Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 51 No. 4 December 2020 ISSN 0046-5828

Soil Model Effects on Deep Excavations Analysis

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ABSTRACT: Nowadays, excavation is considered as one of the sensitive and important steps of urban construction that engineers are always attempting to analyze, design, and construct it by selecting various methods. The importance of this subject is conspicuous when the analysis of displacement and deformations around the excavation is necessary according to the national building regulation due to the presence of buildings in this area, which are of high sensitivity to asymmetric settlement. Therefore, in addition to the stability analysis of excavation, engineers are also dealing with the assessment and prediction of deformations and displacements of its surrounding by using geotechnical site specifications, excavation geometry, surrounding overloads, and simulating the excavations stages. The analysis of displacement and deformation is highly dependent to the constitutive soil model and the use of an appropriate model that imitates the actual behavior of the soil is of significant importance in the simulation of soil behavior in numerical software. In the present study, a comparison investigated between the results obtained from hardening-soil and Mohr-Coulomb constitutive models for a case study of a 16.5m deep excavation in Tehran city with the numerical method of finite element analysis. The results show that the soil behavior and the excavation operations induced displacements are more similar to the reality if the hardening-soil constitutive model is selected compared to the Mohr-Coulomb constitutive model.

KEYWORDS: Excavation, Soil model, Stability, Deformation, Analysis.

1. INTRODUCTION

With the development of urbanization and the increasing development of high-rise structures, there is a definitive need for excavation with higher depths. The important matter to be considered in such cases is providing stability of the excavation to prevent any probable risk in the urban environments. Because of excavation, the soil as a bearing system removed, and consequently, the equilibrium of in-situ stresses in the soil mass and the between-granular stresses are disrupted. If this stress change exceeded the tolerance limit of the soil, the soil would be unstable and, the excavation collapse will be inevitable. Hence, one of the aims of engineers in the assessment of excavation is the stability analysis so that the safety factor must always be above one. In addition to stability analysis and due to the effect of excavation on the surrounding area, deformation and settlement analyses are also necessary for the urban areas (Figure 1). In this regard, it is required to perform a proper simulation of the excavation procedure to predict the deformation and settlement (Hashash and Whittle, 1996).

A precise analysis of the excavation stages and monitoring the performance of the excavation wall and surrounding area are the requirements for a reliable design of the stabilization system and the selection of supporting structure in urban excavations. The form and amount of deformations around the excavation are significantly dependent on the site geotechnical properties, excavation depth, excavation's operation speed, the stiffness of supporting structure, and the construction method (Mana and Clough, 1981). So far, many researchers have attempted to predict the excavation wall and surrounding deformations by evaluating the above parameters. In one of these studies by Rampello et al. (1992), the settlement of ground level behind a retaining wall supporting soft to semi-stiff clay has been investigated using analysis by finite element method and an elastic-perfectly plastic model. It observed that the results from the numerical analysis are not consistent with the measured values of deformation behind the excavation wall. The reason of this inconsistency could be considered because of the effects of some factors such as the nonlinear behavior of soil, stress and strain concentrations, and soil consolidation that the elastic-perfectly plastic model is not able to include it in the stress analysis. Moreover, in another study, Bose and Som (1998), the effect of different factors on the displacement of soil around a supported excavation in soft clay was investigated using numerical analysis, in which the results showed that the ground settlement in the distance equal to 3 times the excavation depth behind the wall tends to zero.

The effect of constitutive soil model has been less considered in the previous studies. Therefore, the present study is to evaluate the constitutive soil model in the accurate prediction of the deformations caused by the excavation operation. The correct prediction of deformation values was always one of the concerns for design engineers in the urban excavations so that there is always the concern about probable life and property losses if the actual deformations exceed the predicted deformations.

The use of finite element method and other experimental and semi-experimental methods are of the conventional methods of estimation and analysis of deformation and settlement caused by excavation. Experimental methods often predict the amounts of settlement and displacement by the excavation geometry and soil characteristics, which could not be responsive in the urban excavations and their risks. In recent studies, a simplified model for predicting the deformation of diaphragm wall in clay proposed by Clough, (1990). In this method, a semi-experimental model is used for predicting the maximum displacement. This relation expressed by excavation geometry, soil characteristics, the wall stiffness, and its embedment depth. Results obtained from the experimental model are consistent with the results of the numerical program (Plaxis), as well as the excavation monitoring results obtained from 21 precise instruments by Zeng et al. (2015).

Nowadays, researchers use finite element method to investigate and analyze soil-supporting structure interaction and its effect on the small strains of soil and common problems of excavation in the urban areas in order to have a correct prediction of the behavior of deformations caused by the excavation. It is shown from the most important achievements of recent studies that the results of numerical analyses are significantly dependent on the soil characteristics, the modeling procedure, simulation and also the constitutive soil model (Schweiger, 2009 and Mu and Huang, 2016). Moreover, the results of different investigations showed that despite the relatively accurate estimation of the maximum bending moment and displacement of retaining walls, the Mohr-Coulomb constitutive model is not able to predict the pattern, severity, and magnitude of deformation of the soil behind the wall. Investigating the effect of different constitutive models on clay and sand indicates that the Mohr-Coulomb constitutive model is not appropriate for the simulation of vertical movement of the soil and the use of it, in most cases, leads to predict uplift instead of settlement in the soil behind the wall (Ong et al. 2003). Engineers are always using numerical methods in various programs with finite element, discrete element, and finite difference substances for modeling the interaction between soil and excavation supporting structure, in the operational and practical scales (Sivakumar et al. 2002, Ong et al. 2003, Ong et al. 2006, Fan and Luo, 2008).

