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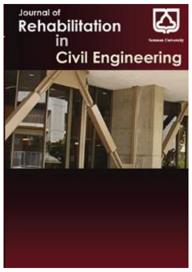

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Investigating Stabilized Excavations Using Soil Nailing Method in Urban Context

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ABSTRACT

There are various methods for stabilizing excavations in urban areas which one of them is the nailing method. Designing a nailing system and analyzing the performance of excavations is done by various software applications. One of these computer programs is PAXIS software which run based on the finite element method (FEM). In the present study, a numerical analysis of the performance of the excavations was investigated under different soil model and the most appropriate model was introduced. In addition, the excavation performance was evaluated based on certain designing conditions affected by the soil resistance specifications (cohesion and internal friction angle) and surcharge. The results indicated that, using an appropriate behavioral model which contains increasing soil stiffness with depth, shows results close to reality. They also indicated that under certain designing conditions, the lateral deformation of the soil nail wall and ground settlement decrease as soil resistance specifications increase.

1. Introduction

Restriction of urban areas and population accumulated environments have led to the vertical extension of the cities and increased use of underground spaces. This includes an extension of building floors into the underground spaces, using channels and tunnels for transferring facilities and developing parking lots. Using such spaces often needs deep excavations and performing construction activities deep into these spaces. Ground excavation makes instability in soil which leads to instability in the space and wall collapse. To avoid such calamities, it is necessary to stabilize these surfaces during construction activities.

Various parameters are involved in selecting the method of excavations stabilization including the type of soil, soil layers, depth of bedrock, level of underground waters, geographical and climate conditions like the amount of rainfall, local seismic conditions,

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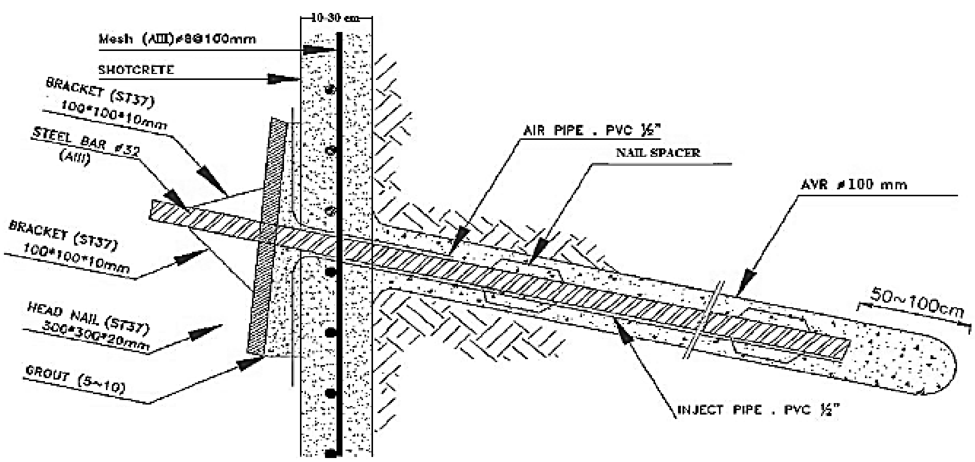
depth of excavation, presence of the load of adjacent constructs and how they are applied on retaining structure, financial limitations of the project, and engineering judgment. One common stabilization method in Iran is using nailing systems which have been noticed considerably in recent years because of its high executive speed. Figure 1 shows an example of excavation and the details of the nailing method.

(a)



(b)

Fig 1. a) A schematic of soil nailing retaining wall, b) details of a typical soil nail method.

Numerical analysis is used widely in geotechnical problems [9, 14]. Investigating the performance of excavation using field studies and numerical analyses has been reported widely in the literature [1,3,7,15]. Numerical analyses were investigated using various methods including the finite element method [12] and the finite difference method [11]. Singh and Babu used the advanced model of hardening soil to model soil behavior numerically [10]. Ghareh investigated the performance of anchored excavation by the combined method of anchor and pile in cohesive and non-cohesive grounds using numerical analysis [5]. Wu et al. studied the influence of cohesion (c) and internal-friction-angle (φ) values on a reinforced slope by a nailing system. They concluded that the c and φ of the soil have significant influence on the stability of the slopes with soil nailing method [13].

In this study, various models of soil behaviors and their effect on excavation performance were investigated using finite element code and the results were compared. Furthermore, sensitivity analysis of excavation was investigated, affected by soil resistance parameters and surcharge. The results have also been presented in the form of lateral deformation, ground settlement, shear force, and bending moment of the soil nail wall. These results showed the direct effect of soil properties on soil nail walls.

