Proceedings of 12th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: October Volume: 12

Numerical Modeling of Shallow Tunnel in Soft Ground: Surface Settlement Analysis

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Abstract

The analysis of shallow tunnel is mainly concerned with the correct evaluation of tunneling-induced ground movements. In case of shallow tunnels, these movements cause even more disturbance on the ground surface as they propagate to the surface forming the settlement basin. Among the various techniques of analysis of tunnel performance, finite element modeling is found to be much more effective. This paper presents a numerical modeling of shallow tunnel elaborated in PLAXIS 2D software. Three tunnels (Green Park, Heathrow Express and Bangkok Sewer) have been selected as case studies and simulated with analytical and experimental solutions for model validation. The idea is to employ simple constitutive model to calculate the surface settlement induced due to tunneling in soft to stiff clay. The soil mass is represented by linear elastic-perfectly plastic model using Mohr Coulomb criteria. The calculated surface settlements of tunnels have shown fairly a good result when compared to the observed field settlements, except in case of Heathrow Express Trial Tunnel which showed slight under estimation of surface settlement. Results show that the depth to diameter ratio of the tunnel (H/D) is one of the important influencing factors affecting the ground settlement.

Keywords

Shallow tunnel, surface settlement, Numerical Modeling

1. Introduction

Due to increasing population and subsequent decrease in the availability of free surface, the demand and planning of underground structures, especially tunnel projects have increased massively in recent years. The underground construction work is a very delicate one because it is often accompanied by ground deformation, which if beyond the permissible limit, can cause serious damage to existing structures. In urban areas, these projects are carried out in a soft ground, where the natural stress state of the soil mass is greatly associated with the changes in strains and displacements. As the stress state of the soil mass is disturbed due to excavation, it results in the movements of surrounding soil mass which can even propagate to ground surface in case of shallow tunnels [1].

Generally, the dimensionless ratio of depth to diameter(H/D) of the tunnel is used to differentiate the shallow and deep tunnels with 10 or smaller values considering the tunnel to be a shallow [2], however there is no accordance with this limit. Shallow tunnels are presented with the ovalized distortion in contrast to deep tunnels which are subjected to radial uniform closure because of the proximity of shallow tunnels to the free ground surface [1]. Furthermore, the magnitude of the surface settlements is higher in case of shallow tunnels with considerable maximum displacement. Therefore, the correct estimate of tunnel induced ground deformation and prediction of ground behavior has become the important component of planning process. The ground conditions, tunneling methods and technical parameters involving depth and geometry of the tunnel, tunnel diameter line grades, track lines etc. are the basic factors affecting the ground deformations [3]. The estimation of tunneling induced ground movements is a complex process involving many variables and uncertainties. It can be done by analytical, empirical or numerical methods. Among different ways, numerical design approaches are considered to be efficient for stability analysis of tunnel and underground excavations as they are convenient, economical and time saving to simulate ground movements and calculate the settlement profile. In this paper, a 2D numerical model is elaborated in a finite element software, PLAXIS to calculate and study the ground settlement.

2. Objectives

The objectives of this study are enlisted below:

1. To develop the simple constitutive numerical model with the use of best set of available data for considered ground condition.
2. To validate the numerical model by comparing with analytical and experimental solutions.
3. To study and calculate the tunneling induced ground settlements.

3. Methodology

The general steps followed to achieve the above-mentioned objectives are as follows:

3.1 Data Collection

The properties of different soil parameters and tunnel geometry and construction, materials are collected based on the previous literatures. Most of the field data except some parameters considered in this study is gathered through literature review. Hence, no data confidentiality is associated with this work.

3.2 Input Parameters

The choice of material properties plays a great role to reflect the system precisely in finite element analysis. In this study, the soil behavior is simulated by using the Mohr Coulomb Model. The parameters of the soil required by PLAXIS to carry out calculations based on this model are Young's Modulus of soil (E), Poisson's ratio of soil (ν), angle of internal friction of soil (ϕ), cohesion of soil (c'), Dilatancy angle of soil (ψ). These parametric values are chosen doing intensive literature-based review and suitable for the given soil condition from previously published research papers and articles. Then these geotechnical parameters are assigned for each layer in PLAXIS software.

3.3 Finite Element Mesh

The plane strain model, considering uniform cross section and no deformation in z- direction is used to develop the model. The mesh is generated with fine element distribution and enhanced mesh refinement.