It is noteworthy that the numerical modeling precision is largely dependent on constitutive model and proper selection of the model variables. Brinkgreve et al. (2006), have shown that in the very small strains (i.e., less than 10^{-5}), the soil stiffness plays an important role on the soil behavior and response in excavations, foundation settlement, and projects with engineering strain levels (i.e., less than 10^{-3}). One of the capabilities of hardening soil model is the ability to using soil stiffness in the very small engineering strains to investigate the influence of more realistic factors (Benz, 2007).

In most of the numerical modeling used from the first order Mohr-Coulomb constitutive model and rarely hardening soil model is used. Unlike the Mohr-Coulomb constitutive model, the hardening soil model is dependent on compression and tension (Calvello and Finno, 2004).

In the present study, one side wall of a deep excavation (16.5 m deep) in a project in the north of Tehran stabilized with Berlin wall, and nailing system investigated to evaluate the capability of both the Mohr-Coulomb (MC) and hardening soil (HS) constitutive models. In the following, a brief description is presented about the Berlin wall and nailing stabilization systems and MC and HS constitutive models.

2. EXCAVATION STABILIZATION WITH VERTICAL ELEMENT AND TENSILE ANCHORS (BERLIN WALL)

Nowadays, the requirement for deep excavations is inevitable in the urban constructions, which various methods always used for stabilizing excavations. What is certain in choosing the stabilization method, is that there are criteria and reasons so that it could not be used any method in any excavation. In the other words, the selected method should be proportionate to the excavation condition, and the project intended requirements. The amount of settlement and displacement around the excavation and the area of the incidence of these settlements is dependent on three main factors including the excavation geometry and depth, the soil characteristics, and the overload around the excavation. Hence, much care should be taken in selecting the appropriate method, because some of the excavation stabilization methods cannot control the amount of displacement.

In the urban area, due to the presence of neighboring old buildings around the excavations and their much sensitivity to settlement and asymmetrical deformations due to lack of load-bearing structure and appropriate foundation, it must be attempted that the chosen method of excavation stabilization has a few displacement and deformation to the extent of the adjacent structure strength. One of the appropriate and conventional methods for decrease and controlling the settlement and displacement caused by excavation and reducing the effects of the excavation on the surrounding area in the urban environments, is the use of a system known as Berlin wall with concurrent use of vertical steel elements (steel sections as soldier piles) and post-tensioned tensile anchors (Anchorage). This stabilization method consists of three main parts: vertical steel members/profiles, post-tensioned tensile anchors for tying back the vertical members to the soil, and the reinforced concrete (RC) wall between the vertical members (shotcrete).

To provide fixity, the length of vertical elements or piles could be more than the total excavation depth, and its end can be lower than the level of the excavation floor (Figure 2). Of the important features of this stabilization method is that by using the vertical steel members and also the use of post-tensioned tensile anchors (strand cables), the amounts of settlement and vertical and horizontal displacements of the wall of excavation and the surrounding area could be reduced and controllable. Thus, this method could be very useful in urban excavations and near sensitive buildings.

3. EXCAVATION STABILIZATION WITH NAILING METHOD

Soil nailing means the passive strengthening of the ground without applying pre-stress loads, which performed by the installation of steel elements or nails. Generally, it is recommended to drive nails into the soil with angles of 10 to 20 degree to the horizontal to use their maximum tensile capacity. To make continuity and involvement between soil and steel elements (nails), it used from cement grouting. A shotcrete layer is also sprayed on the excavation surface to prevent local falling of soil. Commonly, this technique is widely used in urban excavations (Figure 3).

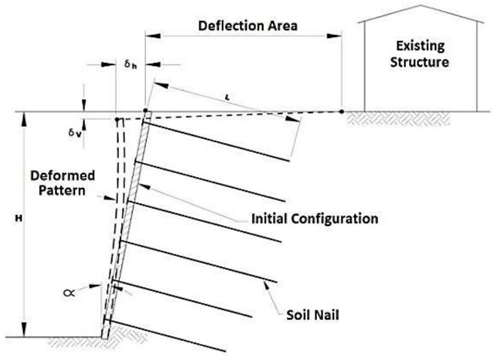

Figure 1 Deformations in soil nailing method of excavation (Sabatini et al. 1999)

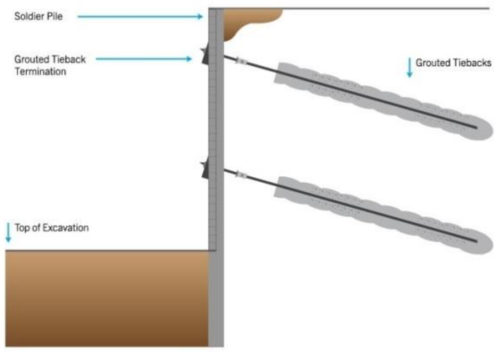

Figure 2 The schematic of stabilization with the Berlin wall method

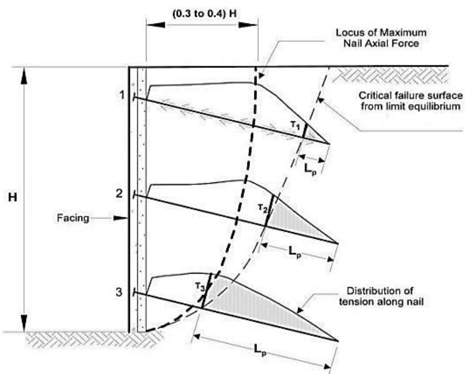

Figure 3 The details of stabilization with soil nailing method

4. SOIL CONSTITUTIVE MODEL

On the expressing of the criterion of material failure at a certain level, in 1900 Coulomb had proposed a simple but very practical criterion that is a function of normal stress in the failure plane. In soil mechanics, this theory is expressed based on the theory of friction strength between soil particles and cohesion. For the expression of linear elastic behavior and plastic behavior of materials in the Mohr-Coulomb (MC) model, five main variables used. This model uses the combination of Hook's law and Coulomb failure criterion.