2. Numerical Analysis

In this study, two-dimensional finite element software, PLAXIS, is used to model the excavation anchored by the nailing system. This computer program has been used widely for the stabilization of slopes, deep excavations and etc. [5, 9]. Excavation modeling is performed in a two-dimensional environment under plane strain conditions. The plane strain is used for structures with a cross section, fixed loading stress, which are relatively long and perpendicular to the section.

Although in be more clear version of Plaxis we are able to use 6 and 15-node elements, we used the 15-node element for the sake of accuracy. We also used Plate element to model the soil nail wall and the nails; this element has two main properties, namely flexural rigidity (EI) and normal stiffness (EA). To model the nails, equivalent stiffness is used [10]. To do so the following relations are used:

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \tag{1}$$

$$EA[kN/m] = \frac{E_{eq}}{S_h}\left(\frac{\pi D_{DH}^2}{4}\right) \tag{2}$$

$$EI[kNm^2/m] = \frac{E_{eq}}{S_h}\left(\frac{\pi D_{DH}^4}{64}\right) \tag{3}$$

In these relations E_n and E_g are elasticity module of steel and grout respectively, A_n is the cross-section area of reinforcement bar, A_g is the cross-section area of grout cover, and A is the total cross-section area of grouted soil nail. Also, D_{DH} is the diameter of the excavation hole and S_h is the horizontal distance between nails. Note that the properties of nails and listed in Table 1.

Table 1. Properties of soil nailing retaining the structure.

Parameter	Value
Vertical height of the wall (m)	15
Diameter of excavation hole (mm)	100
Diameter of reinforcement (mm)	32
Length of nail (m)	8-14
Nail angle (degree)	10
Yield stress of reinforcement (MPa)	400
Yield stress of grout (MPa)	20
E_n (GPa)	210
E_g (GPa)	22
Poisson’s ratio of reinforcement	0.2
Poisson’s ratio of grout	0.2
Spacing Sh × Sv (m × m)	1.5×1.5

In this article, the excavation depth is 15m which consists of 10 stages of excavation. In order to solidify the excavation wall, 9 nail rows with 8, 11 and 14m length were designed. The excavation system properties are shown in figure 2. The simulated ground has 50m length and 35m depth.

Interface roughness is modeled by selecting an appropriate size for strength degradation factor (R_{inter}). According to agreements in Plaxis, strength degradation factor is 0.8-1 between concrete and sand, and 0.7-1 between concrete and clay [8]. In order to apply boundary conditions, horizontal deformation is prevented at vertical boundaries and horizontal and vertical deformations are banned at a lower horizontal boundary. In addition, in all analyses, the adjacent surcharge of excavation is fixed, equal to 20 kPa. In addition, fine mesh containing 807 elements have been used for meshing the model. Figure 2 shows the excavation properties and Table 2 shows the properties of shotcrete.

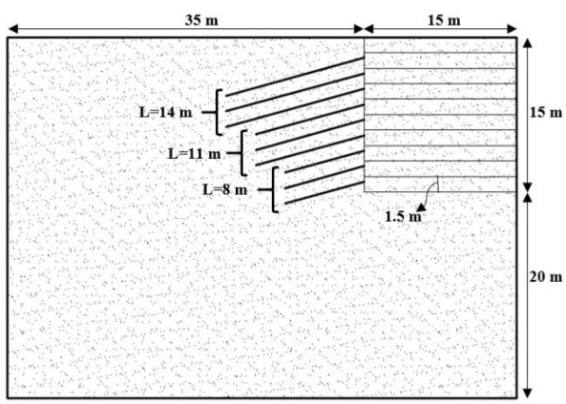


Fig 2. Schematic figure of excavation and nails arrangement.

Table 2. Properties of the shotcrete modelled in Plaxis.

Parameter	Value
Material model	Elastic
Height (m)	15
Thickness (mm)	150
Yield stress of shotcrete (MPa)	30
Young’s modulus of shotcrete (GPa)	27
Poisson’s ratio of shotcrete	0.2

3. Soil Model

Mechanical behavior of soil may be modeled with different precisions. Either soils or rocks may behave linear elastic, nonlinear (linear perfect elastic, linear plastic and so on). The nonlinear stress-strain behavior might be simulated by various behavioral models. Obviously, the more complicated the model, the more the number of parameters required for modeling. The main factors for getting more accurate and reliable results than the numerical analysis include user’s awareness of correct modeling, recognition of different models of soil behavior; and the restrictions are selecting appropriate parameters and user’s capability in engineering judgment while using the results of the analyses. Plaxis computer program supports various advanced models for simulating soil behavior as well as other perimeters including [6, 8]:

Elastoplastic model with Mohr-Coulomb (MC) failure criterion needs five basic parameters to explain the stress-strain behavior. These parameters include elasticity module (E), Poisson’s ratio (ν), internal friction angle of soil (φ), soil cohesion (c), and soil dilation angle (ψ). Among behavioral models, this model is more widely used because of simplicity of the relations and few input data determinable with simple laboratory experiments on soil/rock samples.

