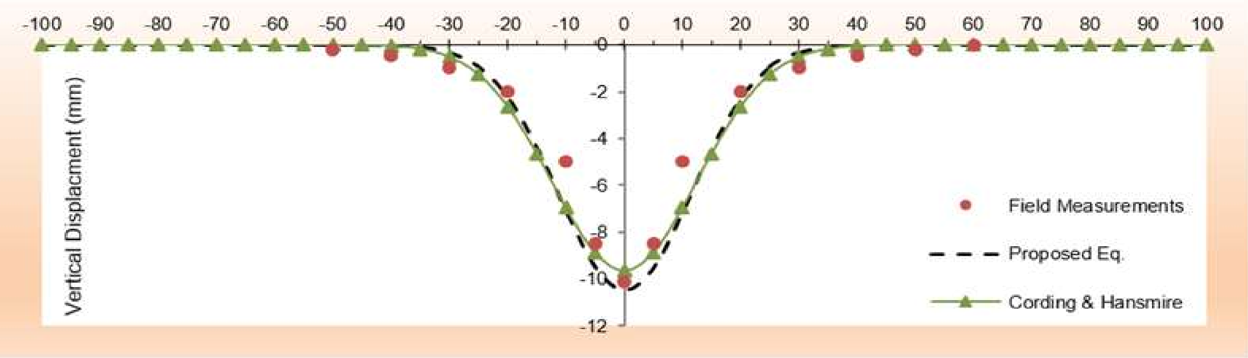

Fig7. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Cording & Hansmire for the case study

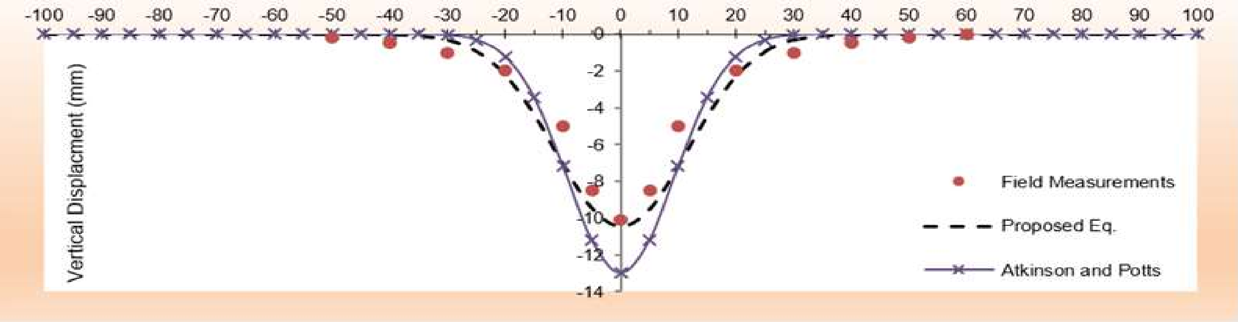

Fig8. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Atkinson & Potts for the case study

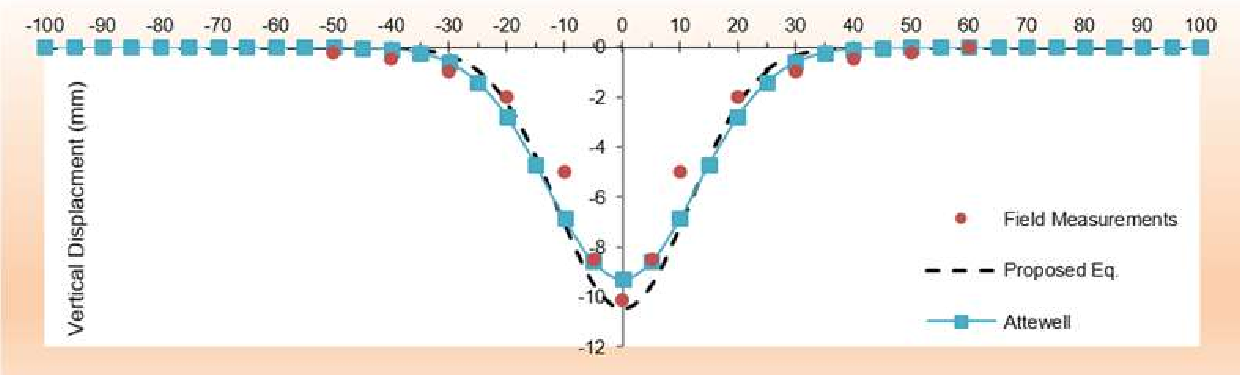

Fig9. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Attewell for the case study