Hardening soil (HS) model is a powerful constitutive model to simulate the behavior of soft and hard soil types. From the main features of this model, it could mentioned the presence of two types of shear and compressive hardening as well as the non-constant failure surface of the model and its change with the increase in the plastic strains. As one of the main differences of the HS model with the MC model, the stiffness corresponded to stress level can mention. The main idea for the model's relations is the hyperbolic relation between axial strain and deviatoric stress in triaxial loading (Figures 4 and 5).

5. MODELING DETAILS AND MATERIAL PROPERTIES

To investigate the capabilities of both Mohr-Coulomb and hardening soil models in the prediction of actual deformations of soil, the data of a 16.5-m-deep excavation in Tehran with the vertical wall surface and horizontal backfill surface has selected as a case study. It should be noted that this excavation stabilized with tensile anchor including three-string strand cables with steel members (double IPE 240) and shotcrete between them for Berlin wall system, and for nailing system, it is stabilized with steel rebars of 32 and 40 mm in diameter and shotcrete between them. According to the results of geotechnical studies and reports, the site of the project includes a one m-thick remolded soil layer and the rest of the soil layering considered as homogenous (Geotechnical report, 2015).

The adjacent structure is a blind alley (also known as cul-de-sac alley), which based on AASHTO 1997 standard an overload equal to 10 kN/m^2 considered for it. In the present study, the wall was designed based on allowable stress method using FHWA regulation and the tenth issue of Iran's national building regulations (Sabatini et al. 1999). The preliminary design was performed using the limit equilibrium software, Geoslope 2012 to obtain the allowable safety factor. The finite element software, Plaxis 8.6 has been selected for numerical modeling, and plane strain condition also used in the conducted analyses. Two constitutive models of Mohr-Coulomb (MC) and hardening soil (HS) used for simulating the behavior of wall soil. The other physical and mechanical properties of the soil in the site of the project obtained from the geotechnical report presented in table 1 for both models. The geometrical properties and other characteristics of the stabilization system summarized in Tables 2, 3, and 4.

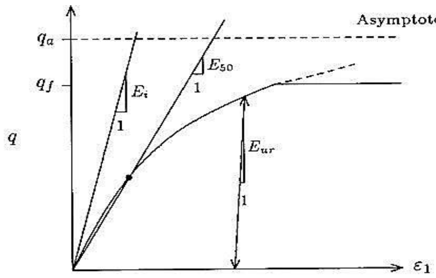

Figure 4 The hyperbolic relation between deviatoric stress and axial strain in the drained triaxial test

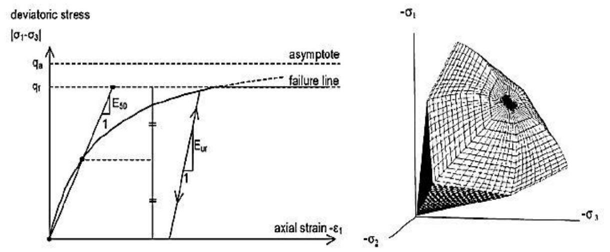

Figure 5 The relation between deviatoric stress and axial strain and failure surface in the HS model

Table 1 Geotechnical parameters for the used constitutive models

Soil Properties	Symbol	Unit	Constitutive model	
			Mohr-Coulomb	**Hardening Soil**
Cohesion	C	*kPa*	18	118
Internal Friction Angle	ϕ	*degree*	33	33
Dilation Angle	ψ	*degree*	5	5
Specific Gravity	γ	*kN/m³*	20	20
Modulus of Elasticity	E	*MPa*	50	-
Secant stiffness in Drained Triaxial Test	E_{50}^{ref}	*MPa*	-	50
Tangent Stiffness for Initial Loading of Odometer	E_{oed}^{ref}	*MPa*	-	50
Unloading–Reloading Stiffness	E_{ur}^{ref}	MPa	150*	150*
Dependency Factor of Stiffness to Stress Level	m	dimensionless	-	0.5
Reference Stress	p^{ref}	kPa	-	100
Poisson's Ratio	ν	dimensionless	0.3	-
Poisson's Ratio of Unloading–Reloading	ν'	dimensionless	-	0.2

* It is considered that: $E_{ur}^{ref} = 3\,E_{50}^{ref}$ (Schanz et al. 1999).

