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THE SLOPE STABILITY OF SAND SLOPE WITH TWO ROWS PILE REINFORCING

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ABSTRACT: Population growth in Indonesia affects the rate of urbanization as the increased construction development decreases the available land. The issue of limited land encourages people to make settlements or buildings near the slope edge. Various mitigation methods can be applied to prevent and avoid landslides and to overcome other problems that arise on the slopes, one of which is by strengthening the slopes. In this study, slope reinforcement was carried out by adding two rows of piles to increase slope safety. Firstly, we observed scaled slope models with or without pile reinforcing. Slope modeling was done with a test container of sand soil with a slope angle of 50° and using an aluminum pipe as a model for reinforcement piles. Pile diameter of the test model was varied on the second row (1.5 cm, 2.0 cm, 2.5 cm, and 3.2 cm). The bearing capacity of the scaled-model test results was used to estimate the increase in factor of safety (FoS) assisted by the finite element method (FEM) application in two-dimensional (2D) and three-dimensional (3D) FEM. According to the FEM test results, the FoS value of a reinforced slope with two rows of piles increased by 9.130% in 2D FEM and 34.296% in 3D FEM compared to an unreinforced slope modeling. The most significant FoS value was found in the second row of piles with the largest diameter of 3.2 cm. Additionally, the test results showed that the reinforced slope is susceptible to rotational slope failure.

Keywords: FEM, Factor of safety, Pile, Slope, Reinforcement

1. INTRODUCTION

Population growth encourages land-use conversion on the unstable slope area because of the limited availability of land. This condition can lead to landslides and threaten people’s lives. Slope stability generally depends on the interaction of the slope angle with the soil parameters. When the slope angle (i) is less than the internal friction angle of the soil (ϕ), the slope is safe against sliding with FS > 1.0. Thus, the slope that does not meet this requirement becomes critical (FS $\leq$ 1) and needs to be stabilized by reducing the driving forces that cause failure, increasing the slope resistance, or combining both methods.

One of the mitigation methods, continuously being investigated by researchers until now, was reinforcing slopes with the pile, which is a cost effective way to prevent landslides. Numerous studies concluded that pile installation strengthens slopes by improving the slope stability and ultimate bearing capacity [1-3]. Also, the reliability and probability of slopes reinforced with pile failure were investigated to identify the optimal placement of piles. The soil arching effect is one of the essential aspects contributing to the substantial impact [4], generally influenced by the position, length, and spacing of piles [5,6].

The previous studies focused on the reinforcement using one row of piles, and the results were diverse and even inconsistent. Yet, the higher the pile position on the slope with one-row pile reinforcement, which is closer to the top slope, the safety factor decreases because of the soil movement between the piles. The slope might slide along another failure plane if the piles were not appropriately placed in the failure plane. Adding piles in two or three rows tends to raise the stability of the slope [7,8]. Since the rows of reinforced piles were installed more, the arching effect became widespread and changed the slip surfaces influencing slope failure.

Due to a significant advancement in computational tools that allow for the integrated analysis of the pile–soil interaction, numerical approaches like the finite element and finite difference methods gained popularity. Over the past few decades, geotechnical engineering applications have frequently used and implemented two-dimensional (2D) and three-dimensional (3D) finite element analysis (FEM). Hence, the slope models with sand soil were tested using experimental and numerical modeling in this study with the addition of a second-row pile reinforcement on the slope under the pile diameter variations.

2. RESEARCH SIGNIFICANCE

In this study, the experimental laboratory tests the slope models with or without pile reinforcement using the small-scale model. The small-scale modeling was conducted to examine the improvement of the ultimate bearing capacity (qu) of the foundation on the reinforced slope. For the numerical tests, PLAXIS 2D and 3D have used 2D and 3D FEM modeling. All the FEM models were identical to the small-scale physical modeling. The 2D and 3D FEM modeling in this study aimed to investigate the influence of the slope on the safety factors and the landslide zones due to the addition of a second-row pile reinforcement on the slope.

