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Deformations Analysis and Finite Element Numerical Modeling of Soil's Excavations Improved by Soil Nailing

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ABSTRACT

Application of soil nailing in stabilization of excavation operations in urban area's constructions is most flexible and capable techniques for earth retention under soil mass instabilities. In general, the implementation of the soil nailing method is step-by-step, and this issue itself causes various and step-by-step changes in the excavation area. Therefore, by studying these stepwise deformations, it can be obtained the development of soil's failure mass step-by-step. In this regard, presented article tried to investigate the stepwise deformations' analysis in soil nailing operation in excavated soils using finite element numerical method and Plaxis2D software. The modeling was performed during four drilling stages and the changes in the slope stability as well as the deformations' expansion in slope mass (sand and clay) were investigated. Based on the simulation results, it has been determined that with increasing depth, the degree of confidence in the slope (safety factor) for 2 different arrangements decreases step-by-step and the plastic area increases towards the bottom of the pit. But the nailing wall shows a good ability to curb instability.

1. Introduction

Soil nailing is a construction stabilization technique to treat unstable soil slopes or trenches that allows the safe over-steepening of new or existing soil slopes (Babu and Singh, 2008). This geotechnical method involves the relatively slender or reinforcement elements insertion into the soil mass or soil slope (mostly rebar, solid nail or hollow-system bars). Solid bars are usually installed into the pre-drilled boreholes and then grouted placed into those holes by separated grout line, whereas hollow bars may be drilled and grouted simultaneously by the use of a sacrificial drill bit and by pumping grout down the hollow bar as drilling progresses (Babu and Singh, 2009). Kinetic procedures of firing relatively short-bars into soil masses (or trenches) have been developed and utilized as well. Bars installed using drilling techniques are usually fully grouted and installed at a slight downward inclination with bars installed at regularly spaced points across the slope face. A shotcrete or isolated soil nail head plates may be conducted at the excavation's surface to inhibit surface failures (Lin et al., 2013). As appropriate alternative a flexible reinforcing mesh (steel meshes) may be held against the soil face beneath the head plates. Rabbit proof wire mesh and environmental erosion control fabrics and may be used in conjunction with flexible mesh facing where environmental conditions dictate (Singh and Babu, 2010). Soil nailing may have performed for retaining-walls' stabilization or existing fill slopes which this has

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normally undertaken as a remedial measure and required stability assessments as well as implementation of preliminary braces for previous excavations (Sharma and Ramkrishnan, 2020).

The first application of soil nailing as modern stabilization techniques conducted in Versailles from 1972 which in that project, an 18-meter-high excavated gable was stabilized using nailing (Han et al., 2020) which introduced the soil nailing as well-established technique for controlling the slope instabilities were flexibility conducted in different soils around the world (Singh and Shrivastava, 2017). The U.S. federal highway administration (FHWA) issued guideline publications about stabilization technique based on soil nailing in 1996 and modified in 2003 which is currently considered as a very important reference in the field implementation of soil nailing (FHWA, 2003). For the first time, Austrian engineers used the nailing method to stabilize rock outcrops and portals' slopes in tunnels back from early 1960s. They dug a network of boreholes in the tunnel's rock mass in arches and walls and inserted steel bars into rock body. As retention, they used the mesh network and shotcrete to isolate the nails ends in tunnel. Then, conducting the concrete's grouting to reinforce drilled holes and spraying the tunnel wall (Lin et al., 2013). This method was later used by German and French engineers for stabilization in earth slopes like embankments and trenches. They generalized the application of nailing technology from tunneling into stabilize excavated slopes and earthen walls and backpacks (Tong and Tang, 2019). After that, the performing of soil nailing method is showed a significant expansion for various construction projects such as stabilization of railway trenches and highways, construction of guard structures excavated in urban areas, high-rise buildings construction, landslides' stabilization, and so on (Cheung and Ho, 2019).