Table 2 The properties of three-string strand cable of tensile anchors used in the simulation of the Berlin wall

Total length (m)	Angle (degree)	L_{bond} (m)	L_{unbond} (m)	Height (m)
15.5	15	5	10.5	15.5
14	15	5	9	13
12.5	15	5	7.5	10.5
11	15	5	6	8
10	15	5	5	5.5
8.5	15	5	3.5	3
7.5	15	5	3.5	1

5.1 Limit Equilibrium Model

As it was mentioned before, before modeling in the finite element software, it is required to perform the modeling in the limit equilibrium state to obtain the stability safety factor. In this regard, the modeling is performed considering dimensions two times the excavation depth, which is adequate for studying the variation and performance of the system. After defining boundary conditions and soil properties, the nails, steel piles, and anchorage elements are drawn and assigned. The results obtain form software calculations (Geoslope 2012) in Figures 6 and 7 show that the stability safety factors are about 1.870 and 1.555 in the Berlin wall and nailing methods, respectively, which are above the acceptable limit of regulations that is equal to 1.5.

5.2 Validation of numerical model with case study

In the present study, the results of monitoring deformation using a micro-geodesy instrumentation during the excavation process and up to three months after the completion of excavation are available, which is used in validating this numerical analysis. In geodetic method, for monitoring a structure in two or more periods of time, a network of fixed points around the excavation is created. Then observations of length and angle used to determine the exact coordinates of these points.

Residual results from geodetic monitoring in urban excavations show that displacement is a nonlinear function of excavation depth, stabilization method and soil specification (Rampello et al. 1992). Comparison of the results of numerical analysis with the track monitoring values for two points of harvesting in the fringe of the hole, which were stably steerable, as well as two points of harvest on the opposite front, which was stabilized by the Berlin wall method are shown in Figures 8 and 9. The alignment of this point of withdrawal is at the zero level of the project and at the top of the track. This comparison shows that at all points of view, the results of numerical analysis with hardening behavior for soil are always closer to reality and better match with the results of monitoring.

5.3 Finite Element Model

In order to build the finite element model, it has used from plane strain condition. The meshing is done by 15-node triangle elements. Figures 10 and 11 illustrate the modeled wall based on the geometrical specifications and boundary conditions. Also, it must note that the reinforcing elements have fined in the meshing with the aim to increase precision. Such as the previous case, after defining various elements, different phases of excavation are defined in every 3 meters of the excavation height.

Table 3 The Modeling and design specifications in the Berlin wall method

Drilling Hole Diameter	0.15 m
Cohesive Strength Between Grout and Soil	45 *kPa*
Horizontal Distance of Tensile Anchors	2 m
Characteristics of Vertical Steed Members	Double IPE 240 Length =20.5 m (4 m Root Length)
Shotcrete Thickness	0.15 m

Table 4 Geometrical properties and the modeling arrangement in the soil nailing method

Nailing Arrangement (m)	Nail Diameter (mm)	The Angle of Nail Execution (degree)	Nail Length (m)	The Level of Nailing Execution (m)
2	32	15	13	15.5
2	32	15	13	13.5
1.5	32	15	12	11.5
1.5	32	15	12	9.5
1.5	42	15	1	7.5
1.5	42	15	10	5.5
1.5	42	15	8	3.5
1.5	42	15	8	1.5

