International Journal of GEOMATE, March., 2024 Vol.26, Issue 115, pp.53-60
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.115.4276
Geotechnique, Construction Materials and Environment

DOUBLE-ROW PILE REINFORCING ON A CRITICAL SLOPE AT NATIONAL ROAD IN TABANAN, BALI

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*Corresponding Author, Received: 19 Nov. 2023, Revised: 08 Jan. 2024, Accepted: 09 Jan. 2024

ABSTRACT: Due to heavy rain, a landslide occurred on the high slope at the National Road in Tabanan, Bali, and is forecasted to reoccur. Thus, the double-row piles will be analyzed as an alternative method to improve allowable bearing capacity (q_a) and slope stability to mitigate this area. This study used various 2D and 3D numerical modeling techniques to analyze the slope model under two variables: the installment of parallel and nonparallel (zigzag) pile configurations and variations in a second-row pile diameter. With the smallest diameter (D = 0.3 m), the first row of piles has a diameter of 0.6 m and a pile spacing of (s) = 4D. The reinforcing piles were installed into the actual slope model. In addition, the second-row pile diameter varies from 0.3 to 0.6 m. Considering the standardized traffic load, PLAXIS and ABAQUS were implemented to numerically analyze the factor of safety (FS) and q_a of the 2D and 3D finite element method (FEM). Compared with the unreinforced reinforcement of two rows of piles arranged in parallel, the FS increased significantly by 33.06% in the 2D FEM and 32.82% in the 3D FEM. Yet, the model with a zigzag configuration enhanced the FS by 33.20% in the 3D FEM. However, the numerical models showed a slight improvement in the q_a in both 2D and 3D FEM. The slope model defined the highest FS and q_a with pile diameter, D2 = 0.6 m (P2D1). Additionally, a rotational type of failure occurred on the slope toe.

Keywords: Double row pile, Numerical analysis, Pile reinforcement, Slope stability

1. INTRODUCTION

Several factors can influence the conditions of the critical soil slope. One of the primary triggers is the reduction in effective stress caused by the accumulation of pore water pressure, which can result in soil instability and erosion [1]. Additionally, slope stability can be impacted by the topography, slope surface, and the physical and mechanical properties of soil [2]. For instance, in October 2020, an inevitable landslide disaster occurred on the National Road section at 39+900 km, Baturiti, Tabanan, Bali, due to heavy rain. Along the high-sloped roads in this area, which are in a critical state, there is a considerable risk of landslides in the future. Thus, this study focuses on the case of a mitigation technique that can be implemented on the critical slope at 39+900 km Tabanan, Bali.

Various techniques for strengthening slopes include installing anchor cables [3], building antislip structures [4], improving the soil with chemical additives [5], and utilizing a confined-to-one-region precise reinforcement approach based on the processes and instability modes of landslides [6]. One practical usage procedure for geotechnical construction is to install retaining structures, such as rigid retaining walls and antislide piles, to reinforce slopes [7].

Strengthening slopes with pile reinforcement is a widespread application. Numerous studies have been carried out to improve the arrangement and examine the efficacy of pile reinforcement. Various prior researches have been conducted to identify the highest slope stability for installing a row of reinforcing piles within a slop. A row of pile reinforcement should be positioned in the upper middle of the slope [8, 9]. In the case of cohesive soils, slope stability can be increased by laying piles in the center of the slope until it reaches its optimum safety factor. In contrast, the one-third center of the slope was the best placement for piles with cohesive soils [10]. Furthermore, using the double-row piles analytical model, the middle-lower region of the reinforced slope was proposed as the critical area for locating the pile in the most advantageous location suggested [11]. However, it has been discovered that the proper position and configuration for pile optimization are essential for the most effective reinforcement influence. The slope may slide along its failure plane if the piles in the failure plane are not correctly adjusted [12–15].

A new multiobjective comprehensive method for improving the performance of antislide piles has been proposed recently: optimizing slope reinforcement using double piles [16–19]. The reliability of a pile-slope system has also been observed to be generally determined by representative failure modes, which may vary due to pile length, pile spacing, and pile location [20, 21]. By placing piles in two or three rows, the slope stability is enhanced [22]. The arching effect extended and altered the slip surfaces as more reinforced pile rows were added, eventually leading to slope failure [23]. Nonetheless, if the spacing between these piles exceeds the critical limit, representing the arching effect using the 2D FE becomes challenging since the soil might spread within gaps without precise direction examination. Consequently, as the spacing effects are complicated to illustrate using the 2D FE, an alternate method utilizing three-dimensional geometry is proposed. Furthermore, the previous research only focused on the performance of the slope on which the reinforcing pile was installed in a parallel configuration.

