Stability analysis of a steep slope reinforced with pressure-grouted soil nails

Sungjune Lee
Depatment of Civil and Environmental Engineering, Cheongju University, Korea

Yongmin Kim
School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

Sangseom Jeong & Kwangwoo Lee
Depatment of Civil and Environmental Engineering, Yonsei University, Korea

ABSTRACT: Soil nails have been commonly used for slope stabilization by enhancing the shear resistance of soil and the pullout resistance at the interface. In this study, a numerical model was proposed for stability analysis of a slope reinforced with pressure-grouted soil nails using the shear strength reduction method. To confirm the effect of grouting pressure on the slope stability, a series of numerical analyses were conducted. Special attention is given to the installation effect of the pressure-grouted soil nail. Results show that the pressure-grouted soil nail increases the safety factor by fifty percent in a slope by increasing the overall stiffness of the nailed slope system. It is also found that the pullout resistance of a soil nail is the main factor for stabilizing slopes rather than the shear resistance of the soil nail.

Keywords: Pressure-grouted soil nail, Slope stability, pullout resistance, Finite element analysis

1 INTRODUCTION

Soil nails have been commonly used for slope stabilization by enhancing the shear resistance of soil and/or the pullout resistance at the interface between the grout and adjacent soil mass because of their low construction cost and simple installation procedure (Chan 2005, Schlosser 1982). Although most of soil nails are installed without pressure (gravity-grouted soil nails), pressure-grouted soil nails installed with a high grouting pressure (300–1000 kPa) have been increasingly used to improve slope stability in South Korea and other places in the world.

The pullout resistance of a pressure-grouted soil nail is the main factor for designing a slope reinforced with soil nails rather than shear resistance of the soil nails to resist the ground movement along the slope failure surface. Thus, many researchers have studied the pullout behavior of pressure-grouted soil nails through laboratory or field tests. Main influencing factors on the fundamental mechanism of the pullout behavior of a soil nail were investigated through laboratory model pullout tests (Chu and Yin 2005, Franzen 1998, Junaideen et al 2004, Su et al 2007, Yin et al 2008) The pullout resistance of pressure-grouted soil nails was obtained from field pullout tests (Pun and Shiu 2007, Seo et al 2012). A numerical analysis method was also developed to investigate the effects of grouting pressure on the pullout resistance of a pressure-grouted soil nail (Su et al 2007). However, while these previous studies were mainly focused on the pullout resistance of a pressure-grouted soil nail itself, few studies have been performed on the reinforcing effects of pressure-grouted soil nails for slope stability.

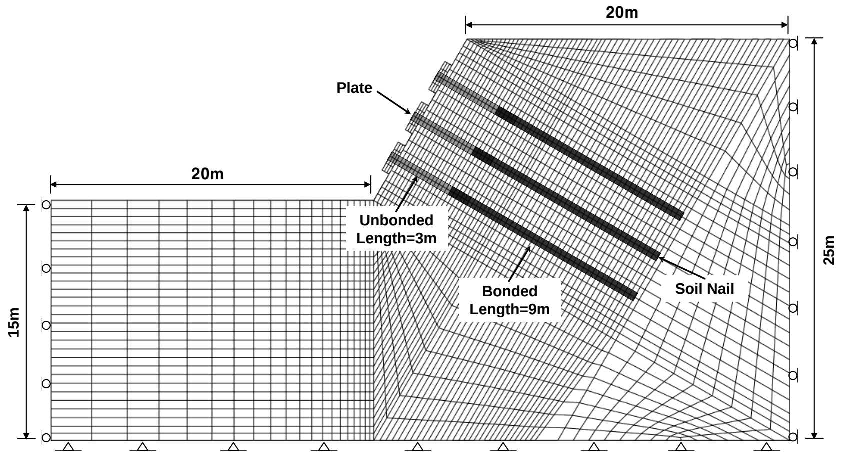
In this study, a new numerical model for slope stability analysis was developed. Special attention is given to the installation effect of the pressure-grouted soil nail using finite element (FE) analysis. A series of numerical analyses for a slope without soil nails, reinforced with gravity-grouted soil nails and reinforced with pressure-grouted soil nails were performed and their results were compared to investigate the effects of pressure-grouted soil nails for slope stability.