3.4 Model Geometry and boundary condition

The lateral and bottom boundaries are located sufficient to our point of interest and where the effect of tunnel excavation would be insignificant. The boundary condition is such that the displacement boundary is fixed at the base, restrained from movement in horizontal direction in lateral sides whereas the top surface is kept free to move.

3.5 Numerical Modeling and Settlement Prediction

Surface settlement calculation is done by applying numerical methods using PLAXIS finite element software code. Various nodes at the surface, on either side of tunnel axis are selected and the surface settlement profile is drawn and compared with the experimental and analytical results from previous study.

3.6 Model Validation

The surface settlement predicted by FEM is compared with previously published papers which have followed analytical and empirical approaches and the similarities in settlement results with past work is an indication that the model is valid.

4. Modeling of Shallow Tunnel in Soft Ground

Although tunnel excavation is a 3D problem and 3D analysis would improve the surface settlement predictions [4], 2D analysis is considered to be flexible, economic and also time saving [5]. The models are created with PLAXIS 2D software considering plane strain model with 15 node element type. The mesh is generated with fine element distribution and enhanced mesh refinement. The soil mass is represented by linearly elastic perfectly plastic model using Mohr Coulomb criteria. The main parameters considered according to this model type are Young's Modulus of soil (E), Poisson's ratio of soil (ν), angle of internal friction of soil (ϕ), Cohesion of soil (c'), dilatancy angle of soil (ψ).

4.1 Green Park Tunnel

The soil profile of the Green Park tunnel consists of 2m of sand and gravel over a thick layer of London Clay which extends sufficiently below the tunnel, which is at a depth of 29.3m from the ground level, as shown in Table 1.

Table 1: Ground Model, Green Park Tunnel

Depth below ground (m)	Soil Type
0-2	Sand and Gravel
>2	London Clay
29.3	Tunnel Centerline

Table 2 shows the geotechnical parameters along with adopted values for numerical analysis of Green Park Tunnel. Suitable values for soil type consisting of sand and gravel at the top surface and host formation- London clay are adopted from the intensive literature review. Some information on subsoil properties can also be found in the work of Attewell and Farmer [6] and Loganathan and Poulos [7].

Figure 1 shows the mesh generated for Green Park Tunnel, situated at 29.4m depth from the ground level. The mesh consists of 957 elements and 7823 nodes generated with fine element distribution and enhanced mesh refinement. The displacement boundary at bottom is fixed in both horizontal and vertical direction whereas the nodes in the sides are restrained from horizontal movement but free to move vertically.

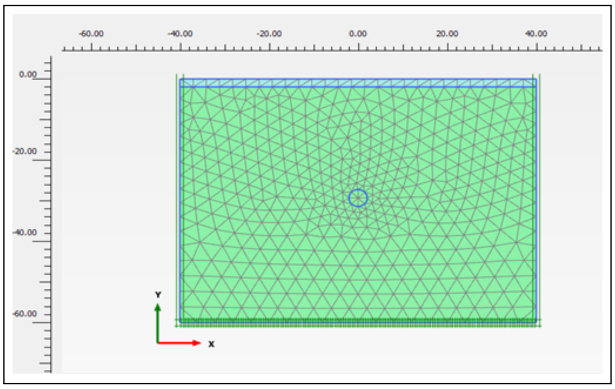

Figure 1: Finite element mesh, Green Park Tunnel

4.2 Heathrow Express Trial Tunnel

Table 3: Ground Model, Heathrow Express Trial Tunnel

Depth below ground (m)	Soil Type
0-2	Fill Ground
2-4	Terrace Gravel
>4	Stiff London Clay
19	Tunnel Center Line

The soil profile of the Heathrow Express Trial Tunnel consists of 2m of fill ground at the top surface. Underneath the fill ground, 2m thickness of terrace gravel is found overlying the stiff London Clay. The tunnel center line is at the depth of 19m from the top surface.Table 3 shows the simplified ground model of Heathrow Express Trial Tunnel.

Table 4 shows the geotechnical parameters and Figure 2 shows the mesh generated for Heathrow Express Tunnel, situated at 19m depth from the ground level. The mesh consists of 856 elements and 6985 nodes generated with fine element distribution and enhanced mesh refinement. The displacement boundary at bottom is fixed in both horizontal and vertical direction whereas the nodes in the sides are restrained from horizontal movement but free to move vertically.