One of the advanced models of soil is hardening soil (HS) model. In this model, all the strains (elastic and plastic) are calculated based on the stiffness of the function of strain level which is different for initial loading and loading-unloading. This behavioral model considers the dependence of strain on stiffness module, which means that stiffness increases with confining pressure. Three types of stiffness are defined in this model:

loading stiffness E_{50}^{ref} and unloading stiffness E_{url}^{ref} based on the triaxial test, and loading stiffness E_{oed}^{ref} based on oedometer test (Unidirectional). The approximate relationship between these stiffness parameters are written as $E_{50}^{ref} \approx E_{oed}^{ref}$ and $E_{url}^{ref} \approx 3E_{oed}^{ref}$ for most of the dusty materials.

Table 3. Properties of soil.

Parameter	MC	HS	HSS
γ_{unsat} (kN/m^3)	18.5	18.5	18.5
γ_{sat} (kN/m^3)	20	20	20
E (kN/m^2)	35000	-	-
ν	0.3	0.2	0.2
c (kN/m^2)	20	20	20
φ (º)	27	27	27
ψ (º)	0	0	0
E_{50}^{ref} (kN/m^2)	-	35000	35000
E_{oed}^{ref} (kN/m^2)	-	35000	35000
E_{url}^{ref} (kN/m^2)	-	105000	105000
G_0 (kN/m^2)	-	-	43751
$\gamma_{0.7}$	-	-	0.0002
P_{ref} (kN/m^2)	-	100	100
m	-	0.5	0.5
R_{inter}	0.8	0.8	0.8

The hardening soil model with small-strain stiffness (HSS) constitutes an extension of the HS model. According to the literature, soil materials exhibit higher stiffness in small strains. However, this is often overlooked in most of the behavioral models such as MC and HS. HSS model is defined with two additional parameters, compared to the HS model. G_0 and $\gamma_{0.7}$ are the initial shear modulus and shear strain in 0.7 shear modulus, respectively. P_{ref} and m are reference pressure and a power constant, respectively and are determined according to the software assumptions.

In this study, geotechnical and the soil nailing design manual in Tehran are used to determine soil properties for excavation with nailing system method according to the above reports excavation was 3 to 6 floors under the ground. Groundwater table (GWT) was not observed in any of these areas. The properties of the materials are shown in Table 3, according to the behavioral models.

4. Validation

In order to investigate the validity of the numerical analysis and corresponding results, the excavation with the height of 10 meters which has been stabilized by nailing system in the study by Singh and Babu was reinvestigated [10]. In that study, the length of the nails was 7 meters, located at 1 meter vertical and horizontal distances. The angle of the nails were considered 15° with horizon. Five excavation phases have been performed in this study; in each phase 2 meters soil was excavated and 2 rows of nails along with a shotcrete of soil nail wall with 20-centimeter thickness were executed. Hardening soil model was used to model the soil behavior. The results of this investigation are shown in figure 3. As it is clear, the results of this study are consistent with the findings by Singh and Babu.

5. Results and Discussion

5.1. Soil Models

In order to study the effect of different soil behavioral models on the performance of the excavation, in this paper were used three models, MC, HS and HSS. Figure 4 show the effect of soil behavioral models on lateral deformation of soil nail wall. As it can be seen, the maximum lateral deformation occurs at the top of the excavation. In addition, the deformation made in MC model is different from the other two models, HS and HSS. It is observed in this figure that the maximum lateral deformation in the HS model is higher than the other two models. According to these observations, it is difficult to select an appropriate model containing the real behavior of the materials. The similarity observed in lateral deformations in HS and HSS models indicates that it is possible to simulate the soil behavior using one of these two models.

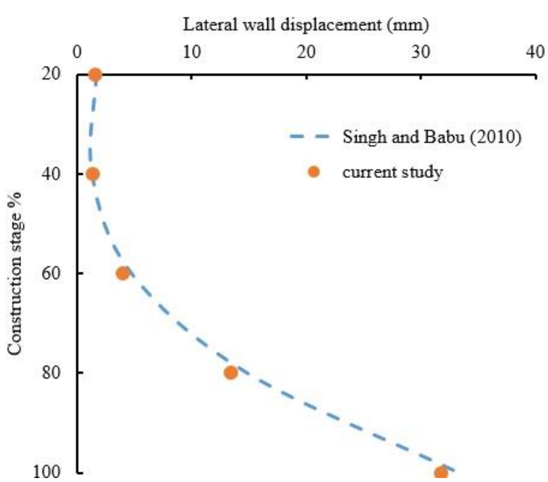


Fig 3. Result of validation (HSS model).