With the prevalence of deep excavations in the urban area and the requirement to prevent damage to adjacent structures, it has led to the increasing use of soil nailing system as flexible stabilization technique in urban area and cities (Pradhan et al., 2006). As geotechnical aspects, the soil nailing due to its technical advantages, safety, less costs and ease of implementation is one of the most recommended procedures to improve the soil properties and strengthens factors (Cheng and Lau, 2014). Three main points to be considered in determining if soil nailing would be an effective retention technique are as follows (Cheung and Ho, 2019):

- The existing ground conditions should be examined,
- The advantages and disadvantages for a soil nail wall should be assessed for the particular application being considered. Then other systems should be considered for the particular application,
- The cost of the soil nail wall should be considered.

Soil nail walls can be used for a variety of soil types and conditions. The most favorable conditions for soil nailing are as follows (Cheung and Ho, 2019):

- The soil should be able to stand unsupported one to two meters high for a minimum of two days when cut vertical or nearly vertical,
- All soil nails within a cross section should be located above the groundwater table.
- If the soil nails are not located above the groundwater table, the groundwater should not negatively affect the face of the excavation, the bond between the ground and the soil nail itself.

Based upon these favorable conditions for soil nailing stiff to hard fine-grained soils which include stiff to hard clays, clayey silts, silty clays, sandy clays, and sandy silts are preferred soils. Sand and gravels which are dense to very dense soils with some apparent cohesion also work well for soil nailing. Weathered rock is also acceptable as long as the rock is weathered evenly throughout (meaning no weakness planes). Finally, glacial soils work well for soil nailing (Pradhan et al., 2006). A list of unfavorable or difficult soil conditions for soil nailing can include dry, poorly graded cohesion-less soils, soils with a high groundwater table, soils with cobbles and boulders, soft to very soft fine-grained soils, highly corrosive soils, weathered rock with unfavorable weakness planes, and loess. Other difficult conditions include prolonged exposure to freezing temperatures, a climate that has a repeated freeze-and-thaw cycle and granular soils that are very loose (Tong and Tang, 2019).

Considering the previous notes about soil nailing, it is considered as most flexible and capable techniques for earth retention under soil mass instabilities especially in urban areas (Sharma and Ramkrishnan, 2020). Thus, the presented study attempted to provide the numerical estimation of implementation of soil nailing technique for step-by-step excavation operations in urban areas with lateral loading of the pit.

2. Numerical Methods

In order to estimate the soil nailing design to provide the slope/trench stabilization mainly use the numerical methods which provide the clear understanding of soil nailing procedure and earth reaction status by conducting the stabilize approach. Among the various numerical methods used in geotechnical engineering that are used for various purposes of stabilization and improvement, the finite element method (FEM) has a special place and has achieved significant success, especially for soil nailing (Sharma and Ramkrishnan, 2020). FEM is the most widely used numerical method for solving engineering, mechanical and mathematical problems which covered all areas of interest include the structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential, geo-structures, soil mechanics, dynamics, etc. The FEM utilized partial differential equations for various variables to solve problems by subdividing the main system into smaller, simpler parts of systems as finite elements or meshes. This is achieved by a particular space discretization in the space dimensions. The FEM method approximates the unknown function over the system to provide the simple equations that model meshes then assembled into main system and solving entire problem (Saran, 2010; Sharma and Ramkrishnan, 2020). This fact used in geotechnical engineering to solving soil mechanical problems as well as civil structural interactions with soil materials. Plaxis2D is very user friendly commercial software developed based on FEM by Plaxis B.V. (American Bentley Systems, Inc.) were widely used in geotechnical evaluations were considered as computer program that performs plane strain and axial symmetry aspects including deformation, stability and water flow. The input procedures enable the enhanced output facilities provide a detailed presentation of computational results (Plaxis, 2019). The presented research uses the Plaxis2D to investigate the development of soil's failure mass step-by-step during soil nailing and obtain the deformation status of the soil body after stepwise drilling and stabilizations.