2 SLOPE STABILITY ANALYSIS FOR A REINFORCED SLOPE WITH PRESSURE-GROUTED SOIL NAILS

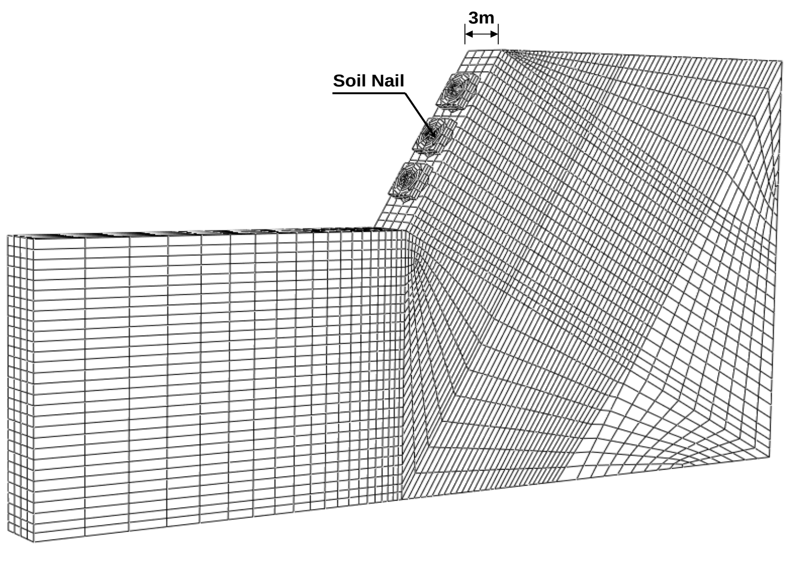
A three-dimensional (3D) finite element (FE) model for the slope stability analysis of a slope reinforced with pressure-grouted soil nails was proposed to obtain the safety factor of the reinforced slope and to investigate their reinforcing effects on the slope stability. The numerical technique for simulating pressure-grouted soil nails was implemented in this 3D FE model. The shear strength reduction method was used for the slope stability analysis to obtain the safety factor of a slope.

2.1 *3D FE model of a reinforce slope with pressure-grouted soil nails*

A 3D FE model to simulate the slope stability analysis for a reinforced slope reinforced with pressure-grouted soil nails using ABAQUS was developed in this study. The 3D FE mesh and boundary conditions used in analysis is shown in Figure 1. The slope composed of weathered soil has an angle of 60 to the horizontal plane, a slope height of 10 m, and a slope width of 3 m. The soil nails installed vertically to the slope surface has a diameter of 105 mm and a total length of 12 m with an unbonded length of 3 m and a bonded length of 9 m. A 5.0 mm thick thin layer of material surrounding the nail was used to simulate the thin localized shear zone. The plates of 2.0x2.0x0.5 m connected to the head of the soil nails were placed on the slope surface to help the soil nails mobilize their pullout resistance fully. The geometry and the boundary conditions applied to the 3D FE model (Figure 1) were selected considering the pressure grouting effects and slope stability analysis. An 8-node linear brick element with reduced integration was used for modeling the 3D FE model.



(a) Plan view (X-Z direction)



(b) 3D view (X-Y-Z direction)

Figure 1. 3D FE mesh and boundary conditions for a slope reinforced with soil nails.

The soil nails and plates were modeled as linear elastic solids. The Mohr-Coulomb model with non-associated flow rule was used for the weathered soil. The material properties used in the 3D FE model are summarized in Table 1 and 2.

2.2 *Numerical procedure of the stability analysis*

Slope stability analysis including the installation process of pressure-grouted soil nails were performed based on the 3D FE model described above to obtain the safety factor for a reinforced slope. The following seven steps are required for the slope stability analysis (Figure 2):

Step 1) The 3D FE mesh including the soil nail and the plate is generated (Figure 2(a)).

