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An Experimental Study of Bearing Capacity and Slope Stability of Residual Slope Model with Pile Reinforcement

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Abstract Based on its geographical location, most of Indonesia's territory consists of residual soil. Residual soil on slopes has been a problem that often occurs and causes landslides. We can use various efforts to prevent landslides and overcome other issues on slopes, especially residual soil, by providing reinforcement. In this study, we can increase the strength of the slopes to be more stable by providing pile reinforcement to improve the safety of the slopes. First, we observed a scaled slope model with and without pile reinforcement. Residual slope modeling was carried out using a test box with a slope inclination of 37° and using a composite concrete pile as a model for pile reinforcement. Test models with different diameters (2.54 cm, 3.175 cm, and 3.81 cm) and the pile spacing were varied (7.5 cm, 10 cm, and 12.5 cm). This test was performed using an experimental model in the laboratory aimed at understanding the failure mechanism or failure of the slope. We identified the maximum failure load value for the slope to resist sliding. Problems in the laboratory were analyzed using the finite element method by changing the form of 3D slope modeling to 2D modeling. Then, we compared the experimental results in the laboratory with the finite element analysis method. Based on the FE Method test results, the SF of slopes reinforced with single-row experienced a safety factor improvement of 17.621 % in FEM (2D) compared to slopes modeled without reinforcement. The most significant bearing capacity and SF value were found in the diameter of 3.175 cm and a distance of 10 cm. The effect of diameter and spacing between piles on slope stability is when the pile diameter increases, the pile spacing becomes smaller, and the critical slip surface also becomes deeper until a specific diameter and distance are reached. This condition causes the slope to become stable. In addition, the study result showed that reinforced slopes are prone to failure of the rotational slope.

Keywords Pile Reinforcement, Residual Slope Model, Bearing Capacity, Safety Factor, Finite Element Method

1. Introduction

Due to its geographical location, most of Indonesia's territory has residual soil. Residual soil is the result of the physical and chemical weathering of rocks. The increasing development activity has caused many hills to change their function into housing, agriculture, plantations, and roads, thus triggering the conversion of land functions in unstable slope areas due to increasingly limited land. This situation can cause the soil to become unstable and endanger people's lives.

Slope stability generally depends on the interaction between slope and soil parameters. Slopes are declared stable if they are less than the internal shear angle (ϕ).

Most previous studies investigated reinforcement using sandy soil types, whereas laboratory model studies using residual soil were rarely conducted. This is because the soil already has complex problems, while most of the research examines the parameters of the residual soil itself. In addition to the very complicated issue of strengthening slopes using piles in cohesive (especially residual) soils, has not been conducted a proper stability analysis of reinforced piles in this soil type. In several studies, the installation of piles is used to strengthen slopes by increasing the slope's safety and ultimate bearing capacity [1-3].

The reliability and probability of slope failure are investigated to identify optimal pile placement in the failure plane. The effect of soil arching is a critical aspect that has a significant impact [4], mainly influenced by the pile placement, the length of the pile, the diameter, and the spacing of the piles on the safety factor of the slope [5,6]. One way to avoid and overcome this is to strengthen the slope by installing and driving the piles. The pile driving method is carried out at the top of the slope, which functions as a retaining element as well as retaining lateral forces, which work by reducing lateral forces and transferring these forces to piles driven at a specific spacing on the slope.

Finite element-type numerical methods are gaining popularity due to significant advances in computational tools that comprehensively analyze soil-piled interactions. In recent decades, finite element analysis (FEM) has been frequently used and applied in geotechnical engineering applications. Therefore, in this study, the slope model with residual soil was tested by experiments and numerical simulations, and the slope was reinforced with piles of different diameters and distances.

2. Objective of Research

In this study, an experimental laboratory tested residual soil slope models with and without pile reinforcement using small-scale models. We conducted small-scale modeling to test the increase in the ultimate bearing capacity of a reinforced slope foundation. FE Method (2D) modeling with Plaxis software was used for the numerical tests. All FE Method models are the same small-scale physical model. The FE Method (2D) modeling aims in this study to determine the effect of residual soil slope on the safety factor and the area of landslides generated by the reinforced piles.

3. Literature

3.1. Previous Studies on Residual Soil

Basically, slope stability in geotechnical engineering is an unexpected problem facing different natural slope construction sites and can be reduced to uncertainty. Furthermore, this problem becomes more serious when the slope is in residual soils: unlike sedimentary soils, the soil strength parameters cannot be obtained from the stress-strain relationship discussed by Asoudeh [7]. Asoudeh concluded that there have been efforts to overcome slope failure, especially residual soil by using pile reinforcement. Residual soil which has cohesion below 10 kPa can no longer be repaired but there is still a possibility for residual soil which has cohesion above that value. So for this test, the researchers focused more on examining the handling of residual soil with soil cohesion above 10 kPa. Wesley presents the basic aspects of residual soil and properties that geotechnical engineers must consider when working with this type of soil. Salih [8] explained that soil strength properties play an essential role in slope stability trends due to the importance of soil moisture content. Salih concluded that the slope's safety factor decreases with the height of steep slopes. Rahman et al [9] performed a testing program on reinforced and unreinforced residual soil samples considering six different stress-strain pathways, then, they simulated the finite element analysis of the reinforced residual soil and as a result, they found good agreement between the numerical simulation results and the measurable response. Chang and Broms [10] investigated the reinforcement of drilled piles **into the residual soil** based on site performance data. They concluded that the results of the load test experiments on the piles indicated that the drilled piles in the residual soil in Singapore behaved in the same way as in stiff clay and rock, where the load transfer on the working load is dominated by shaft friction. Goh et al [11] analyzed the stability and evaluated the improvement of residual soil slopes, they compared the residual slope reinforcement by means of ground anchors, soil nailing, geo-fabric, and driven pile. Driven Pile is the best load to be used in strengthening soil structures. Their research produced positive results with the achievement of up to 82.49% increase in stability (SF) in the correct position of the reinforcement load added to the failure of the slip surface on the slope.

