Effect of Stratification on Underground Opening: A Numerical Approach

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Abstract Due to the increase in urbanization and requirement of rapid transportation and storage purpose, the demand for various underground structures has been exponentially increased. Underground structures like tunnel, subways, and storage tank have been constructed to fulfill the requirement of the urban society. In the present paper, two-dimensional finite element analysis has been performed using finite element program, ABAQUS. The settlement and the effective stresses in the tunnel liner due to the stratification of soil have been analyzed. The geostatic stress of soil has been calculated to fix the initial condition of site which is used for simulating the other phase of construction. It has been found that stratification has not much affected the stresses on the liner. Maximum value of stresses has been observed at the Springer level and crown level. However, the vertical displacement has been reduced by 27% when the silty sand (SM) layer moves closer to the crown of opening. Lateral displacement has not much affected by the stratification. However, the maximum value of lateral displacement was reported near mid-axis of opening in each case.

Keywords Transportation · Urbanization · Underground · Structure · Finite element method · Springer level

1 Introduction

For the better facilities and employment purpose, most of the people have been migrating to the metro cities which lead to increase in urbanization. Various surveys have been done to predict the population of the metro cities for providing the required infrastructure and facilities. A report of UN-Habitat (2008) has shown that 50% of

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the world's population now lives in cities and the rate of urbanization is such that this proportion will reach 70% up to 2050 [10]. Despite this huge pressure, the protection of natural spaces and provision of good facilities remains a major challenge in the effort to limit horizontal urban drift. The influence of these two constraints, i.e., huge pressure and property economics, leads mechanically to the vertical development of urban area [3].

Owing to advancement of the technology, various methods have been developed for the excavation of underground opening. Mechanized tunneling like (NATM) has proved well-established tunnel construction technique to excavate tunnels in complex ground conditions as well as in vulnerable built-up areas. NATM has characterized by a repeated sequence of these individual steps: The pressure of the TBM through hydraulic jacks that has concurrent with the excavation of the soil at the face by the cutter head and the installation of a tunnel lining with synchronous tail void grouting.

2   Previous Studies

Several parameters have been found responsible for the deformation and the stresses in the lining of the tunnel such as depth of the tunnel, types of soil, liner material, diameter of tunnel, surcharge loading (e.g., building and seismic loading, stratification of soil, etc.). Very few researches have been found which deal with the layering effect on liner. Nunes and Meguid [11] had evaluated the effects of overlying sandy layers above a tunnel excavated in soft ground. They had concluded that the bending stresses reduce up to 70% when the stiff layer (sand) was closer to the tunnel as compared to the case of homogeneous clay. The volume loss (the ratio of the difference between excavated soil volume and tunnel volume over excavated soil volume) in stratified soil had influence on the deformation and stresses of underground opening as reported by Mazek and Almannaei [10]. They observed that 1.5–4.5% of volume loss influences the stresses and displacement in underground opening. Similarly, Katebi et al. [7] had performed a finite element analysis and observed the existence of surface buildings in layered soil under 2D plane-strained condition. It was observed that bending moment increases 20% when depth of tunnel varied up to 2 times the tunnel diameter as compared to the greenfield condition. Zhang et al. [14] had also investigated the influence of the layered soils in terms of their relative stiffness and thickness of layer on the lining behavior. It had been observed that, for two-layered soil conditions, the increase of the relative stiffness of the overlying sandy layer leads approximately to 45% reduction of the bending moment and 50% reduction of the convergence and for a three-layered soil condition, the increase of the relative thickness of the sandwiched clay layer leads to an increase of approximately 90% of both the moment and the convergence. The soil structure interaction played the important role to improve the computed surface settlement trough for Shanghai soft clay in layered soil. Soil structure interaction has modified the result for estimating the horizontal and vertical displacement. The Horizontal displacement had increased by 21% in layered soil when considering the soil structure interaction as compared

to greenfield condition studied by the Bian et al. [4]. Effect of seismic wave on liner in stratified soil had been studied by several researchers (e.g., [1, 2, 5, 9]).