3. LITERATURES

3.1 Slope Stability with Pile Reinforcing

The piles used in slope stabilization are usually affected by lateral forces of horizontal displacement of the surrounding soil. Therefore, piles embedded in the slopes are considered passive piles. Several methods are used to analyze the amount of soil pressure acting on the slopes with the pile reinforcement. The Ito and Matsui Method [1] and Cai and Ugai Method [2] illustrated a theoretical approach that is still used today. This method was initially presented to evaluate soil pressure at boundary conditions for pile reinforced slopes using plastic deformation. According to the Mohr–Coulomb criteria, this method can predict the soil pressure when it reaches plastic equilibrium.

$$\mathbf{p_{(z)}} = \mathbf{c'.D_1}\left(\frac{\mathbf{D_1}}{\mathbf{D_2}}\right)^{\mathbf{A}}\left[\frac{\mathbf{1}}{\mathbf{N_\phi tan\phi}}\left\{\mathbf{B - 2N_\phi{}^{1/2}\,tan\phi - 1}\right\} + \frac{\mathbf{C}}{\mathbf{A}}\right]$$

$$-\mathbf{c'}\left\{\mathbf{D_1\frac{C}{A} - 2D_2.N_\phi{}^{-1/2}}\right\} + \frac{\mathbf{\gamma.z}}{\mathbf{N_\phi}}\left\{\mathbf{D_1}\left(\frac{\mathbf{D_1}}{\mathbf{D_2}}\right)^{\mathbf{A}}\mathbf{.\,B - D_2}\right\} \quad (1)$$

with $$\mathbf{A} = \left(\mathbf{N_\phi{}^{1/2}\,tan\phi + N_\phi - 1}\right) \quad (2)$$

$$\mathbf{B} = \mathbf{exp}\left[\frac{\mathbf{D_1 - D_2}}{\mathbf{D_2}}\,\mathbf{N_\phi.\,tan\phi.\,tan}\left(\frac{\pi}{8} + \frac{\phi}{2}\right)\right] \quad (3)$$

$$\mathbf{C} = \mathbf{2.\,tan\phi + 2.\,N_\phi{}^{1/2} + 2.\,N_\phi{}^{-1/2}} \quad (4)$$

$$\mathbf{N_\phi} = \mathbf{tan^2}\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \quad (5)$$

where D_1 = center-to-center piles distance, D_2 = piles spacing, γ = unit weight of the soil, and z = arbitrary depth of the soil layer from the surface.

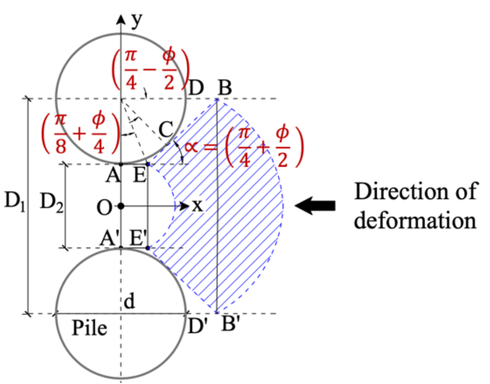


Fig. 1 Plastic deformation around the pile area [1]

3.2 FEM Slope Stability Analysis

Calculating slope stability using the FEM requires fewer assumptions than the conventional method, making the minimum safety coefficient more accurate when compared to using the wedge method. When using the FEM to study the interaction of slope–pile reinforcement, piles are usually considered elastic, which leads to the original condition that only deformation and internal forces can be analyzed.

The SRF method was performed as the fundamental calculating principle for the global FS on the PLAXIS, which reduced soil strength (cohesion/ c and tangent of friction angle/ tanϕ) to the point of failure. The SRF is regulated by the total multiplier $\sum M_{sf}$, which is also regarded as the equivalent of FS in the limit equilibrium analysis.

$$\sum M_{sf} = \frac{c_{input}}{c_{reduced}} = \frac{tan\phi_{input}}{tan\phi_{reduced}} > 1 \quad (6)$$

$$FS = \frac{\text{Available strength}}{\text{Strength at failure}} = \sum M_{sf\,\text{at failure}} > 1 \quad (7)$$

4. RESEARCH METHOD

4.1 Slope Test Model Design

The slope stability without pile reinforcement (unreinforced slope) and one-row pile reinforcement are evaluated as the comparison data for the slope model with two-row pile reinforcement. The slope model tests the two-row pile reinforcement with four diameter variations (Table 1).