3.2. Slope Stability with Pile Reinforcement

Placing a shallow foundation on the surface of a slope causes the bearing capacity of the foundation to decrease depending on the location of the foundation against the slope. In slope reinforcement systems, this problem can be solved by installing and driving composite concrete piles. The pile driving method is carried out on the slope surface which functions as a retaining element as well as retaining lateral forces which work by reducing lateral forces and transferring these forces to composite concrete piles.

Several studies have been carried out using piles as slope reinforcement elements to increase the stability of slopes both analytically, experimentally, and numerically.

Laboratory model studies of reinforced piles especially on sandy soil types, such as Sawwaf [12], used reinforced piles made of aluminum and steel piles; Boominathan [13] studied reinforcement of aluminum piles in clay. Kusakabe [14] investigated the bearing capacity of clay soils on continuously loaded slopes using the upper limit theorem method; Azzam [15] conducted a study using strip foundation reinforcement, which compared the bearing capacity of soil on experimental and numerical sandy slopes. Kumar [16] studied sandy soils with geogrid reinforcement, both experimentally and numerically. Huang et al [17] conducted a study using geotextile reinforcement. Most of the studies above conducted tests using sandy soil as a model scale in the laboratory.

3.3. Slope Stability Analysis

Analysis of soil-bearing capacity studies the ability of soil to support the foundation load acting on it. Bearing capacity represents the shear strength of the soil to resist settlement due to loading, namely the shear strength that the soil along its shear plane can generate. The bearing capacity of slopes without pile reinforcement can be analyzed using the analysis method for flat soils by adding the influence factor of the slope. The main difference between LE and FE methods is that LE methods are based on static equilibrium, while FE methods use stress-strain relationships or constitutive laws. Among the LE methods is the Bishop simplified (BS), Janbu simplified (JS), Janbu GPS methods, and Morgenstern-Price method (M-PM). BS and JS methods satisfy only force equilibrium, while Janbu GPS and The M-PM method balance forces and moments. In addition, M-PM enables variable pattern functionality between layers. A comparative study using the LE method showed that under normal circular shear plane analysis conditions, BSM is as good as M-PM.

It can be concluded that LEM-based analysis shows a circular slip surface, whereas FEM-based research shows a non-circular slip surface. Bishop's Modified Method includes interslice normal forces but ignores the interslice shear forces. Bishop's method also only satisfies moment equilibrium. Circular slip surfaces are the only ones that satisfy moment equilibrium, while they satisfy vertical force equilibrium. However, they do not satisfy horizontal force equilibrium. Morgenstern and Price's Method is the limit equilibrium technique of slices primarily based on basic terms on the concepts of statics, that is, the summation of moments, vertical forces, and horizontal forces for more complex problems involving highly heterogeneous ground with different materials between adjacent layers, where the interslice shear force is expected to vary. This method offers several advantages, including the ability to accommodate slip surfaces of any shape, the satisfaction of all conditions of equilibrium, and the flexibility to vary side force orientations.

Duncan [18] stated that the stability analysis of the pile-reinforced slope could be adopted in the same way as the unreinforced slope stability analysis, where the pile reinforcement forces contribute to the equilibrium forces in the stability equation for unreinforced slopes.

He concludes that the FE method for slope stability analysis is a more robust alternative to the traditional limit equilibrium method. And its widespread use should now become the standard in engineering practice geotechnics.

This study uses the finite element method from the Plaxis program to solve problems in slope stability analysis. The safety factor of reinforced slope stability is as follows:

$$SF_{slope} = \frac{M_r}{M_d} = \frac{M_{rs} + M_{rp}}{M_d} \tag{1}$$

Where:
M_{rp} = Added resistance pile reinforcement moment
M_r = resistance moment
M_d = driving moment
M_{rs} = resistance moment along the critical circle
M_{rp} = added resistance pile reinforcement moment

The slope stability is determined based on the Bowles safety factor classification [19] shown in Table 1.

Table 1. Bowles safety factor classification

Safety factor	Slope condition
SF ≥ 1.25	Stable
1.07 ≤ SF ≤ 1.25	Critical
SF ≤ 1.07	Unstable

3.3.1. Analysis of Bearing Capacity'using the Finite Element Method'

This study used the PLAXIS 2D program as the FE Method to analyze the slope safety factor (SF). 2D modeling with PLAXIS 2D is different from laboratory modeling, which is 3D modeling. It is impossible to directly enter material values into the initial input to determine the effect of diameter and spacing pile. We must change the diameter and the distance between the piles in the form of EI and EA. Further, the EI and EA values for both the pile and the soil are transformed into the equivalent EI form.

Steward and Randolph [20] performed a plain strain analysis by equating the piles used in the modeling with a sheet pile wall having the same stiffness as the average stiffness of the piles and the soil itself, as shown in Figure 1. Thus, the analysis can be carried out by using the transformation value of the pile and soil into the equivalent EI form.