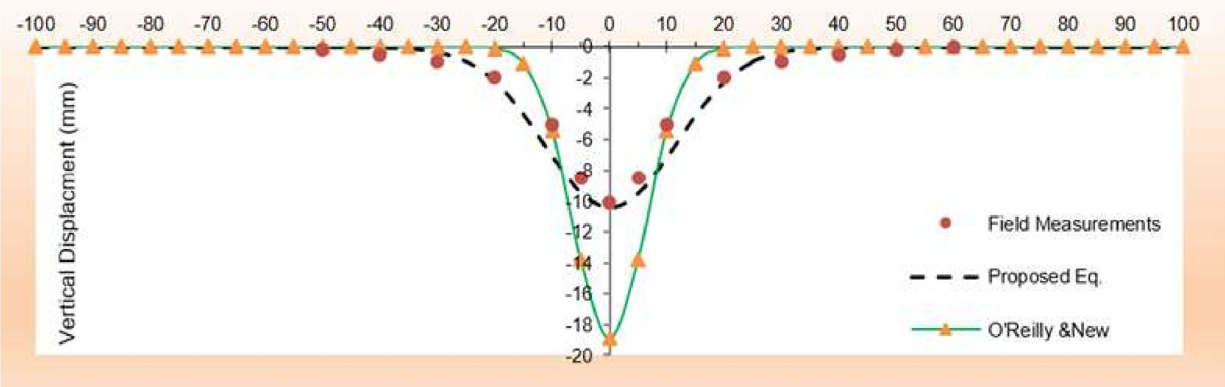

Fig10. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and O'Reilly& New for the case study

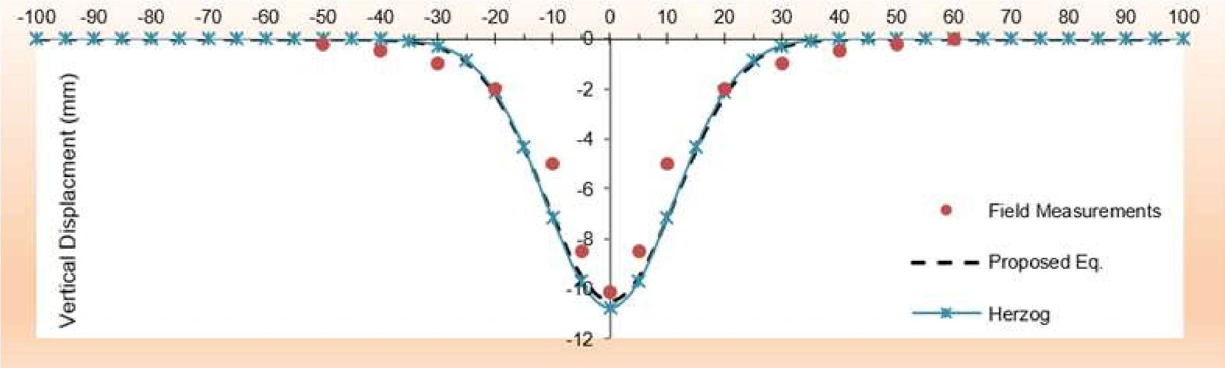

Fig11. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Herzog for the case study