2.1 Geometric Modeling

The tunnel has been considered as a circular shape with diameter of 8 m and to be constructed at a depth of 18.3 m below the ground surface. Stresses and displacement have been measured on the tunnel invert, springing zone, and crown level by numerical approach. Length and height of soil domain have been chosen in such a way that it simulates the actual behavior of the tunnel in the field condition. Boundaries are adopted at 7.5 d from center of the tunnel from various sensitivity analyses as shown in Fig. 1, where d is the diameter of the tunnel equal to 8 m. At the lateral boundaries, displacements perpendicular to boundaries have restrained, whereas fix support has been applied to the bottom boundary.

2.2 Constitutive Material Modeling

Tunneling in the soft soil has proved difficult task due to volume loss (e.g., shield loss, tail void loss, lining losses, uncertainty in soil behavior, etc.). To understand the response of liner in stratified soil, two types of soil have been chosen in this study as shown in Fig. 3. Soil domain has been modeled by using Mohr–Coulomb's constitutive model with nonassociative flow rule, and liner has discretized by elasticity model in finite element program. In this study, shield tunneling has simulated by considering the suitable stiffness of liner material as shown in Table 2. Physical and
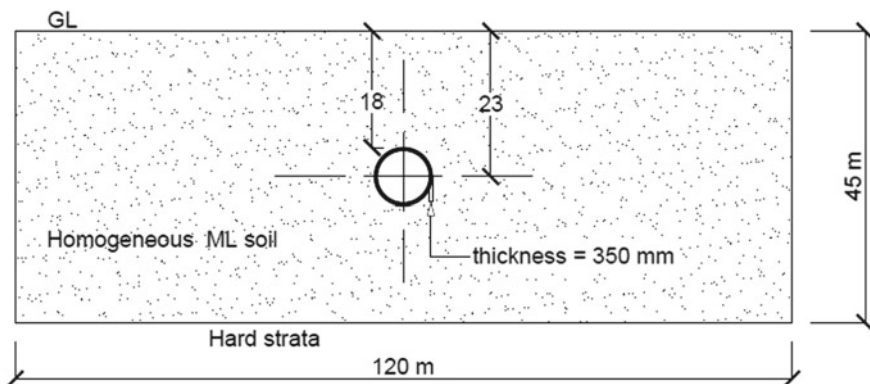

Fig. 1 Geometric features of the present study

mechanical properties of soil and lining material have been taken from the research paper of Katebi et al. [7].

3   Numerical Modeling

Although empirical–experimental method has been developed to analyze the forces and deformation in tunnel liner, they have limited application due to various assumptions to calculate the required output in a particular problem. The advancement of technology has developed various numerical techniques of analysis in all fields of engineering on the basis of DEM, FEM, LEM, FDM, etc. to expedite the computational process. Several different approaches have been developed to represent the soil structure within a constitutive modeling framework, but Mohr–Coulomb's plasticity is one of the most popular methods widely used for modeling the soil domain in the finite element program.

In this study, it has been assumed that the behavior of the tunnel liner is linear elastic and that of the ground is governed by an elastic-perfectly plastic constitutive relation. In this study, numerical simulations have been performed by means of ABAQUS a finite difference element solver. Tunnels have often 3D model (e.g., [8, 12]) but it need extra computational resources, hence 2D modeling has been preferred as many researchers (e.g., [6, 13]) have simulated the same. Soil domain and liner material have been discretized by a four-node bilinear plain strain quadrilateral, reduced integration, and hourglass control (CPE4R). Mesh type and size have been selected by several sensitivity analyses which not influenced the result. Mesh consists of 21,161 quad-type elements uniformly spaced in soil domain and 92 elements in liner material. For avoiding the distortion of element, local seed has also been adopted as shown in Fig. 2. Numerical analysis has been simulating in the following three steps.
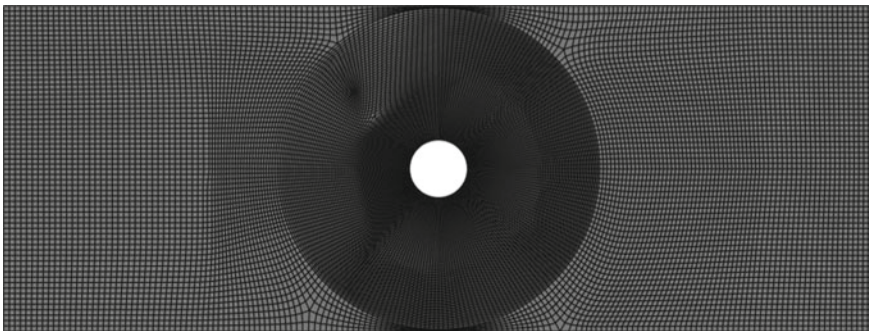
Fig. 2   The mesh density of the proposed study

3.1 Geostatic Step

Initial stresses in soil before excavation have been calculated in this step. In Abaqus continuum geostatic step has an advantage to show the zero displacement. The elements that are within the excavation of the tunnel are active, and the elements of the liner are not active (i.e., the tunnel has not been excavated yet).