In this study, two-dimensional (2D) and three-dimensional (3D) slope models were evaluated under numerical analysis with the finite element method (FEM) using PLAXIS 2D, PLAXIS 3D, and ABAQUS 3D to define the differences in the spacing effect under 2D and 3D modeling as the slope existing condition at National Road in Tabanan, Bali. This study aims to determine the enhancement of the allowable bearing capacity (q_a) on the double-row piles' slope with the study case being the National Road section at 39+900 km, Baturiti, Tabanan, Bali. Subsequently, the q_a obtained from this reinforcement is compared with the q_a of unreinforced slopes.

The FEM models were analyzed under two different variables, which include the second-row pile diameter and the piles configuration installation that use a parallel and nonparallel (zigzag) configuration. The study methodology will provide an overview of details of slope modeling followed by the outcomes of double-row pile reinforcing and their discussion that might be taken into consideration while establishing an alternate strategy to mitigate landslides on the slope, particularly along the National Road section, specifically at 39+900 km, Baturiti, Tabanan, Bali.

2. RESEARCH SIGNIFICANCE

Slope modeling, either with or without pile reinforcement, was analyzed numerically in this study. With the use of the PLAXIS and ABAQUS software, the allowable bearing capacity (q_a) and its bearing capacity improvement (BCI) were examined in the 2D and 3D models due to second-row pile reinforcement. Using parameters derived from the secondary data, each FEM model represented the actual slope model with the existing soil conditions and identical slope geometry. The variation in the second-row pile diameter when placed both in parallel and zigzag configurations was also examined to assess its impact on the possibility of strengthening the unreinforced slope.

3. SLOPE MODELING

The secondary data used in this study included reports, published or unpublished research archives, and previous research findings. The secondary data was obtained from PT. Adiya Widyajasa and PT. Wiswakarma Consulindo that managed the slope project for the Singaraja–Mengwitani road section at 37+900 km in 2020. Furthermore, laboratory data comprising field data such as location maps, slope topography, and standard penetration test results, was acquired from the Soil Mechanics Laboratory, Department of Civil Engineering, Warmadewa University, Denpasar. The slope models precisely represented the actual slope's circumstances without the presence of a groundwater table.

Table 1 Soils profile

Parameters	Units	Soil Layer			
		1	2	3	4
Cohesion (c)	kN/m^2	24.30	32.67	35.27	27.97
Friction angle (ϕ)	º	14.97	14.36	16.27	22.06
E_{soil}	kN/m^2	2700	7800	7200	8400
Saturation unit weight of soil (γ_{sat})	kN/m^3	16.18	16.57	16.57	15.00
Poisson's ratio (ν)	-	0.3	0.3	0.3	0.3

The pile data was obtained from the PC Piles WIKA brochure, referring to ACI 543R as a structural material that accomplishes the specifications for piles without seismic loading. SNI 2847-2013 was used as the reference on standards for structural concrete and manufacturing, including Production Manufacturing Procedures for WB-PCP-PS-05 and WB-PCP-PS-16.

Table 2. Pile characteristics

Parameters	Values
Elastic Modulus (E)	33.89 kN/m^2
Density (ρ)	23.14 kN/m^3
Diameters (D)	First row : 0.6 m Second row : 0.6 m, 0.5 m, 0.4 m, and 0.3 m
Thickness (t)	0.1 m

Demonstrating a 2D FEM-reinforced slope with piles has been used extensively to resolve landslide issues. Moreover, using the 2D FEM for assessing the arching effect and soil movement between piles, which are influenced by pile spacing, is challenging to accomplish. When the spacing extends further than s = 4d, the 2D FEM is inadequate. Since the soil can easily flow between the piles, it is difficult to visualize the arching effect with the 2D FEM when the spacing exceeds the critical value [24]. To adequately account for the spacing effects in cost design, 3D geometry proves to be a more efficient approach compared with 2D FEM. 3D FEM modeling can be implemented when boundary conditions can be reliably established [25, 26]. Besides, The 3D analyses using ABAQUS 3D performed more thorough parametric studies that took precise geometry into account [27, 28].

A numerical method based on the FEM and utilizing ABAQUS 3D, PLAXIS 2D, and PLAXIS 3D was used in the present study, which aims to determine and investigate the extent to which double-row piles for slope reinforcement affect the q_a of the slope. The q_a was initially defined and analyzed on the unreinforced slope and subsequently, the reinforced slope was examined.

Based on the results of previous studies, the pile placement on the slope model provided the most significant safety factor for slopes. By positioning the pile in the center of the slope, previous studies have identified the maximum safety factor for slopes on cohesionless soil [24]. The most convenient location for the piles was also proposed in the upper–lower section of the reinforced slope with the double-row piles [10]. As a result, the first row of piles was placed at 0.9 (Lx_1/L) and the second-row pile at 0.7 (Lx_2/L) from the slope's toe.

