Scientia Iranica A (2018) 25(1), 140–151

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
http://scientiairanica.sharif.edu

Numerical investigation into the static behavior of stepped soil nail walls

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Received 12 January 2016; received in revised form 23 June 2016; accepted 24 April 2017

KEYWORDS
Soil nailing;
Optimal step depth;
Minimum step width;
Deep excavation;
Numerical analysis.

Abstract. This paper presents a numerical investigation into the static behavior of stepped soil nail walls constructed in dry sandy soils. The finite element method was used to study influence of wall geometry and soil parameters on behavior of the walls. We analyzed walls with heights of 10, 15, and 20 m. This study shows that the wall deformation and the nail tensile forces of the stepped soil nail wall are smaller than those of the typical soil nail wall. If properties of soils such as friction angle, cohesion, and elastic modulus decrease, more decrease in the wall lateral displacement and nail tensile forces of a stepped soil nail wall would occur. Therefore, stepped soil nail walls are more effective in soft soils than in hard soils. When a step is located at the middle of the wall height, the wall lateral displacement and nail tensile forces are minimized; hence, the ratio of the optimal step depth to the wall height is 0.5. As the step width increases, the wall deformation and nail forces decrease. Numerical analysis demonstrates that the minimum step width is approximately 0.1 times the wall height.

1. Introduction

Soil nailing is an in situ method to increase stability of a soil mass by using passive reinforcements [1]. The main application of the method is to stabilize soil in excavations; however, it has also been used to improve the stability of existing slopes. Construction of a soil nail wall is performed in vertical steps, with construction starting at the top of the excavation and continuing down [2]. After each phase of excavation, steel bars called "nails" are placed in predrilled holes [3]. The nails are not pre-stressed [1]. If movement in the soil mass occurs near the wall, tensile loads will be produced in nails, and these loads will prevent further movement. This technique produces a reinforced section, which is stable by itself, and it is able to retain the soil around it; moreover, it can carry external loads applied to the ground [3].

A stepped soil nail wall is a new type of a common soil nail wall, and it is constructed by building a step in a typical soil nail wall [4]. Figure 1 presents a schematic diagram of an ordinary stepped soil nail wall.

The depth and width of the step play a crucial role in behavior of a stepped soil nail wall. To study the optimal depth and minimum width of steps, it is needed to examine the influence of wall geometry and soil parameters on behavior of stepped soil nail walls. This paper describes the static behavior of stepped soil nail walls constructed in dry sands, and it suggests optimal depth and minimum width of steps in various geometric conditions. Soil nail walls and stepped soil nail walls are analyzed herein by using the finite element method.

In a soil nail wall, nails are circular in cross-

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doi: 10.24200/sci.2017.4532

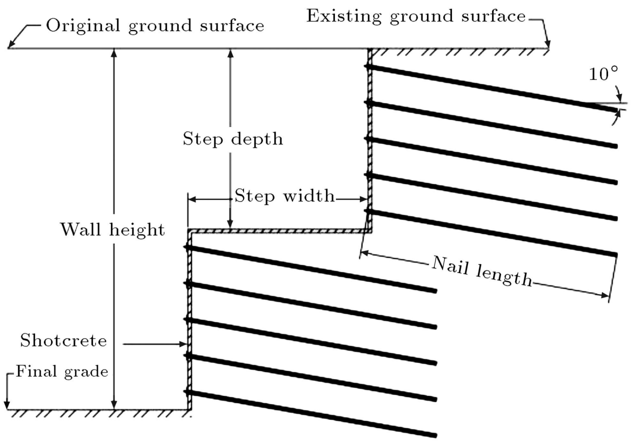


Figure 1. Schematic diagram of a stepped soil nail wall (redrawn form [2]).

section; moreover, they are installed at specified horizontal spacing. Therefore, a soil nail wall has three-dimensional geometry. As a result, a two-dimensional model that assumes plane strain conditions cannot be used to model a soil nail wall. Accordingly, it is necessary to develop methods in order to model a soil nail wall with a two-dimensional analysis [5]. Unterreiner et al. [5] describe approaches which can be used to model a soil nail wall with a two-dimensional model. Furthermore, Babu and Singh [6] illustrate how to calculate equivalent properties for nails in order to use a two-dimensional model to analyze a soil nail wall. Eq. (1) was used to calculate the equivalent plain strain elastic modulus of nails for plane strain analyses in this study:

$$E_{2D} = \frac{E_{\text{nail}}}{S_h}, \quad (1)$$

where E_{2D} is the nail elastic modulus used in two-dimensional model; E_{nail} is the nail elastic modulus; and S_h is horizontal spacing of soil nails.

The soil-nail interaction has a significant effect on the behavior of a soil nail wall. Chu and Yin [7] conducted several direct shear box tests and pullout tests to investigate the shear stress-strain behavior and ultimate shear strength at the interface between the cement-grout nail and the surrounding soil. Their research indicated that interface friction angle and soil-cement adhesion were approximately similar to soil friction angle and soil cohesion, respectively [7]. Wu and Zhang [8] also conducted laboratory tests and field pullout tests to study the interface resistance between nails and soil. Their study showed that the shear behavior at the soil-nail interface followed the Mohr-Coulomb failure criterion [8]. Thus, it is reasonable to make an assumption in the numerical model that the shear parameters of the soil around nails are similar to those of the surrounding soil; furthermore, Mohr-Coulomb failure criterion can be used for the soil around nails.

The friction mobilized between the soil and nails influences the deformation and strength of soil nail walls. Milligan and Tei [9] conducted several pull-out tests on model soil nail walls in order to study the fundamental interaction mechanisms between a nail and soil. They found out that the apparent coefficient of bond friction between nails and soil was affected by the friction angle of the soil, the rate of soil dilation during shear, the stiffness of the soil, and diameter of the nail in relation to mean particle size of the soil [9]. Wang and Richwien [10] also studied the friction mobilized between the soil and nails by comparing results of pull-out tests and direct shear tests. They observed that the mobilized friction between soil and nails was mainly dependent on the elastic parameters of the soil and its dilatancy angle. Furthermore, they demonstrated that the friction mobilized between the soil and nails measured by pull-out tests was much larger than the results of the direct shear tests. They mentioned that due to dilatancy angle of sands, the maximum friction angle between the soil and nails was bigger than the friction angle of the soil [10]. Therefore, it is appropriate to assume rigid interface between nails and the soil in numerical models. As a result, relative displacement between nails and the soil was neglected in the numerical model.

The embedded element technique in Abaqus program was used to model rigid interface between nails and the soil. In this technique, the soil element that is near a nail is constrained to the translational degrees of freedom of the nail nodes [11]. Hence, if the soil around nails deforms, tensile forces will be developed in nails, and these tensile forces will prevent further movement in the soil mass.