3. Material and Methods

In this study, finite element numerical method and Plaxis2D software were used to evaluate the deformations condition in the excavated slope during the step drilling operation and soil nailing which is provide in 4 step drilling procedure. In this regard, nonlinear Mohr-Coulomb behavioral model is used to describe the soil's time-dependent behavior. Loading conditions and border conditions can be modeled using 6-node and 15-node triangular elements which in this work, 15-node and fine mesh used for implementation of the basic model. Also, nailing information and permissible deformability characteristics have been extracted and applied from the FHWA regulations as well as presented in Tables 1 and 2.

Table 1. FHWA regulations regarding to the maximum allowable deformation of the pit wall (FHWA, 2003)

Variable	Weathered Rock and Stiff Soil	Sandy Soil	Fine-Grained Soil
δ_h/H	1/1,000	1/500	1/333
δ_v/H	1/1,000	1/500	1/333
C	1.25	0.8	0.7

Table 2. FHWA regulations regarding to the nailing operation specifications (FHWA, 2003)

Element	Unit	Value
Rebar specifications (nails)		
Rebar diameter	mm	25
Rebar type	-	A III
Yield stress (F_y)	Kg/cm^2	4000
Elastic modulus (E)	kPa	2×10^8
Poisson's ratio (υ)	-	0.3

Table 2. Continued (FHWA, 2003)

Element	Unit	Value
Grout specifications		
Hole diameter	mm	90
Axis to axis distance	m	1.5
Elastic modulus (E)	kPa	2×10^7
Characteristic resistance (f')	MPa	21
Equivalent elastic modulus and equivalent axial stiffness		
Equivalent elastic modulus	kPa	35318975
Equivalent axial stiffness	kN/m	2×10^5

The choice of different dimensions of model meshes can also affect the results. The use of coarse meshes may reduce computational accuracy and increase error, while small meshes may increase computational accuracy and require more time for analysis and computation. Now the mesh used must meet the calculation time and accuracy of expectations. Plaxis software has 5 sizes for networking that can be determined uniformly or non-uniformly. The use of finer meshes around the studied elements such as nails is recommended to achieve high accuracy results (Ehrlich et al., 2020).

In this research, fine meshes around the mentioned elements have been used. Figure 1 is presents the sensitivity analysis of different meshes' dimensions in estimation of deformation values. As seen in this figure, there are few changes between 'fine' and 'very fine' meshes. So, in order to evaluate the nail-soil and top-soil interactions used the fine grad meshes as well as illustrated in Fig. 2.

In order to analyze the expansion of the plastic area and to evaluate the deformation in the drilled mass during the construction operation, this has been gradually improved by soil nailing. Numerical simulation has been done in stages including geometric model preparation, behavioral model and boundary conditions, assignment of material properties and mechanical analysis. Figure 3 shows the geometrical model prepared from the drilling operation. During this model, it can be seen that the study pit is drilled in 4 stage and the resulting deformations in the body of the mass are calculated.

The boundary conditions of the model are automatically selected and the Mohr-Coulomb behavior criterion is used to evaluate the behavior of the host mass. In terms of evaluation geo-materials, two groups of materials, including clay and sand materials have been used to soil and also, the reliability and stability of these masses have been tried separately during drilling and nailing operations. The standard properties of ideal sand ($C=0$, $\phi=30^o$) and clay ($C=100$ kPa, $\phi=0$) are considered in the study. Also, in order to evaluate the performance ability of the nailing, 2 different arrangements (5 m and 6 m) have been used for each of these arrangements a separate reliability coefficient has been calculated.