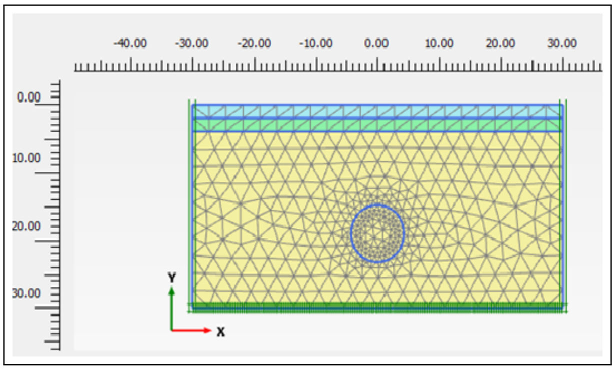

Figure 2: Finite element mesh,Heathrow Express Trial Tunnel

4.3 Bangkok Sewer Tunnel

The ground model of the Bangkok Sewer Tunnel consists of 12m thick soft clay at the top level. Underneath there is the stiff clay with thickness of about 13m which extends up to the depth of 25m. The tunnel is driven at the depth of 18m. A layer of fine to medium dense sand appears to be under the stiff clay with total thickness of about 10m. Table 5 shows the simplified ground model with soil type for Bangkok Sewer Tunnel.

Table 5: Ground Model, Bangkok Sewer Tunnel

Depth below ground (m)	Soil Type
0-12	Soft Clay
12-25	Stiff Clay
25-35	Medium dense sand
18	Tunnel Center Line

The geotechnical parameters are assigned for

Table 2: Geotechnical Parameters, Green Park Tunnel

Soil	γ_{sat} (KN/m^2)	C'(KPa)	ϕ (°)	S_u (KPa)	E' (MPa)	E_u (MPa)	ν'	ν_u
Sand and Gravel	20.5	0.2	35	-	50	-	0.25	-
London Clay	19.5	-	-	50+4.5z	-	12.5+1.07z	-	0.495

Table 4: Geotechnical Parameters, Heathrow Express Trial Tunnel

Soil	γ_{sat} (KN/m^2)	C'(KPa)	ϕ (°)	S_u (KPa)	E' (MPa)	E_u (MPa)	ν'	ν_u
Fill Ground	18	0.2	30	-	20	-	0.3	-
Terrace Gravel	19.5	0.2	-	-	75	-	0.3	-
Stiff London Clay	19.5	-	-	50+7.33z	12.5+1.5z	-	-	0.49

undrained condition to analyze the short-term settlement produced due to tunnel excavation based on the field observations done by Phienwej [8] (refer Table 6). Similarly, on the basis of finite element back analyses done by Taparaksa [9], Phienwej [10] and Mirjalili [11], suitable Eu/Su ratio is adopted for the sub soil consisting of soft and stiff clay in Bangkok.

Figure 3 shows the finite element mesh generated for Bangkok Sewer Tunnel, situated at the depth of 18m from the ground level. The mesh consists of 662 elements and 5437 nodes generated with fine element distribution and enhanced mesh refinement. The displacement boundary at bottom is fixed in both horizontal and vertical direction whereas the nodes in the sides are restrained from horizontal movement but free to move vertically.

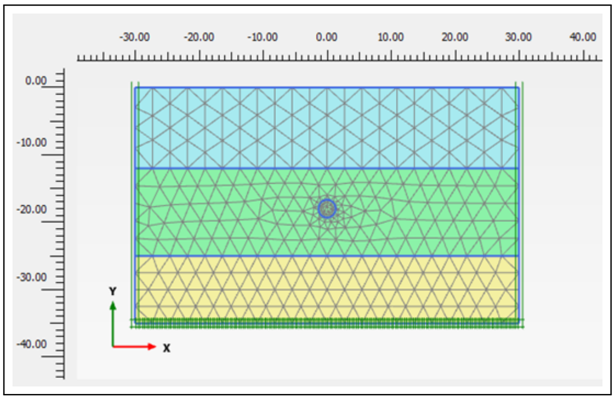

Figure 3: Finite element mesh, Bangkok Sewer Tunnel

5. Results

The Green Park tunnel- previously described by Attewell and Farmer [6] and analyzed by Loganathan and Poulos [7], The Heathrow Express Trial Tunnel- previously described by Deane and Bassett [12] and analyzed by Loganathan and Poulos [7] and The Bangkok Sewer Tunnel- previously described by Phienwej [8] and analyzed by Loganathan and Poulos [7] are studied with a 2D plane strain FEM to see if the settlement profile can be drawn that would resemble the observed field data employing a linear elastic perfectly plastic constitutive law. The numerical analysis has shown a good match with the short-term displacements produced with field observations and analytical results. Figure 4, 6 and 8 show the total vertical displacements of the soil occured due to tunnel excavation in Green Park, Heathrow Express and Bangkok Sewer Tunnel respectively. The nodes are selected on the surfaces at some distances away from the centre line for all three tunnels to record the surface settlement at those position as well and the recorded values are shown in table 7, 8 and 9 and the settlement profile is compared with experimental and analytical results (refer figure 5, 7 and 9).