It is important in any numerical simulation to determine where to place the boundaries so far that effect of boundaries on the result can be minimized. Briaud and Lim [12] have done a three-dimensional nonlinear finite-element analysis to study the behavior of soil nail walls, which were built under a bridge abutment. By doing numerical simulations, they suggested where to place the boundaries in order to have minimum influence of boundaries on the numerical simulation of a soil nail wall [12]. This information was used to place the boundaries of numerical models in the current research.

Wang et al. conducted a research on the behavior of stepped soil nail walls [4]. They found out that building a step in a typical soil nail wall would increase stability of the wall, and it would decrease the wall deformation and nail tensile forces. According to the numerical calculation, they stated that the ratio of the optimal step depth to the wall height was 0.6. Additionally, they indicated that the step width, i.e. the horizontal setback, should not be less than 0.1 times the wall height based on engineering experience [4].

Furthermore, Lazarte et al. [2] indicated that when the step width was larger than the height of the lower wall, each individual wall would behave autonomously.

The study of Wang et al. [4] on the optimal step depth is not sufficient, because they did not consider all possible positions of the step in their research. Moreover, influence of soil parameters and wall geometry on the optimal depth and minimum width of steps was not studied. Therefore, this paper mainly focuses on the subjects which have not been adequately studied.

2. Numerical modeling of soil nail walls

2.1. Finite element modeling

The unified finite element program Abaqus was used to model both soil nail walls and stepped soil nail walls numerically. Figure 2 shows a typical geometry of a stepped soil nail.

Nails consisted of steel bars with a diameter of 28 mm surrounded by grouts of 10 cm diameter. Because grout cracked at a slight deformation, the strength contributed by the grout was ignored in the parametric study. The wall height, H, the step depth, D, and the step width, W, were changed to study their influence on the behavior of stepped soil nail walls. Wall heights, H, of 10, 15, and 20 m were numerically analyzed.

In engineering practice, the common values for the ratio of the nail length to the wall height, L/H, and nail inclination are approximately 0.7 and 10 degrees, respectively; therefore, these values were chosen for the parametric study. Both vertical and horizontal spacing of nails is 1 m. It should be noted that results of the research are somewhat restricted to these conditions. Soil parameters such as elastic modulus, E, angle of internal friction, ϕ, angle of dilation, ψ, and cohesion, c, varied in the analyses. Figure 3 shows the finite element mesh and boundary conditions of a soil nail wall. The wall height is 10 m. As shown in the figure,

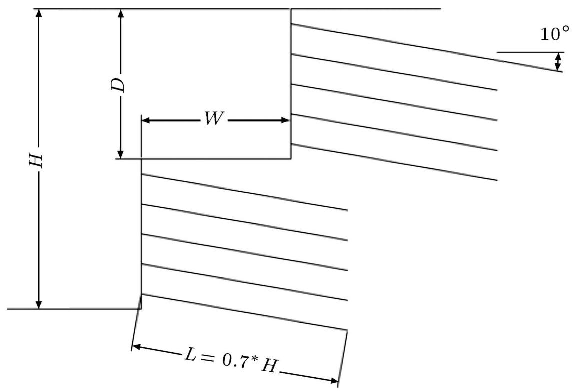


Figure 2. Geometric profile of soil nail walls analyzed in this paper.

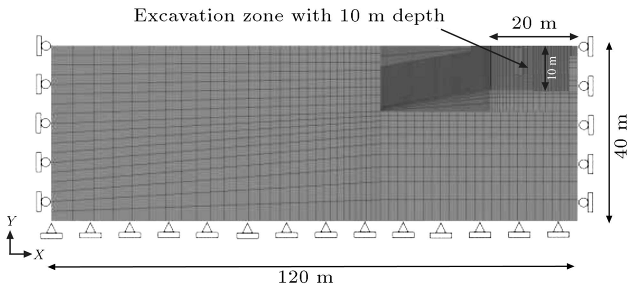


Figure 3. Finite element mesh and boundary conditions of the soil nail wall with the height of 10 m.

the bottom of the model is restricted in both X and Y directions, and both sides of the model can move in the Y direction, but they are restricted in the X direction. As previously mentioned, the boundaries of the model are placed based on the information Briaud and Lim [12] provided. The finite element mesh has 6530 elements and 6821 nodes. As aforementioned, the embedded element technique is used to simulate rigid interface between nails and the soil. In this technique, in order to have accurate results, it is necessary to have at least one node of the soil mass near each node of a nail element. Therefore, the mesh density of the soil mass in the vicinity of nails is increased to have accurate results.

2.2. Numerical modeling of soil, shotcrete facing, nails, and soil nail interface

Soil elements are 4-node bilinear plane strain quadrilateral elements. The Mohr-Coulomb constitutive model was used to model the stress-strain behavior of the soil. In granular soils, as confining stress increases, the elastic modulus increases. In order to model this condition, Eq. (2) was used in this parametric study:

$$E = K \times P_a \left(\frac{\sigma_3}{P_a}\right)^n, \qquad (2)$$

where E is the soil elastic modulus; σ_3 is the minor principal stresses; K is a modulus parameter; n is the exponent determining the rate of variation of the elastic modulus with σ_3, and P_a is atmospheric pressure. In this study, n and K for the soil are 0.5 and 1100, respectively. Figure 4 shows the variation of soil elastic modulus with depth. The soil which is situated at the depth of more than 25 m is considered to be harder than the soil above it, and its elastic modulus is 250 MPa.

Shotcrete facing elements are 4-node bilinear plane strain quadrilateral elements. The elastic model was employed to model the facing. In addition, nail elements are 2-node linear beam elements. The elastic perfectly plastic model was used to model the nails. Table 1 shows properties of the soil, facing, and nails used in the parametric study.

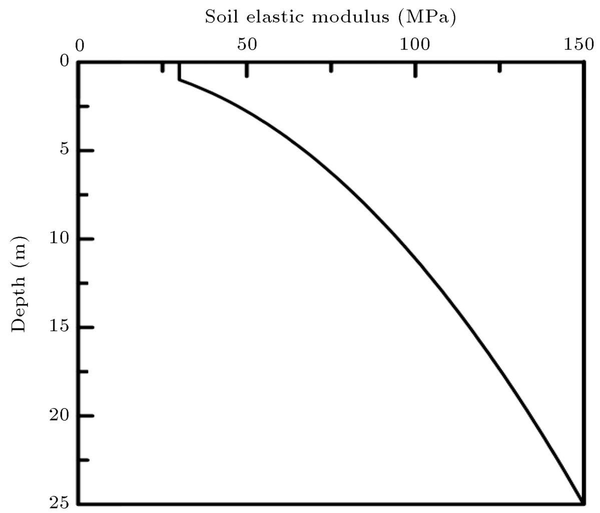


Figure 4. Variation of elastic modulus of the soil with the depth used in the numerical analyses.