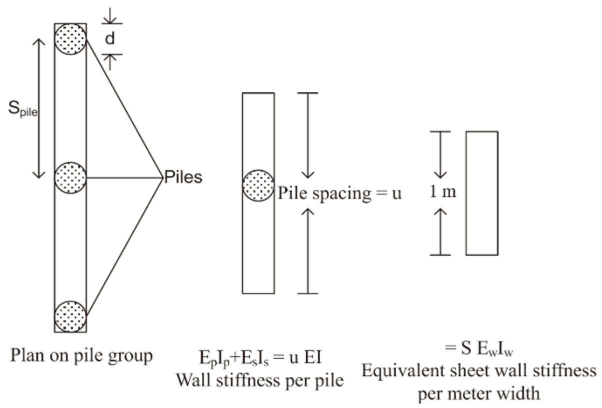


Figure 1. Equivalent Sheet Pile for Plane Strain Finite Element Analysis

3.4. Bearing Capacity Improvement and Safety Factor Improvement Analysis

The reinforcement to increase the ultimate soil bearing capacity is called Bearing Capacity Ratio (BCR). Researchers who carried out the bearing capacity test included an increase in bearing capacity expressed in the form of a non-dimensional quantity called the Bearing Capacity Ratio (BCR) [21-23]. Zahmatkesh [24] also stated that the increase in ultimate bearing capacity due to stone columns was considered through a non-dimensional parameter, namely the Bearing Capacity Ratio (BCR). Marandi [25] used BCR to evaluate the increase in bearing capacity with two bases, namely the ultimate bearing capacity and the bearing capacity based on the same decrease. Munawir [26] used the term Bearing Capacity Improvement (BCI). He reviewed BCI in two aspects, Bearing Capacity Improvement ultimate (BCIu) and Bearing Capacity Improvement at the same settlement (BCIs). In this article, we use the term Bearing Capacity Improvement (BCI) to determine the increase in bearing capacity. BCI is the comparison between the bearing capacity of reinforced and unreinforced piles. The increase in the BCI value illustrates the increase in the bearing capacity of the slopes after strengthening.

$$BCI_u = \frac{q_u(R)}{q_u} \qquad BCI_s = \frac{q(R)}{q} \tag{2}$$

where:
$q_{u(R)}$ = maximum bearing capacity with reinforcement (kN/m^2)
q_u = maximum bearing capacity unreinforced (kN/m^2)
$q_{(R)}$ = bearing capacity with reinforcement at a settlement of s (kN/m^2)
q = unreinforced bearing capacity at a settlement of s (kN/m^2)
Meanwhile, the percentage SF deviation is defined using:

$$SFI = \frac{SF_R - SF_{un}}{SF_{un}} \tag{3}$$

Where :
SFI = Safety Factor Improvement
SF_R = percentage SF deviation to pile reinforced slope
SF_{un} = percentage SF deviation to pile unreinforced slope

4. Materials and Methods

This experimental research material used residual soil and the material was put into the experimental box. The research was conducted at the Brawijaya Laboratory, Malang City. The research flowchart is as follows:

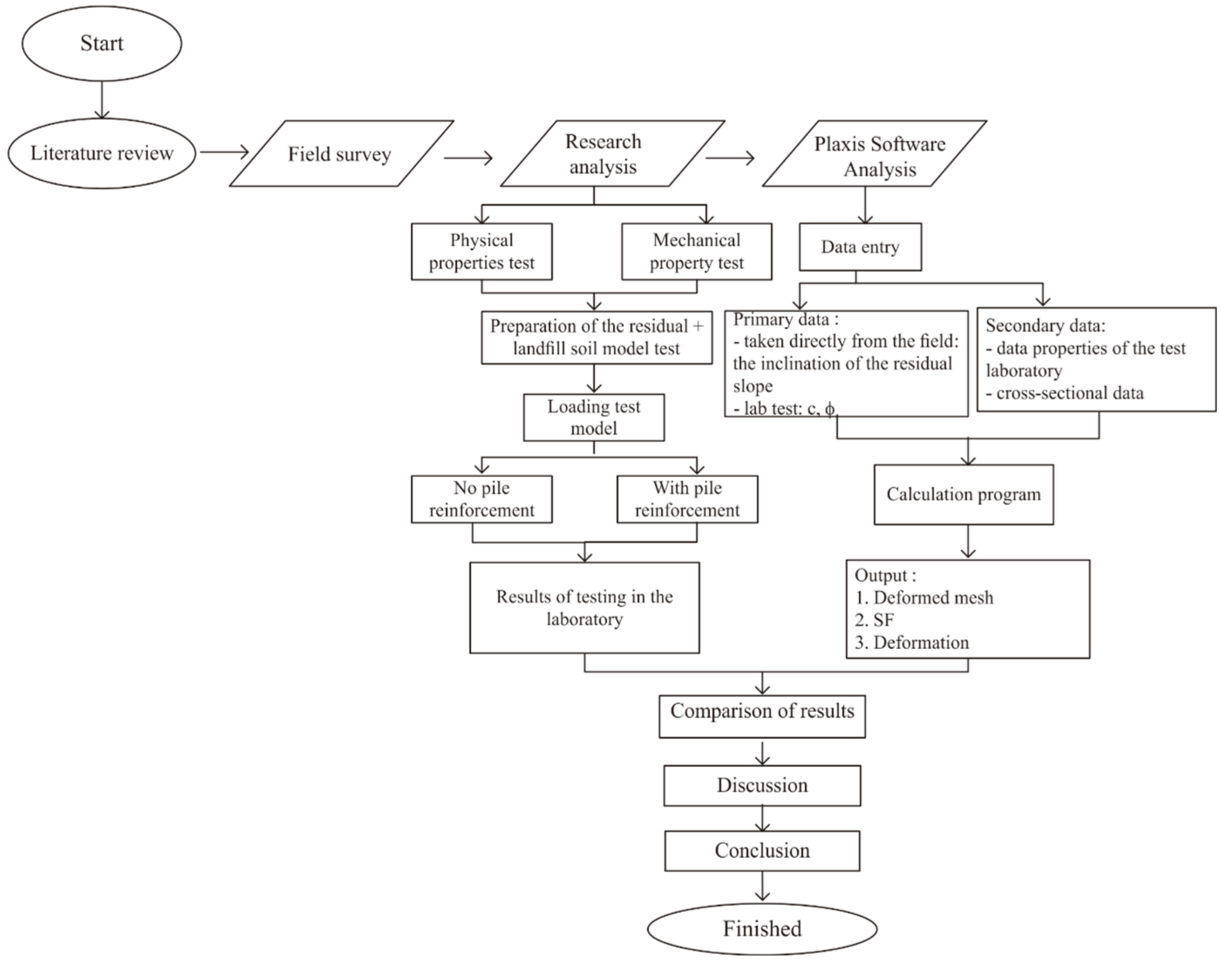


Figure 2. Research flow chart

4.1. Research Procedure

4.1.1. Testing of Residual Soil Materials

Residual soil parameters (according to USCS) can be seen in Table 2.

We did the research test without piles with a slope of 37^o residual soil and nine experiments with reinforced piles. Variations in diameter of the pile (D) used were: 3.81 cm, 3.175 cm, and 2.54 cm; the distance of pile (S) between the pile was 7.5 cm; 10 cm and 12.5 cm; the position of the pile from the toe of the slope was above Lx/L = 0.75, the ratio of the slope of the subgrade (residual soil) α = 35^o and the slope of the landfill soil (β) was 37^o, the length of the pile (H) = 60 cm, the width of the foundation (B) = 12 cm, the length of the strip footing was 100 cm and the height 10 cm, the distance of the load from the edge of slope = 5 cm.

The design of the residual slope model variable, which will be tested in the laboratory, is shown in Table 3.

This experiment provided load and settlement data. These bearing capacity values and the BCI's value can be considered the final results.

4.1.2. Small-Scaled Physical Modeling Test

We used low plasticity residual soil (according to USCS) to create small-scale physical slope models. The soil was compacted in a rigid steel container 1.5 m long, 1.0 m wide, and 1.0 m high. At the bottom of the box, gravel is compacted to a depth of 10 cm, then each 10 cm layer of residual soil is compacted until 70 cm high, and on top of the residual soil, the landfill was compacted to a height of 20 cm and formed at a slope angle of 37°. Reinforced concrete piles were used as a model of pile reinforcement with variations in diameter and distance between the piles. The foundation was placed on the slope's surface, and the load began to be given gradually with a hydraulic jack with a tension control system until the load reached the collapse load.

Previous studies have obtained the ultimate factor of safety for slopes with non-cohesive soils by placing the piles at the top of the slope (Lx/L=0.69) [5]. Therefore, the pile's position on this study's slope model is Lx/L = 0.75.

The fiberglass is expected to be used to be observed and seen during implementation. The experimental box is shown in Figure 3.

Table 2. Residual Soil Parameters

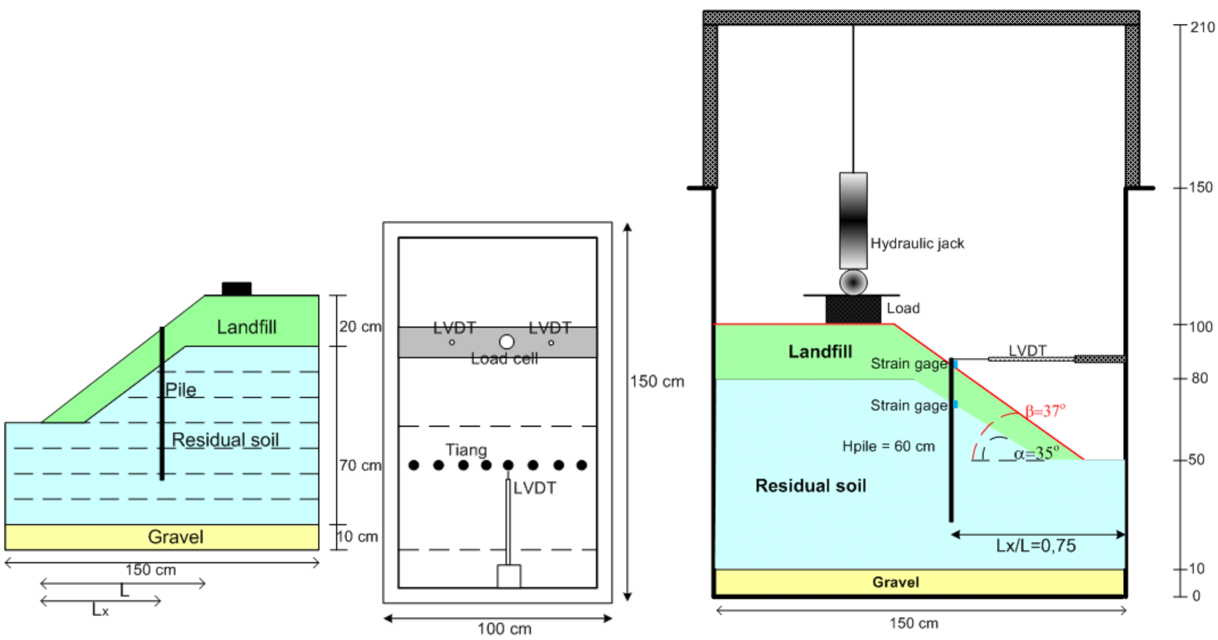
Test 'Model Parameters'	Unit	'Information
Sample depth		-1.00 m
Depth of ground water table		0.00 m
Water content (w_c)	%	69.76
γ_t	gr/cm^3	1.25
γ_d	gr/cm^3	1.085
γ_{sat}	gr/cm^3	1.61
Spesific'gravity (G_s)		2.285
Degree of'saturation (Sr)	%	57
Pore'ratio (e)		1.106
Porosity'(n)	%	52,5
Liquid limit	%	71.8
Plastis limit	%	67.67
Shrinkage limit	%	60.602
Plastisity index	%	4.085
Classification'of USCS		ML
Classification'of AASHTO		A-5 (silty soil)
Classification'of USDA		Vertisol soil
Cohesion (c)	kg/cm^2	0.19
Friction angle' (ϕ)	°	32.38