Step 2) The natural slope is modeled by removing the plate elements and by using soil properties for the soil nail elements. All boundaries of the model are fixed against displacements. Initial ground stresses are applied to the 3D FE model (Figure 2(b)).

Step 3) The elements for the soil nails are removed to simulate the drilling process, then grouting pressures are applied at the boundaries of the boreholes for the bonded zone while the boundaries of boreholes for the unbounded zone are fixed against displacements (Figure 2(c)).

Step 4) The boundaries of the borehole for the bonded zone are fixed against displacements after finishing the pressure grouting process (Figure 2(d)).

Step 5) The elements for the plates and the soil nails are added with their material properties while the displacement boundaries for the shafts of the soil nails remain fixed (Figure 2(e)).

Step 6) The displacement boundaries for the shafts of the soil nails are removed to release and transmit the locked-in stresses and displacement in the surrounding soil to the soil nail elements (Figure 2(f)).

Step 7) The slope stability analysis is performed by applying the gravity forces with unfixed boundaries for the upper sides of the model (Figure 2(g)).

On the other hand, same analysis procedure except the steps for the pressure grouting is used for the stability analysis of a slope reinforced with gravity-grouted soil nails.

3 REINFORCING EFFECTS OF PRESSURE-GROUTED SOILS ON SLOPE STABILITY

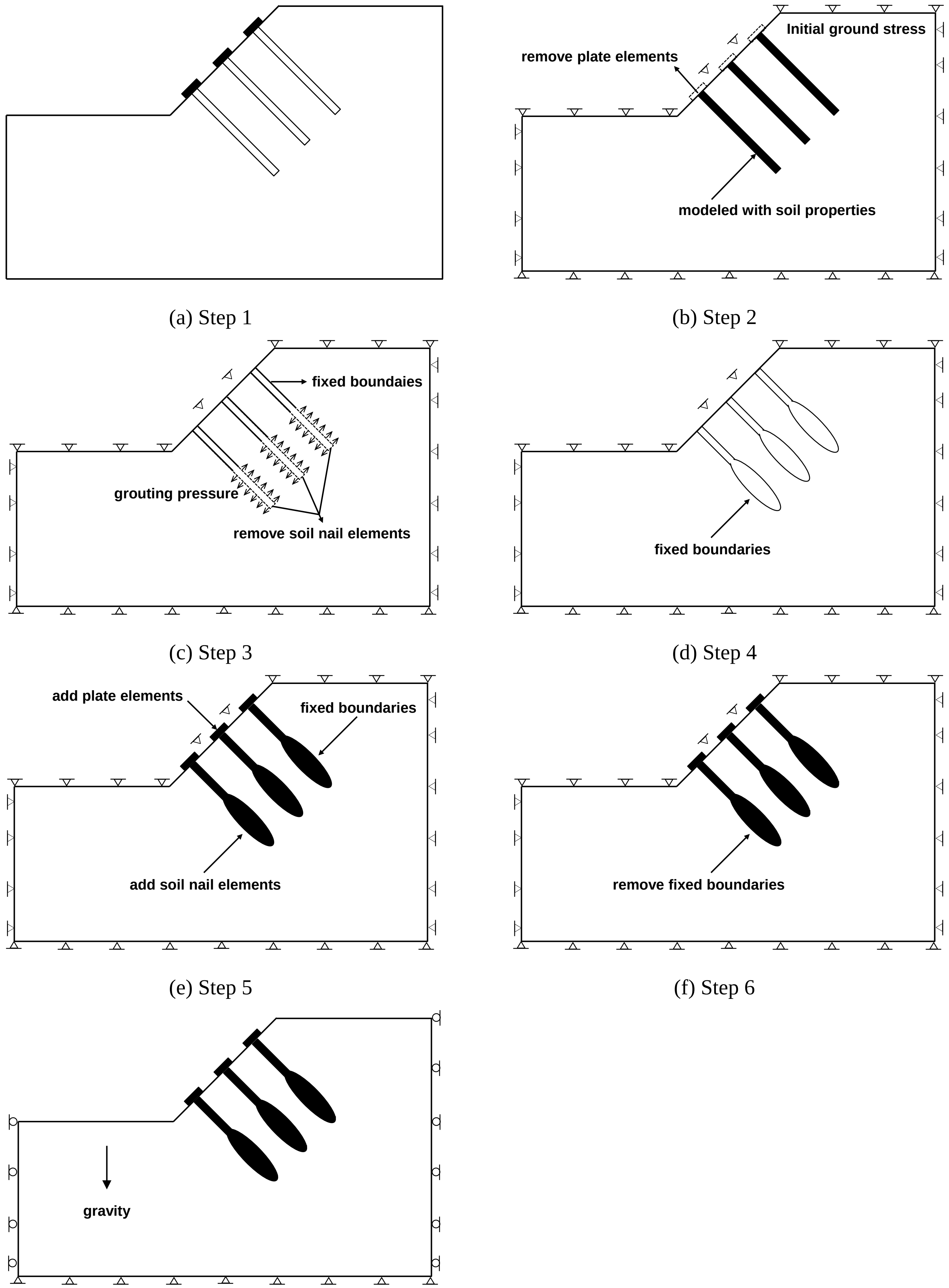
To investigate the reinforcing effects of the pressure-grouted soil nails, numerical slope stability analyses for a slope were performed under three different conditions: 1) natural slope without any reinforcement; 2) reinforced slope with gravity-grouted soil nails; and 3) reinforced slope with pressure-grouted soil nails. Figure 3 shows results of stability analyses for a slope under these three different reinforcement conditions. Safety factors for the natural slope, the gravity-grouted soil nail reinforced slope and the pressure-grouted soil nail reinforced slope are 1.15, 1.55 and 1.72 respectively. Based on the analysis results, using pressure-grouted soil nails exhibits obvious reinforcing effect for the slope stability with increasing the safety factor by around fifty and eleven percent compared with safety factors for natural slope and gravity-grouted reinforced slope, respectively.