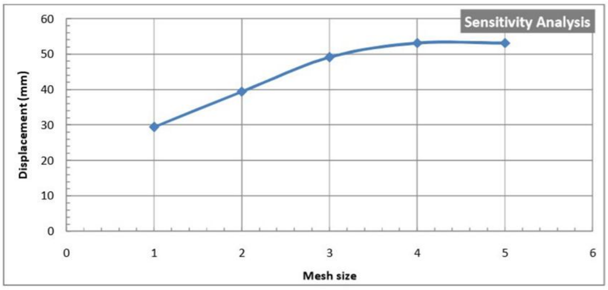

Figure 1. The sensitivity analysis of mesh sizes in Plaxis

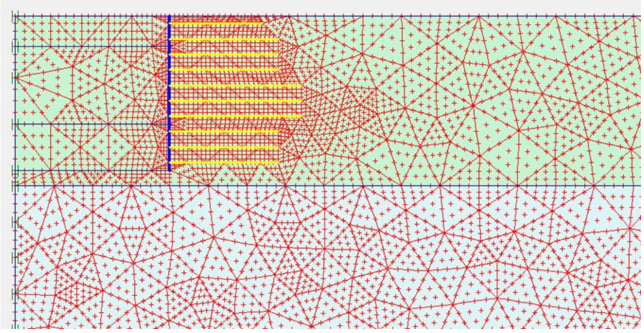

Figure 2. The mesh status in studied numerical model for soil nailing stabilizations

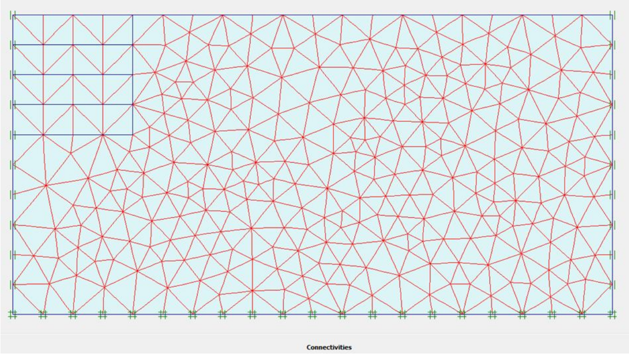

Figure 3. The geometrical model of studied numerical model for soil nailing stabilizations

4. Results and Discussions

For mechanical solution, the mass is prepared for drilling and the initial drilling step is performed according to Fig. 4. The deformation meshes are then evaluated and generated by the model. As can be seen in this figure, the pit is unstable. Therefore, a nailing system is used to solve this problem. Then we dig the next steps in this way and improve with the nails. During each step, the amounts of errors as well as the status of the deformations are checked (Fig. 5). For this purpose, first start with 5 meter long nails and evaluates the errors. Then the length of the nails becomes 6 meters as well as shows in Figs. 6 and 7.