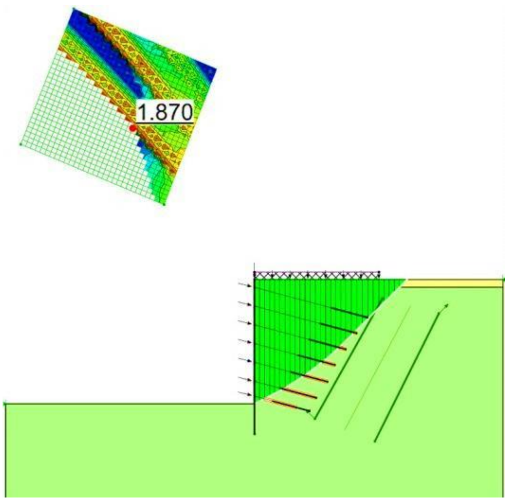

Figure 6 Limit equilibrium modeling in the Berlin wall method

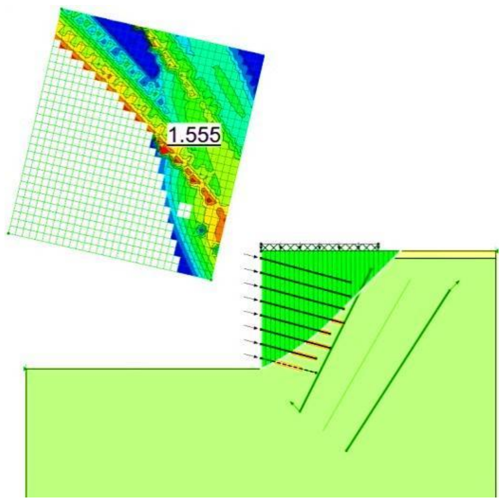

Figure 7 Limit equilibrium modeling in the nailing method

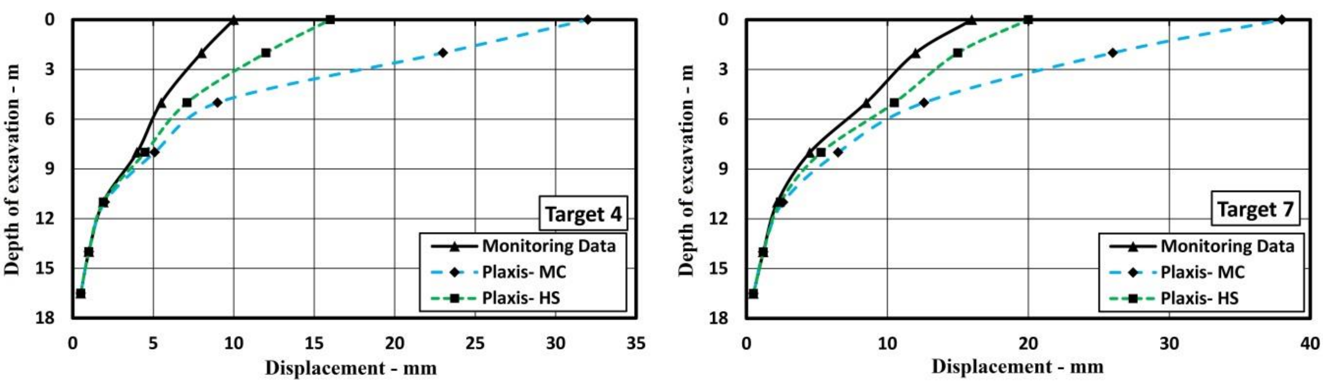

Figure 8 Comparison of monitoring results with numerical analysis in nailing method

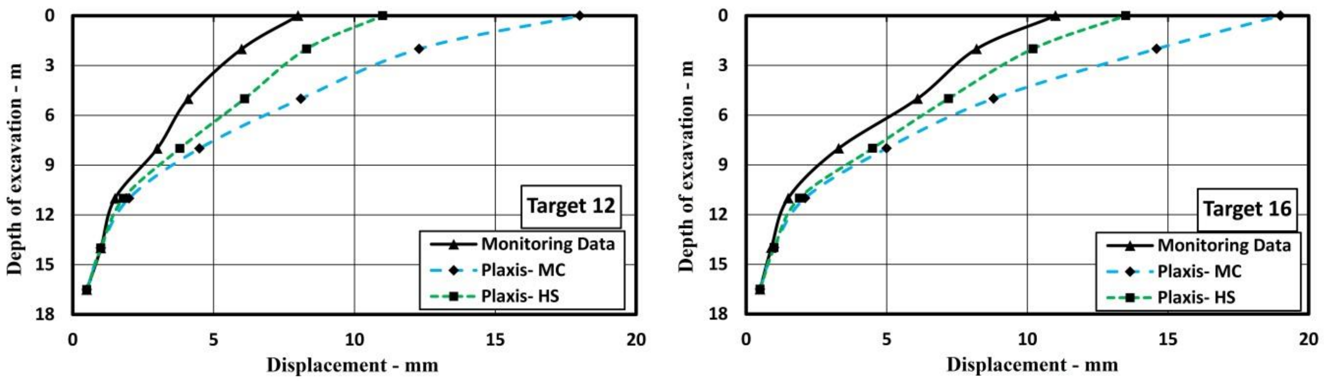

Figure 9 Comparison of monitoring results with numerical analysis in Berlin wall method

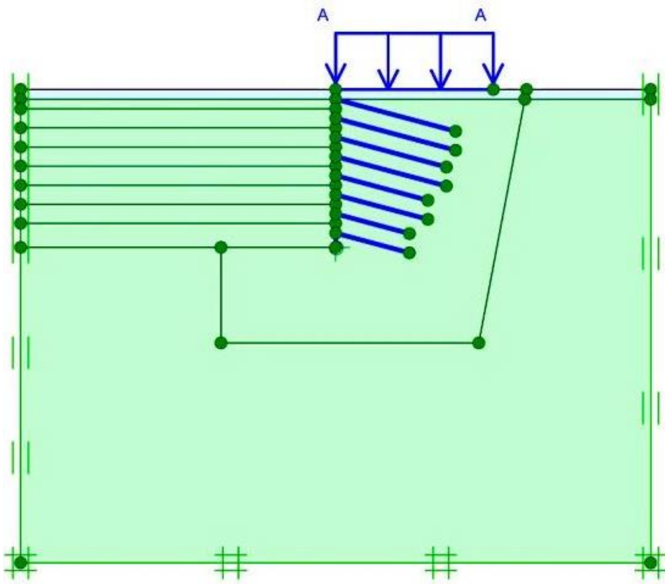

Figure 10 Finite element model in the nailing method

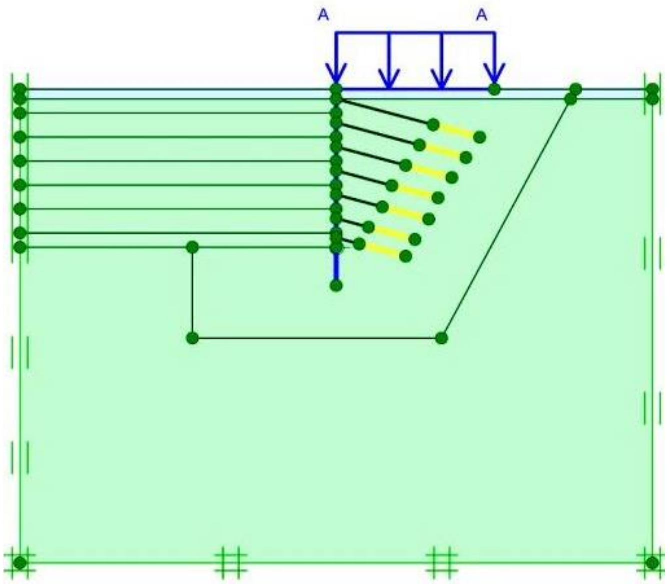

Figure 11 Finite element model in the Berlin wall method

Using the presented results, the excavation was numerically modeled in completely similar conditions regarding geometry and soil characteristics but different regarding the constitutive model. In this regard, the analysis using two Mohr-Coulomb and hardening soil constitutive models investigated, and the obtained results could express as following. The assessment, prediction, and controlling of displacement and settlement caused by excavation operation in the urban area are of special importance. Since, due to the lack of excavation floor protection during construction, unbalanced forces are created that could lead to the floor deformation in the form of swelling, and it could be one of the instability factors named "bearing capacity failure" (Zhang et al. 2015).