Table 1. Equivalent material properties of the soil nail used in numerical analysis.

		Material Properties				
		Diameter, D (m)	Area, A (m2)	Unit weight, γ (kN/m3)	Elastic modulus, E (MPa)	Poisson's ratio, ν
Steel bar	Original Property	0.029	0.00066	77.0	210,000	0.2
Grout		0.076	0.008	24.0	23,000	0.3
Soil nail	Equivalent Property	-		28	37,250	0.29

Table 2. Material properties for the 3D FE model for slope stability analysis.

	Material Properties					
	Elastic modulus, E (MPa)	Poisson's ratio, ν	Friction angle ϕ (deg)	Dilatancy angle, ψ (deg)	Cohesion, c (kPa)	Unit weight, γ (kN/m3)
Weathered soil	100	0.30	25	0	20.0	20.0



(a) Step 1 (b) Step 2

(c) Step 3 (d) Step 4

(e) Step 5 (f) Step 6

(g) Step 7

Figure 2. Numerical procedure of slope stability analysis for a slope reinforced with pressure-grouted soil nails.

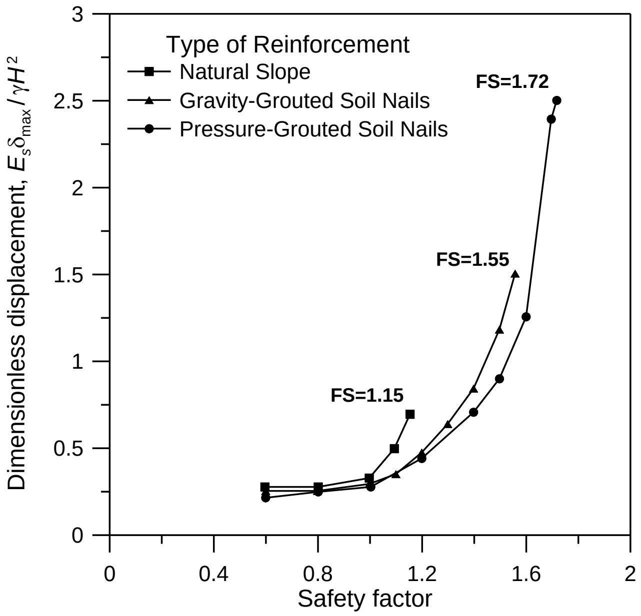
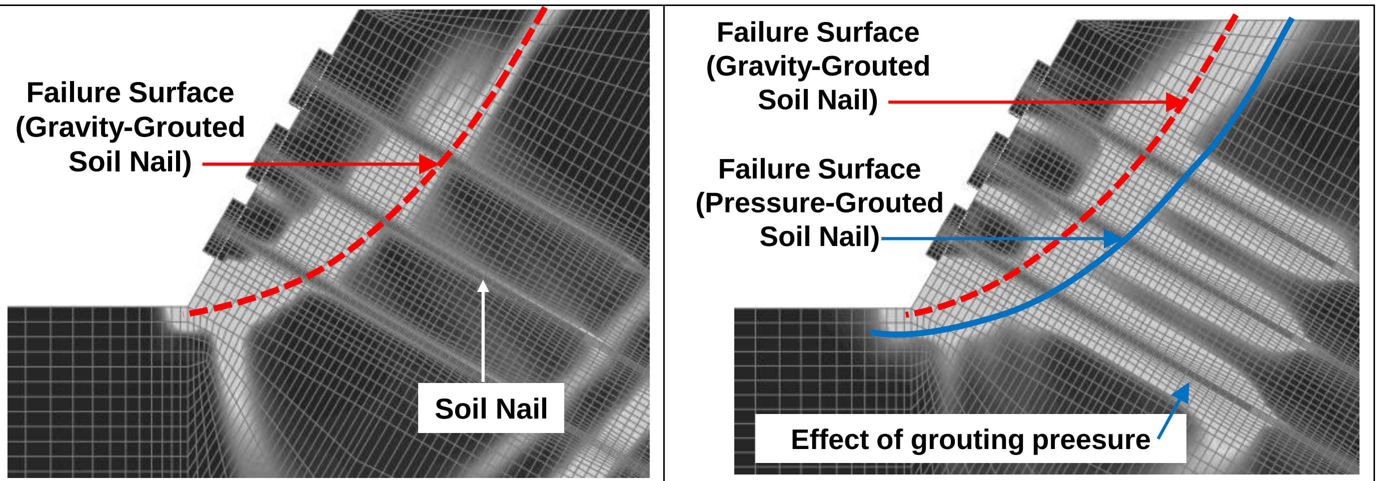


Figure 3. Safety factors for a slope under three different reinforcement conditions.

Figure 4 shows developed slope failure surfaces for the gravity-grouted and pressure-grouted soil nails from the maximum plastic strain distribution plots. The slope reinforced with pressure-grouted soil nails exhibits expanded failure surface from the slope surface compared with that for the gravity-grouted reinforced slope. This expanded failure surface was also observed in the laboratory load tests on the model soil nail reinforced retaining wall performed by Kim et al. (2004). It was found from their tests that the failure surface expanded toward the backfill as the stiffness of the wall increased. Therefore, it is presumed that the grouting pressure may increase the stiffness of the reinforced slope system.