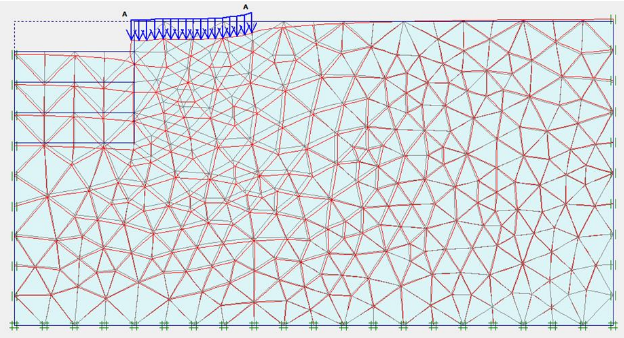

Figure 4. The deformation meshes for first step of excavation

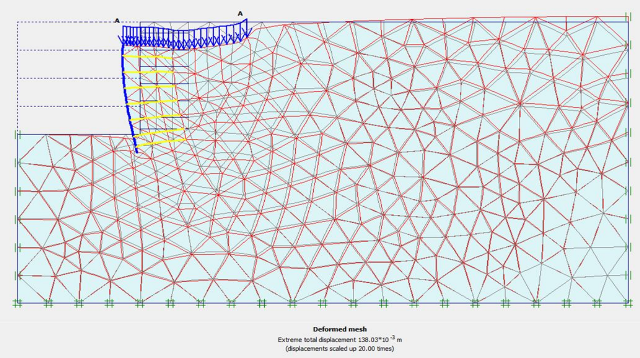

Figure 5. The deformation meshes for final step of excavation

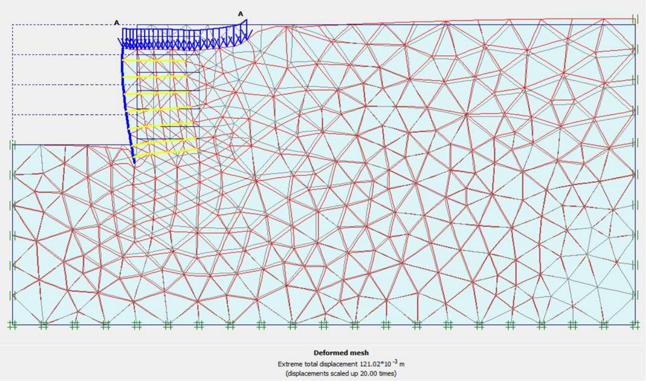