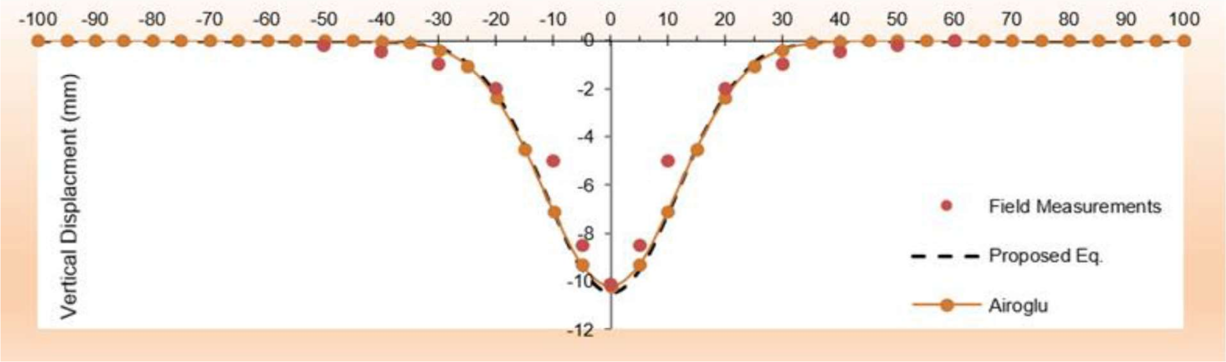

Figure12. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Arioglu for the case study

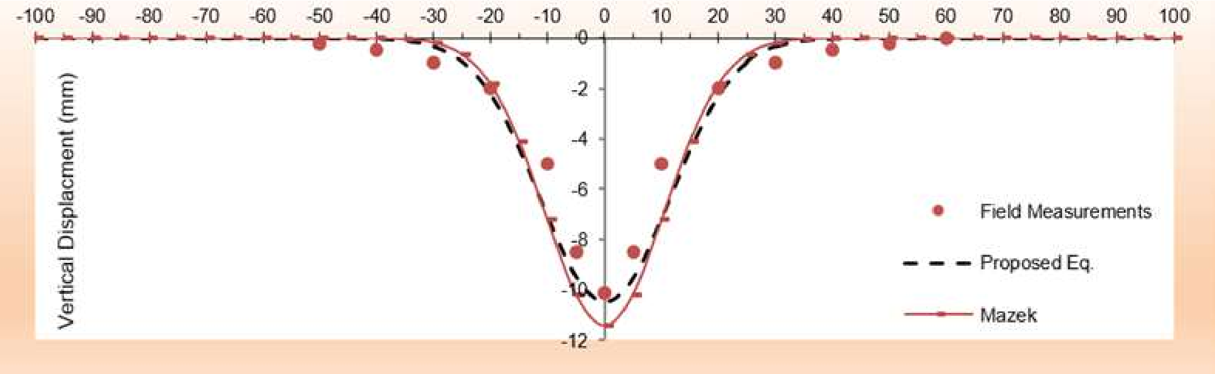

Fig13. Comparison between field measurements and vertical surface displacements calculated by the proposed equation and Mazek for the case study

By dissecting the presented results from the showed comparison in Figures 6 to 13 for different empirical solutions for surface settlement trough, it is noticed that there is good agreement between the field measurements and the computed vertical surface displacements for most of the different considered empirical methods. The main points can be summarized as follows:

- A good convergence in results for methods; Cording & Hansmire, Attewell, Herzog, Arioglu, and Mazek comparing with the field measurements and the proposed equation where the maximum surface settlement ranges from9.27-11.40 mm as shown in Fig.7, Fig. 9, Fig. 11, Fig. 12 and Fig. 13.
- A marginal agreement in results for methods; Peck and Atkinson & Potts comparing with the field measurements and the proposed equation as shown in Fig. 6 and Fig. 8.
- A noticeable diversion in results for O'Reilly and New's method comparing with the field measurements and the proposed equation as shown in Fig. 10.

These comparisons show that there are significant discrepancies between empirical solutions to predict surface settlement trough because of different interpretation and database collection proposed by different authors.

6. EXAMINATION OF THE PROPOSAL FORMULA IN DIFFERENT SAND SOIL DENSITIES

As mentioned before, most empirical solutions don't take into consideration the effect of the changed densities in the sandy soil on the surface settlement caused by tunneling. A few studies avoid this shortage such as Mazek[10]. A good solution presented by Mazek [10]by substituting in eq. 4 where the values of α and n depending on sand density and it can be summarized in table 4.

Table 4. α and n parameters for different sand soil densities, Mazek[10]

Sandy soil condition	α parameter	n parameter
loose sand	0.92-0.95	1
medium sand	0.89-0.92	1
dense sand	0.86-0.89	1
very dense sand	0.82-0.86	1

For the same case study loose, medium, dense, and very dense sand are considered around tunnel instead of the given sand layer to calculate the surface settlement due to tunneling in different cases in cohesionless soil. In this part, values of the angle of internal friction (φ) of sandy soils can be assumed as presented in table 5 for each type of cohesionless soil density based on the classification presented by Meyerhof [11].