Table 3. The Model Variable of Residual Slope'

No	Constant parameter'	'Independent variable'	Exp.
1	Non reinforcement'	b = 0,42 B	-
2	Lx/L = 0.75' α/β = 0.95 H/B = 5	D/B = 0.212; 0.265; 0.318' S/B = 0.625; 0.833; 1.042	row

Figure 3. Experimental Box

The geometry and parameters of the pile sections can be seen in Figure 4.



a. Cross sectional view from the side
b. Cross sectional view from
c. Research plan on the experimental box

Figure 4. Geometry and cross section of the pile

Table 4. The slope soil layers and pile properties

		Soil		
Soil layer	Symbol	1	2	3
Identification	-	Landfill	Residual soil	Gravel
Material Model	-	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
General properties	γ_{unsat} (kN/m^2)	16.18	12.26	14.93
	γ_{sat} (kN/m^2)	18.85	15.79	19.63
Strength	C (kN/m^2)	2.8	1.96	0
	ϕ (°)	30	32.38	40
	ψ (°)	0	2.38	10
Stiffness	E_{soil} (kN/m^2)	10500	14710	100000
	v	0.3	0.3	0.3
		Pile		
Diameter	D (cm)		2.54, 3.175, 3.81	
Spacing	S (cm)		7.5, 10, 12.5	
Stiffness	E_{pile} (kN/m^2)		19640000	
Thickness	(m)		0.002	

5. Result and Discussion

5.1. Soil Parameter and Pile Properties

Initially, pre-tests were carried out in the laboratory with ASTM standards to determine the soil and pile modulus for the residual slope model. Data of soil and pile parameters are shown in Table 4, and the results of this research are used as parameters of slope, physics, and FE method models.

5.2. Bearing Capacity and Slope Safety Factor

Load tests continue until a critical value/collapse slope is reached. The test results showed that the maximum bearing capacity reached 205.04 kN/m^2 in the D2S2 model (d = 3.175 cm, S = 10 cm). According to the test results, the reinforcement of a single row of piles increases the ultimate bearing capacity of the slope. The bearing capacity results during the loading test on the residual slope model are shown in Figure 5.

The effect of pile diameter and pile spacing on foundation bearing capacity is known from experiments with three variations of diameter (2.54 cm, 3.175 cm, and 3.81 cm) and three variations of pile spacing (7.5 cm, 10 cm, 12.5 cm) at the top of the slope Lx/L = 0.75, the slope β = 37°, the length of the pile is 60 cm.

The value of the slope-bearing capacity and safety factor is shown in Table 5.

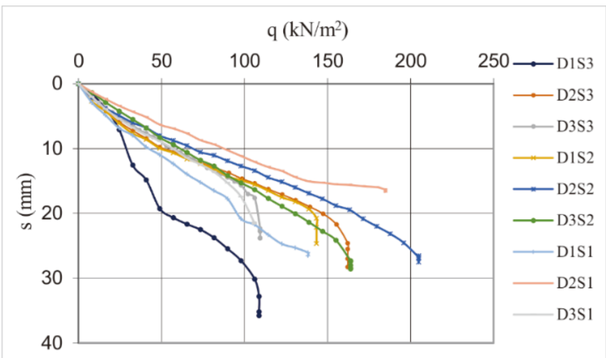


Figure 5. The model bearing capacity (q) on position Lx/L=0.75 and slope inclination β = 37°

Table 5. Bearing capacity and slope stability values

No	Independent variable		q_{ult} (kN/m^2)	BCIu	BCIs	SF	SFI (%)
	Diameter pile	Spacing pile					
1	ϕ = 2,54 cm	S = 7.5 cm	138.314	1.307	1.05	1.311	17.263
2	ϕ = 3,175 cm	S = 7.5 cm	184.528	1.744	1.40	1.315	17.621
3	ϕ = 3,81 cm	S = 7.5 cm	105.911	1.001	0.81	1.310	17.174
4	ϕ = 2,54 cm	S = 10 cm	162.229	1.534	1.09	1.312	17.352
5	ϕ = 3,175 cm	S = 10 cm	205.040	1.937	1.56	1.303	16.547
6	ϕ = 3,81 cm	S = 10 cm	163.934	1.549	1.25	1.307	16.905
7	ϕ = 2,54 cm	S = 12.5' cm	108.812	1.028	0.83	1.309	17.084
8	ϕ = 3,175 cm	S = 12.5' cm	162.299	1.534	1.24	1.313	17.442
9	ϕ = 3,81 cm	S = 12.5' cm	109.548	1.035	0.83	1.314	17.531
10	No reinforcement		105.830			1.118	

5.3. The Effect of Pile Diameter on Bearing Capacity and Slope Stability

The results of tests conducted in the laboratory and analysis using the finite element method show that pile reinforcement can increase the bearing capacity and safety factor of slopes at a specific diameter.