3.2 Excavation

Excavation has been simulated by the stiffness reduction method in which soil element of excavation area was deactivated and the elements of the liner were activated. Compatibility of deformations between the liner and the ground is ensured by requiring the nodes of the elements of the ground in contact using general surface-to-surface contact.

3.3 Effect of Stratification

Effect of stratification has been simulated by considering the two-layer soil whose properties have been mentioned in Table 1. For comparison purpose, single layer of low plastic silt (ML) has treated as ideal condition. Depth of stiff layer of sand (SM) has been varied from top to bottom as shown in Fig. 3.

In the present study, it has been simulated that minimum stresses and deformation occur at which condition to minimize the effect surcharge on the secondary support. For this purpose, two-layer system condition has been adopted. To observe the effect of SM layer on liner, a different depth has been chosen which has been shown in Table 2.

Table 1 Properties of the soil and liner material opted in the present study [7]

Type of material	Dry density (kg/m^3)	Wet density (kg/m^3)	Permeability (m/s)	Elastic modulus Pa	Poisson ratio (ν)	Cohesion (pa)	Internal friction	Dilation angle
Silty sand (SM)	1625	2000	1E−08	40E06	0.3	7000	34	3
Low plastic silt (ML)	1680	2035	5E−09	25E06	0.35	17,000	25	0
R.C.C. liner	2500	–	–	25.2E09	0.2	–	–	–
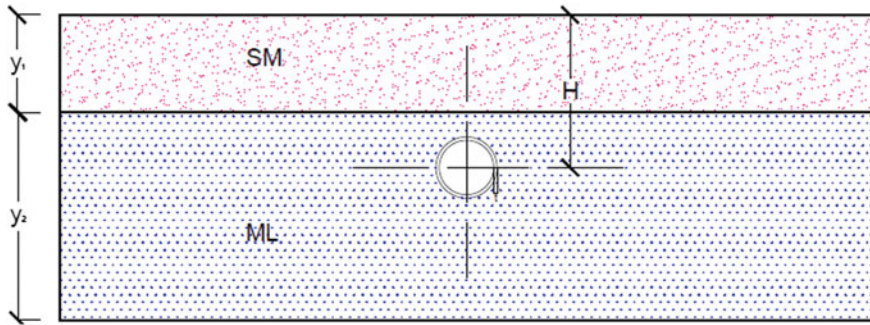
Fig. 3 Variation of silty sand in the proposed study

Table 2 Variation of silty sand (SM) along depth

S. no	Depth of SM from top, y_1 (m)	Depth of ML, y_2 (m)	Remark
1	0	45	Fully plastic silt
2	10.7	34.3	Both SM and ML
3	18.33	26.67	SM up to crown
4	22.5	22.5	SM up to spring
5	28.9	16.1	SM below invert
6	45	0	Fully SM

4   Results and Discussion

Numerical analysis has been carried out to observe the effect of stratification of soil around the opening using ABAQUS/Standard program. The observation has been made on underground structure excavated in low plastic soil in terms of displacement and stresses; further, its response has compared with underground opening in two-layered soil. More than 30 plain strain models have been simulated to study the response of stratification on the liner at different depths mentioned in Table 2.

