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THE EFFECT OF DOUBLE ROW PILE SPACING REINFORCEMENT ON SAND SLOPE STABILITY

*As'ad Munawir[1], Yulvi Zaika[1], and Eko Andi Suryo[1]

[1]Faculty of Engineering, University of Brawijaya, Indonesia

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ABSTRACT: This study aims to evaluate and analyze the improvement of Factor of Safety (FS) using double-row pile addition on the critical sand slope modeling with slope angles 50°. Experimental and numerical modeling was conducted in this study. The small-scaled slope model of sand soil compacted on the steel container (1.5x1.0x1.0 m) was used in the experimental test. Reinforcement piles using aluminum tubes are installed on compacted sandy soil with Rc 88%. The diameter of the first row of piles is 3.2 cm with a pile spacing (D1) of 10 cm, yet the diameter of the second row is 2.0 cm with varied pile spacing from 2d to 5d. The LVDT was installed on the pile, and the model would gradually be loaded using a hydraulic jack until the slope collapsed. The unreinforced slope bearing capacity (qu) on the loading test was used as the external load to numerically analyze the FS of the 2D and 3D FEM using PLAXIS. The results showed that the FS increased against the unreinforced reinforcement of two rows of piles with external load by 7.18% in the 2D FEM and 29.05% in the 3D FEM. The results obtained for the loaded slopes model with one row of pile reinforcement are 4.38% in 2D FEM and 1.49% in 3D FEM. The slope model with the highest FS was the slope model with pile spacing, D1=2d. The type of slope failure was rotational.

Keywords: Double-row, FEM, Factor of safety, Pile, Slope reinforcement

1. INTRODUCTION

Installing retaining structures, for instance, anti-slide piles and rigid retaining walls, was an effective way to reinforce slopes according to geotechnical engineering's practical implementation technique [1]. One engineering solution constantly being researched as a practical method for preventing landslides is reinforcing slopes with anti-slide piles. According to several studies [2-4], pile installation has reinforced the slopes by increasing their stability and bearing capacity. In general, if the factor of safety (FS) of the slope are less than or equal to 1 (FS ≤ 1), it would be critical and highly likely possibilities to fail. This circumstance might occur when the slope angle (i) was as greater than the soil's internal friction angle (ϕ) since the interaction of those parameters affects the slope stability.

To choose the perfect location and arrangement for the piles, it was also necessary to analyze the reliability and probability of slopes reinforced with the pile. One of the major factors contributing to the significant impact is the soil arching effect, which is often affected by the placement of the pile on the slope, pile length, pile diameters, and pile spacing [5-7]. The results of the prior research, which concentrated on the reinforcement with a single row of piles, were varied. If the piles are not correctly adjusted in the failure plane, the slope can slide along its failure plane.

The slope stability increases by adding piles in two or three rows [8]. As more reinforced pile rows were installed, the arching effect extended and altered the slip surfaces, which caused slope failure [9]. Two-dimensional (2D) and three-dimensional (3D) finite element analyses have been widely used and used in geotechnical engineering applications throughout the past few decades (FEM). Therefore, the slope models with sand soil were examined using experimental and numerical modeling in this study, including a second-row pile reinforcement on the slope under the variations in pile spacing. With slope angles of 50°, the critical sand slope modeling attempts to investigate and analyze the improvement of Factor of Safety (FS) caused by the double-row pile installation.

2. RESEARCH SIGNIFICANCE

This study uses a small-scale model in the experimental slope modeling with or without pile reinforcement. The ultimate bearing capacity (qu) improvement of the foundation on the reinforced slope was investigated by a series of experimental tests in the laboratory. The two-dimensional (2D) and three-dimensional (3D) PLAXIS software were used for the numerical test of 2D and 3D FEM models. Each FEM model represented the small-scale slope model identically in shape and parameters. This study used 2D and 3D FEM modeling to examine how adding second-row pile reinforcement to the slope impacted safety factors and landslide zones. In this study, the pile spacing on the second-row pile was applied and varied to evaluate its effect on the qu and FS of reinforcing slope for increasing the probabilities of the slope becoming stable, either the unreinforced slope or reinforced slope with the pile.