Figure 5 shows the amount of settlement on the adjacent surface after excavation. The form of settlement in the MC model is different rather than the HS and HSS models. Ground settlement and uplift movement on the surface adjacent to excavation are observed in the MC model, while in the other settlement models it have been occurred by excavation. Also, the maximum settlement was observed on the surface adjacent to the excavation. According to the settlements, selecting an appropriate model seems difficult. However, due to the deformation process observed in HS and HSS models, it was shown that the simulation of soil behavior is closer to these two models.

According to the FHWA instructions, if residential building or special structure is not present in the adjacent area, the nailing wall's deformation is limited to 0.005H (H is the excavation depth) [4]. In this case, the nailing system's performance is satisfactory. Since, the excavation depth is 15m, the maximum horizontal displacement will be 75 mm. According to figure 5, horizontal displacement of excavation wall is within the allowable limit.

It is important to control the deformations resulted from the excavation. Failure to protecting the bottom of the excavation leads to unbalanced forces which can result in the displacement of the bottom of excavation upward or toward the inside of the excavation that a state called bedrock inflation. This kind of deformation can lead to rapture resulted from bearing capacity. Accordingly, the maximum vertical deformation due to excavation (base heave) upon increasing the depth of excavation is shown in Figure 6. As the depth of excavation increases, the amount of deformation at the bottom of the excavation increases. Comparison of the results shows that for the soils modeled by HS and HSS the amount of uplift movement of the ground is similar, while it is considerably higher for the model MC. These results are consistent with the findings by Brinkgreve et al. [2].

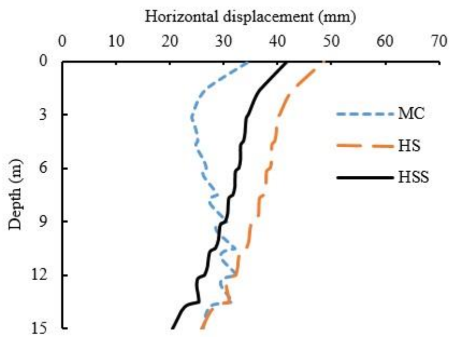


Fig 4. Effect of soil behavior on the variation of wall horizontal displacement.

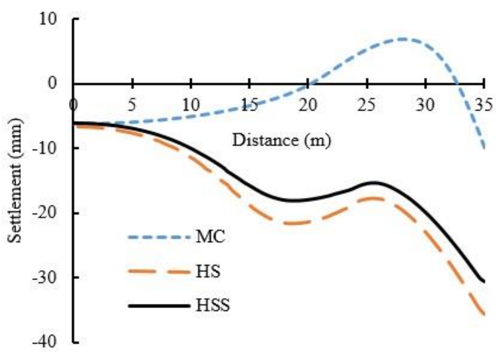


Fig 5. Effect of soil behavior on the ground settlement.

The analysis of different behavioral models shows that in the MC model, we consider a fixed average stiffness for each layer. Therefore the fixed stiffness and its independence from soil stress lead to errors in excavation modeling. Since MC is a perfect elastoplastic model, hardening or softening is not important in it; and once the yield stress value has been achieved, it will be fixed as the plastic strains increase which is different from the real behavior of most types of soils. In behavioral models HS and HSS the unloading module (E_{ur}) and initial loading module (E_{50}) increase with the confining pressure. Hence, the deeper layers of the soil have a higher stiffness than the low depth layers. This procedure decreases a lot of the errors of the analyses and models the soil behavior close to the real behavior. Accordingly in the paper used HS model for continuing the study.

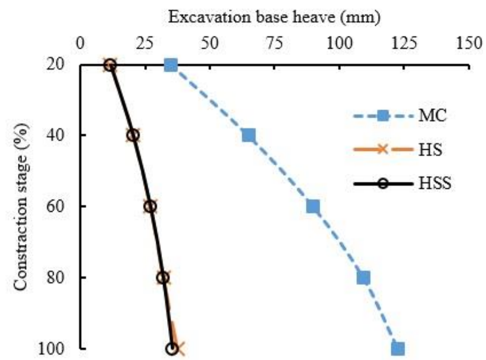


Fig 6. Effect of soil behavior on the excavation base heave.

5.2. Effect of Surcharge

According to the investigations, there are buildings with different number of floors adjacent to the excavation site. Hence, investigating the excavation behavior under different surcharges might show the performance of the excavation upon the effect of the surcharges. According to internal guidelines, we can apply a 10 kPa surcharge per floor. In the present study we have used the weight of the buildings with 2, 4, and 6 floors as well as adjacent ground without surcharge in order to investigate the performance of the excavation.

