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NUMERICAL ANALYSIS OF SHALLOW TUNNELS IN SOFT GROUND USING PLAXIS2D

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Abstract— Numerical modelling is found to be very effective for determining the perfomance of a tunnel system. The calculation of settlements and movements to adjacent soil and structures caused by tunneling is a significant challenge faced by geotechnical engineers. This thesis represents numerical modelling of a shallow tunnel in soft ground using PLAXIS 2D. Thus making it possible to evaluate the displacements due to tunneling. A comparative study of analytical and numerical methods were carried out. Then , model validation was done by comparing with the values drawn from the literature. Also carried out a parametric study to find out the influence of various geometrical parameters on the performance of the tunneling. Lastly, evaluated the behaviour of tunnel due to the presence of structures near the tunnel. Results obtained shows a good agreement with those in literature.
Index Terms— Deformed mesh, Finite element modelling,Model Validation, Numerical Modelling, Plaxis, Shallow tunnel

1 INTRODUCTION

With an increasing population and expanding urban areas, there is a need for tunnels that are used for efficient transportation, water supply, sewage disposal and communications. In urban areas, tunnelling is often out in soft ground and this process inevitably leads to a change in stress state of the ground with associated changes in strains and displacements, which could potentially result in damage to existing surface and subsurface structures. In low permeability soils, a change in stress state induces excess pore pressures that, in the long-term, dissipate into a new equilibrium regime leading to further ground displacement and complex loading on tunnel supports. As part of the planning process, knowledge of the magnitudes of these ground displacements is often required. Finite element analysis can be used for predicting these ground movements and ground loading on the tunnel lining.

1.1 Importance of Tunnel Analysis

A number of collapses of shallow tunnels excavated in soils with 'manual' or mechanical methods have occurred in the past due to inadequate support considered for the openings or other unforeseen conditions in the ground. Now a days there are many metro tunnel projects are doing in India, mainly for transportation and also for other purposes. Hence studies of analysis of tunnels are required.

Economic yet safe and flexible designs of tunnel supports can be achieved with better understanding of the relationships that govern the stability of shallow tunnels, especially the relationship between support pressure, soil cover above the tunnel, size of the tunnel and the mechanical strength of the ground hosting the tunnel. Such understanding could be gained by availability of simple analytical relationships that allow examination of the dependence of variables involved in the problem. Perhaps more important, these analytical relationships can allow implementation of probabilistic analyses for computing probability of failure (and therefore reliability of designs) for tunnel fronts and sections, as it is current practice for other geotechnical structures, such as natural and man-made slopes (including embankments).

In the present study, finite element technique is used to model tunnel system performance based on the case study. The effects are expressed in terms of surface displacement and soil stress change caused by tunnelling. The subsoil stresses undergo three phases of change. At these phases, the loading steps of the tunnel construction are predicted using the 2-D finite element analysis. Ground movement and construction influence are obtained by the numerical model.

Several tunnels have been constructed around the world and in Egypt to solve the transportation problems such as the Greater Cairo metro and the El-Azhar road tunnels .These tunnels are considered as major projects in Cairo city. There are technologies to assist in excavation such as tunnelling boring machine (TBM), new Austrian tunnelling method (NATM), immersed-tube tunnelling system, and cut and cover method. It is necessary to investigate the geotechnical problems for better understanding the performance of the tunnel system. Many geotechnical problems were encountered during the construction of the Greater Cairo metro, El-Azhar road tunnels, and the Greater Cairo sewage tunnel. Most problems are related to the damage of surrounding buildings due to surface and subsurface ground subsidence. Finite element method is considered as the most appropriate analytical technique to solve geotechnical problems.

2 SHALLOW TUNNEL ANALYSIS

Construction of shallow tunnels in soft clay can result in significant surface settlements. since tunnel construction often takes place beneath urban areas, engineers are faced with the problem of predicting these settlements.In most analysis of geotechnical problems, simple elastic or elastic-plastic models are used to represent the behaviour of soils. However, in the analysis of shallow tunnelling, this simplification can result in inaccurate predicted settlement profiles. A more practical model which can account for the realistic behaviour of soils is required.