Table 1 The specimen's configuration

Variable of Specimens	Code	Diameter Pile 1st row $Lx_1/L = 0.9$	Diameter Pile 2nd Row $Lx_2/L = 0.5$
Unreinforced	D0D0	-	-
One-row pile reinforcement	D1D0	3.2 cm	-
Two-row piles reinforcement	D1D1	3.2 cm	3.2 cm
	D1D2	3.2 cm	2.5 cm
	D1D3	3.2 cm	2.0 cm
	D1D4	3.2 cm	1.5 cm

In this study, the experimental laboratory test on the slope models, both the unreinforced and reinforced slope models were tested using the small-scale physical modeling method to investigate the bearing capacity of continuous footing. Regardless of the structure interaction problems that are more effective in prototype dimensions, small-scale physical modeling provides a low-cost approach that enables model observations of the soil compared to prototype testing [9]. The slope physical modeling is conducted on a steel container (1.5 × 1.0 × 1.0 m).

On the other hand, 2D FEM modeling has been frequently used to solve landslide issues and reinforce slopes using piles. Moreover, it is difficult to estimate the arching effect and soil movement between piles using the 2D FEM, which is affected by the pile spacing. To resolve this issue, 3D FEM modeling is used, as its precision with the boundary conditions can approach reality conditions [10,11]. The finite element programs, PLAXIS 2D and PLAXIS 3D, are used to conduct numerous 2D and 3D FEM modelings to evaluate the factor of safety (FoS) of the pile reinforced slope.

4.2 Small-Scaled Physical Modeling Test

We used poorly graded sand (based on the USCS) to form the small-scaled physical slope modeling. The sand was discharged and compacted in a rigid steel container with dimensions of 1.5 m length, 1.0 m width, and 1.0 m height. Each layer of sand, as high as 10 cm, was compacted by the concrete cylinder until it reached a height of 70 cm and was modeled with a slope angle of 50°.

The aluminum pipe was used as the model reinforcement piles. The pile placement on the slope model achieved the maximum safety factor for slopes and was based on the results of previous studies. The earlier studies obtained the maximum safety factor for slopes with cohesionless soil by placing the pile in the middle of the slope [12]. The middle-lower area of the reinforced slope with the double-row piles was also suggested as the most effective pile placement position [13]. Therefore, the first row pile position on the slope model was $Lx_1/L = 0.9$ and the second row was $Lx_2/L = 0.5$.

The whole model piles were positioned at least 5D from each container side [14] and 10 cm from the base to ensure the reduction of the boundary effect. Also, each pile was inserted with a center-to-center distance (D_1) of 10 cm. The D_1 was chosen considering the arching effect. The arching area would be ineffective if the clear spacing between the piles (D_2) is more than 8D [15]. Consequently, the D_1 was selected considering the reduction by all the pile diameter variations in this study, so the D_2 < 8. The pile diameter on the first row was 3.2 cm, while the pile diameter on the second row varied from 1.5, 2.0, 2.5, to 3.2 cm.

The rigid steel container was equipped one-side on fiberglass, intended to facilitate observations during the loading test. For the loading test on the slope model, a hydraulic jack with a 10-ton capacity was used and connected to the top of the continuous footing model (90 × 15 × 9 cm). The loading is concentrated and then transmitted by beams to a create uniform load. Dial gauges were utilized to measure the settlement in the foundation due to the loading test, in which every 40-kg load was read by the load cell. The loading was constantly incremented until the slope failure.

4.3 Slope Analysis with 2D FEM and 3D FEM

The numerical analysis was used to determine the FoS and landslide zones that occur due to different pile diameter variations in the slopes using the FEM analytical software, PLAXIS 2D, and PLAXIS 3D. The 2D and 3D FEM models were tested under six different conditions (Table 2). The external load was provided by the ultimate qu values from the small-scaled slope model without pile reinforcement.

Table 2 The FEM modeling test conditions

Conditions	Description of Slope Conditions	
	Reinforcement	External Loads
1st	Unreinforced	Unloaded
2nd	One-row pile	Unloaded
3rd	Two-row pile	Unloaded
4th	Unreinforced	Loaded
5th	One-row pile	Loaded
6th	Two-row pile	Loaded

The 2D FEM model geometry is simulated using a plane strain model assuming a constant cross-section on the slope width, including the constant reinforcing pile spacing. While, the 3D