The amount of bed swelling or the maximum amount of vertical and upward movement of the excavation floor, in the front of the wall, are shown in Figures 12 and 13, resulted from two different constitutive models (MC and HS models). These results indicate that the amount of bed swelling in the Mohr-Coulomb constitutive model predicted extremely larger than the hardening soil constitutive model. It is because that the MC model does not differentiate between modulus of elasticity in the loading and unloading states, whereas, the soil layers experience different stresses during excavation. Thus, they must be differentiated. This difference considered in the HS model. There is good consistency between these results and the results from previous studies (Ong et al. 2003).

Figures 14 and 15 represent the amount and the manner of the excavation wall deformation based on the two different soil constitutive models. Evaluating the results of this analysis and those of excavation monitoring by the instrumentation method indicate that the predicted deformations in hardening soil constitutive model are much closer to reality. In other words, the deformations obtained from Mohr-Coulomb constitutive model will not occur in practice. Moreover, these deformations, which are representing the horizontal movement of the wall, clearly indicate that in the hardening soil constitutive model the maximum horizontal displacement is larger than its corresponding value in the Mohr-Coulomb constitutive model. In the investigation of another effect of the constitutive model, Figures 16 and 17 represent the severity and amount of horizontal deformations in both constitutive models. As it could be observed, in the hardening soil model, the onionskin shape contours are not observable due to considering the distinct modulus of elasticity in loading and unloading. These results also show that the maximum horizontal displacement does not occur in the same place for both models. As is shown, the maximum displacement in the Mohr-Coulomb constitutive model is below the excavation floor, while for the hardening soil model it occurs at the region of excavation wall.

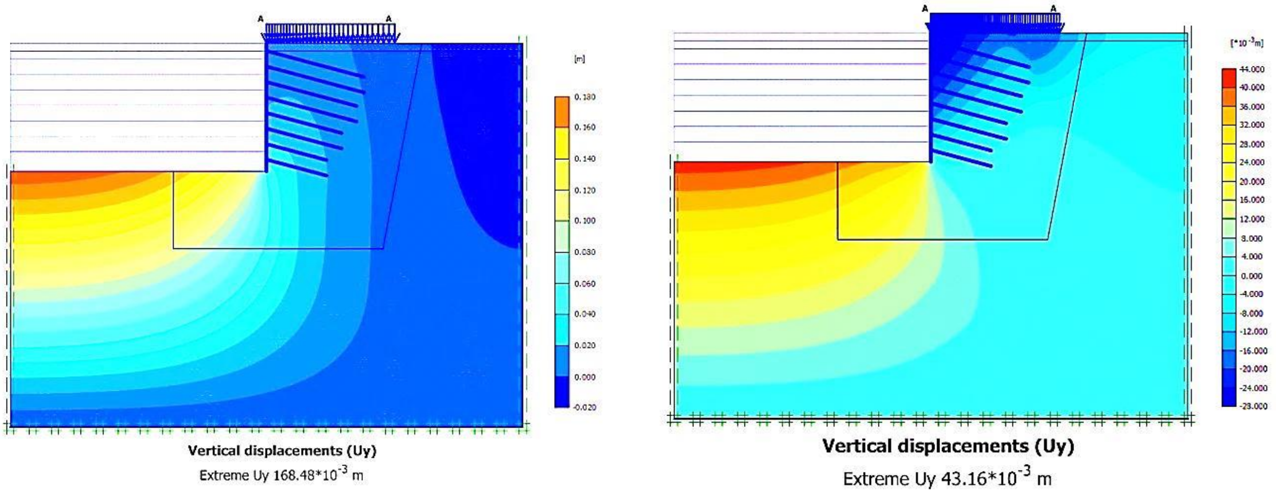

Figure 12 The effect of constitutive soil model on the vertical deformation and bed swelling in nailing method (a) Mohr-Coulomb model, (b) Hardening soil model