3. SMALL-SCALED SLOPE MODEL TESTS

3.1 Experimental Model Test Container

The 1.5 x 1.0 x 1.0 m model test container used in this study is made from sufficiently stiff steel materials (Figure 1). WF beams were set up as the container's frame, while the steel plate (t = 6 mm) was used for the body. Steel plate with a thickness of t = 12 mm was utilized for the container base, which was thicker than the body plate steel. Additionally, the container has one clear fiberglass side with a t = 8 mm thickness that observes the model's slope. Angle plates L 40.40.4 have been used to reinforce the container all the way around, including the clear side, to make it sufficiently rigid.

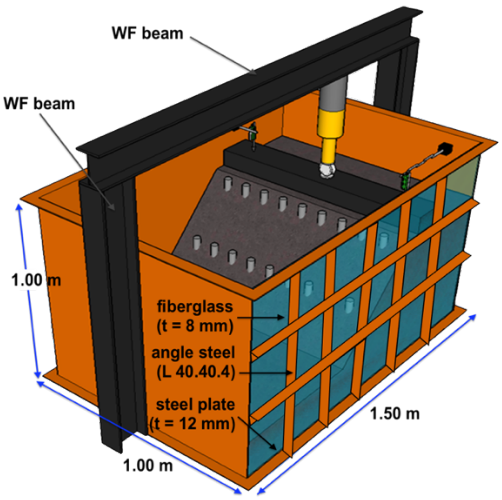


Fig. 1 Experimental model test container

3.2 Material

3.2.1 Sand Properties

To identify the soil classification and its properties used as the slope model, pre-laboratory testing procedures, such as grain sizes test, specific gravity test, standard compaction test, direct shear test, and Saturated Surface Dry (SSD) test, were carried out by ASTM standards. Both on the physical and FEM test models, the results of these tests were regarded as slope model parameters (Table 1). Unified Soil Classification Systems (USCS) would be used to classify the soil. As shown in Table 1, the soil used as a model is poorly graded sans (SP). The sand was first sieved using sieve No. 4 before being used to create the slope model. The estimated volume of sand needed for each slope model is around 750,000 cm^3.

Table 1 Sand soil properties

Properties	Values
Soil classification, USCS	SP (poorly graded sand)
Specific gravity (G_s)	2.666
Poisson's ratio (μ)	0.3
The dry density of soil (γ_d)	SSD : 1.718 gr/cm^3 Rc 88% : 1.512 gr/cm^3
Shear strength of soil	ϕ : 35.77° c : 0.03 kg/cm^2
Saturated Surface Dry (SSD)	0.76%
Dilatancy angle (ψ)	5.38°
Modulus of Elasticity (E_{soil})	7.231 kg/cm^2

3.2.2 Pile Properties

Models of reinforcing piles were using round aluminum tubes. The precise diameters (d) and thicknesses (t) of the model aluminum piles were measured with a vernier caliper. Five-round aluminum tubes were subjected to the measurement test to determine the average diameter and thickness. The modulus of elasticity on the pile is obtained from the stress-strain graph from the compressive laboratory test results using a Compression Testing Machine (CTM) configured with Linear Variable Displacement Transducer (LVDT) and data logger. The aluminum pile properties are shown in Table 2.

Table 2 Reinforcing pile properties

Properties	Values
Outer diameters (d)	$d_{1\ (first\ row)}$: 3.2 cm $d_{2\ (second\ row)}$: 2.0 cm
Inner diameters (d_{inner})	$d_{1\ inner\ (first\ row)}$: 3.0 cm $d_{2\ inner\ (second\ row)}$: 1.8 cm
Thickness (t)	2 mm
Modulus of Elasticity (E_{pile})	1.498 x 10^5 kg/cm^2

3.3 Preparation and Experimental Procedure

The poorly graded sand was gradually discharged and compacted in the model test container to construct the small-scaled slope model with a layer-by-layer compaction procedure. The compaction was done with each layer of sand being as thick as 10 cm until it reached a height of 70 cm (seven layers). The concrete cylinders (d = 15 cm, h = 30 cm) were used for the compaction process on sand layers, which applied the general compaction technique of the construction roller on the site; likewise, the compaction held until the sand layer achieved the controlled dry density. In this study, we constructed the small-scaled slope model with a slope angle of 50 degrees and a relative density (Rc) of 88%, which is the dry density of 1.512 gr/cm^2.