Table 1. Material properties of the soil, nail, and shotcrete facing used in the parametric study.

Soil	
Unit weight, γ (kN/m^3)	17
Cohesion, c (kPa)	5 and 10
Internal friction angle, φ (°)	30°, 34°, and 38°
Angle of dilation, ψ (°)	0°and 8°
Exponent, n	0.5
Modulus parameter, K	1100
Poisson's ratio, ν	0.3
Nail	
Density, ρ (kg/m^3)	7860
Elastic modulus, E (GPa)	200
Poisson's ratio, ν	0.3
Yield strength, f_y (MPa)	275
Shotcrete	
Unit weight, γ (kN/m^3)	24
Elastic modulus, E (GPa)	16
Poisson's ratio, ν	0.2

2.3. Verification of the model

To verify the model, the construction of the full-scale experimental soil nail wall built as part of the French national research project, called CLOUTERRE [13], is modeled. The CLOUTERRE project was conducted from 1986 to 1991 in order to investigate the behavior of soil nail walls during construction, in service, and at failure [5]. The soil nail wall is 7 m high and 7.5 m wide. The soil nail wall was constructed in the backfill, which was built with special care on a dense sand formation. The backfill was constructed between two lateral walls, which were covered with a double-layer polyethylene sheet to create plane strain condition [13]. Figure 5 displays the cross-section of the soil nail wall.

The soil nail wall was constructed by excavating soil in seven phases. The depth of the excavation lifts was 1 m. The facing was made of a mesh-reinforced shotcrete, and the thickness of the facing was 8 cm. The nails consisted of hollow aluminum tubes grouted in the soil, and they were inclined at 10° with respect to the horizontal plane. The construction sequence of the soil nail wall was modeled by the excavation of 1 m of soil followed by the installation of nails and shotcrete [13]. As shown in Figure 5, five types of nails marked with A, B, C, D, and E were used in the project. The properties of the nails are shown in Table 2. The nails were spaced 1 m vertically and 1.15 m horizontally [13]. Two-dimensional and three-dimensional finite element simulations were run for the soil nail wall of the CLOUTERRE project. Eq. (3) was used to calculate the equivalent modulus of elasticity of the grouted soil nail. In addition, for the two-dimensional models, plane strain condition, Eq. (1) was also used.

$$E_{eq} = a \times \left(E_b \left(\frac{A_b}{A} \right) + E_g \left(\frac{A_g}{A} \right) \right), \tag{3}$$

where E_g is the elastic modulus of grout; E_b is the elastic modulus of bar; E_{eq} is the equivalent elastic modulus of the grouted soil nail; A is the total cross-sectional area of the grouted soil nail; A_b is the cross-sectional area of the bar; A_g is the cross-sectional area of the grout cover; and a is the stiffness reduction factor to decrease the elastic modulus of the nail due to cracks which happen in grout.

The pressuremeter test was done in the CLOUTERRE project. Many correlations have been suggested between the Menard pressuremeter modulus, E_m, and the soil elastic modulus, E. The ratio of E/E_m varies between 2 and 4, and it depends mostly on the type of soil and the level of deformation [5]. Unterreiner et al. [5] determined that the ratio of E/E_m for soil of the CLOUTERRE project should be between 2.2 and 2.8; thus, the ratio of 2.5 was chosen for the numerical models. The elastic modulus used in the numerical model and the elastic modulus calculated from the pressuremeter test are compared in Figure 6. The properties of the soil and the shotcrete are shown in Table 2.

Figure 7 shows the finite element mesh of three-dimensional model of the soil nail wall. The finite element mesh consists of 9615 elements and 15828 nodes. Briaud and Lim [12] stated that it was enough to model one column of nails in a three-dimensional analysis [12]. Since the nails were installed in the repetitive arrangement along the length of the excavation, only one column of the nails and a slice of the soil between two vertical planes midway between the adjacent columns of the nails were analyzed in the three-dimensional model. The thickness of the three-dimensional model was 1.15 m.

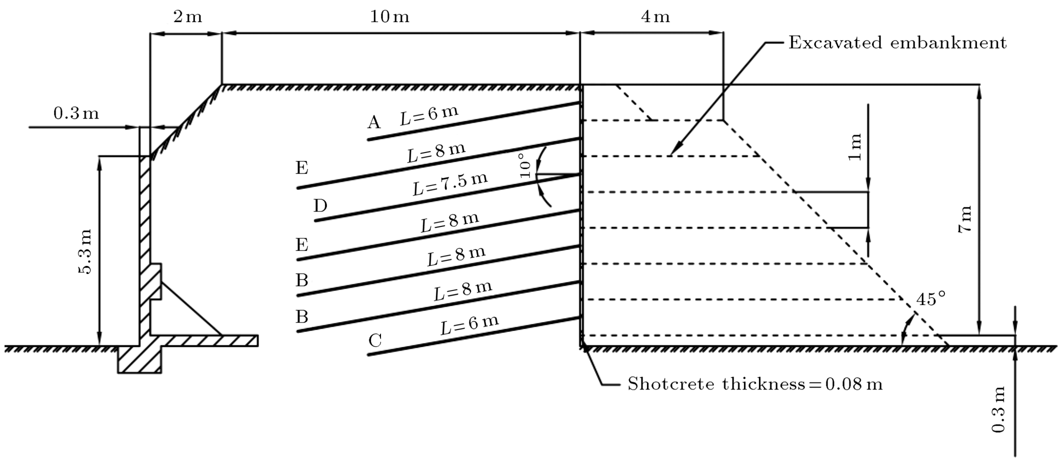


Figure 5. Geometric profile of the soil nail wall constructed in the CLOUTERRE project (redrawn from [5]).

Table 2. Properties of soils, nails, and shotcrete facing used in the numerical analysis for the soil nail wall of the CLOUTERRE project.

Soils		
	Backfill soils	**Foundation soils**
Unit weight, γ (kN/m^3)	16.6	17
Cohesion, c (kPa)	3	5
Internal friction angle, φ (°)	38°	38°
Poisson's ratio, ν	0.37	0.37
Angle of dilation, ψ (°)	0°	0°

Shotcrete	
Unit weight, γ (kN/m^3)	24
Elastic modulus, E (GPa)	16
Poisson's ratio, ν	0.2

Nails					
	A	**B**	**C**	**E**	**D**
Density, ρ (kg/m^3)			7860		
Length (m)	6	8	6	8	7.5
Tube thickness (mm)	1	2	1	1	1
Tube diameter (mm)	16	30	40	40	40
Grouted diameter (mm)			63		
Elastic modulus of the aluminum bar (GPa)			70		
Elastic modulus of the grout (GPa)			16		
Stiffness reduction factor, a	0.1	0.3	0.3		0.3
Poisson's ratio, ν			0.2		