The slope model with a specific diameter significantly increases the bearing capacity of the most significant single-row pile reinforcement at BCIu = 1.937 and BCIs = 1.56. The single-row piles with a D/B ratio of 0.265 (d=3.175 cm) have the largest BCIu and BCIs at the top center pile position Lx/L=0.75 and a slope of 37°. Also, slopes with single-row reinforced piles can add the SF compared to unreinforced piles. Single-row piles with a D/B ratio of 0.265 (d = 3.175 cm) have the largest SF of 1.315 at the top center of Lx/L=0.75 and a slope of 37°, as shown in Table 5 and Figure 6.

a)

b)

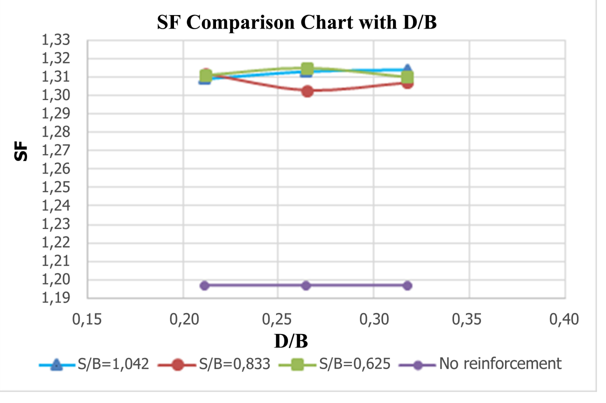


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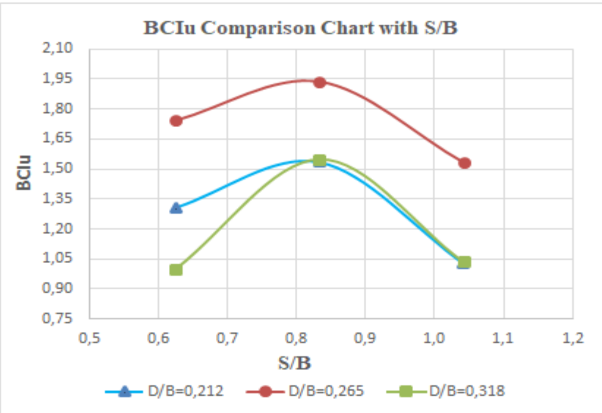
Figure 6. Graph of comparison of BCI and SF with variations in pile diameter. a) Graph of comparison of BCIu values with variations in pile diameter b) Graph of comparison of BCIs values with variations in pile diameter c) Graph of comparison of slope safety figures with variations in pile diameter

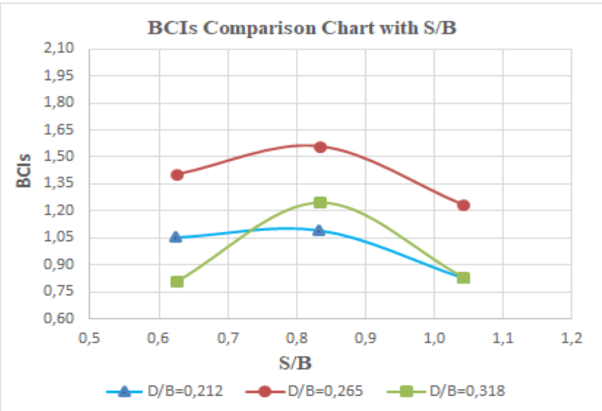
5.4. The Effect of Pile‘Spacing on Bearing Capacity and Slope Stability

The results of tests conducted in the laboratory and analysis using the finite element method show that pile reinforcement can increase the bearing capacity and safety factor of slopes at a specific spacing.

The slope model with a specific spacing significantly increases the bearing capacity of the largest single-row pile reinforcement at BCIu = 1.937 and BCIs = 1.56. The single-row piles with S/B = 0.833 (pile spacing= 10 cm) have the most significant BCIu and BCIs at the top center pile position Lx/L = 0.75 and a slope of 37º. Also, slopes with a single row of reinforced piles can increase the SF compared to unreinforced piles. Single-row piles with S/B = 0.625 (S = 7.5 cm) have the largest SF of 1.315. In general, the reinforced SF is said to be stable at the top of a slope with Lx/L=0.75 and a slope of 37°, as shown in Table 5 and Figure 7.



a)



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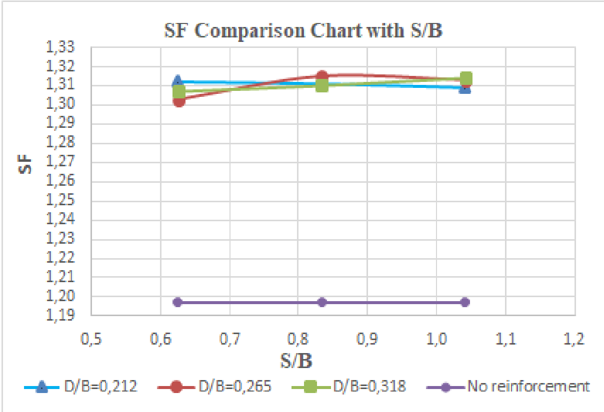

c)

Figure 7. Comparison graph of BCI and SF with variations in pile spacing. a) Graph of comparison of BCIu values with variations in pile spacing b) Graph of comparison of BCIs values with variations in pile spacing c) Graph of comparison of slope safety figures with variations in pile spacing

The slope model with a specific diameter significantly increases the bearing capacity at the slope of the single-row pile reinforcement by 1.937 (table 5). Therefore, these results indicate that the D2S2 condition (d = 3.175 cm and pile spacing = 10 cm) is the optimum diameter and distance to maximize ultimate bearing capacity. In addition to diameter and spacing, they must be carefully selected during construction to ensure slope and pile stability.