The diameters (d) of the aluminum round tubes utilized as the reinforcing piles are d_1 = 3.2 cm for the first row and d_2 = 2.0 cm for the second row. The previous study suggested the location of the piles on the slope model. The upper-middle portion of the slope is a suitable site for a row of reinforcement [10, 11]. The middle-lower section of the reinforced slope with the double-row piles was proposed as the most efficient pile placement position, according to the other test result of the prior study [12]. It may increase the slope's stability up to its maximum safety factor. The first-row pile location of the slope model in this study was Lx_1/L = 0.9, and its second-row pile position was Lx_2/L = 0.5.

The center-to-center distance (D_1) of the first row reinforcing pile was set at 10 cm. Yet, the second-row center-to-center spacing was varied under four different distances from 2d to 5d. The arching effect of soil between the piles influenced the selection of the D_1. If the clear gaps (D_2) were more significant than 8d [13], the arching area would be inefficient. On the reinforced slope, $D_1 \leq$ 5d was proposed as the pile spacing to avoid the soil flowing freely between the piles at these spacing ranges. This distance is adequate for the pile spacing required to generate the optimal soil arching effect between the piles [14].

The slope model was loaded gradually by 40 kg using a hydraulic jack configured with the load cell during the loading test. The strip footing model, made of wood, had a dimension of 90x15x9 cm. The load cell was positioned on top of it, 5 cm from the edge. The loading is concentrated and then transmitted by beams to establish a uniform load. With LVDT, the settlement for each loading increment was recorded, and the slope movement was examined until the failure was visible. The complete test setup is illustrated in Figure 2 and Table 3.

Table 3 The configuration of the specimens

Speci-mens	Piles Spacing (cm)		Number of piles	
	Row 1 Lx_1/L=0.9	Row 2 Lx_2/L=0.6	Row 1 Lx_1/L=0.9	Row 2 Lx_2/L=0.6
D0P0	-	-	-	-
D0P1	10	-	9	-
D5P2	10	10	9	9
D4P2	10	8	9	12
D3P2	10	6	9	16
D2P2	10	4	9	24

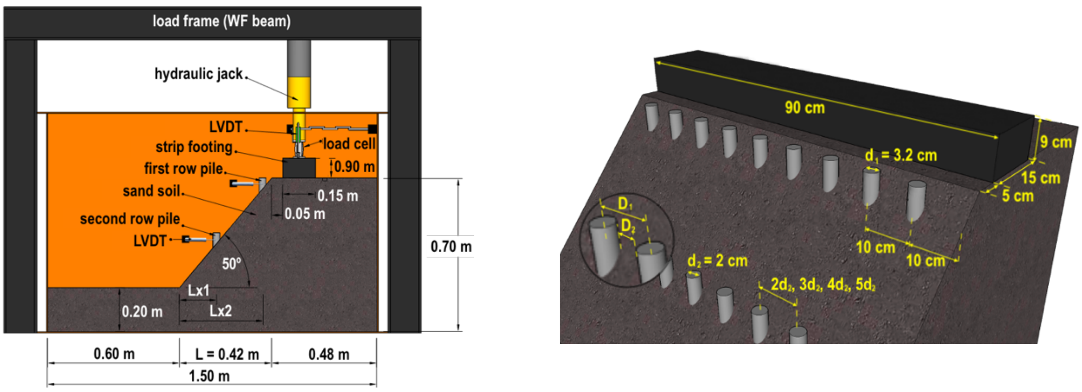
3.4 Numerical Analysis

The FEM analytical software was used for the numerical analysis. Numerous 2D and 3D FEM modelings are carried out using the finite element programs PLAXIS 2D and PLAXIS 3D to analyze the Factor of Safety (FS) of the pile-reinforced slope in this study. In addition, the slope factor of safety is defined as a result of the FEM analytical process, which rapidly reduces the soil cohesion (c) with the soil shear angle (ϕ) until the slope failure. The 2D and 3D FEM modeling were done in three different simulations with two different types of loaded (loaded and unloaded). The small-scaled slope model without pile reinforcement's ultimate qu values was used as the external load.