Figure 8 compares the computed lateral displacement of the wall with the experimental data [13] at the end of construction. It illustrates that both the three-dimensional and the two-dimensional models can appropriately simulate the construction of the soil nail wall. According to this figure, while computed lateral displacement of the wall has the stepwise curves, the measured values do not have these curves. As mentioned, excavation of the soil was simulated in the numerical models. After each phase of excavation, deformation of the soil mass was computed. Generally, deformation of soils is a time-dependent process. It should be noted that the time-dependent behavior of the soil was not simulated in the numerical models. It means that after each phase of excavation in the numerical model, the surface of the soil mass would

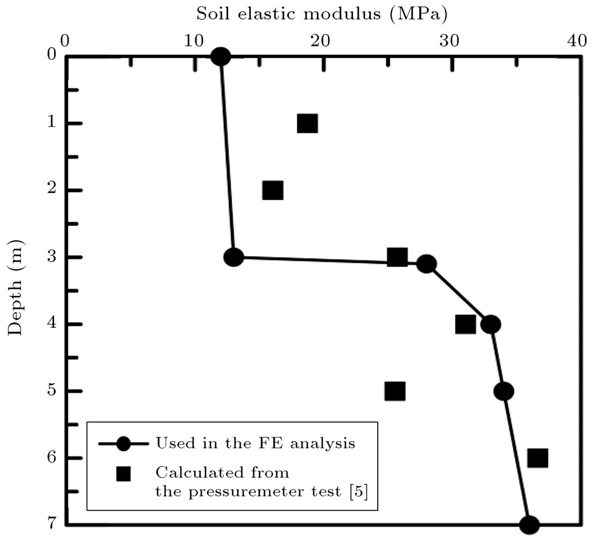


Figure 6. Comparison of the soil elastic modulus used in the numerical model with the elastic modulus calculated in the pressuremeter test for the soil nail wall in the CLOUTERRE project.

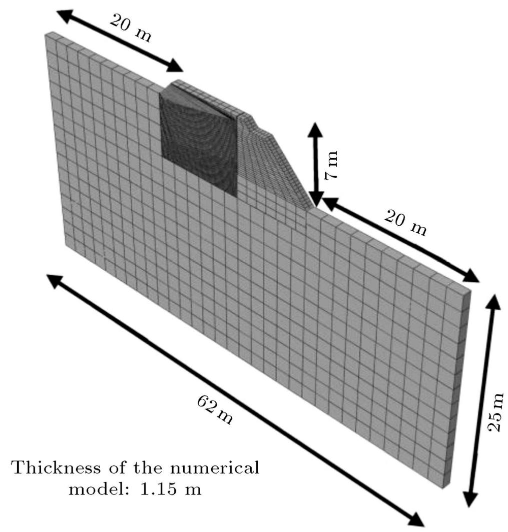


Figure 7. Finite element mesh of the soil nail wall for the CLOUTERRE project.

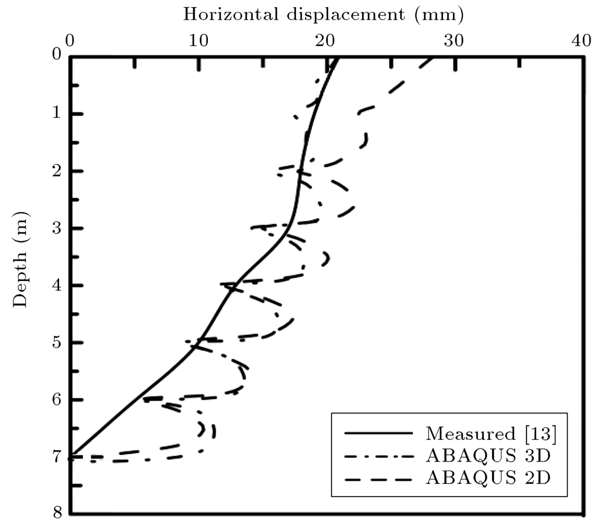


Figure 8. Comparison of the computed lateral displacement of the facing with the measured results [13] at the end of construction.

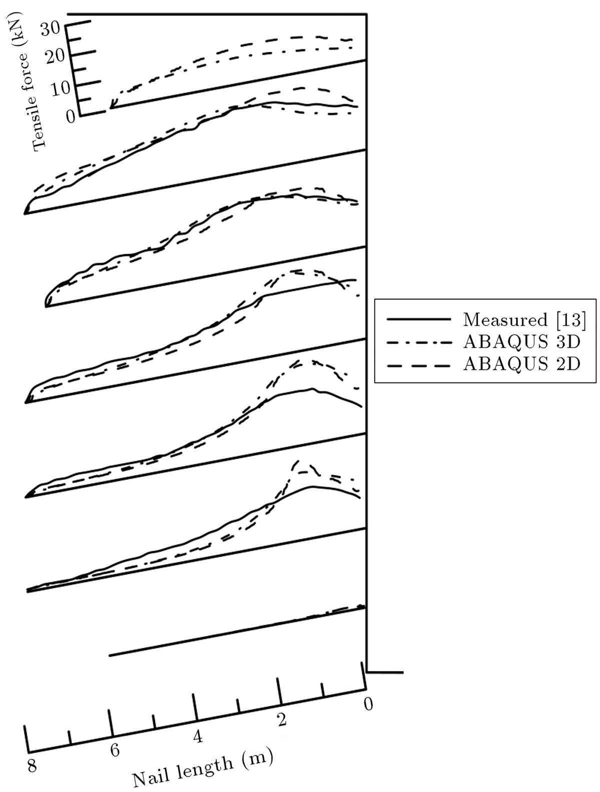


Figure 9. Comparison of the computed tensile forces in nails with the measured results [13] at the end of construction.

be uncovered for a long time; then, the facing would be applied to the surface. However, in reality, the shotcrete facing was installed immediately after each phase of excavation. This is the main reason that small local plastic zones were observed on the surface of the soil mass in the numerical models, and these plastic zones created the stepwise curves on computed lateral displacement of the wall facing. Figure 8 also demonstrates that the result of the three-dimensional model is more accurate than the result of the two-dimensional model. One feasible explanation of the discrepancy may be that the transfer of stress in the soil above a nail to below it can be properly modeled in the three-dimensional model.

Comparison of the computed tensile forces in nails with the measured results [13] at the end of construction is shown in Figure 9. The nail was located at the top row broke at the end of construction [13]; consequently, the measured result for this nail is not available. As a whole, the computed tensile forces agree well with the measured results. Generally, when a nail is installed in a pre-drilled hole on a facing of a soil nail wall, tensile force of the nail is zero. According to Figure 9, this behavior was completely simulated in the numerical models. This figure demonstrates that at the end of the construction, tensile forces only in the six upper rows of nails were generated; furthermore, the tensile forces in the seventh row of the nails were zero. Tensile forces would be generated in the bottom row of the nails if construction goes further or if the wall deforms due to external loads.