Figure 7 shows the deformation of different walls upon different surcharges. As can be seen, lateral deformation of the soil nail wall increases as the surcharge grows, and the maximum deformation occurs at top of the wall. It is observed that, the deformation of the soil nail wall is bilinear and occurs at a depth of 2 meters. Wall deformation under a 20 kPa surcharge occurred in a range of 26-

48 mm in the excavated wall. Similarly, the lateral deformation is in a range of 38-83 mm for a 60 kPa surcharge. As a result, when the surcharge increases from 20 kPa to 60 kPa, the maximum lateral deformation will increase to 31% - 42%.

Since the allowable limit for horizontal displacement is 75 mm, therefore the designed nailing system is allowable for buildings with a maximum of four stories. It's because the maximum displacement for 60 kPa overload is over 80 mm.

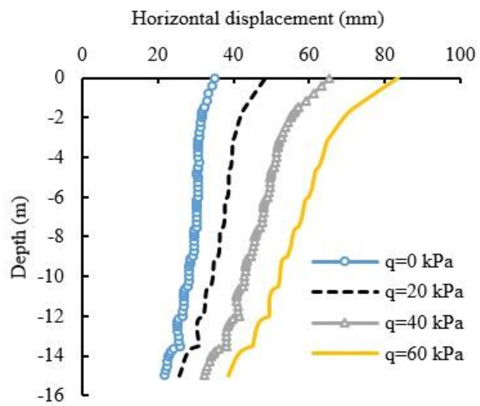


Fig 7. Effect of surcharge on the variation of wall horizontal displacement.

Figure 8 shows the effect of different surcharges on the settlement of the ground adjacent to the excavation. Increasing settlement due to the surcharge increase is clearly seen in this figure. It is clear from this figure that the type of settlement is in correspondence with the process of lateral deformation. Such that the maximum amount of lateral deformation on the upper part of the wall leads to the maximum amount of settlement of the ground adjacent to the soil nail wall. The amount of ground settlement is 37 mm at the surcharge of 20 kPa, and is 61 millimeters at the surcharge of 60kPa. Hence, as the surcharge increases from 20 to 60 kPa, the ground settlement increases by 39%.

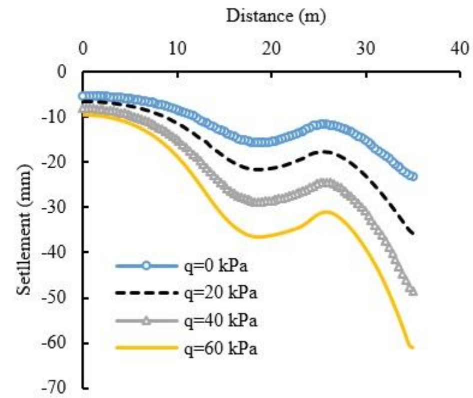


Fig 8. Effect of surcharge on the ground settlement.

Designing the shotcrete wall requires shear force and bending moment. The effect of different surcharges on shear force and bending moment of the shotcrete soil nail wall are shown in Figures 9 and 10. The maximum surcharge leads to a large shear force and bending moment in the wall. The effect of the nails can lead to breaking the shear force from positive values to negative values in the diagram. In addition, using nails lead to a considerable decrease in the bending moment of the wall. According to figure 9, as the surcharge increases from 20 kPa to 60 kPa, the shear force increases by 13%. Similarly, according to figure 10, the bending moment increases by 20%.

5.3. Effect of Soil Cohesion

Cohesion is the force between particles of soil which holds the particles together. According to the geotechnical properties of different areas, a wide range of cohesion has been reported. Hence, in this study we used four cohesion values, 1, 10, 20, and 30 kPa to investigate the performance of the excavation. Gharah showed that when soil cohesion is zero (for example in non-cohesive soils), the lateral deformation is high [5]. So, in order to prevent the possible errors in analysis, we used the least cohesion which is 1 kPa.

The effects of cohesion have been shown in Figures 11 to 14. Figure 11 shows the deformation of the soil nail wall for different values of soil cohesion. It is observed that as the soil cohesion increases, the deformation of the soil nail wall decreases and the maximum amount of deformation occurs on the top. According to this figure, all deformation curves are linear except for 1 kPa cohesion. When the cohesion value increases from 1 to 10, the maximum amount of wall deformation increases by 53%. This reduction in the deformation indicates that low cohesion can have a considerable effect on lateral deformation.