Table 4 The FEM modeling test conditions

Simu-lations	Reinforcement conditions	Tested condition of the slope model	
1st	Unreinforced	Unloaded	Loaded
2nd	One-row pile	Unloaded	Loaded
3rd	Two-row pile	Unloaded	Loaded

Modeling a 2D FEM-reinforced slope with piles has been used frequently to overcome landslide concerns. Furthermore, it is challenging to evaluate the arching effect and soil movement between piles, which is impacted by pile spacing, using the 2D FEM. The 2D FE analysis is



(a) (b)

Fig. 2 Small-scaled test model configuration, (a) cross-section; (b) detail of pile placement insufficient when the spacing is more than 4d. It is hard to visualize the arching effect with the 2D FE when the spacing is greater than a critical value since the soil can flow between the piles easily [15]. To accurately describe the spacing effects as adequate cost design considerations; instead, 3D geometry is a more effective method than the 2D FEM. The capability to establish boundary conditions reliably allows for the implementation of 3D FEM modeling [16,17].

The reinforced slope with pile on the FEM models had been analyzed with the same size as the small-scale modeling. An automated mesh generated from the PLAXIS was applied to the FEM model. Due to its properties, the poorly graded sand was represented as drained material with soil parameters of the laboratory test results. The interface components simulate the interaction between the piles and the surrounding soil, assuming the piles are elastic.

4. RESULTS AND DISCUSSION

4.1 Bearing Capacity of Small-Scaled Model

The foundation width used in this study is 15 cm. The 0.1B method (s/B = 0.1) determined the soil-bearing capacity [18]. Hence, the bearing capacity (qu) was reached when the foundation settlement 1.5 cm. The qu of each model tested, both unreinforced and reinforced slope models, was shown in Table 5.

Table 5 The qu of the small-scaled slope model

Speci-mens	qu (kN/m^2)	qu deviation (%)	
		Unreinforced slope	One-row pile reinforced slope
D0P0	34.355	-	-
D0P1	42.245	22.97	-
D5P2	61.599	79.30	45.81
D4P2	74.770	117.64	76.99
D3P2	84.347	145.52	99.66
D2P2	87.781	155.51	107.79

The slope with the reinforcing pile, particularly on the slope with a double row of the reinforcing pile, may improve the bearing capacity (qu). The test results indicated that the bearing capacity increased along with the reduction of pile spacing. The slope with the closest spacing of the second-row pile (D2P2 with D1 = 2d) achieved the highest bearing capacity, qu = 87.781 kN/m^2. Compared to slopes without reinforcement and one-row pile reinforcement, the slope model with double-row pile reinforcement (D2P2) could increase the qu by up to 155.51% and 107.79% in sequences.

The pile spacing had a substantial impact on the soil-pile interaction. To optimize soil arching potential while reducing soil flow rate between the piles, the area affected by pile spacing must be carefully designed [19]. During construction, the pile spacing should also be carefully planned. Even if the slope and pile will be stable with the narrow pile spacing [17, 20], the cost of a slope reinforced with piles is significantly impacted by pile spacing; as pile spacing (S/D) decreases, costs will begin to increase. Due to the pile spacing getting smaller, more piles were installed on-site.

4.2 Factor of Safety (FS) of Slope Model

The 2D and 3D PLAXIS tested the FEM slope models to evaluate the effectiveness of pile reinforcement on the slope. From the FEM model results, the value of FS was identified since it was particularly needed while examining the level of slope stability. FEM 2D and 3D analysis results of the slope model without reinforcement and with one pile reinforcement were used to compare the slope FS due to the second-row addition. The numerical analysis of FEM models was also performed by simulating whether unloaded or loaded conditions (Tables 6 and 7).