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2.1 PLAXIS

Plaxis is a finite element programme for geotechnical applications in which soil models are used to simulate the soil behaviour. Plaxis code and soil models are developed with greater care. Plaxis 2D Tunnel is a finite element package that has been developed specifically for the analysis of deformation and stability in tunnel projects. The simple graphical input procedures enable a quick generation of complex finite element models and the enhanced output facilities provide a detailed presentation of computational results.Software is based on the finite element method and intended for 2-Dimensional and 3-Dimensional geotechnical analysis of deformation and stability of soil structures, as well as groundwater and heat flow, in geo-engineering applications such as excavation, foundations, embankments and tunnels. Input features includes;

- Automatic mesh generation
- Graphical input of geometry model
- Plates
- Structural elements
- Point loads
- Distributed loads

In Plaxis the following soil models are available: Linear elastic, Mohr-Coulomb, Hardening Soil and Soft Soil Creep model. In addition to these soil models an anistropic model for rock is offered: The Jointed Rock model: This is an anistropic elasto-plastic model where plastic shearing can only occur in a limited number of shearing directions. This model can be used to simulate the behaviour of stratified or jointed rock.

2.2 Objectives Of Proposed Work

The main objective of proposed work is to establish an appropriate soil model for the prediction of the settlement profile due to the construction of a single shallow tunnel in soft ground. Since field observations have shown that a significant part of the total settlement occurs over a relatively short period during tunnel construction in clays, undrained conditions are investigated. The determination of surface settlements is an important aspect of the shallow tunnelling problem. The use of finite element methods for this purpose has been continually growing and it has become the most efficient tool for this goal. Analytical methods are also useful for checking numerical analysis. Although, the tunnel excavation process is a 3D problem, 2D analysis provide a good insight into the issue and reduce computational needs and time.

2 GEOTECHNICAL PROBLEMS DUE TO TUNNELLING

The prediction and mitigation of damage caused by construction-induced ground movements represents a major factor in the design of tunnels. This is an especially important problem for shallow tunnels excavated in soft soils, where expensive remedial measures such as compensation grouting or structural underpinning must be considered prior to construction. Ground movements arise from changes in soil stresses around the tunnel face and the over-excavation of the final tunnel cavity, often referred to as ‘ground loss’. Sources of movements are closely related to the method of tunnel construction ranging from a) closed-face systems such as tunnel boring machines (with earth pressure or slurry shields), where overcutting occurs around the face and shield (‘tail void’) while local ground loss is constrained by grout injected between the soil and precast lining system; to b) open-face systems (such as the New Austrian Tunnelling Method, NATM) where ground loss around the heading is controlled by expeditious installation of lining systems in contact with the soil (typically steel rib or lattice girder and shotcrete) with additional face support provided by a shield or other mechanical reinforcement (soil nails, sub-horizontal jet grouting etc.). In all cases, it is easy to appreciate the complexity of the mechanisms causing ground movement and their close relationship with construction details, especially given the non-linear, time dependent mechanical properties of soils, and their linkage to groundwater flows. This complexity has encouraged the widespread use of numerical analyses, particularly non-linear finite element methods, over a period of more than 30 years (e.g., review by Gioda & Swoboda, 1999). Although these powerful numerical analyses undoubtedly provide the most comprehensive framework for modeling tunnelling processes and interactions with other existing structures (e.g., Potts & Addenbrooke, 1997), their predictive accuracy is also closely tied to the knowledge of in situ conditions and the modeling of soil behaviour.

4 METHODOLOGY

- Data collection from reported case studies
- By using the laboratory data and field observation justifying the range of parameters assigned in the analysis.
- First of all, establishment of conceptual model according to the data collected.
- Determination of the usage of Finite Element Method by PLAXIS 2D program , as it is suitable for the study.
- Justifying the parameters of input in the program according to the data collected.
- Before the computational analysis, the PLAXIS 2D program is verified by comparing the numerical method with analytical method .
- The numerical analysis will be carried out after verifying the program as reliable.

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- The validated model obtained from the present study will be used to evaluate the behaviour of the reported case studies of tunnels in India.