4.1   Geostatic Step

In this step, it was observed that displacement in the vertical and horizontal direction is almost zero because tunnel had not excavated as shown in Fig. 4a. Radial stresses along the circumferential path have also been calculated to understand the initial stress in the liner. It has been found that maximum geostatic stresses occur at the crown. It provides the initial value of stresses in liner and soil needed for calculating the increase or decrease in stresses at various phases of construction.
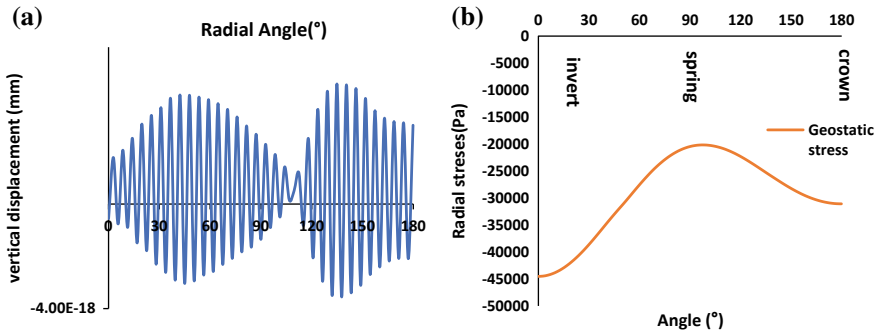
Fig. 4 Variation of vertical displacement (**a**) and radial stress (**b**) with radial angle in geostatic step

4.2 *Effect of Stratification*

Stratification has been simulated by choosing two types of soil ML followed by SM as shown in Fig. 3. Homogeneous ML layer has been considered as ideal condition for all the simulations. It has been observed that horizontal displacement does not get influenced by the stratification. Affected area of soil in horizontal direction has been shown in Fig. 5 due to tunneling in the silty soil. Radial stresses and tangential stresses have been simulated at different depths of the SM from top surface shown in Table 2. It has been observed that stiff layer (SM) closer to liner reduces the liner stresses effectively. The response of stratification on the liner stresses has been shown in Figs. 6, 7, and 8.

It has been observed that the horizontal displacement has maximum value on the springer zone or center of tunnel axis which has been shown in Fig. 5. It provides the base to fix the lateral boundaries in simulation. Radial and tangential stresses have also been plotted for various depths of silty soil. It has been found that the maximum value of radial stresses occurs at springer level and has not much affected
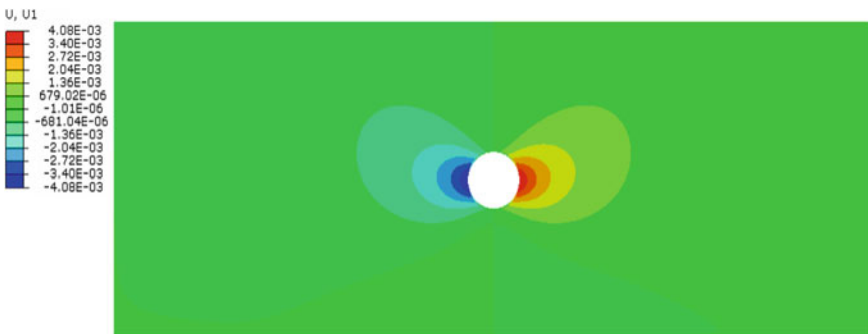

Fig. 5 Contour of the lateral displacement of low plastic silty soil (ML)

Fig. 6 Contour of tangential stresses in low plastic soil (ML)
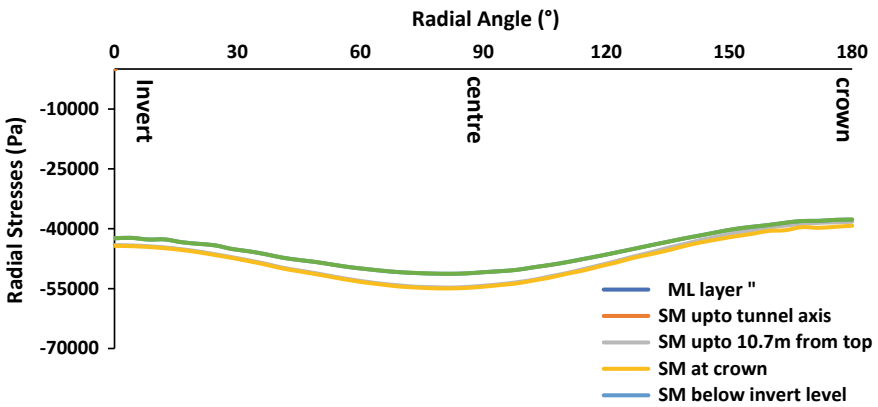