Table 5. Angle of internal friction (φ) of different sand soil densities

Cohesionless soil density	Friction angle φ (degree)
Loose	27
Medium	32
Dense	38
Very dense	43

Based on the good agreements in results of calculation of the surface settlements due to tunneling in different densities in sandy soil depending on the pre-presented solutionby Mazek [10].Thus, the calculated vertical displacements by the proposed equation can be compared with the calculated by Mazek's solution for different densities in sandy soil.

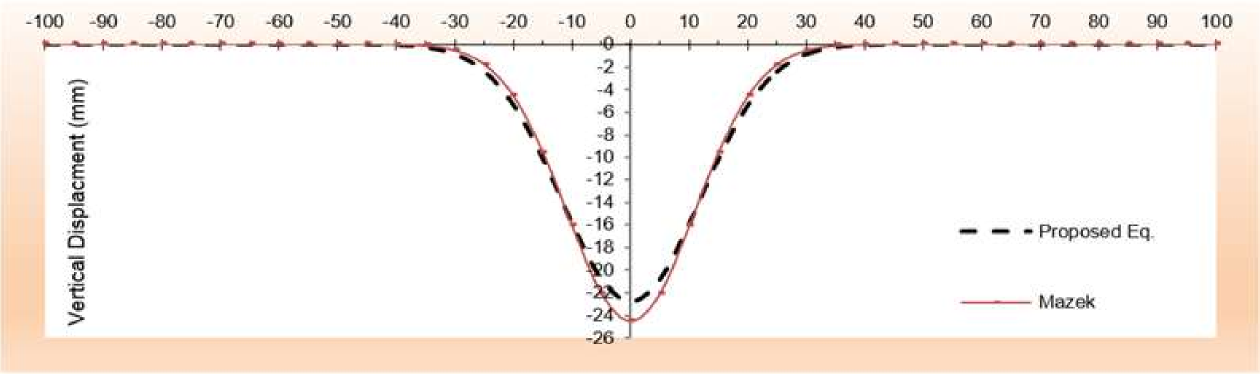

Fig14. Vertical surface displacement obtained by the proposed equation and Mazek in loose sand

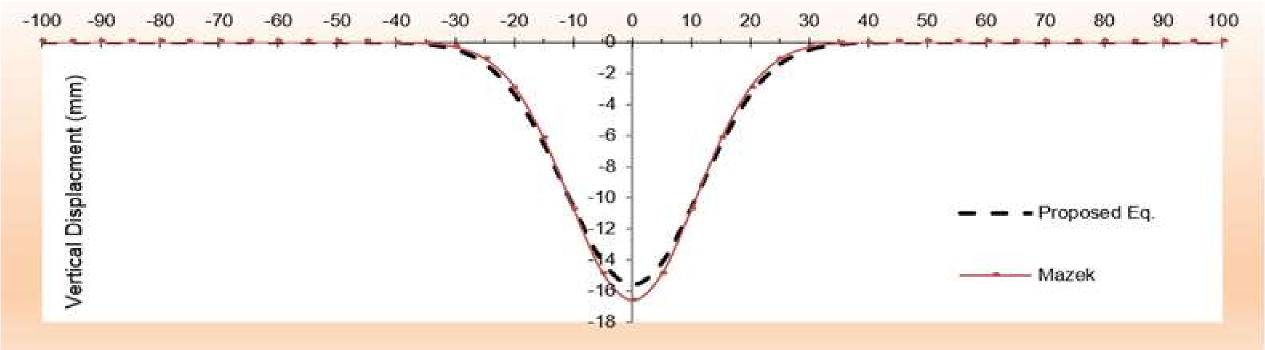

Fig15. Vertical surface displacement obtained by the proposed equation and Mazek in medium sand