3. Optimal step depth

The stepped soil nail walls whose step depths, D, changed from the top of the walls to the bottom of the walls were analyzed in order to evaluate the influence of step depths on the behavior of these kinds of walls. Figure 10 shows the horizontal displacement of the stepped soil nail walls with a height of 10 m. The step width, W, is 1 m. The internal friction angle and the cohesion of the soil are 38° and 5 kPa, respectively. Figure 10 illustrates that the horizontal displacement of the stepped soil nail wall is smaller than that of the ordinary soil nail wall. Moreover, according to the figure, when the step depth, D, is 1 and 9 m, the lateral displacement for the two walls is the same, but not identical. The main reason is that in both conditions the stepped soil nail wall approximately behaves as a combination of two soil nail walls with heights of 1 and 9 m. When D is 1 m, the section of the wall with the height of 9 m would be constructed after the construction of the top section with height of 1 m. Therefore, the lateral displacement of the stepped soil nail wall would be roughly similar to the lateral displacement of a soil nail wall with height of 9 m. However, when D is 9 m, the bottom section of the wall with the height of 1 m would be constructed after building the top section of the wall with the height of 9 m. As a result, building the bottom section would cause more deformation on the top section of the wall with the height of 9 m. Thus, the lateral displacement of the stepped soil nail wall would be more than the horizontal displacement of a soil nail wall with height of 9 m. As a result, when D is 9 m, the horizontal displacement at top of the wall is more than the lateral displacement at top of the wall when D is 1 m.

To investigate the optimal step depth, Figure 11 demonstrates the horizontal wall displacement at the top of the stepped soil nail walls, δ_{stepped}, versus step depths, D. Figure 11 shows that when the step is located at the depth of 5 m, horizontal displacement of the wall is minimized. Hence, the optimal step depth for this wall is 5 m. Furthermore, the figure exhibits that when the step is located close to the top of the wall or the bottom of the wall, horizontal displacement of the stepped soil nail wall is same as that of the corresponding soil nail wall; hence, the stepped soil nail wall would be less effective.

To study the influence of soil parameters, such as angle of internal friction, angle of dilation, cohesion, and elastic modulus on the optimal step depth, these parameters were changed and the behavior of stepped soil nail walls was analyzed. Figure 12 shows the effect of the step depth on the percentage decrease in the horizontal displacement at the top of the walls for five different soils. The parameter in the horizontal axis is calculated by comparing the lateral wall displacement at the top of stepped soil nail walls with that of the corresponding soil nail walls. The parameter in

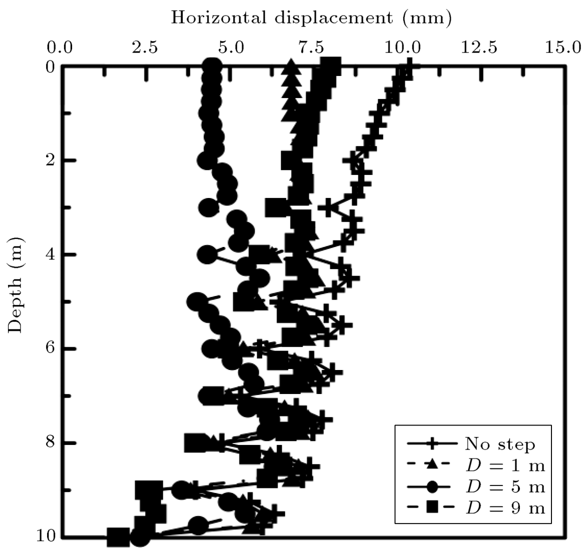


Figure 10. Lateral displacement of stepped soil nail walls with a height of 10 m and various step depths.

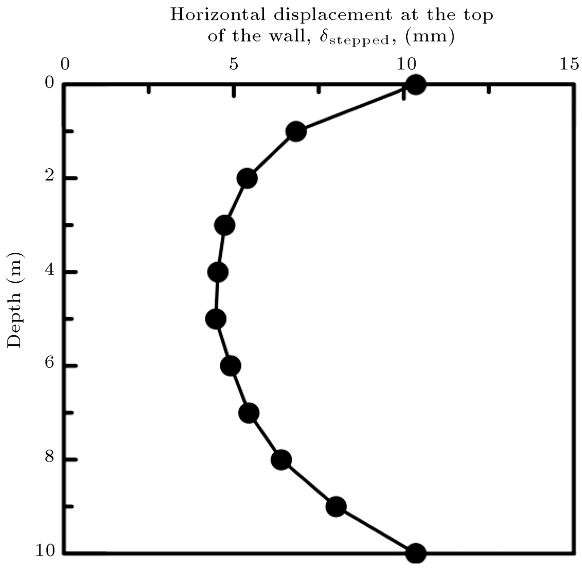


Figure 11. Influence of the step depth on the lateral displacement at the top of the stepped soil nail walls with a height of 10 m.

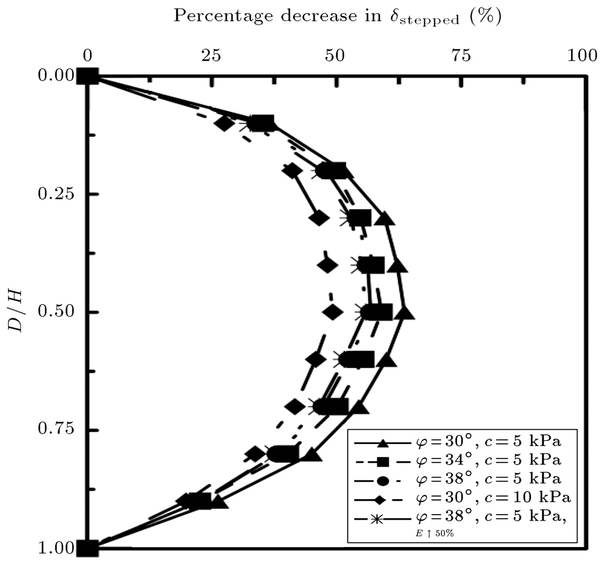


Figure 12. Effect of the step depth on the percentage decrease in the horizontal wall displacement at the top of stepped soil nail walls with a height of 10 m.