Table 6 The FS of 2D FEM slope models

Specimens	Factor of Safety (FS)		Deviations (%)
	Unloaded	Loaded	
D0P0	2.831	0.918	(67.58)
D0P1	3.173	0.943	(70.30)
D5P2	3.211	0.968	(69.84)
D4P2	3.215	0.973	(69.73)
D3P2	3.221	0.980	(69.58)
D2P2	3.224	0.984	(69.49)

Table 7 The FS of 3D FEM slope models

Specimens	Factor of Safety (FS)		Deviations (%)
	Unloaded	Loaded	
D0P0	3.399	1.112	(67.28)
D0P1	4.117	1.414	(65.65)
D5P2	4.120	1.421	(65.51)
D4P2	4.124	1.425	(65.45)
D3P2	4.131	1.428	(65.43)
D2P2	4.136	1.435	(65.30)

The slope factor of safety (FS) was reduced drastically by the presence of additional stresses from the external load on the slopes. On the FEM 2D model, the decrease of FS reached 70.30% (D0P1), while the FS of the FEM 3D model reduced to 67.28% (D0P0). The decrease in the FS from all the slope models shown under the circumstance of receiving external loads denotes a change in the slope model of more than 60%. Thus, this condition should be considered while designing the pile reinforcement on a critical slope to ensure its stability and improve the effectiveness of this mitigation method.

According to the FEM modeling results, reinforcing the slopes with piles could improve the Factor of Safety (FS). The second-row variation in pile spacing implies that the FS enhanced along with the decrease of the pile spacing. Nevertheless, the number of piles would increase and affect the construction expenses if the pile spacing slightly decreased. The deviations of the FS on the FEM model are shown in Table 8 and Table 9.

The analysis of the 2D FEM modeling revealed that the slope reinforced by two rows of piles had the unreinforced slope and the slope with one row of reinforcement; the FS continued to increase by up to 13.88% and 1.61%, respectively. The analysis using 3D FEM modeling presented different outcomes (Table 9); the slope is capable of increasing the FS up to 29.05% against slopes without reinforcement and 1.46% against slopes with one row of pile reinforcement under loaded conditions. The results of two different FEM approached modeling, in both 2D FEM and 3D FEM, showed that the pile with the narrow spacing (2d) generates the highest factor of safety (FS).

In this study, the observation limitation led to a slight improvement of the FS of the critical slope, which was mainly focused on pile spacing. Although the pile positioning configuration, parallel to the first-row or zigzag, on the second-row pile design also impacted the direction of soil flow. To evaluate and comprehend the details of the pile arrangement in the second row, further investigation is necessary.

The selected pile spacing considerably impacted the soil-pile interaction [19]. To optimize the soil arching effect while decreasing the soil flow rate between the piles, the influenced zone of the soil flow by the pile spacing might be carefully calculated. The clear spaces between the piles would be less the nearer each pile is placed to one other. Additionally, since retained soil was confined within the pile's cross-sectional area, there was a reduction in soil flow through the piles. Regardless of the slope stability and the soil arching area between the piles, the construction cost of the slope reinforcement should be considered while choosing the pile spacing. The reason behind this was that as the pile spacing decreased, on the other hand, the construction costs increased because the number of piles would automatically increase. Thus, the most effective pile spacing for practical use is at least 3d to 5d.

The limitations of the 2D FEM and different calculation approaches were the causes of the results, which also differ between the 2D FEM and 3D FEM modeling. In contrast to the small-scaled slope model, the 2D FEM modeling could only define the x-axis and y-axis, not the slope's width dimensions (z-axis) or the precise pile spacing. According to the experimental model slope geometry, the 3D FEM modeling of the slope can be represented similarly.

The failure zone of the slope is observed using the addition of lime upon each layer of soil in the small-scaled slope test model. It would be observed that the results of the experimental investigation and the numerical analysis using the FEM model were verified with one another (Figures 3 to 6). The type of landslide that occurred was a rotational landslide. This type of rotational landslide is distinguished by the slide plane that creates a basin against the slope.