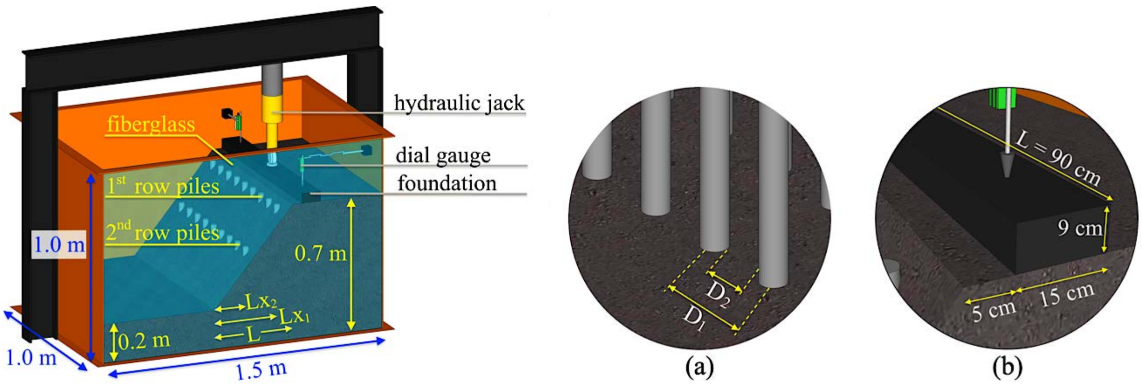
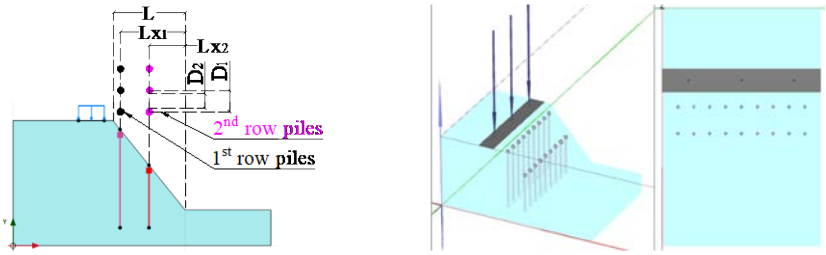


Fig. 2 The slope model configuration: (a) details of piles and (b) details of continuous footing



(a) (b)

Fig. 3 The FEM slope modeling with two rows of piles: (a) 2D FEM and (b) 3D FEM

FEM model was examined using a homogeneous slope model to improve the analysis result. The FEM models of the slope with pile reinforcement were identical in size to the small-scaled modeling.

The FEM model used an automatic mesh generated from the PLAXIS. The elastic–plastic Mohr–Coulomb constitutive law is used in this study to simulate the material behavior of soil, as it does not require complex parameters. The sand soil was modeled as drained material because of its characteristics. The piles are assumed to be elastic, and the interface components simulate the interaction between the piles and surrounding soil.

5. RESULTS AND DISCUSSION

5.1 Soil Parameter and Pile Properties

Initially, pre-laboratory testing based on ASTM standards was performed to determine the soil and the pile parameters used in slope modeling. The results of this test were used as given parameters for the slope models, both physical and FEM.

Table 3 Sand soil and piles properties

Parameter	Description
Soil (Rc = 88%)	
Soil type, USCS	SP (poorly graded sand)
Cohesion (c)	1.9 kN/m^2
Friction angle (ϕ)	33.95°
E_{soil}	388 kN/m^2
Dry weight (γ_d)	15.12 kN/m^3
Piles	
Diameters	1.5, 2.0, 2.5, and 3.2 cm
E_{pile}	~15000000 kN/m^2
Thickness	0.002 m

5.2 Soil Bearing Capacity

The loading test is continuously carried out until the critical value/slope failure is reached. The 0.1B method, the log–log tangent intersection method, and the hyperbolic method were used in earlier studies to evaluate the ultimate qu using a footing loading test. Compared to all these methods, the hyperbolic and 0.1B methods showed a higher settlement (s) on the qu [16]. The qu is obtained when the settlement-to-foundation width (B) ratio is 10% in the 0.1B method.

The maximum qu was reached on the D_2/D_1 = 0.68 (d = 3.2 cm) model, at 76.024 kN/m². Based on the test results, the two-row pile reinforcement increased the qu of the slope model.