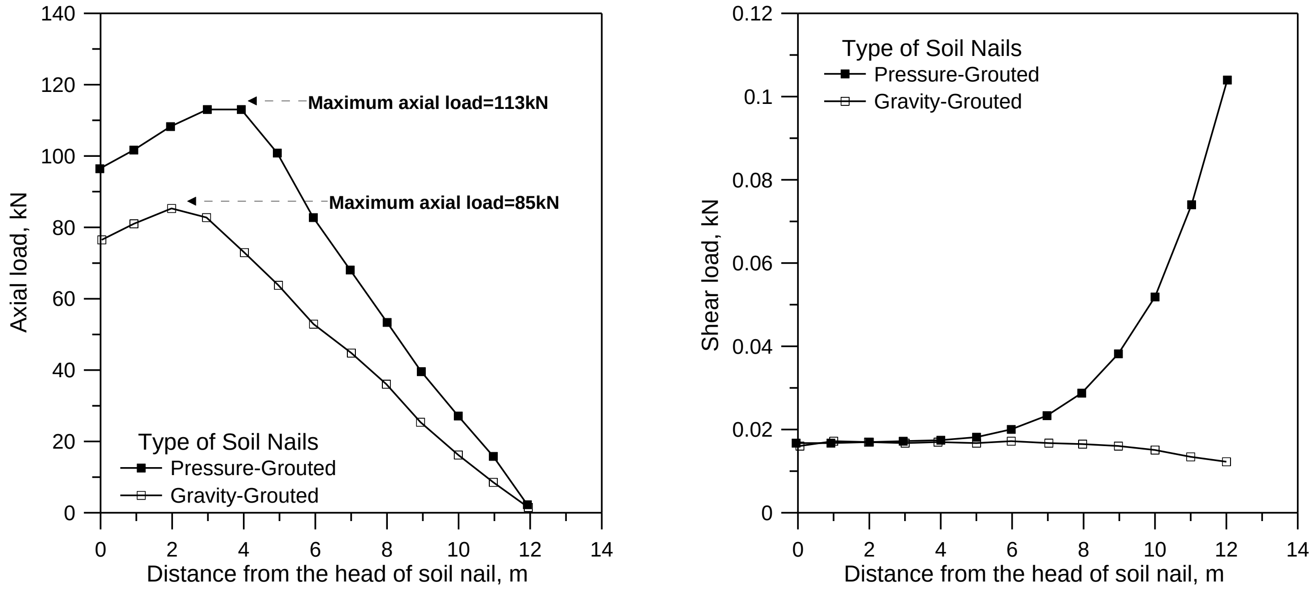
4 BEHAVIOR OF A PRESSURE-GROUTED SOIL NAIL INSTALLED IN THE REINFORCED SLOPE

The axial and shear loads developed along the soil nails are obtained from the previous analysis results to investigate the reinforcing effects of soil nails for slope stability. Figure 5 illustrates the distributions of axial loads and shear loads developed along the lower soil nails for both gravity-grouted and pressure-grouted soil nail reinforced slopes at the limit state. It is noted that higher axial loads distribution is observed for the pressure-grouted soil nail than the gravity-grouted soil nail, whereas the shear loads developed along both types of soil nails are very low and can be ignored.



(a) Gravity-grouted soil nails
(b) Pressure-grouted soil nails

Figure 4. Failure surfaces for a reinforced slope with the maximum plastic strain distribution plots.