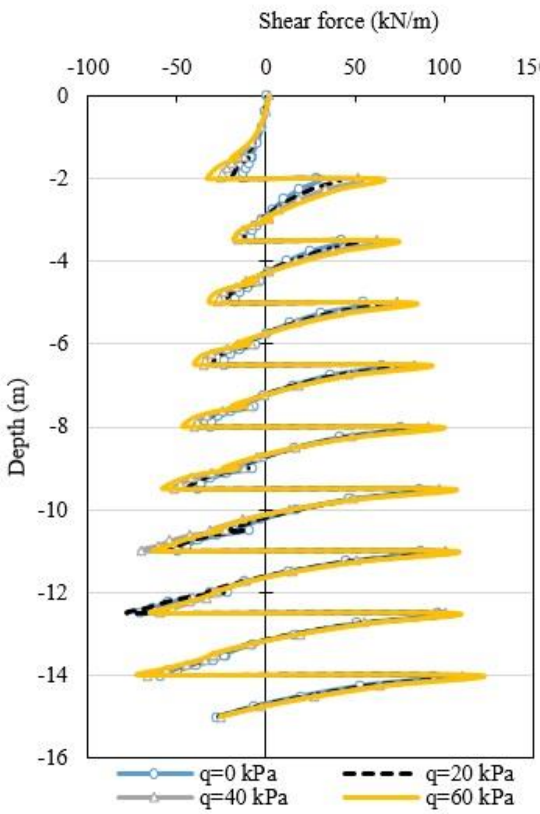


Fig 9. Effect of surcharge on the variation of shear force along the soil nailing retaining wall.

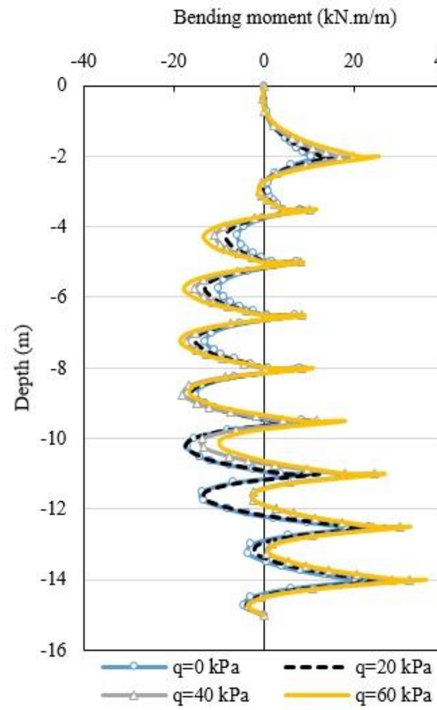


Fig 10. Effect of surcharge on the variation of bending moment along the soil nailing retaining wall.

According to the allowable limit for horizontal displacement of excavation wall, which is determined by FHWA (75 mm), if cohesion exceeds 10 kPa, then horizontal displacement will be in the allowable range.

Figure 12 shows the effect of soil cohesion on the amount of the settlement of the ground adjacent to the excavation. You can see that these results are correspondent with the process of lateral deformation of the soil nail wall. Such that the maximum amount of ground settlement occurs near the excavation, where the wall deformation is maximum. According to this figure, as the soil cohesion increases, ground settlement exhibits reduction. When soil cohesion increases from 1 kPa to 10 kPa, the maximum amount of settlement reduces by 89%.

Figures 13 and 14 show the effects of soil cohesion on shear force and bending moment. The shear force of the shotcrete wall increases with depth. In addition, in most parts of the wall height, as the soil cohesion increases, shear force decreases. Shear force ranges from -60.2 to 105.7 kN/m for the soil cohesion of 1 kPa. Also, for soil cohesion of 30 kPa, the shear force changes from -59.1 to 105.9 kN/m. according to Figure 14, the maximum bending moment occurs where the shear force is zero. According to this figure, as the soil cohesion increases, the bending moment in the shotcrete wall decreases. It is observed that when soil cohesion is low, large amounts of bending moment occurs at the lower layers of the excavation. Such that maximum amount of bending moment is 48.5 kN m/m for soil cohesion of 1 kPa, and 18.4 kN m/m for the cohesion of 30 kPa.

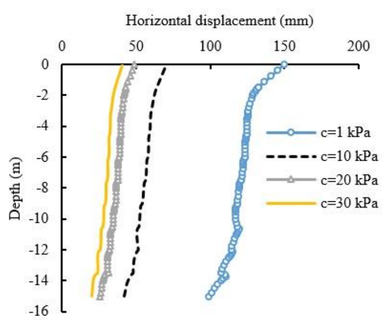


Fig 11. Effect of soil cohesion on the variation of wall horizontal displacement.

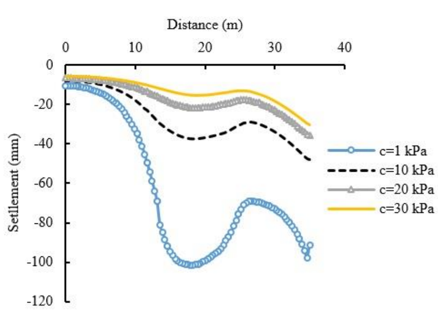


Fig 12. Effect of soil cohesion on the ground settlement.