Table 4 Bearing capacity during loading test on slope models

Slope Modeling	Diameter Pile (D_2/D_1) 1st row (Lx_1/L = 0.9)	2nd Row (Lx_2/L = 0.5)	qu (kN/m^2)
D0D0	-	-	26.454
D1D0	3.2 cm (0.68)	-	29.218
D1D1	3.2 cm (0.68)	3.2 cm (0.68)	76.024
D1D2	3.2 cm (0.68)	2.5 cm (0.75)	59.579
D1D3	3.2 cm (0.68)	2.0 cm (0.80)	53.507
D1D4	3.2 cm (0.68)	1.5 cm (0.85)	52.842

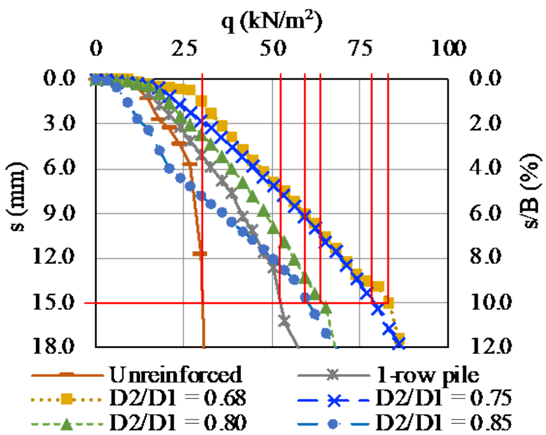


Fig. 4 The model bearing capacity (qu) on 0.1B

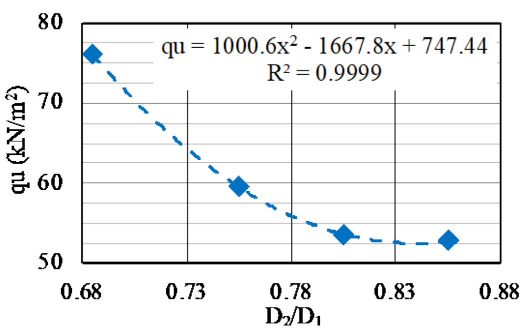


Fig. 5 Relation between D_2/D_1 and qu

The bearing capacity improvement (BCI) of the two-row pile reinforcement is calculated using Eq. (8) and Eq. (9):

$$BCI_{un} = \frac{qu_{p2\ rows}}{qu_{un}} \quad (8)$$

$$BCI_{p1\ row} = \frac{qu_{p2\ rows}}{qu_{p1\ row}} \quad (9)$$

where BCI_{un} = BCI to unreinforced slope, $BCI_{p1\ row}$ = BCI to one-row pile reinforced slope, qu_{un} = unreinforced slope qu' $qu_{p1\ row}$ = one-row pile reinforced slope qu, and $qu_{p2\ rows}$ = two-row pile reinforced slope qu.

Table 5 BCI of two-row pile reinforced slopes

Slope Modeling	qu (kN/m²)	BCI	
		Unreinforced slope	One-row pile reinforced
D1D1	76.024	2.874	2.602
D1D2	59.579	2.252	2.039
D1D3	53.507	2.023	1.831
D1D4	52.842	1.998	1.809

The slope model with the largest diameter on the second row significantly improved the qu of the unreinforced slope and the one-row pile reinforced slope by 2.874 and 2.602, respectively (Table 5). Therefore, these results show that the D_2/D_1 ratio of 0.68 (d = 3.2 cm) is the optimum diameter to maximize the qu. In addition to the pile position and spacing, the pile diameter and pile length should also be carefully chosen, during construction, which will provide stability to the slope and pile [17,18].

The soil–pile interaction had been significantly influenced by the pile diameter, commonly referred to as the "scale effect" [19]. The spacing area affected by the pile diameter must be planned accurately to maximize the soil arching ability while minimizing the soil flow rate between the piles. The smaller the pile diameter, the greater the clear space between the piles. The movement of soil flow through the piles is also highly significant, whereas the retained soil is limited to the pile cross-sectional area.

5.3 Factor of Safety with Variation Diameter Piles on Second Row

The slope with two-row pile reinforcement can increase FoS compared to both without pile reinforcement and one-row pile reinforcement. Furthermore, the largest second row of pile with the D_2/D_1 ratio of 0.68 (d = 3.2 cm) has the most significant FoS in each condition, as shown in Table 6 and Table 7.