The landslide zone of the slope without load was visible on the toe of the slope, either the slope with or without the reinforced pile. In contrast, the landslide zone was seen on the top to middle slope of the model with external loaded. Each model's highest displacement was discovered directly beneath the load—this failure zone was similar to the failure zone on the small-scaled slope model. As the spacing increased, the failure zone deepened.

Table 8 The FS deviations of 2D FEM slope models

Specimens	FS of Unloaded Slope	Deviations (%)		FS of Loaded Slope	Deviations (%)	
		Unreinforced *(2.831)*	One-row Pile *(3.173)*		Unreinforced *(0.918)*	One-row Pile *(0.943)*
D5P2	3.211	13.42	1.20	0.968	5.50	2.75
D4P2	3.215	13.56	1.32	0.973	6.01	3.25
D3P2	3.221	13.78	1.51	0.980	6.75	3.97
D2P2	3.224	13.88	1.61	0.984	7.18	4.38

Table 9 The FS deviations of 3D FEM slope models

Specimens	FS of Unloaded Slope	Deviations (%)		FS of Loaded Slope	Deviations (%)	
		Unreinforced *(3.399)*	One-row Pile *(4.117)*		Unreinforced *(1.112)*	One-row Pile *(1.414)*
D5P2	4.120	21.21	0.07	1.421	27.79	0.50
D4P2	4.124	21.33	0.17	1.425	28.15	0.78
D3P2	4.131	21.54	0.34	1.428	28.42	0.99
D2P2	4.136	21.68	0.46	1.435	29.05	1.49

(a) (b) (c) (d)

Fig. 3 The small-scaled model failure zone with the double-row pile, (a) D_1=5d; (b) D_1=4d; (c) 3d; (d) D_1=2d