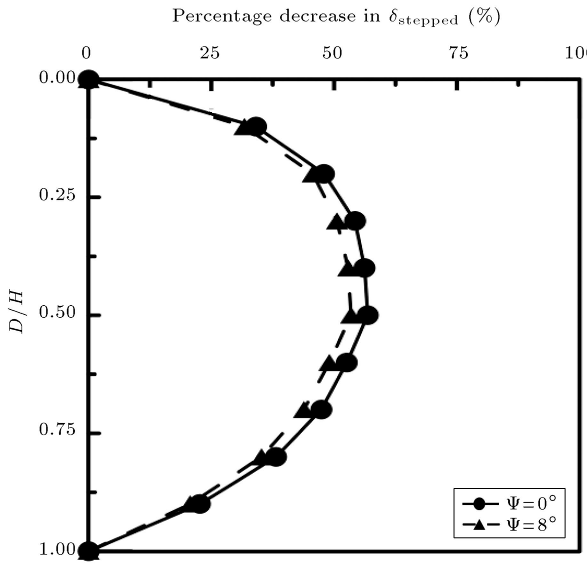
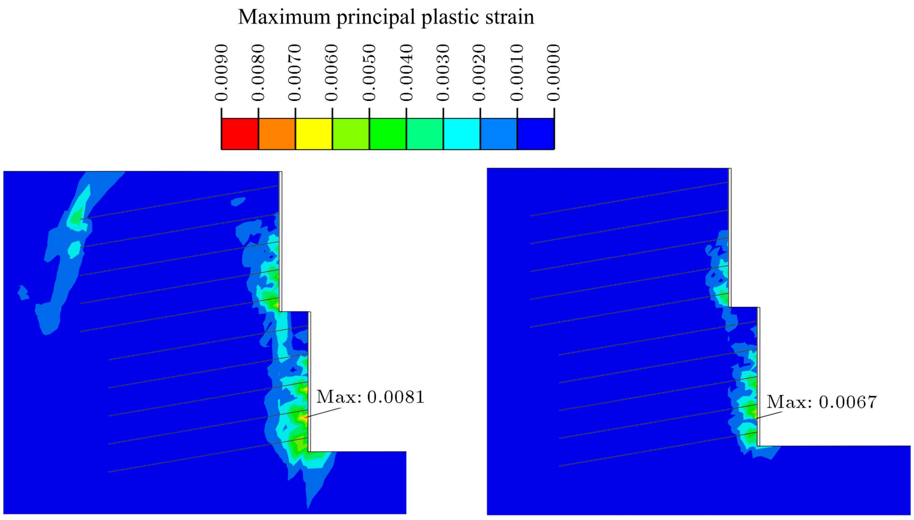


Figure 14. Influence of the angle of dilation on the percentage decrease in the horizontal wall displacement at the top of stepped soil nail walls with a height of 10 m.

the vertical axis is the ratio of step depth, D, to the wall height, H. Figure 12 illustrates that when properties of soils such as friction angle, cohesion, and elastic modulus decrease, plastic deformation of the wall increases; this will lead to more decrease in the wall displacement. Figure 13 is provided to explain this behavior more. Figure 13 demonstrates that when the friction angle of the soil mass decreases from 38° to 30°, maximum principal plastic strain of the soil mass increases; furthermore, a larger area of the soil mass undergoes plastic deformation. As a result, when these parameters decrease, plastic deformation of a typical soil nail wall increases; therefore, building a step in an ordinary soil nail wall becomes more effective. As a result, the stepped soil nail wall would be more effective in soft soils than in hard soils. Moreover, Figure 12 demonstrates that the maximal decrease in the wall displacement happens when the step is located in the middle of the wall; therefore, the ratio of the optimal step depth to the wall height is 0.5.

To investigate the effect of the angle of dilation of soil on the behavior of the soil nail walls, the angle of dilation increased from 0° to 8°. The internal friction angle and the cohesion of the soil were 38° and 5 kPa, respectively. Figure 14 demonstrates that when the angle of dilation increases, the percentage decreases



(a) $\varphi = 30°$, $c = 5$ kPa (b) $\varphi = 38°$, $c = 5$ kPa

Figure 13. Contour of Maximum principal plastic strain of a stepped soil nail wall with a height of 10 m: (a) Friction angle of soil is 30°, and (b) friction angle of soil is 38°. In both figures cohesion of the soil is 5 kPa.

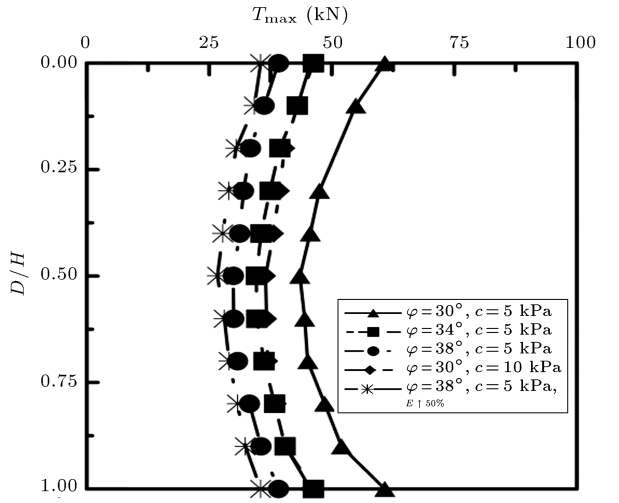


Figure 15. Influence of the step depth on maximum tensile forces in nails of the stepped soil nail walls with a height of 10 m.

in the wall displacement decrease. In addition, when the ratio of D/H is 0.5, the maximal decrease in the wall displacement happens; therefore, the location of the optimal step depth is in the middle of the wall for both soils. Furthermore, Figure 14 illustrates that the angle of dilation does not have a significant effect on the behavior of the soil nail walls. Thus, in this study, it is assumed that the angle of dilation of soil is 0°.

Figure 15 displays effect of step depths on maximum tensile forces in nails of stepped soil nail walls, T_{max}. The height of the walls is 10 m. Figure 15 shows that building a step in a typical soil nail wall decreases the maximum tensile forces in nails. Furthermore, when the ratio of D/H is 0.5, the maximum tensile forces in nails are minimized.

To examine the effect of the wall height on the optimal step depth, stepped soil nail walls with heights of 15 m and 20 m were analyzed. Figure 16 shows influence of the step depth on the percentage decrease in the horizontal wall displacement at the top of walls. The internal friction angle and the cohesion of the soil are 38° and 5 kPa, respectively. Figure 16 demonstrates that when the ratio of D/H is approximately 0.5, the horizontal wall displacement at the top of stepped soil nail walls is minimized; therefore, the optimal step depth is in the middle of the height of a stepped soil nail wall.