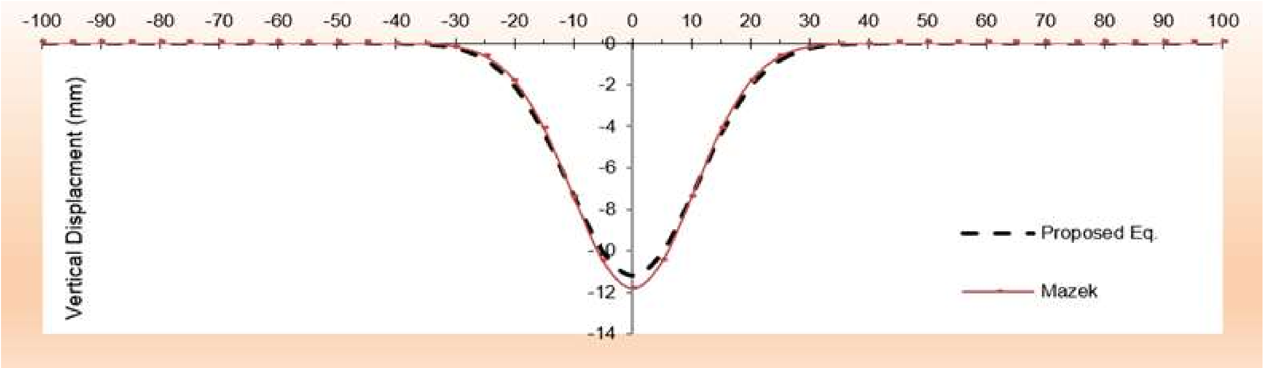

Fig16. Vertical surface displacement obtained by the proposed equation and Mazek in dense sand

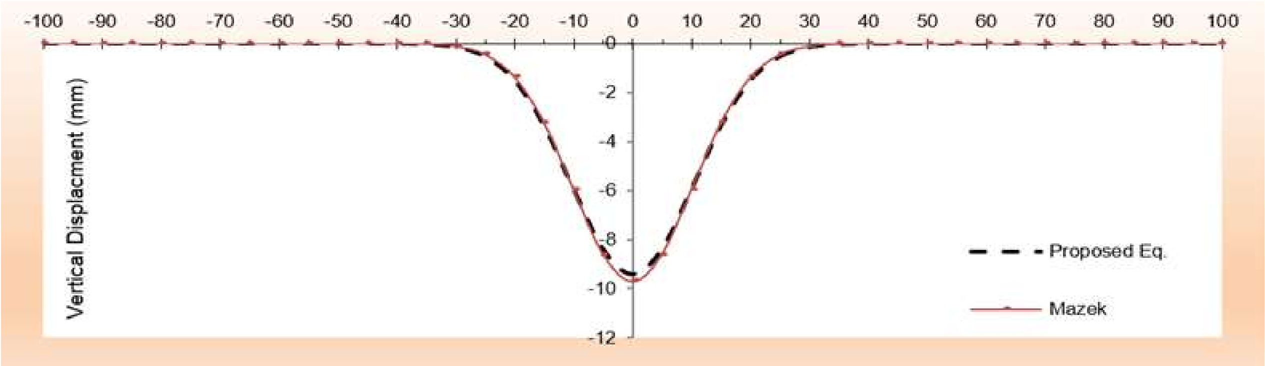

Fig17. Vertical surface displacement obtained by the proposed equation and Mazek in very dense sand

Figures 14 to 17 show a good agreement by comparing the shape of settlement trough and the vertical surface displacements calculated by the proposed equation and Mazek's solution for each different density in sandy soil. Any divergence in results in the calculated surface settlement between the two methods may be referred to the assumed range of α parameter in Mazek's solution, as it can be shown in case of loose sand as shown in Fig.14,but it give a good agreement in settlement trough shape in the same state.

7. CONCLUSIONS

Despite of unsuitability of the empirical methods for all different soil conditions and all variable site circumstances to calculate the ground surface displacements due to tunneling. However, it is preferable to using these methods because of its simplicity in the solution to get primary results. Thus it is useful to develop these methods to be suitable for different soil conditions. In this paper, a proposed formula is presented for estimating 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 results show that the maximum surface settlement obtained from the proposed equation has a better consistency with the field measurements.
- The results show that the maximum surface settlement obtained from the proposed equation has a good agreement with most of empirical solutions.
- Some of the empirical solutions didn't acceptability predict the field measurements especially O'Reilly and New's solution.

- The proposed formula is useful for forecasting the surface displacement at the different sandy soil cases, where the obtained results give a good agreement with Mazek's solution.
- The main advantage of using the proposed equation that it can be used easily more than the other solutions for different cases in sand soil, where it just need to substitute directly in the equation by internal angle of friction value of sand instead of using any assumed factors or using any charts.

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