Figure 6. The deformation meshes for 5 m nailing in excavation operation

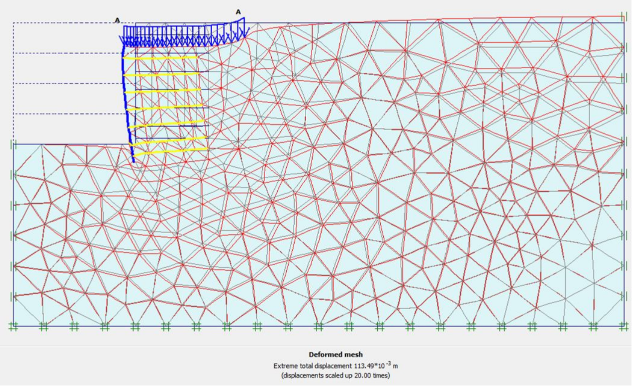

Figure 7. The deformation meshes for 5 m nailing in excavation operation

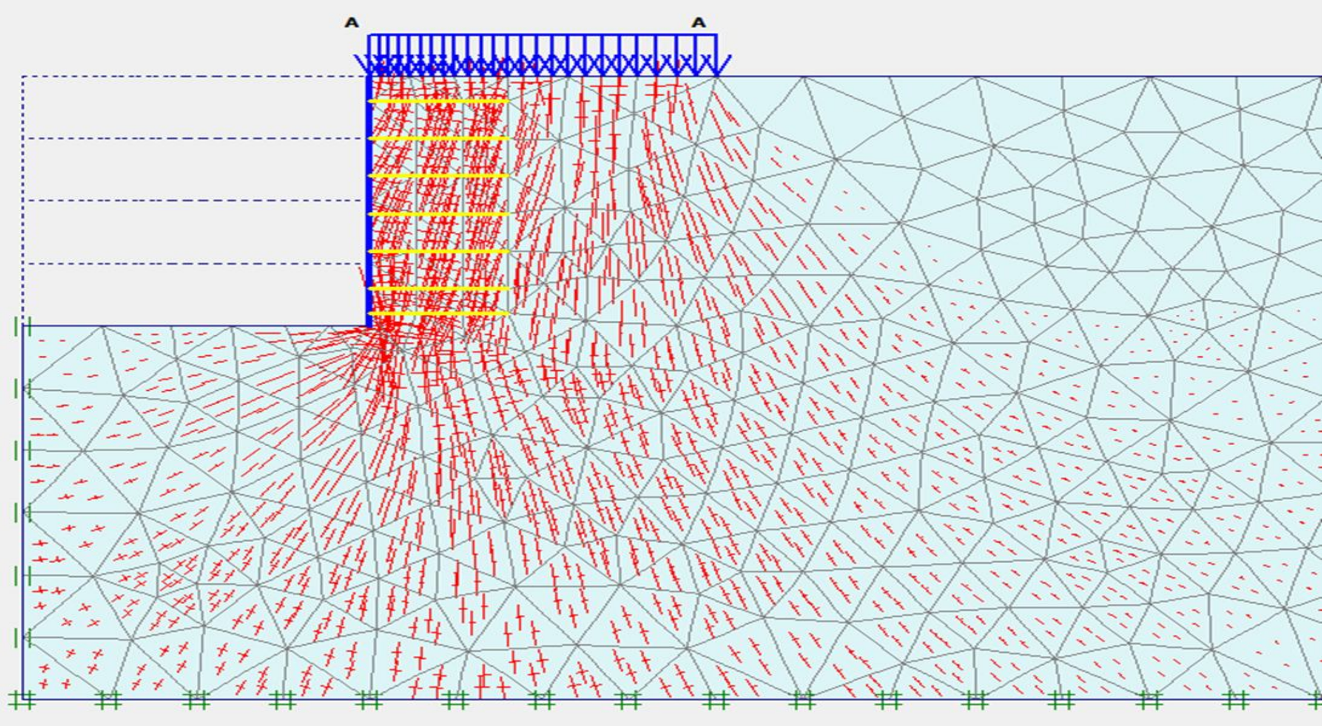

Figure 8. The in-situ stress field estimated for final stage of soil nailing operation