4. Minimum step width

The stepped soil nail walls with various step widths, W, were analyzed in order to study the influence of step widths on the behavior of these kinds of walls. According to the previous section, the ratio of the optimal step depth to the wall height is 0.5; hence, in this section, the steps are located in the middle

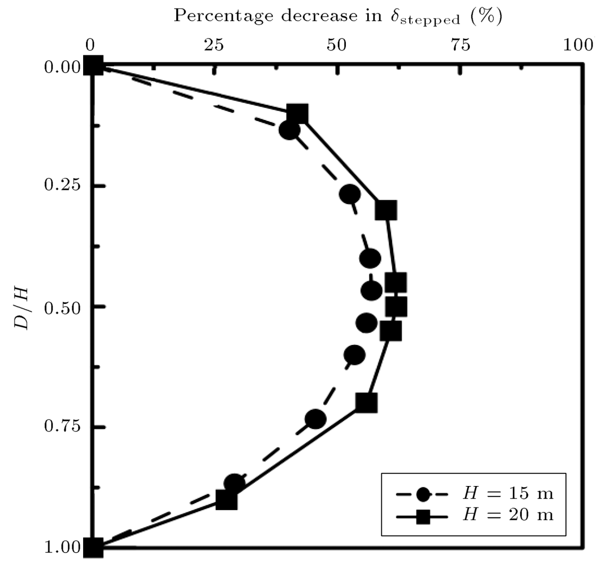


Figure 16. Effect of the step depth on the percentage decrease in the horizontal wall displacement at the top of the stepped soil nail walls with heights of 15 m and 20 m.

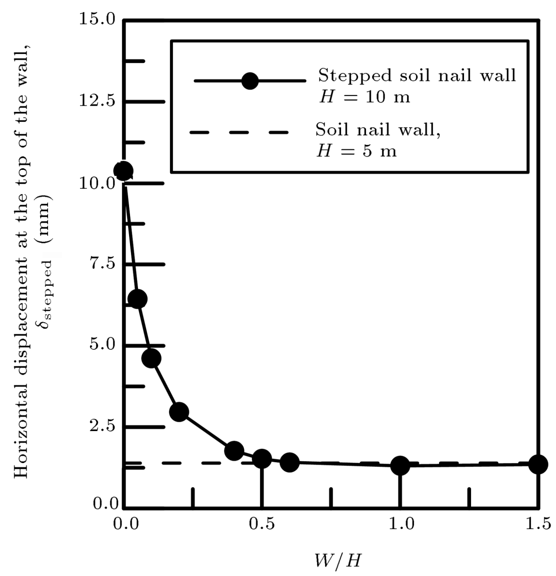


Figure 17. Influence of the ratio of the step width to the wall height on the lateral displacement at the top of the stepped soil nail walls with a height of 10 m.

of the wall heights. Figure 17 shows the horizontal displacement at the top of stepped soil nail walls versus the ratio of the step width, W, to the wall height, H. The height of the wall is 10 m and the depth of the step is 5 m. The internal friction angle and the cohesion of the soil are 38° and 5 kPa, respectively. Figure 17 illustrates that when the step width increases, the horizontal wall displacement at the top of the stepped soil nail wall decreases. When the step width is small, increasing the step width significantly reduces the wall deformation. However, when the step width is large, reduction in the wall deformation by increasing the step width is negligible. Furthermore, Figure 17 shows that when the ratio of the step width to the wall is 0.5, the horizontal wall displacement at the top of the stepped soil nail wall with the height of 10 m is approximately the horizontal displacement at the top of the soil nail wall with the height of 5 m. Moreover, if the ratio of the step width to the wall becomes greater than 0.5, the horizontal wall displacement at the top of the stepped soil nail wall does not decrease noticeably.

Results of the numerical simulations show that when the step width increases, the maximum tensile forces in the nail decrease. Moreover, by increasing the step width, maximum tensile forces in nails of stepped soil nail walls with the height of 10 m move towards maximum tensile forces in nails of the soil nail wall with the height of 5 m.

It should be mentioned that the minimum step width in this research is defined as a minimum width, which should be considered for building a stepped soil nail wall. Since, if a step width becomes less than the minimum step width, the step would not considerably decrease the deformation of the wall. Furthermore, when the step width is less than the minimum step width, as the step width decreases, the deformation of the wall increases considerably and it goes towards the deformation of a wall without the step.

Figure 18 is used to calculate the minimum step width for this wall. In the figure, the parameter in the vertical axis is the ratio of the horizontal wall displacement at the top of the stepped soil nail wall, δ_{stepped} to that of the corresponding soil nail wall, δ. In Figure 18, two tangents are drawn at both the beginning and the ending of the curve. The intersection of these lines shows the minimum step width. Figure 18 demonstrates that the ratio of the minimum step width to the wall height, $W_{\min}/H$, is 0.11.

The influences of the internal friction angle of soil on the minimum step width were studied. Figure 19 shows variation of the ratio of $W_{\min}/H$ with the angle of internal friction of soil for stepped soil nail walls with heights of 10 m, 15 m, and 20 m. The cohesion of the soil is 5 kPa. The figure illustrates that the ratio of $W_{\min}/H$ is approximately 0.1.

To study the influence of the soil elastic modulus on the ratio of $W_{\min}/H$, the elastic modulus of the soil is increased by 50 percent. As a result, the ratio changes from 0.116 to 0.119. Therefore, the minimum width does not alter considerably when the elastic modulus of the soil changes. In addition, numerical simulations depict that the ratio increases from 0.116 to 0.135 when the soil cohesion is increased from 5 kPa to 10 kPa. In these two simulations, the soil internal friction angle is 38°.

Figure 20 shows the effect of the step width on the percentage decrease in the horizontal wall displacement at the top of stepped soil nail walls. The internal friction angle and the cohesion of the soil are 30° and 5 kPa, respectively. Figure 20 demonstrates that when the ratio of the step width to the wall height becomes greater than 0.5, the percentage decrease in lateral displacement of the wall does not increase noticeably. In addition, the analyses show that the lateral displacement at the top of both sections of the stepped soil nail wall is almost equal to the horizontal displacement at the top of the soil nail wall whose height is half the height of the stepped soil nail wall.

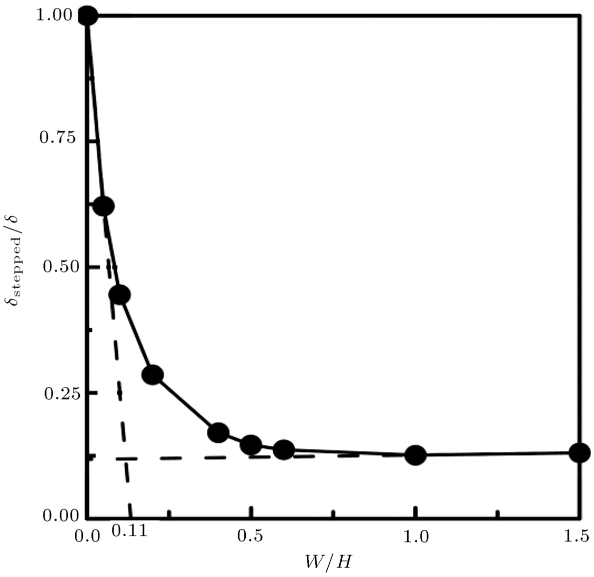


Figure 18. Effect of the ratio of the step width to the wall height on the ratio of the horizontal wall displacement at the top of the stepped soil nail wall to that of the corresponding soil nail wall, $H = 10$ m.