Table 6 FoS on the 2D FEM Analysis

Conditions	FoS of Slope Modeling			
	D1D1	D1D2	D1D3	D1D4
1	2.524	2.524	2.524	2.524
2	2.804	2.804	2.804	2.804
3	2.859	2.855	2.849	2.845
4	0.886	0.886	0.886	0.886
5	0.919	0.919	0.919	0.919
6	0.967	0.962	0.947	0.941

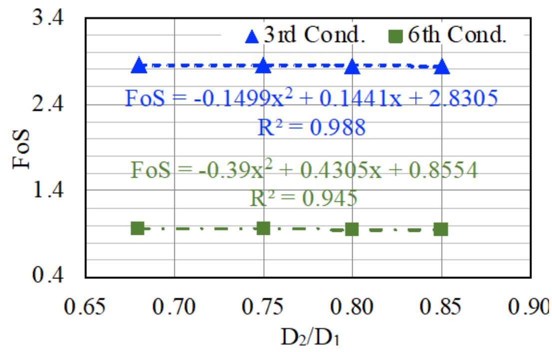


Fig. 6 FoS vs. D_2/D_1 on 2D FEM

Table 7 FoS on the 3D FEM Analysis

Conditions	FoS of Slope Modeling			
	D1D1	D1D2	D1D3	D1D4
1	3.073	3.073	3.073	3.073
2	3.803	3.803	3.803	3.803
3	4.106	4.073	4.042	3.995
4	1.073	1.073	1.073	1.073
5	1.391	1.391	1.391	1.391
6	1.441	1.432	1.424	1.413

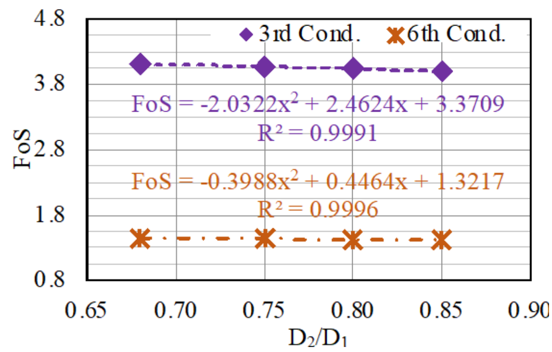


Fig. 7 FoS vs. D_2/D_1 on 3D FEM

The difference in the FoS of the 2D FEM and 3D FEM slope modeling was quite significant. It was due to the different approaches of those two methods, where 3D FEM modeling was the most similar to the actual slope conditions. In terms of construction design, the used FoS value was the critical condition (6th condition), considering the safety on the slope with pile reinforcement. Several results of the 2D FEM approach have been used to solve engineering issues due to its convenience and computing limitations. However, it was discovered that the 2D results were more conservative, often leading to higher costs when applied in construction. The percentange FoS deviation is defined using Eq. (10) and Eq. (11):

$$FSI_{un} = \frac{FoS_{p2\ rows} - FoS_{un}}{FoS_{un}} x100\% \quad (10)$$

$$FSI_{p1\ row} = \frac{FoS_{p2\ rows} - FoS_{p1\ row}}{FoS_{p1\ row}} x100\% \quad (11)$$

where FSI_{un} = percentage FoS deviation to an unreinforced slope, $FSI_{p1\ row}$ = percentage FoS deviation to a one-row pile reinforced slope, FoS_{un} = FoS of an unreinforced slope, $FoS_{p1\ row}$ = FoS of a one-row pile reinforced slope, and $FS_{p2\ rows}$ = FoS of a two-row pile reinforced slope.

Table 8 2D FEM FSI of two-row pile reinforced

Slope Modeling	FoS	FSI (%)	
		Unreinforced slope	One-row pile reinforced
D0D0	0.886	-	-
D1D0	0.919	-	-
D1D1	0.967	9.130	5.177
D1D2	0.962	8.566	4.633
D1D3	0.947	6.816	2.948
D1D4	0.941	6.173	2.328

Table 9 3D FEM FSI of two-row pile reinforced

Slope Modeling	FoS	FSI (%)	
		Unreinforced slope	One-row pile reinforced
D0D0	1.073	-	-
D1D0	1.391	-	-
D1D1	1.441	34.296	3.595
D1D2	1.432	33.458	2.948
D1D3	1.424	32.712	2.372
D1D4	1.413	31.687	1.582

As shown in Table 8 with the 2D FEM, the slope with two-row pile reinforcement with a larger diameter in the second row of the pile can increase the value of FoS compared to the slope without pile reinforcement and the slope with one-row pile reinforcement, respectively. at sequence 9.103% and 5.177%. While according to 3D FEM analysis (Table 9), the slope with two-row pile reinforcement with a larger pile diameter in the second row can increase the FoS by 34.296% compared to the unreinforced slope and 3.595% compared to the one-row pile reinforced slope.