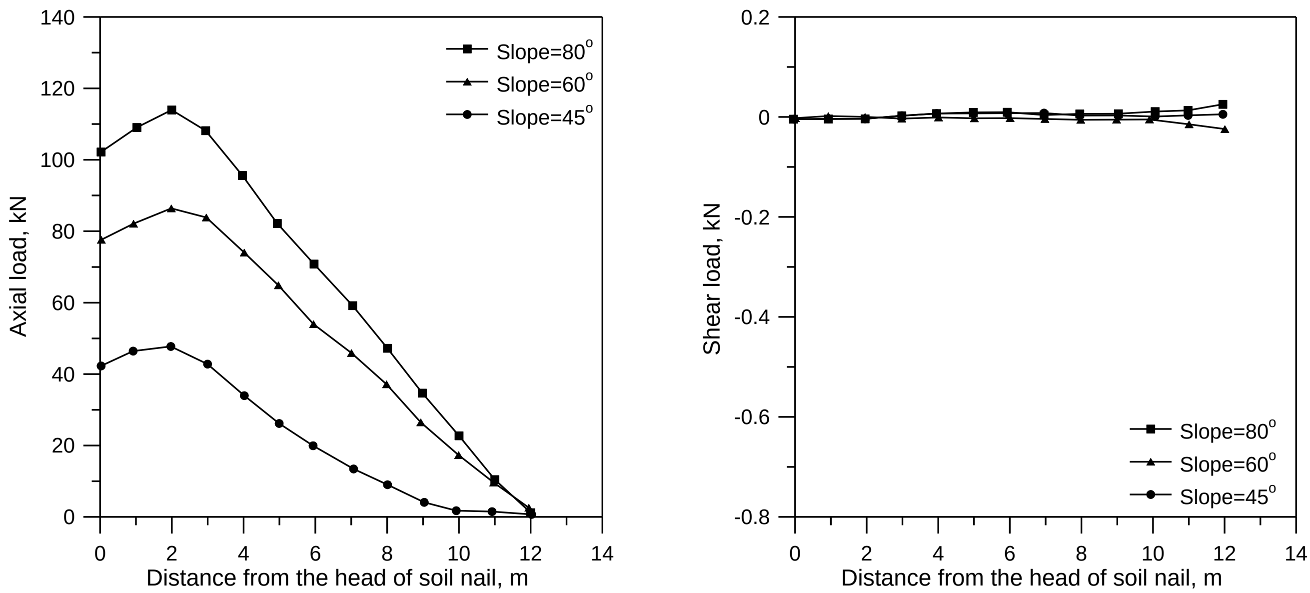


(a) Axial loads (b) Shear loads

Figure 5. Distribution of loads developed along the soil nail for two different types of soil nails.

Basically, the axial loads may develop at the soil-grout interface in the form of shear stresses around the soil nail perimeter. These shear stresses are represented by the axial loads within the soil nail. Since the shear stresses act along the circumferential area of the soil nail, the axial loads at the ends of the soil nails must be zero. And the maximum axial loads were developed at the upper part of soil nail (2 to 4m from the soil nail head) where shear stresses at the soil-grout interface reverse directions. The location of maximum axial loads may coincide with the divide between the active soil wedge and the stationary soil mass. However, the actual magnitude and location of maximum axial loads varies with the soil deformation pattern, construction sequence, and required reinforcement (Banerjee et al 1998).

Additional slope stability analyses are performed for three different slope angles of 45°, 60° and 80° to investigate the effects of slope angle on the behavior of soil nails. Figure 6 show the distributions of axial and shear loads developed along the soil nails with different slope angles. The distribution of axial resistance increases with increase in the slope angle. Changes in the distributions of shear loads with different slope angles are negligible and the overall values of shear loads are very low and can be ignored. Therefore, as shown in Figure 5 and 6, it is shown that the pullout resistance of a soil nails is the main factor for reinforcing the slope stability rather than shear resistance along the failure surface, regardless of the nail location and angle of soil nail.



(a) Axial loads (b) Shear loads

Figure 6. Distribution of loads developed along the soil nail for three different angles of slope

5 CONCLUSIONS

In this study, a 3D FE model for stability analysis of a slope reinforced with pressure-grouted soil nails was proposed using the shear strength reduction method. A series of numerical slope stability analyses were performed for three different types of slopes to investigate the effects of grouting pressure on the slope stability and the behavior of the soil nails at the limit state. Based on the findings of this study, the following conclusions can be drawn:

1. The pressure-grouted soil nails exhibited obvious reinforcing effects for the slope stability with increasing the safety factor by around fifty and eleven percent compared with safety factors for natural slope and gravity-grouted reinforced slope, respectively. In addition, the slope reinforced with pressure-grouted soil nails exhibited expanded failure surface from the slope surface compared with that for the gravity-grouted reinforced slope. The expanded failure surface can be explained by the increased stiffness of the reinforced slope system due to grouting pressure.
2. Higher pullout resistance distribution was observed for the pressure-grouted soil nail than the gravity-grouted soil nail. The shear resistance developed along both types of soil nails were very low and can be ignored. The distribution of pullout resistance increases with increase in the slope angle while the negligibly low shear resistance was developed along the soil nail without reference to the slope angle. These analysis results confirm the fact that the pullout resistance of a soil nail is the main factor for stabilizing slopes.

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