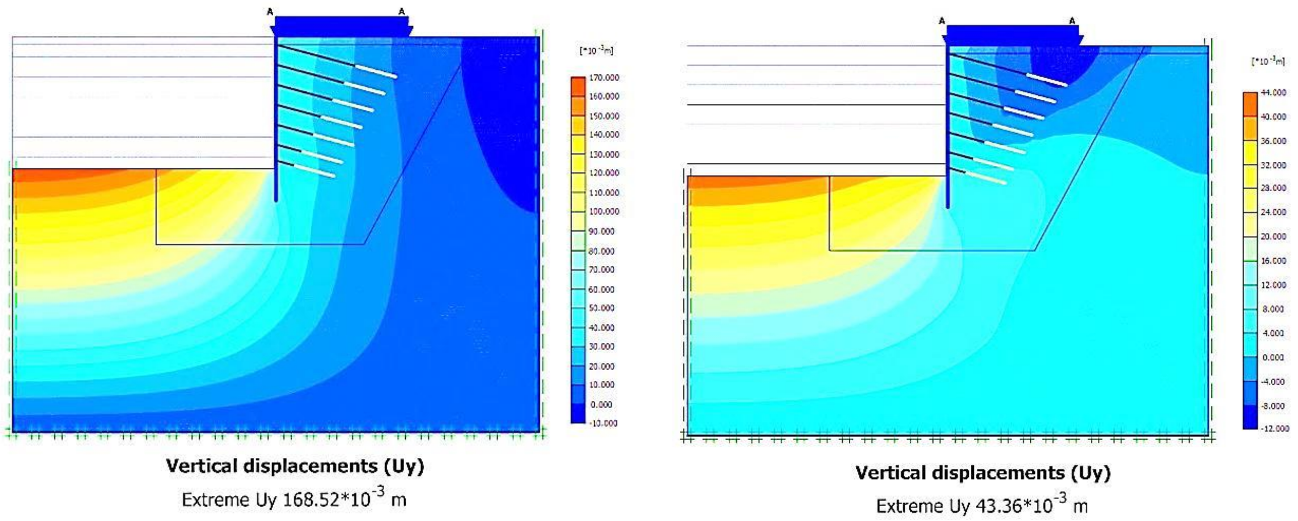

Figure 13 The effect of constitutive soil model on the vertical deformation and bed swelling in berlin wall method (a) Mohr-Coulomb model, (b) Hardening soil model

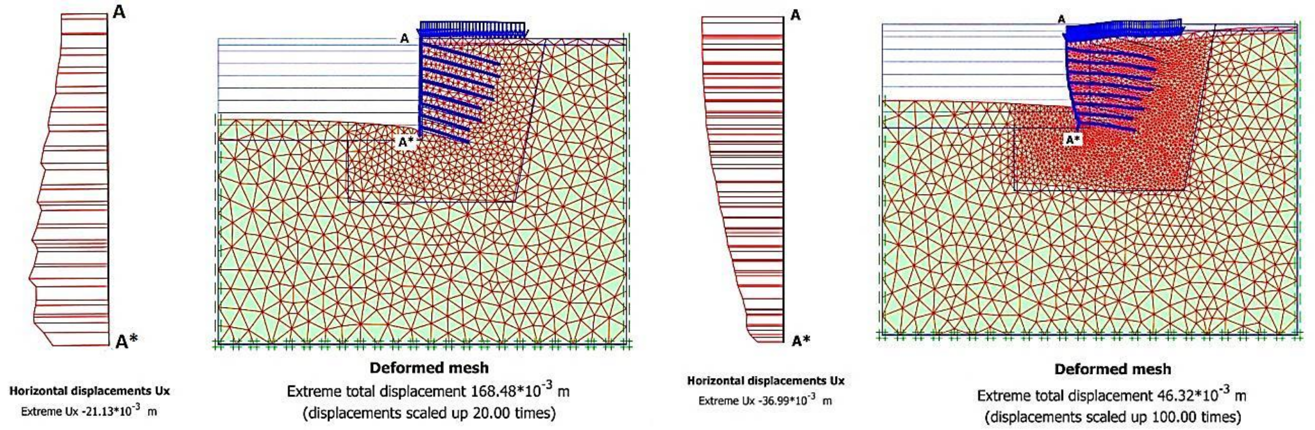

Figure 14 The effect of constitutive soil model on the horizontal deformation of the excavation in nailing method (a) Mohr-Coulomb model, (b) Hardening soil model.

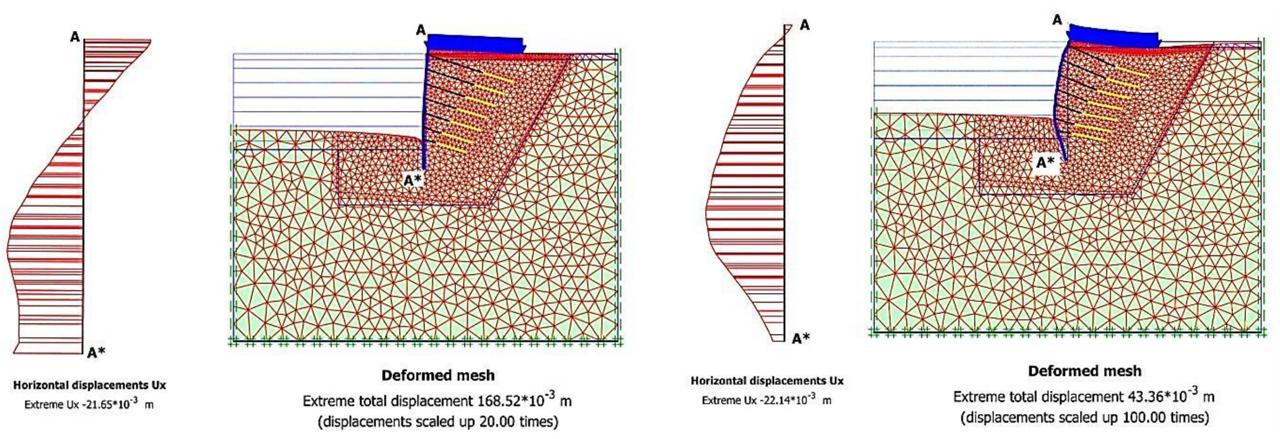

Figure 15 The effect of constitutive soil model on the horizontal deformation of the excavation in Berlin wall method (a) Mohr-Coulomb model, (b) Hardening soil model