The difference in values between the test results shown by FEM 2D and FEM 3D is due to the difference in dimensions when modeling the physical slope. 2D FEM cannot model width dimensions or use the basic strain principle, which is different from 3D FEM. However, both FEM analyses determined the optimum FoS at the largest diameter, a D_2/D_1 ratio of 0.68 (d = 3.2 cm), or the D1D1 model. Increased pile diameter reinforcement improved the FoS [5,20].

For practical use, the construction cost of the slope reinforced should also be considered when choosing the pile diameter and the number of rows, regardless of the soil arching area between piles and the slope stability (FoS). It is because the construction costs reduced as the diameter pile and the number of rows decreased.

5.4 Landslide Zone

The suspected failure slope based on 2D FEM and 3D FEM applications is the rotational failure type. Landslides occur on the middle slope of the unreinforced slope type. In contrast, it appears on the bottom slope (toe) with the reinforced pile. The displacement occurs on the slope scaled automatically by the PLAXIS programs, representing the slope failure for each model, as shown from Fig. 8 to Fig. 10.

The differences in the landslide zone indicate that the load distribution on the slopes without reinforcement is restrained after reinforcement with the pile. The second-row pile reinforcement's diameter variation on the slope led to the deepening of the critical slip surface of the landslide zone as the diameter of the pile increased. The increase in the pile spacing causes this condition [21]. As a result, the slip surfaces will influence slope failure once the reinforcement pile is placed. Still, the original overall critical slip surface will no longer control the failure since the pile will obstruct the failure.