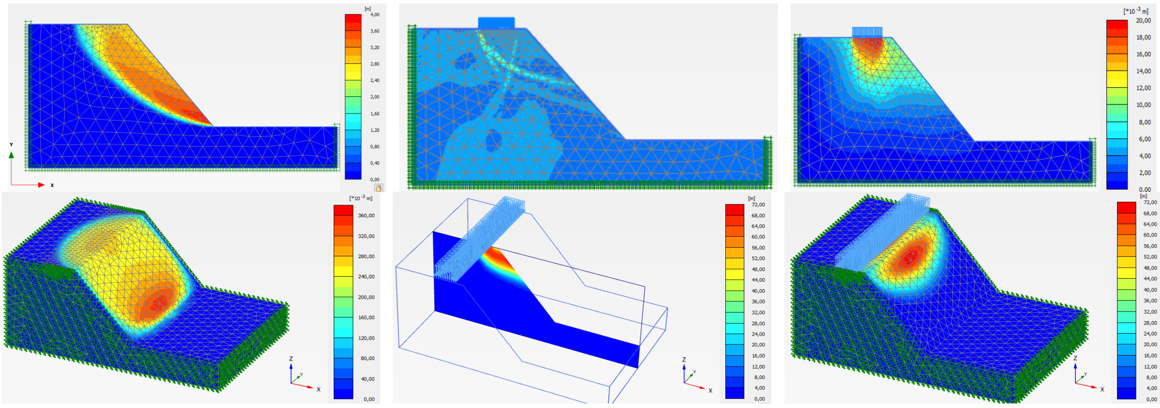


Fig. 4 The failure zone of 2D and 3D FEM unreinforced slope model

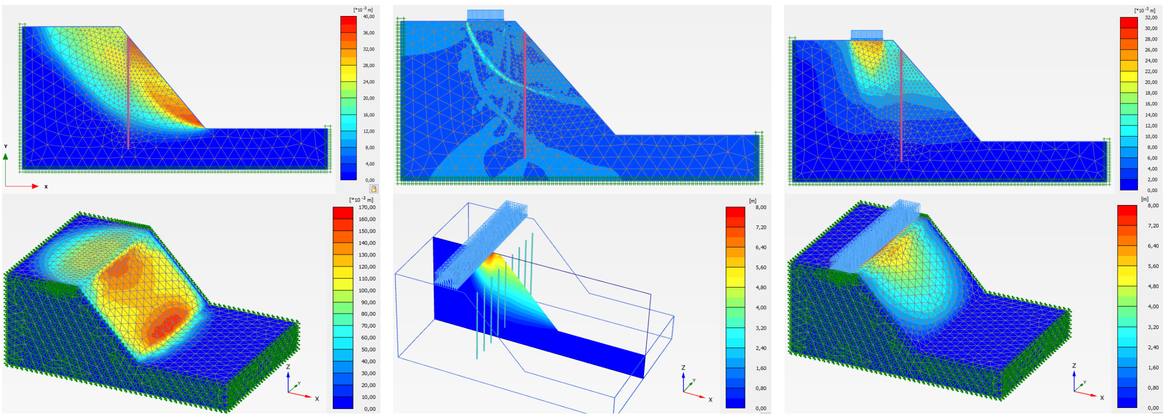
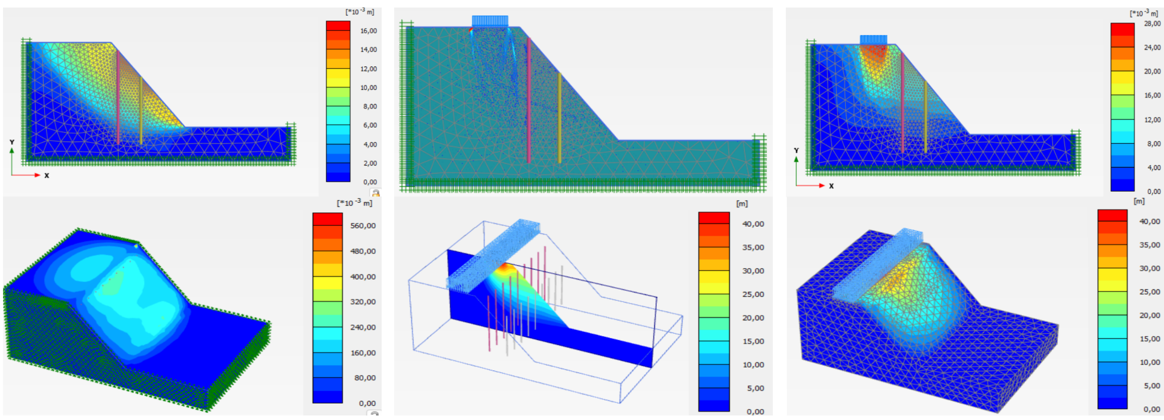


Fig. 5 The failure zone of 2D and 3D FEM one-row pile slope model



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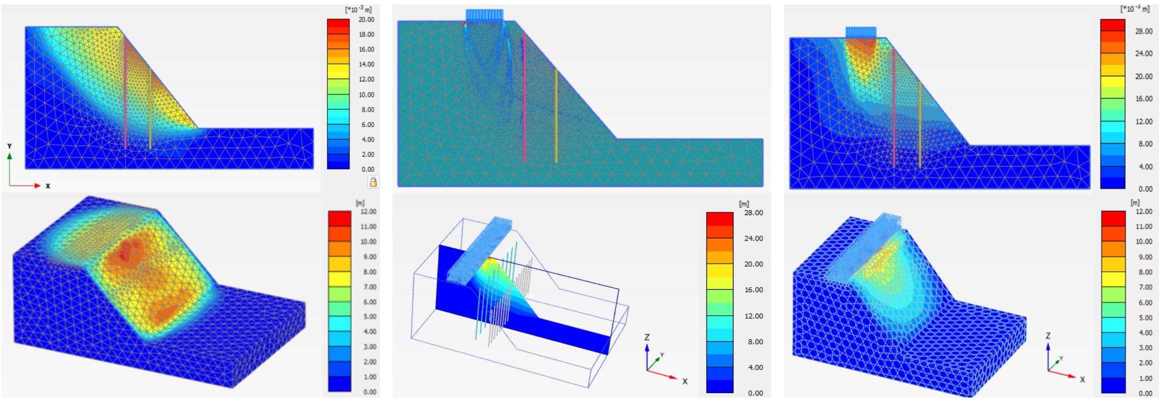