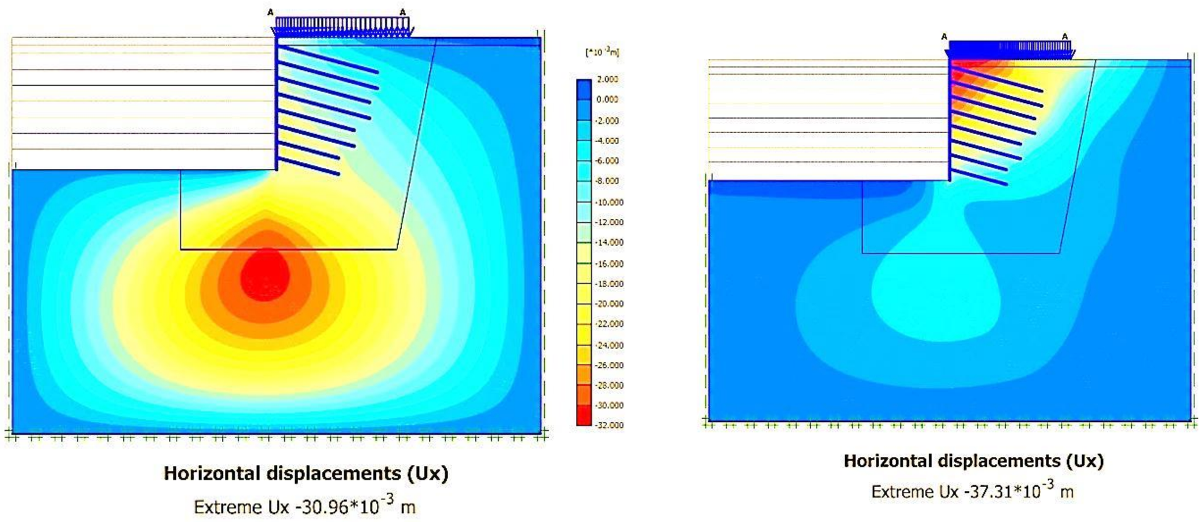

Figure 16 The effect of constitutive soil model on the horizontal deformation in nailing method (a) Mohr-Coulomb model, (b) Hardening soil model

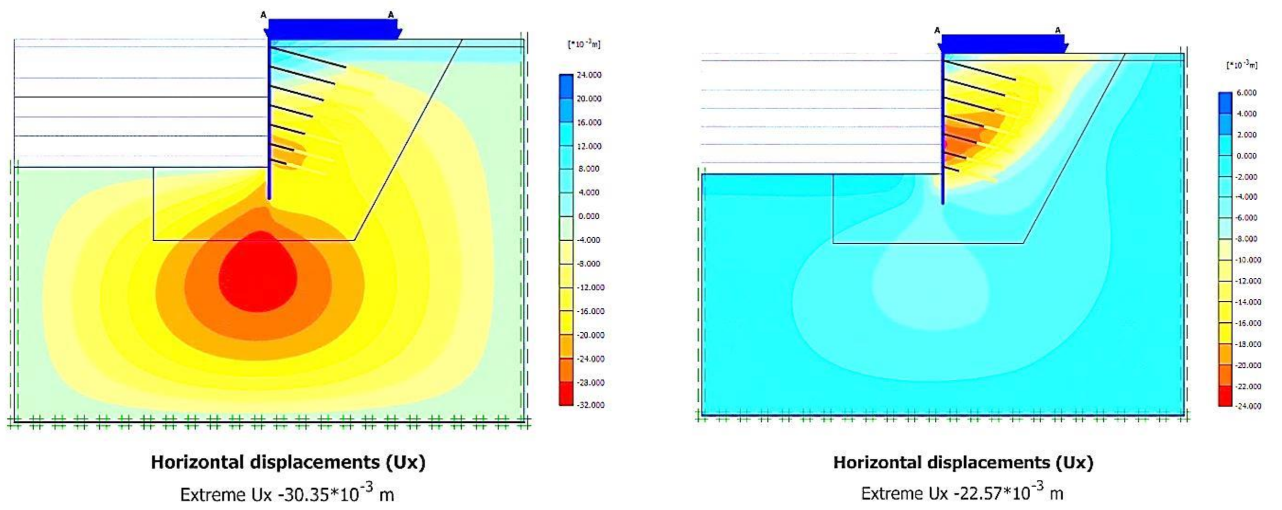

Figure 17 The effect of constitutive soil model on the horizontal deformation of the excavation wall in Berlin wall method (a) Mohr-Coulomb model, (b) Hardening soil model

6. SUMMARY AND CONCLUSION

In the present study, the influence of constitutive soil model on the behavior of deep urban excavations and the amount of settlement and displacement of the excavation wall and surrounding area have evaluated. In this regard, in a 16.5-m-deep excavation in Tehran, Mohr-Coulomb and hardening soil constitutive models were taken into comparison for the prediction of deformation values and comparing them with actual soil deformations that have been measured by precise instrumentation. Also, the used stabilization methods in the present study were including the method consisting of vertical and post-tensioned tensile members known as Berlin wall method, and the soil nailing method, which is widely applicated in the deep urban excavations to reduce and control deformation values. Finite element analysis using Plaxis version 8.6 for both of these two constitutive models revealed that the Mohr-Coulomb model does not provide an appropriate pattern of the general trend of the wall deformation. Also, due to not differentiating the loading and unloading modulus of elasticity, this model gives a larger amount of the floor bed swelling in comparison with the hardening soil model. The amount of maximum displacement in the hardening soil constitutive model was found to be larger than the Mohr-Coulomb model. The results indicated that the excavation wall displacement in the case of hardening model is more than the case of the Mohr-Coulomb model.

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