5 ANALYSIS AND MODELLING OF SHALLOW TUNNELS IN SOFT GROUND

The forecast of settlement and movements caused by tunneling represents a significant challenge of technology. The evaluation of these movements is indeed of primary importance in order to prevent them. The methods of calculation making it possible to evaluate displacements and deformations in the ground due to tunneling give only one approximation of the true amplitudes of the movements in the ground. It is one of the assets of the Finite Element Method (FEM) which makes it possible a prior to treat configurations more complex and closer to reality. Our objective in this study is to calculate numerically the various movements caused by the construction of a shallow tunnel using a shield using PLAXIS 2D, the behavior of the ground is described by a perfectly plastic elastic model based on the criterion of Mohr-Coulomb.

Soil conditions for tunnels are selected and properties of soil regarding different parameters were collected from literature. Parameters are selected based on the soft ground tunnelling. Hypothetical modelling done with uniform soil condition like uniform sand or clay. After analysing the model for uniform soil condition modelling carried out for mixed soil condition.

6 MODEL VALIDATION

6.1 Presentation of The Calculation Model

It is about a sandy ground which consisted of only one layer (Fig. 1), where a tunnel was built. The characteristics of the model are drawn from the literature, and they will be modified one by one in order to see the behavior of the ground in response to each modification.

Our initial objective is to evaluate the movements (vertical and horizontal) generated by the construction of a tunnel by the technique of the shield. In the presentation of the results, we will be interested in settlements and displacements induced after digging, because the concept of safety in underground constructions relates displacements to constraints. In the second part, the problem of the influence of the construction of a tunnel on a building will be exposed at various levels in terms of settlements on the surface.

6.2 Geometry And Data of The Model

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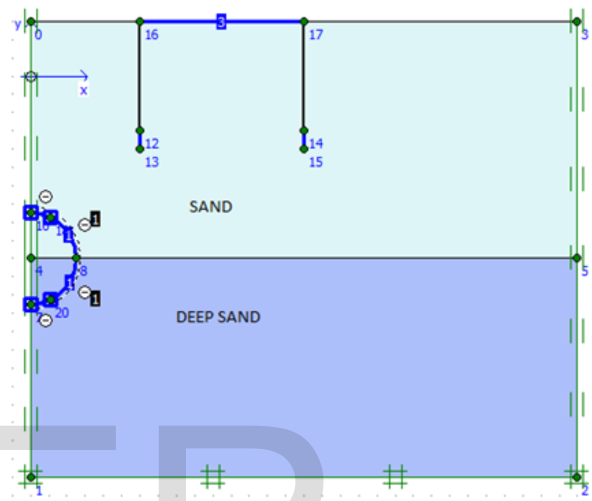

Fig . 1. Geometry of the tunnel project with an indication of soil layers

6.3 Characteristics of Materials

The properties of the ground and the lining which PLAXIS needs to be able to carry out calculations are summarized in Table 1. These characteristics of materials are choosen from the selected literature based on the needed soil condition. Then the material properties are assigned using plaxis to each layer. Also properties of lining assigned to the tunnel lining.

6.4 2D FE Numerical Modeling

The mesh selected is presented in Fig. 2. In this example, the element with 15 nodes is employed. The model is symmetrical, then, only a half of the model is studied. The mesh includes 320 triangular elements and 2698 nodes. There must be relatively regular elements and of small size near the tunnel; on the one hand to obtain a good estimate of the initial state and on the other hand to obtain a field of more displacement. The mesh will be more refined on the level of the tunnel, because of the concentration of constraints at these places.

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TABLE 1
Characteristics of the soil and lining

SOIL PROPERTIES		UNIT
Type of model	Mohr Coulomb	-
Type of behavior	Drained	-
Soil weight above phr.level	17	kN/m3
Soil weight below phr.level	21	kN/m^3
Young modulus	1.2 x 105	kN/m^2
Poisson's ratio	0.3	-
Cohesion	1	kN/m^2
Angle of friction	33	Degree
Angle of dilatancy	3	Degree
LINING PROPERTIES		**UNIT**
Type of behavior	Elastic	-
Normal rigidity	1.4 x 107	kN/m
Rigidity of inflection	1.43 x 105	kNm^2/m
Equivalent thickness	0.35	M
Weight	8.4	kN/m/m
Poisson's ratio	0.15	-