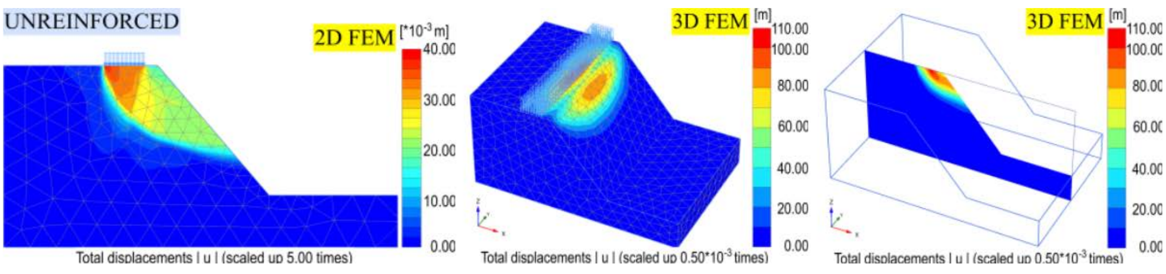


Fig. 8 Landslide zone of unreinforced slope

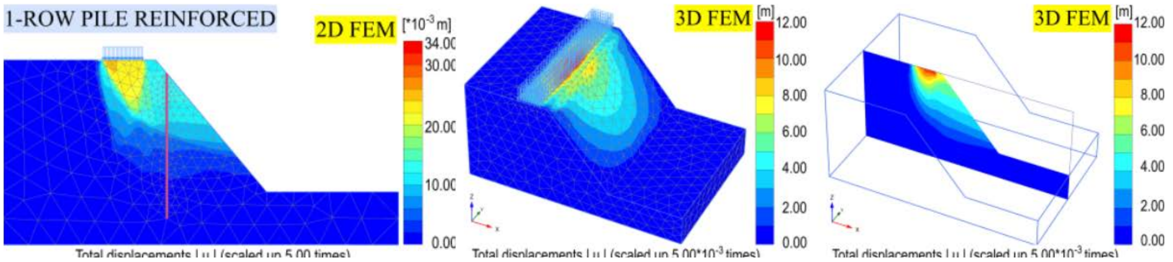


Fig. 9 Landslide zone of one-row pile reinforced slope

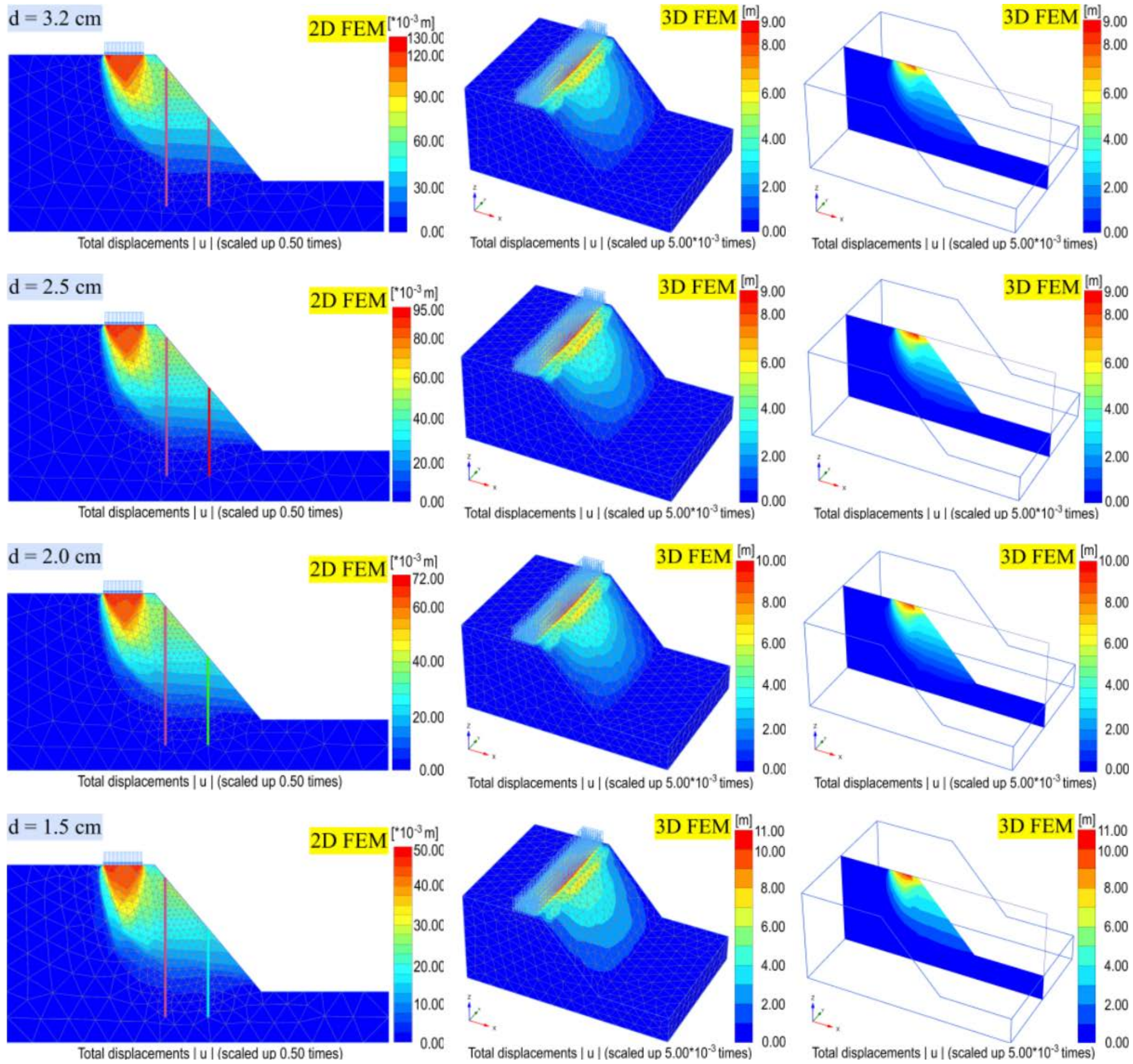


Fig. 10 Landslide zone of two-row pile reinforced slope

6. CONCLUSIONS

From the test results of both the experimental and numerical (FEM 2D and 3D) tests, we confirmed that the reinforcement of the slopes with two-row piles using a variation in the diameter, improved the qu and FoS. The qu and FoS were increased as the diameter of the reinforcement pile increased. The optimal diameter that can resist slope failure is the largest (3.2 cm), with a D_2/D_1 ratio of 0.68. In addition, compared to the slope with one-row pile reinforcement, the slope reinforced with two-row pile can improve the FoS by 5.177% (2D FEM) and 3.595% (3D FEM).

The type of slope failure that occurs based on the 2D and 3D FEM is rotational failure. The failure of the unreinforced slope appears on the middle slope. In contrast, it appears at the bottom (toe) of the slope reinforced with piles. The landslide zones deepened as the diameter of the pile increased.

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