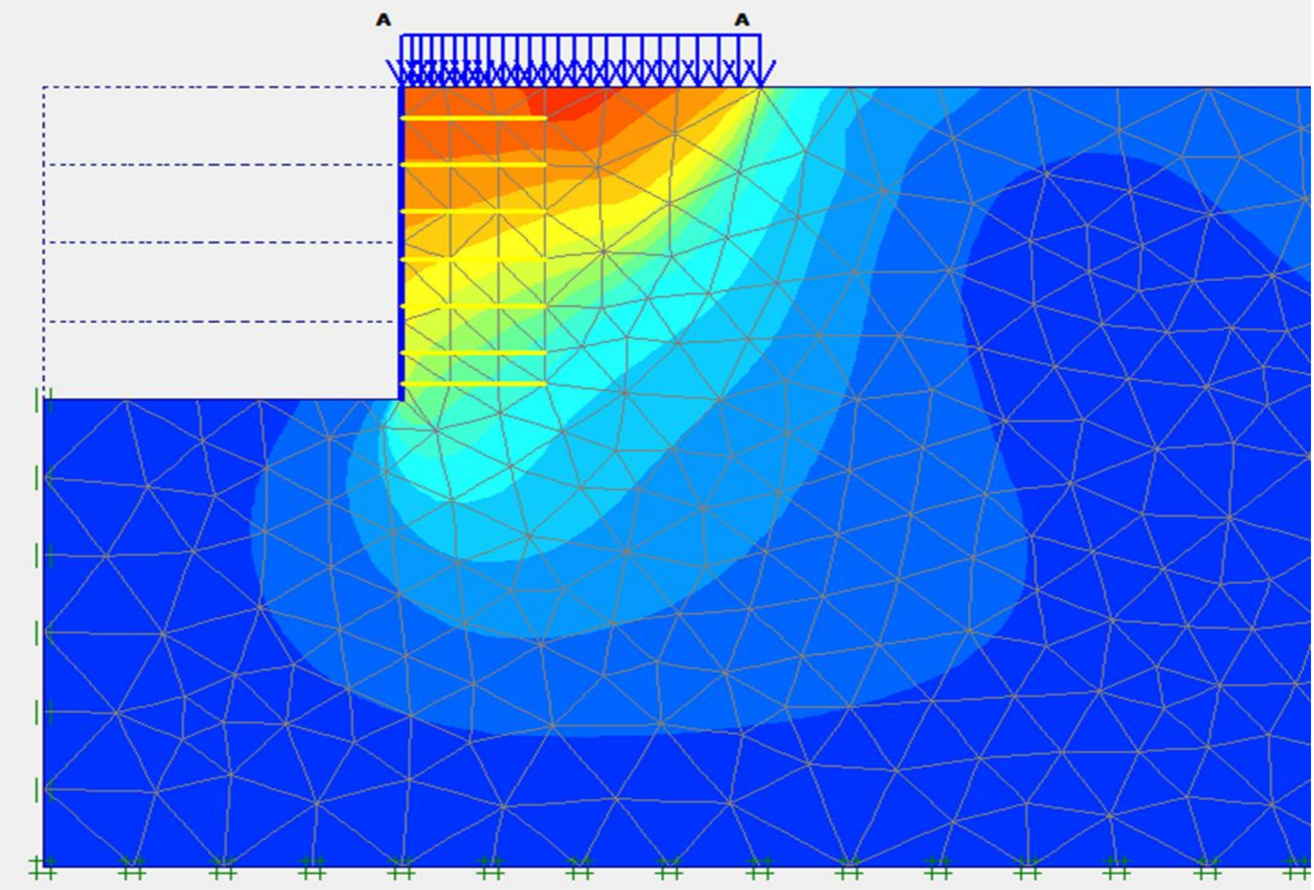

Figure 9. The total displacement estimated for 5 m nailing in excavation operation