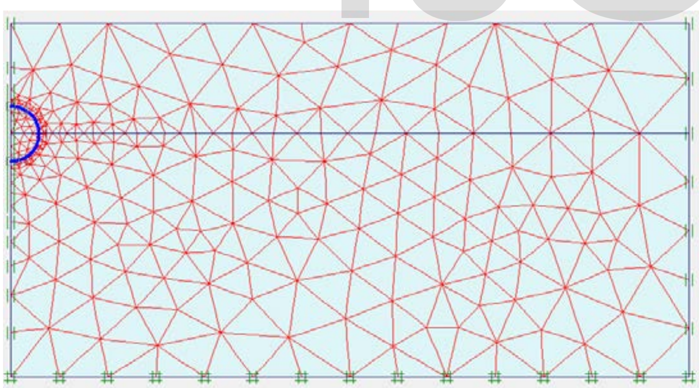

Fig. 2. Finite Element Mesh

TABLE 2
Material properties of the plates

Parameter	Name	Lining	Piletoe	Building	Unit
Type of behaviour	Type	Elastic	Elastic	Elastic	
Normal stiffness	EA	$1.4.10^{7}$	2.10^{6}	1.10^{10}	KN/m
Flexural rigidity	EI	$1.43.10^{5}$	8.10^{3}	1.10^{10}	KNm^2/m
Equivalent thickness	D	0.35	0.219	3.464	M
Weight	W	8.4	2.0	25	KN
Poisson's ratio	v	0.15	0.2	0.0	-

TABLE 3
Material properties of the anchors

Parameter	Name	Pile	Unit
Material Type	Type	Elastic	
Normal stiffness	EA	2.10^{6}	KN
Spacingbetween	$L_{spacing}$	1	m
Anchors			

6.5 Generation of Hydraulic Conditions

The generation of pore water pressure will be carried out starting from the phreatic level (Fig. 3) at a level of y = 0.The voluminal weight of water is taken equal to 10 kN/m3.

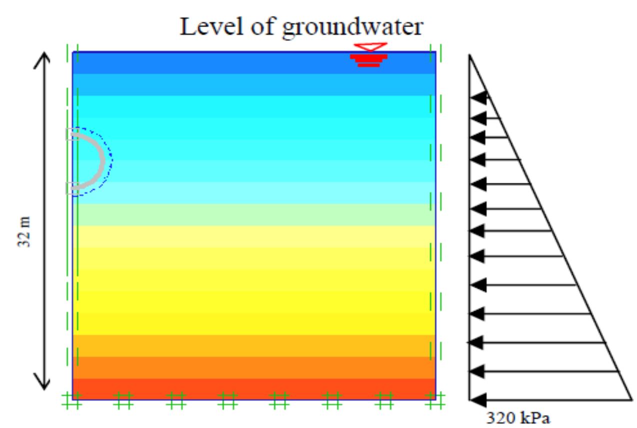

Fig. 3. Generation of the initial pore water

6.6 Generation Of Initial Constraints

In order that PLAXIS calculates the initial constraints, it is necessary to decontaminate the structural elements (tunnel lining), by taking the values of K_0 by defect. The value of the coefficient of grounds at rest is calculated by the software by defect using the formula of Jaky (K_0= 1- sin ϕ). (Fig. 4)

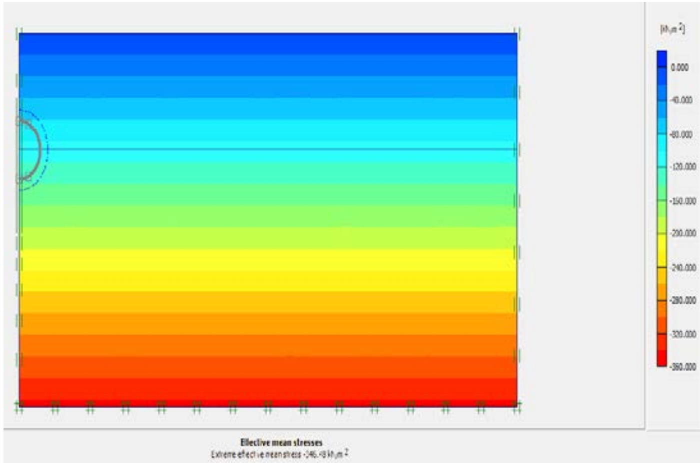

Fig. 4. Generation of the field of initial constraints

6.7 Analysis And Discussion of The Results

The major calculated stress rate is about 346.48 kN/m². Maximum stress obtained at a depth of 20 m from tunnel center. (TABLE 4) .Here the negative sign shows the pressure stresses. Effective stress can be plotted using contour shading and principal directions varying with depth is shown in the Fig 4.