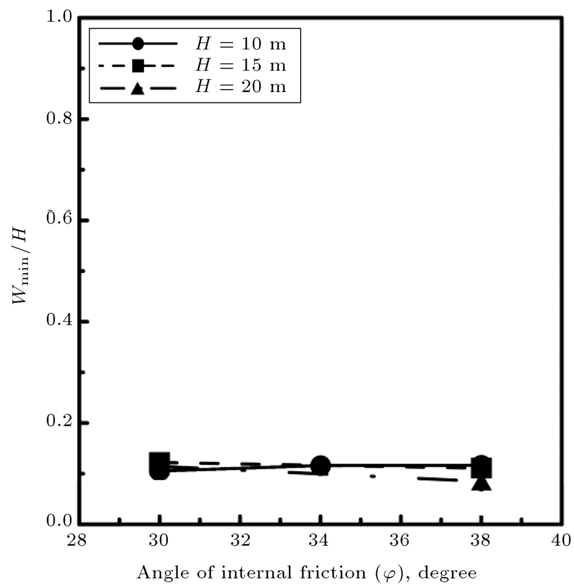


Figure 19. Effect of the wall height and the angle of internal friction on the ratio of the minimum step width to the wall height.

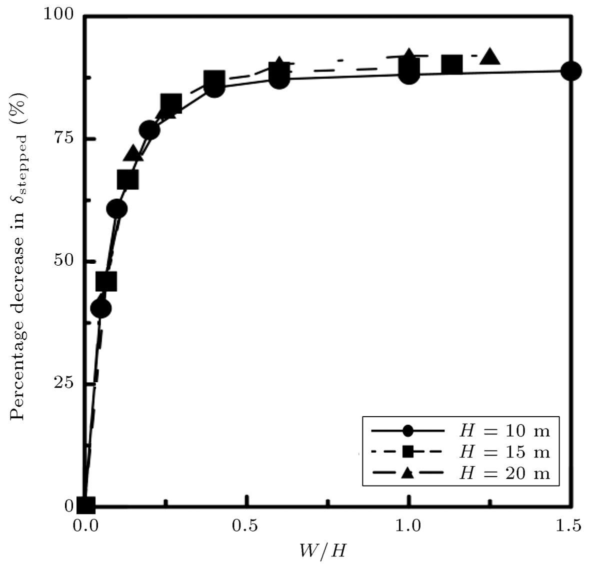


Figure 20. Effect of the step width on the percentage decrease in the horizontal wall displacement at the top of stepped soil nail walls with heights of 10 m, 15 m, and 20 m.

5. Conclusions

In this paper, it is demonstrated via the finite element method that soil parameters and wall geometries, including step depth and step width have a considerable influence on the static behavior of stepped soil nail walls in dry sandy soils. The construction of a full-scale experimental soil nail wall was simulated to verify the numerical model. Then, a parametric study was conducted. In the numerical models, the common practice values for the ratio of the nail length to the wall height and nail inclination were considered. Moreover, reasonable assumptions were made in order to develop the numerical model, which necessarily restricted the results in some way. This study shows that a stepped soil nail wall is more effective in soft soils than in hard soils. When properties of soils such as angle of internal friction, cohesion, and elastic modulus decrease, plastic deformation of a soil nail wall increases; thus, building a step in a typical soil nail wall in soft soils would considerably decrease the wall deformation and nail tensile forces. When a step is placed at the middle height of the wall, the wall lateral displacement and nail tensile forces are minimized. Therefore, the ratio of the optimal step depth to the wall height is approximately 0.5. When the step width increases, the wall deformation and nail forces of both sections of the stepped soil nail wall approach those of the soil nail wall with the height half that of the stepped soil nail wall. Moreover, when the ratio of the step width to the wall height is more than 0.5, increasing the step width does not decrease the deformation of the wall noticeably. When the step width is less than about 0.1 times the wall height, the step would negligibly decrease the wall deformation; hence, the ratio of the minimum step width to the wall height is approximately 0.1.

References

1. Abramson, L.W., Lee, T.S., Sharma, S. and Boyce, G.M., *Slope Stability and Stabilization Methods*, 2nd Edn., pp. 497-507, John Wiley & sons, New York, USA (2002).
2. Lazarte, C.A., Elias, V., Espinoza, D. and Sabatini, P.J. "Geotechnical engineering circular No. 7 soil nail walls", Report FHWA0-IF-03-017, Washington D.C., Federal Highway Admin (2003).
3. Giri, D. and Sengupta, A. "Dynamic behavior of small scale nailed soil slopes", *Geotechnical and Geological Engineering*, **27**(6), pp. 687-698 (2009).
4. Wang, S.G., Duan, Q.W. and Li, Q.R. "Behavior of stepped soil-nail wall", *Chinese Journal of Geotechnical Engineering*, **33**(1), pp. 207-210 (2011).
5. Unterreiner, P., Benhamiday, B. and Schlosser, F. "Finite element modeling of the construction of a full-scale experimental soil-nailed wall. French National Research Project CLOUTERRE", *Ground Improvement*, **1**(1), pp. 1-8 (1997).
6. Babu, G. and Pratap Singh, V. "Simulation of soil nail structures using PLAXIS 2D", *Plaxis Bulletin Spring issue*, pp. 16-22 (2009).
7. Chu, L.M. and Yin, J.H. "Comparison of interface shear strength of soil nails measured by both direct shear box tests and pullout tests", *Journal of Geotechnical and Geoenvironmental Engineering*, **131**(9), pp. 1097-1107 (2005).
8. Wu, J.Y. and Zhang, Z.M. "Evaluations of pullout resistance of grouted soil nails", In *Slope Stability, Retaining Walls, and Foundations: Selected Papers from the 2009 GeoHunan International Conference*, Changsha, Hunan, China, pp. 108-114 (2009).
9. Milligan, G.W.E. and Tei, K. "The pull-out resistance of model soil nails", *Soils and Foundation*, **38**(2), pp. 179-190 (1998).
10. Wang, Z. and Richwien, W. "A study of soil-reinforcement interface friction", *Journal of Geotechnical and Geoenvironmental Engineering*, **128**(1), pp. 92-94 (2002).
11. Dassault Systèmes Simulia Corpration, *Abaqus Analysis User's Manual*, Waltham, Massachusetts, United States (2011).
12. Briaud, J.L. and Lim, Y. "Soil-nailed wall under pilled bridge abutment: simulation and guidelines", *Journal of Geotechnical and Geoenvironmental Engineering*, **123**(11), pp. 1043-1050 (1997).
13. Plumelle, C., Schlosser, F., Delage, P., and Knochenmus, G. "French national research project on soil nailing: CLOUTERRE", In *Design and Performance of Earth Retaining Structures*, American Society of Civil Engineers, Geotechnical Special Publication, **25**, pp. 660-675 (1990).

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