5.1 Green Park Tunnel

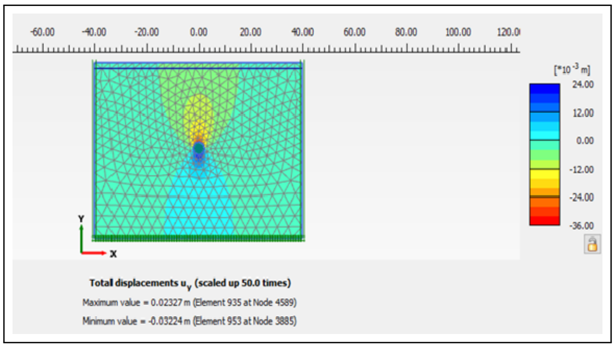

Figure 4: Total vertical displacement, Green Park Tunnel

Table 6: Geotechnical Parameters, Bangkok Sewer Tunnel

Soil	γ_{sat} (KN/m^2)	C'(KPa)	ϕ (°)	S_u (KPa)	E' (MPa)	E_u (MPa)	ν'	ν_u
Soft Clay	16	-	-	20	-	10	-	0.4
Stiff Clay	17	-	-	50	-	20	-	0.4
Medium Dense Sand	20	5	35	-	70	-	0.25	0

Table 7: Calculated Surface Settlement, Green Park Tunnel with Horizontal Distance from center line

SN	Horizontal Distance (m)	Settlement (mm)
1	0	5.55
2	5	5.22
3	10	4.40
4	15	3.59
5	20	2.76

Table 8: Calculated Surface Settlement, Heathrow Express Trial Tunnel with Horizontal Distance from center line

SN	Horizontal Distance (m)	Settlement (mm)
1	0	26
2	5	20.03
3	10	14.25
4	15	9.00
5	20	5.84

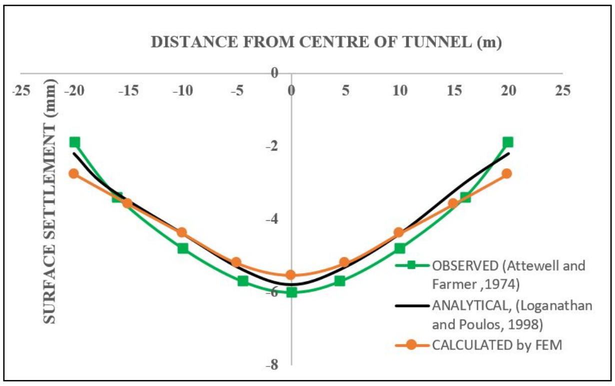

Figure 5: Comparisons of Surface Settlements (Vertical displacements at ground surface), Green Park Tunnel

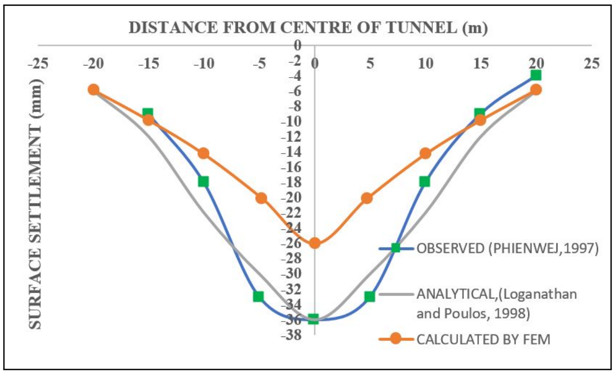

Figure 7: Comparisons of Surface Settlements (Vertical displacements at ground surface), Heathrow Express Trial Tunnel