TABLE 4
Results

Constraints	Numerical calculations	Analytical calculations
Maximum effective stress: σ′=σ-Uw	348.85 kPa	346.48 kPa

7 PARAMETRIC STUDY: EFFECTS OF GEOMETRICAL AND GEOTECHNICAL PARAMETERS

The impact of the tunneling on the soil depends on various factors, such as the deformation properties of the soils met and their stratification, the size tunnel, its form and its depth, the method of execution adopted and the succession of the various phases of construction. In this section, we will study the influence of depth and diameter of the tunnel, as well as certain mechanical characteristics, such as the coefficient of the grounds at rest, the angle of friction, the Poisson's ratio and the angle of dilatancy on the movements in the soil. The behaviour of tunnel can be analysed by changing the geometrical and geotechnical properties. Study includes;

- Effect of Diameter of the Tunnel
- Effect of Coefficient of the Grounds at Rest (K_0)
- Effect of Angle of Friction of the Ground (ϕ)
- Effect of Poisson's Ratio (ν)
- Effect of Angle of Dilatancy (Ψ)

TABLE 4
Influence of diameter of the tunnel on the movements of the ground

Diameter (m)	Effective stress (kPa)	Vertical diplacements (mm)	Horizontal displacements (mm)
4	299.05	33.57	19.83
5 (model of ref.)	346.48	44.73	24.52
6	300.13	53.99	28.80

TABLE 5
Influence of coefficient of the grounds at rest

Ko	Effective stress (kPa)	Vertical displacements (mm)	Horizontal displacements (mm)
0.455 (model of ref.)	346.48	44.73	24.52
0.5	363.63	45.06	24.68
1	545.23	45.03	24.75

TABLE 6
Influence of ϕ

Angle of friction	Effective stress (kPa)	Vertical displacements (mm)	Horizontal displacements (mm)
30°	302.89	46.25	24.22
33° (model of ref.)	346.48	44.73	24.52
38°	278.46	46.25	24.22

TABLE 7
Influence of ν

ν	Effective stress (kPa)	Vertical displacements (mm)	Horizontal displacements (mm)
0.1	292.17	44.28	24.51
0.3(model of ref.)	346.48	44.73	24.52
0.4	309.73	44.08	24.57

TABLE 8

Influence of angle of dilatancy ψ

Angle of dilatancy ψ	Effective stress (kPa)	Vertical displace-ments (mm)	Horizontal displace-ments (mm)
0	399.94	46.02	24.42
3 (model of ref.)	346.48	44.73	24.52
5	287.53	42.65	24.69

8 CONCLUSION

As mentioned in pervious sections, in tunnel excavation projects and underground maintenance, stress redistribution and soil deformations due to tunnel excavation cannot negligible. Indeed the programs in construction and post construction stage are affected from this matter. Stress variation around the tunnel is important in selection of tunnel concrete lining or types and amount of forces has generated in supports. Overall, the results of this investigation showed the ability of a 2D elastoplastic finite element analysis to evaluate the deformations induced in residual soils by shallow tunnel excavations. Key elements in such simulations are: 1)the use of advanced constitutive models, calibrated using the results from careful laboratory testing programs, 2) the use a finite element code capable of accommodating problems in the tunnel construction stages, and 3) the determination of coefficients proposed in this study to simulate the tunneling process. Ground movement and construction influence are obtained by the numerical model. Ground loss is an important parameter effect on the performance of the metro tunnel system. A 2-D numerical model is applicable to analyze and predict the detailed performance of the tunnel system. The soil is generally over-excavated, which means that the cross sectional area occupied by the final tunnel lining is always less than the excavated soil area. Although measures are taken to fill up this gap, one cannot avoid stress re-distributions and deformations in the soil as a result of the tunnel construction process. To avoid damage to existing buildings or foundations on the soil above, it is necessary to predict these effects and to take proper measures. Such an analysis can be performed by means of the finite element method.

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