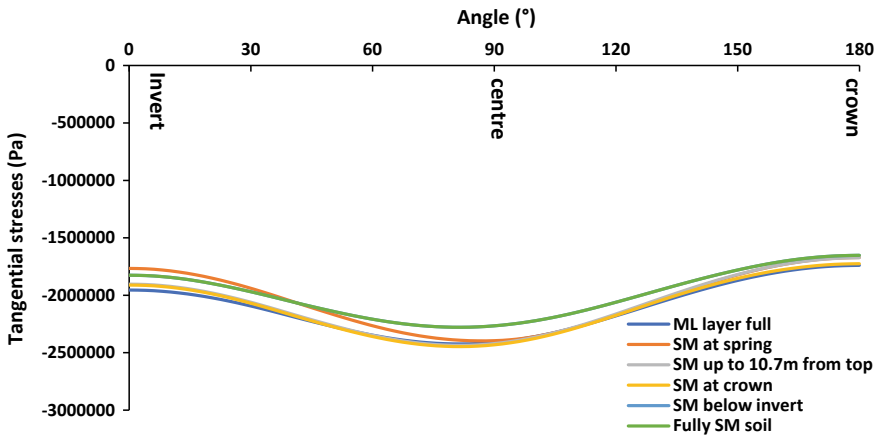**Fig. 7** Effect of stratification on radial stresses in tunnel liner

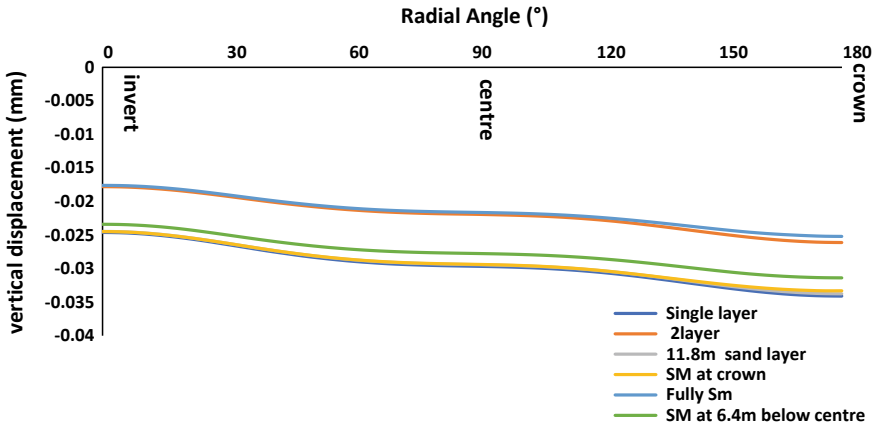**Fig. 8** Layering effect on tangential stresses at the liner

Fig. 9 Effect of stratification on the vertical displacement

by the stratification of soil. Tangential stresses have found maximum value at springer level and decrease about 10–12% when stiff layer moves toward the crown. Vertical displacement has been found to reduce 27% when the silty soil (SM) passes from springer line as shown in Fig. 9. Vertical settlement of liner is the important parameter which could not neglect while adopting the rational and economic design of the liner. Figure 9 also depicts the Maximum value of vertical settlement occurs at crown in homogeneous silty clay soil which reduces to 25 mm when silty sand was present up to the center of tunnel axis.

5 Conclusion

Numerical analysis has been carried out using finite element package Abaqus. Material behavior of soil has been incorporated through well-known Mohr–Columb's constitutive model. Effect of stratification has been simulated, and it has been found that consideration of soil stratification will lead to economic and rational design of the liner in soft soil.

- Soil has been modeled using Mohr–Columb's plasticity with nonassociative flow rule in 2D plain strain numerical model.
- It has been observed that vertical displacement decreased by 27% as compared to low plastic silty (ML) soil.
- Radial stresses in the liner have not been affected by the stratification as stresses reduce only 5–6% when SM layer moves toward the liner.
- Tangential stresses have been found maximum at springer level and decrease by the 10–12% when SM layer is closer to the crown.

- Horizontal displacement has not much affected by the stratification but has maximum value at spring level which helps to decide the lateral boundaries of soil domain.
- From the above study, it has been recommended that excavation should be done in above type of soil condition with little care to reduce the volume loss.

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