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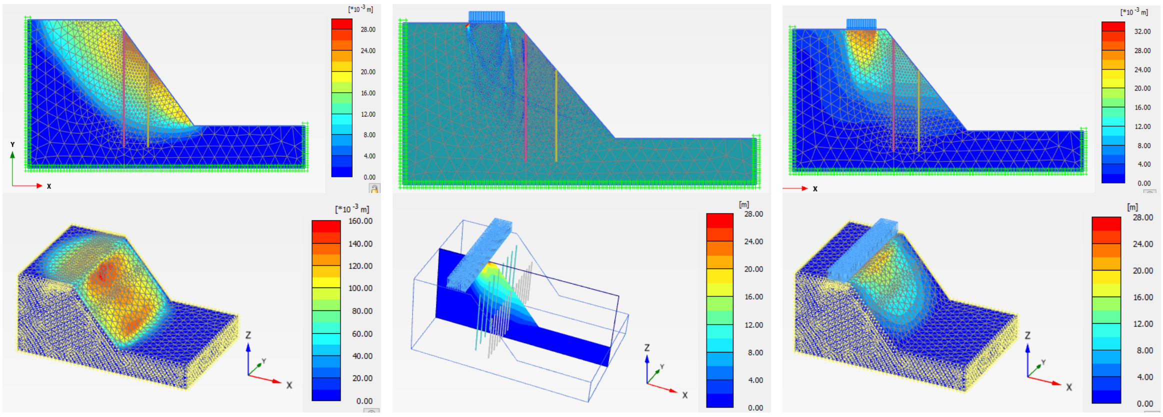
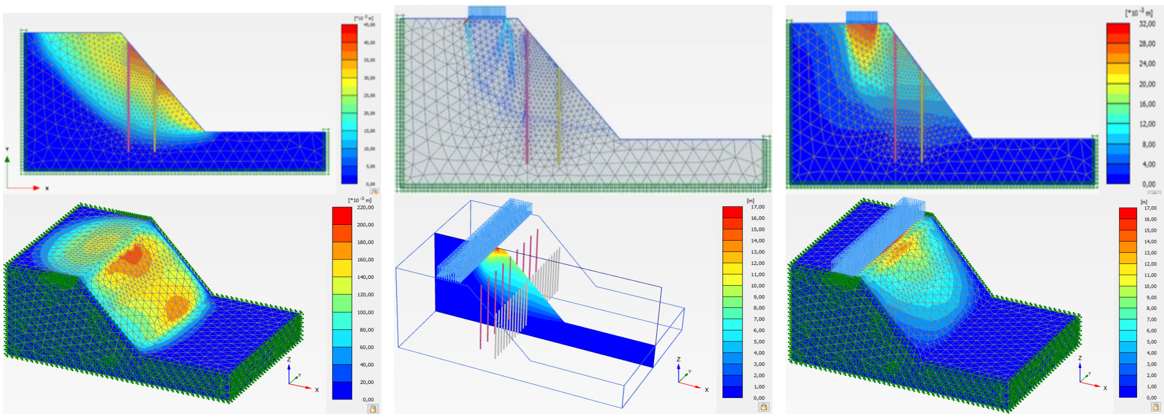


(c)



(d)

Fig. 6 The failure zone of 2D and 3D FEM double-row pile slope models, (a) D_1=5d; (b) D_1=4d; (c) D_1=3d; (d) D_1=2d

5. CONCLUSION

The slope-bearing capacity (qu) and Factor of Safety (FS) improved due to reinforcing the critical sand slopes with piles. The pile reinforcement enhanced the FS, especially if the slope had double reinforcement. However, as the second-row reinforcement pile spacing is widened, the qu and FS decrease. Despite that, the construction cost went higher as more piles would have to be installed to reinforce a row of piles with close-spaced piles. Regarding practical use, pile spacings ranging from 3d to 5d are suggested.

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