The reaction of the soil pile is greatly affected by the diameter of the pile, commonly known as the scaling effect. The range of spacing affected by pile diameter must be accurately planned to maximize soil bending capacity while reducing the soil flow between piles. The smaller the diameter of the pile, the greater the distance between the piles. This condition leaves a lot of free space. The movement of soil flow through the pile is also essential, while retained soil is limited to the cross-section of the pile.

5.5. Landslide Zone

The type of failure that occurred in this study based on the application of the FE Method (2D) was the rotational type, as shown in figures 8-17. The failure occurred at the slope's edge and in the middle of the unreinforced slope model. The difference in the failure zone shows that the load distribution on the unreinforced slope did not change after pile reinforcement, so the slope becomes stable. As the pile diameter increases, the critical slip surface deepens in the failure zone. But lower the slip line until a certain diameter. The increased free space between the piles causes this condition. Likewise, when the distance between the piles is enlarged, the slip surface will also be deeper. Therefore, the slip surface will affect the failure of the pile after the reinforcement is installed.

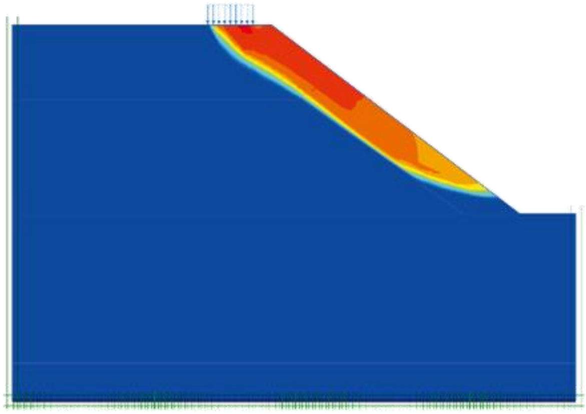

Figure 8. Landslide zone of unreinforced slope SF = 1.118

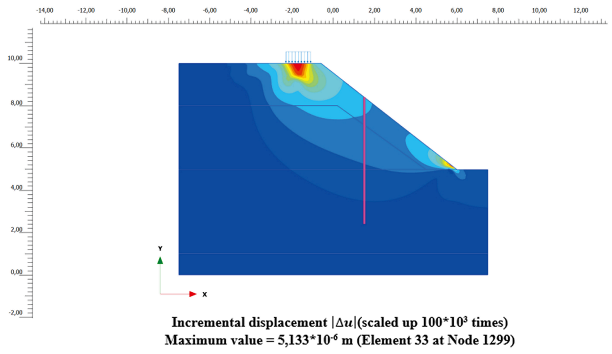

Figure 9. Landslide zone of profile 1 where d=2.54 cm and S=7.5 cm, SF = 1.311

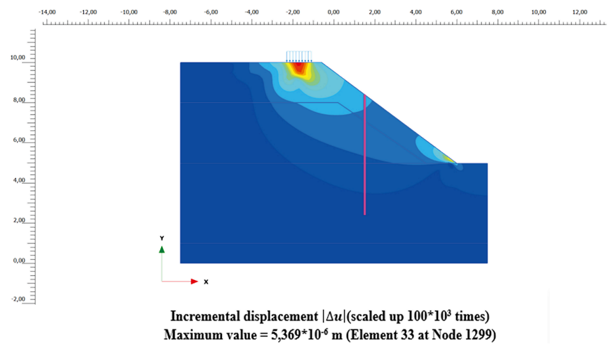

Figure 10. Landslide zone of profile 2, where d=3.175 cm and S=7.5 cm, SF = 1.315