5.2 Heathrow Express Trail Tunnel

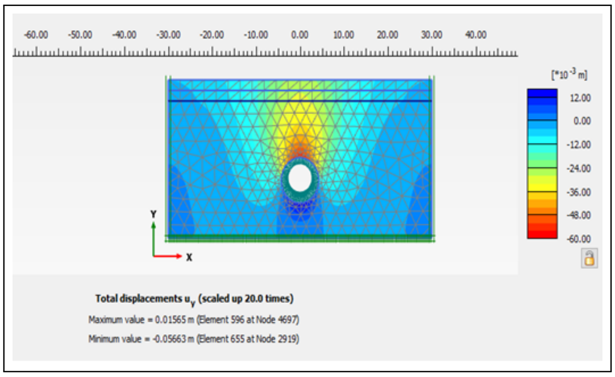

Figure 6: Total vertical displacement, Heathrow Express Trial Tunnel

5.3 Bangkok Sewer Tunnel

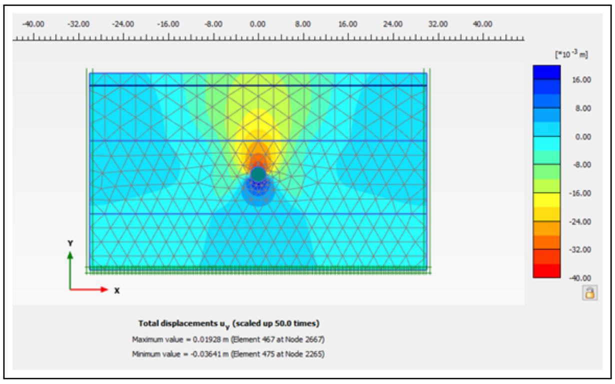

Figure 8: Total vertical displacement, Bangkok Sewer Tunnel

Table 9: Calculated Surface Settlement, Bangkok Sewer Tunnel with Horizontal Distance from center line

SN	Horizontal Distance (m)	Settlement (mm)
1	0	13
2	5	11
3	10	7
4	15	2.78
5	20	2.19

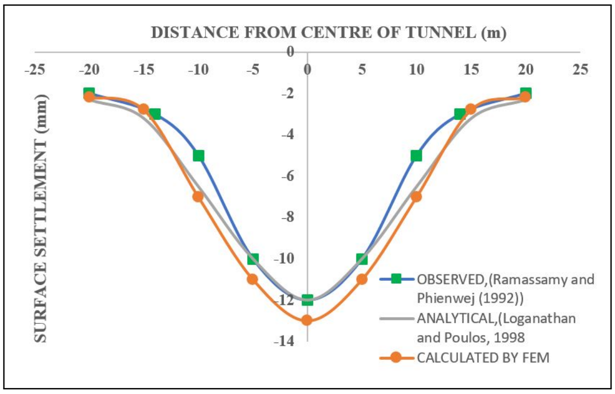

Figure 9: Comparisons of Surface Settlements (Vertical displacements at ground surface), Bangkok Sewer Tunnel

6. Conclusion and Recommendation

In this paper, three real tunnels are analyzed using PLAXIS 2D finite element software to predict the ground settlement and produce the settlement profile to check if it would resemble to the actual field measurement. All the geotechnical parameters are assigned with the most realistic values, considering the stratification of soil mass. The three case studies considered encompass the tunnels built in over consolidated soft to stiff clay at a depth of 18m to 30m with tunnel diameter ranging from 2.5m to 8.5m. The depth to diameter ratio of the tunnel and strength and stiffness parameter,which includes shear strength and Young's Modulus of soil are found to be major influencing factors in the settlement. To study the impact of tunnel geometry and H/D in a more detailed way, different values of tunnel depth and diameter were also tried for which the maximum settlement has also behaved accordingly. The low cover to diameter ratio in Heathrow Express Trial Tunnel (H/D=2.22) has produced significant surface settlement, whereas the Green Park Tunnel (H/D=7) and Bangkok Sewer Tunnel (H/D=6.7) have produced comparatively less surface settlement. Furthermore, the maximum settlement in case of shallow tunnel produces bigger values in comparison to deeper tunnels which seem to provide lesser vertical displacements. The use of FEM approach used in this paper could provide realistic settlement values for other soft ground conditions as well as the empirical and analytical methods are suited to particular ground conditions and tunnel geometry and these approaches are limited to very few parameters so their applicability in varied soil conditions is a matter of concern. However, proper use of input parameters can play significant role in the result of PLAXIS analysis.This study encompasses the three tunnels built in soft to stiff clay and is limited fairly by the narrow sets of parameters. Similar studies can be done in the future considering structural parameters as well, and covering wide range of soil conditions.

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