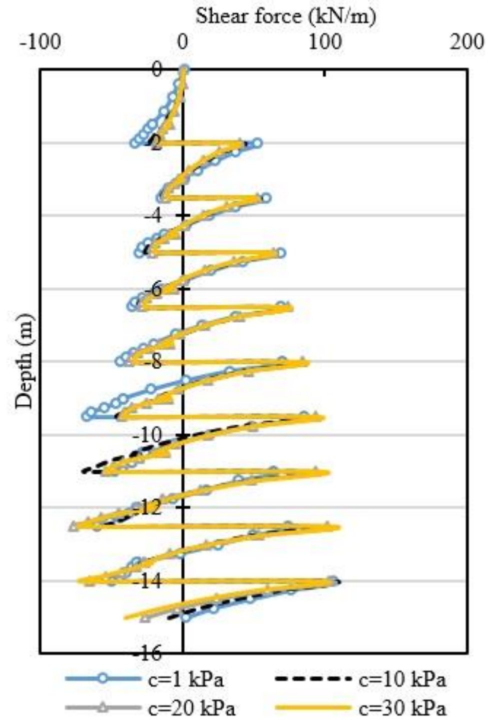


Fig 13. Effect of soil cohesion on the variation of shear force along the soil nailing retaining wall.

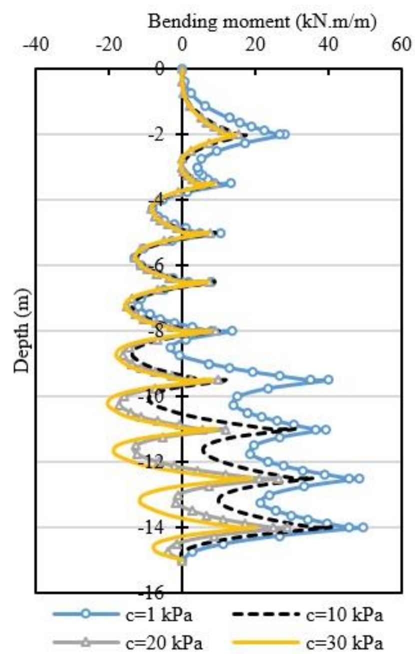


Fig 14. Effect of soil cohesion on the variation of bending moment along the soil nailing retaining wall.

5.4. Effect of Soil Internal Friction Angle

Soil internal friction angle (φ) is an important parameter in designing retaining walls. Because the lateral pressure of soil depends on the coefficient of lateral earth pressure (k) which is obtained as $k = 1 - \sin\varphi$ according to internal friction angle. As it can be seen in this equation, when the soil internal friction angle increases, the coefficient of lateral earth pressure decreases leading to a reduction of earth pressure on the soil nail walls. In the present study, we used internal friction angles equal to 20, 27, and 34 degrees to investigate the effects of the internal friction angle; and the results are shown in Figures 15 to 18. Figure 15 shows the lateral deformation of the soil nail wall for different soil internal friction angles. It is seen that as the soil internal friction angle increases, the amount of wall deformation decreases, which is partly because of the reduced lateral pressure. In addition the curve of lateral deformation is linear and as the depth increases, it decreases. Also, the maximum amount of deformation occurs on the top. The maximum deformation for internal friction angles 20, 27, and 34 degrees are equal to 80.2, 25.8, and 11.2 mm respectively. Non-uniform deformation (between the maximum point and the end of the wall) is similar almost in all models which is equal to 22 mm. For friction angles over 27 degrees, horizontal displacement is less than the 75 mm limit.

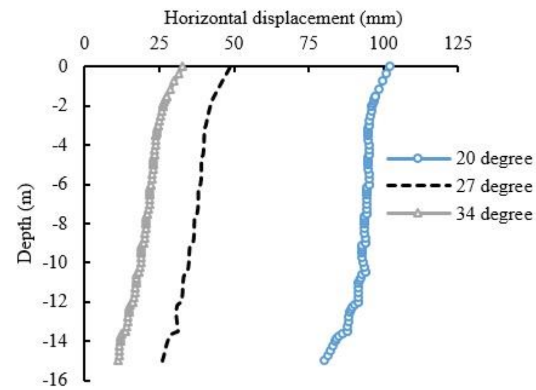


Fig 15. Effect of soil friction angle on the variation of wall horizontal displacement.