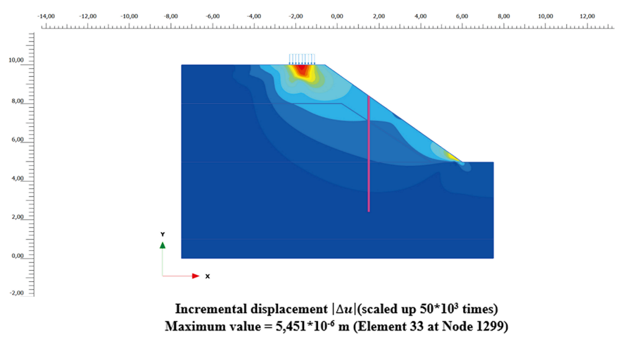

Figure 11. Landslide zone of profile 3, where d=3.81 cm and S=7.5 cm, SF = 1.310

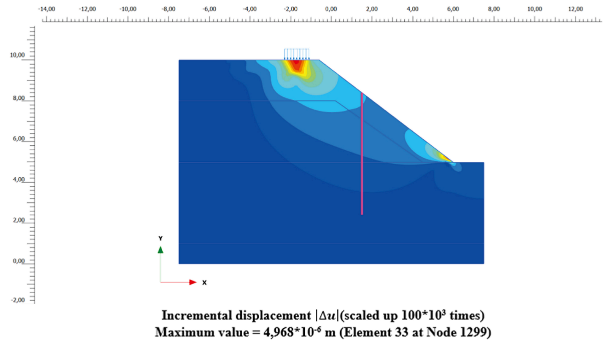

Figure 12. Landslide zone of profile 4, where d=2.54 cm and S=10 cm, SF = 1.312

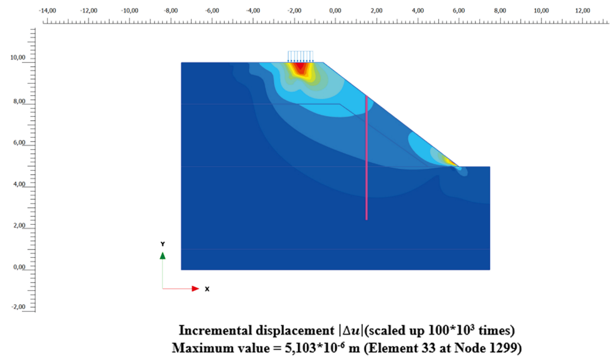

Figure 13. Landslide zone of profile 5, where d=3.175 cm and S=10 cm, SF = 1.303

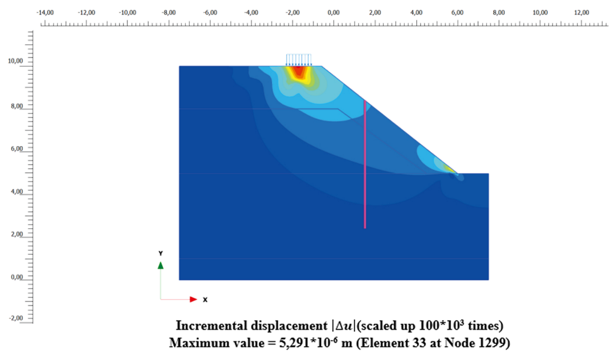

Figure 14. Landslide zone of profile 6, where d=3.81 cm and S=10 cm, SF = 1.307

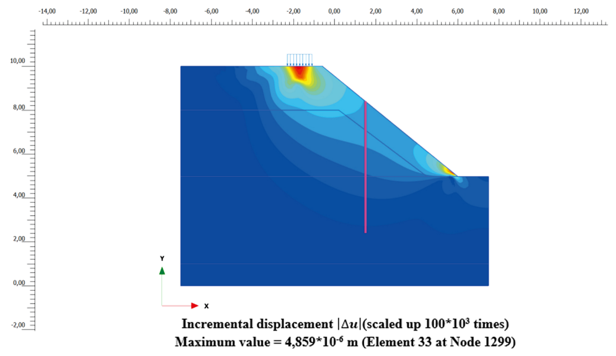

Figure 15. Landslide zone of profile 7, where d=2.54 cm and S=12.5 cm, SF = 1.309

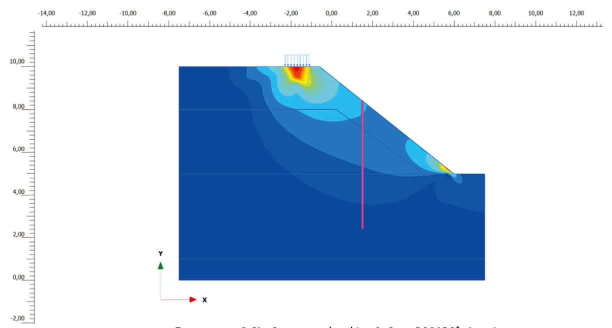

Figure 16. Landslide zone of profile 8, where d=3.175 cm and S=7.5 cm, SF = 1.313

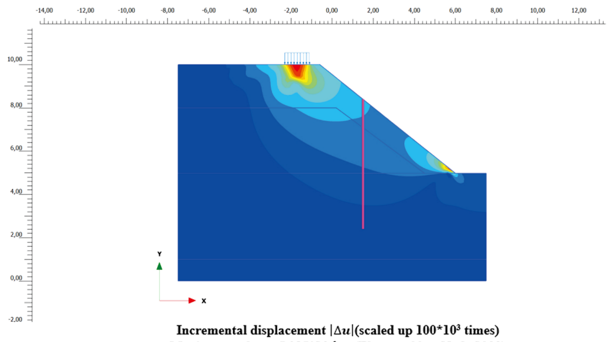

Figure 17. Landslide zone of profile 9, where d=3.81 cm and S=7.5 cm, SF = 1.314

6. Conclusions

Based on experimental results and numerical tests (FEM 2D), we conclude that using single-row piles for slope reinforcement and different pile diameters and spacing increases residual soil's bearing capacity and slope stability. The optimal ultimate bearing capacity and safety factor (SF) occur at a specific diameter and pile spacing. The optimal diameter to resist slope collapse is 3.175 cm with a D/B ratio of 0.265, while the optimal pile spacing is 10 cm with an S/B ratio of 0.833. So when the pile diameter increases, the pile spacing becomes smaller, and the critical slip surface will also be deeper until the optimal diameter and spacing. In addition, the SF value of slopes reinforced with single-row piles increased by 17.621% compared to slopes modeled without reinforcement. The type of slope failure based on the finite element (2D) method is a rotational failure. Unreinforced slope failure can be seen on the edge of the slope and in the middle of the unreinforced slope model using the FE (2D) method. Instead, it occurs at the bottom (toe) of a slope with piles. The increased free space between stacks causes this condition. Therefore, the slip surface will affect the failure of the pile after the reinforcement is installed.

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