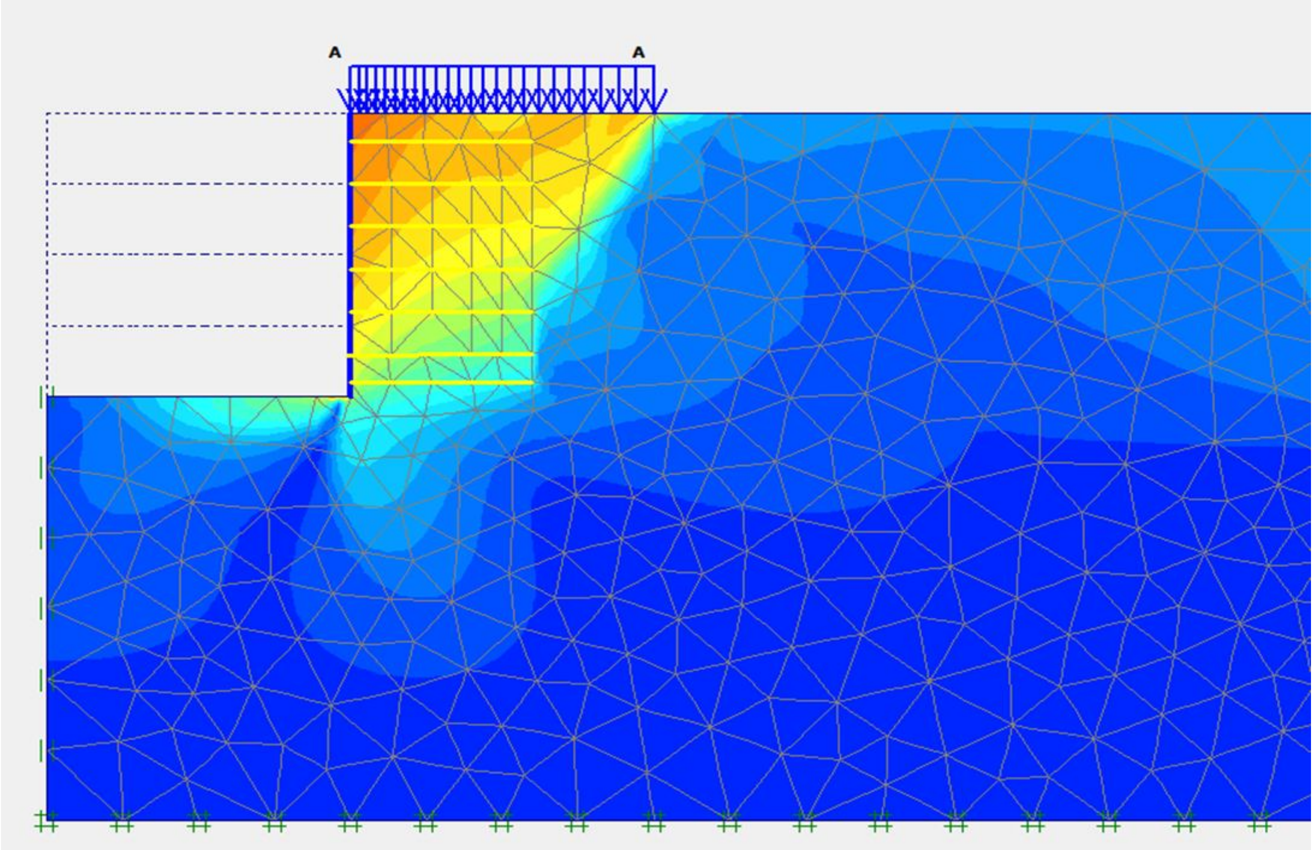

Figure 10. The total displacement estimated for 6 m nailing in excavation operation

Table 3. Safety factor changes according to soil type in nailing operation

Nail depth	Factor of Safety (Sand)		Factor of Safety (Clay)	
	S_v=1.0 m	S_v=10 m	S_v=1.0 m	S_v=10 m
0	1.661	1.356	1.514	1.429
2	1.522	1.266	1.442	1.350
4	1.403	1.201	1.363	1.256
6	1.268	1.129	1.288	1.180
8	1.119	1.100	1.109	0.667
10	0.895	0.725	1.000	0.399

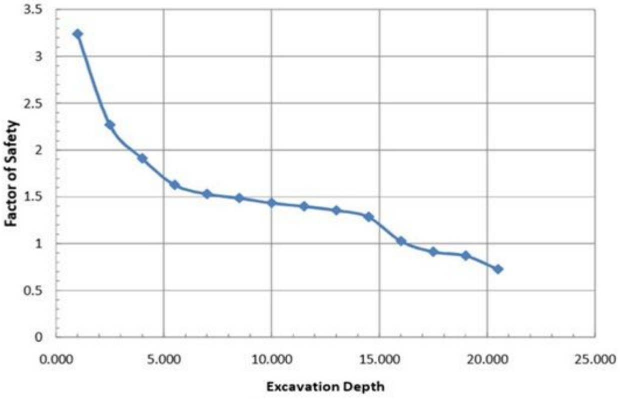

Figure 11. Reliability values of the nailing system used at different depths of the excavation

Now, considering the deformations created in the final stages of nailing, the displacement values and in situ stress are calculated for the improved mass. Figs. 8 to 10 show the results of these evaluations. Also, considering the two different soil types evaluated, the values of stability reliability for soils have been calculated, which is presented in Table 3 and Fig. 11.

5. Conclusion

Current study tried to investigate the stepwise deformations occurred by implementation of step-by-step soil nailing stabilization method. In this regard, the finite element numerical method and Plaxis2D software was used for modeling and estimation of displacement-deformation status. Numerical simulation has been done in stages including geometric model preparation, behavioral model and boundary conditions, assignment of material properties and mechanical analysis which conducted for both sand and clay materials under Mohr-Coulomb behavior criterion. Based on the simulation results, it has been determined that with increasing depth, the degree of confidence in the slope (safety factor) for 2 different arrangements decreases step-by-step (5 m and 6 m nails length) and the plastic area increases towards the bottom of the pit. But the nailing wall shows a good ability to curb instability.

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