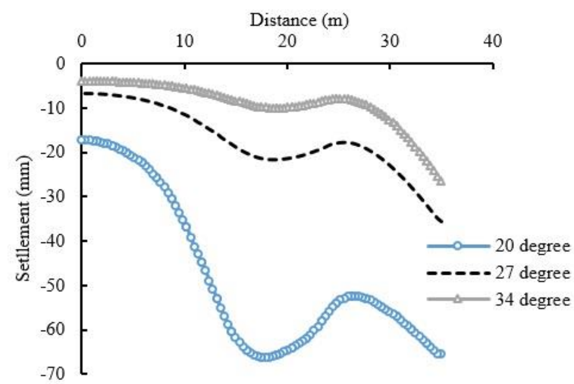


Fig 16. Effect of soil friction angle on the ground settlement.

Figure 16 shows the ground settlement for different soil internal friction angles. It can be seen that following the diagram of the lateral deformation, the maximum amount of ground settlement occurs in the vicinity of the excavation. Also, as the distance from the edge of the excavation increases, the amount of ground settlement decreases. In this figure, when the lateral friction angle increases and as a result the lateral pressure decreases, the ground settlement decrease too. The maximum amounts of ground settlement for soils with internal friction angles of 20, 27, and 34 degrees are 65.3, 35.7, and 26.3 mm respectively.

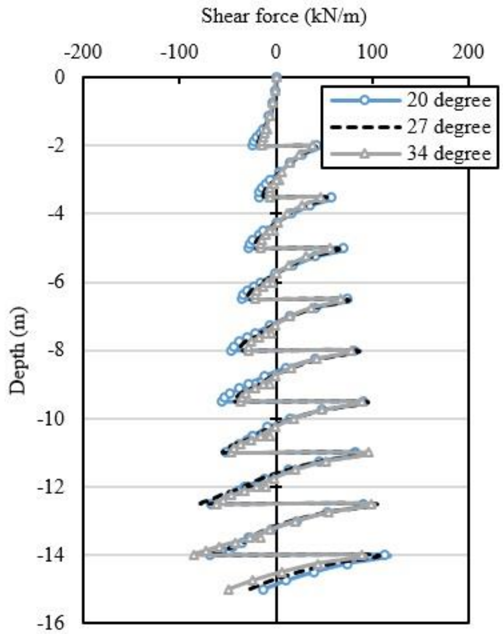


Fig 17. Effect of soil friction angle on the variation of shear force along the soil nailing retaining wall.

The effect of internal friction angle on shear force and bending moment of the shotcrete wall is shown in Figures 17 and 18. In these figures that the increase of the internal friction angle leads to the reduction of shear force and bending moment. Also with the increase of depth, the shear force increases too, and its maximum amount is at the depth of 14 meters which is equal to 113.4 kN/m for the soil with friction angle of 20 degrees. It should be noticed that the changes in shear force are not considerable in different soils and as we go deeper, they will be fewer. According to Figure 18, the changes in the bending moment have increased in depths more than 7 meters. The maximum values of bending moment of the wall have been equal to 42.9 and 25.1 kN.m/m for friction angles of 20 and 34 (°) respectively.

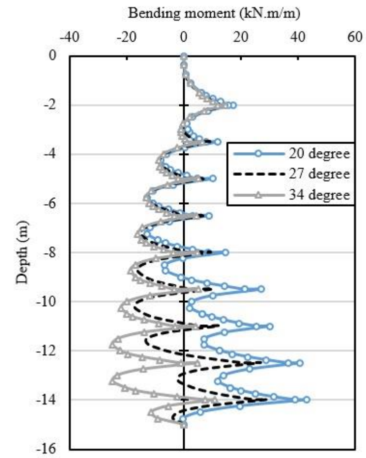


Fig 18. Effect of soil friction angle on the variation of bending moment along the soil nailing retaining wall.

6. Conclusion

In the present study, we investigated the performance of excavation under the effects of behavioral models and soil resistance properties and the value of surcharge, using numerical analysis. The most important results of this study are as follow:

1. In the Mohr-Coulomb model, a constant average stiffness is considered for each soil layer. This constant stiffness, and its independence from the soil stress cause error in the excavation models. Since Mohr-Coulomb is a perfect elastoplastic model, stiffening and softening is not considered in it and after reaching the yielding stress, the stress amount remains constant with the increase of plastic strain. It’s different with natural behavior of most soils. However, in HSS and HS constitutive models, both of unloading modulus E_{url} and the initial loading modulus E_{50} are dependent to the confining pressure. Therefore, deep layers have greater stiffness compared to shallow layers. It reduces many errors present in prior analysis and is closer to the natural behavior of soil.

2. Considering surcharge in the form of the equivalent load is common in design. Increasing surcharge in a certain nailing design leads to the increase of lateral deformation of soil nail wall, ground settlement, bending moment, and shear force.
3. The effects of soil resistance properties in a certain nailing system showed that as the soil cohesion and soil internal friction angle increase, lateral deformation of soil nail wall decreases considerably and consequently ground settlement reduces as well. Also, an increase of soil resistance properties had positive effects on shear force and bending moment of the soil nail wall.

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