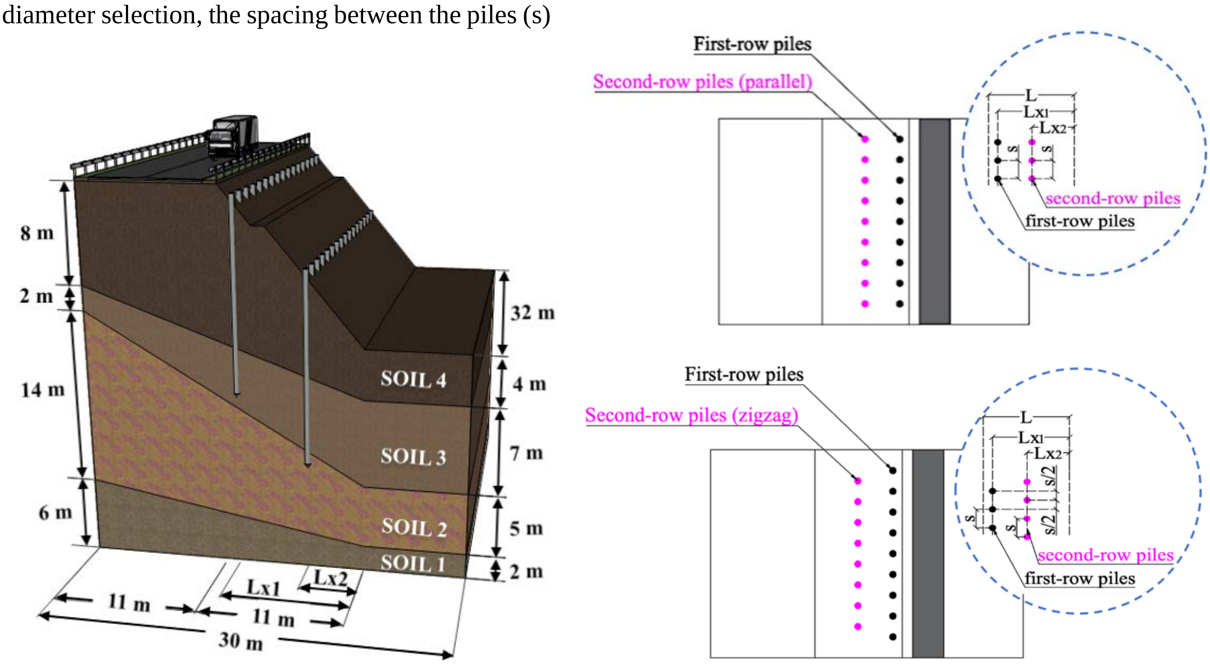
While considering the arching effect of soil between the piles, which was influenced by the pile diameter selection, the spacing between the piles (s) was determined to be 120 cm using the smallest diameter (D = 0.3 m) and s = 4d. For a zigzag configuration on the second-row pile, the pile is placed in between two piles in the first row to enhance the arching effect (Fig. 1). An inefficient arching area would arise with the clear spacing (D) considerably more prominent than 8d [21]. $D \leq 5d$ was suggested as the pile spacing on the reinforced slope to prevent the soil from freely flowing between the piles at these spacing ranges. The pile spacing required to achieve the best possible soil arching effect between the piles is accomplished by this distance [11, 29].

Table 3. FEM Model Meshing

Parameters	PLAXIS 2D	PLAXIS 3D	ABAQUS 3D
Type	Triangular (15 nodes)	Tetrahedral (10 nodes)	Hexahedral (8 nodes)
Mesh generation	Medium	Medium	Medium

Table 4 The slope model detail in parallel (p) and zigzag (z) configurations

Type of Reinforcement	Model	Diameter of Pile	
		Row 1, D1 (m)	Row 2, D2 (m)
Unreinforced	P0D0	-	-
Double pile	P2D1	0.60	0.60
	P2D2	0.60	0.50
	P2D3	0.60	0.40
	P2D4	0.60	0.30



(a) cross section (b) top view

Fig. 1 The slope model illustration

4. RESULTS AND DISCUSSION

4.1 Slope Allowable Bearing Capacity (q_a)

Utilizing ABAQUS 3D, PLAXIS 2D, and PLAXIS 3D, the FEM was used to define the q_a of the slope. The Department of Settlements and Regional Infrastructure, and the Ministry of Public Works and Housing, established traffic loads that were used to load the slope model. The bearing capacity defined in this study was not the ultimate value. Yet, the bearing capacity value was measured when the soil had attained a total settlement of 100 mm as standardized by the Ministry of Public Works and Housing on the Road Pavement Design Manual, namely allowable bearing capacity (q_a).

Two configurations of second-row piles—parallel and zigzag—were examined in the slope model. Nevertheless, due to the limitation of the 2D FEM to provide precise pile spacing in the z-axis along the slope, the slope models with a zigzag pile placement were only examined in the 3D FEM model. The q_a of each model is shown in Table 5, and the BCI between the unreinforced and reinforced slopes was compared, as shown as Figure 2 and Figure 3.

The q_a may be improved on the slope with the reinforcing pile, notably on the slope with a double row of the pile. Moreover, the results showed a slight improvement of q_a due to the bearing capacity measured in the model with the soil settlement of 100 mm. Hence, further research is needed to examine the slope under ultimate conditions.

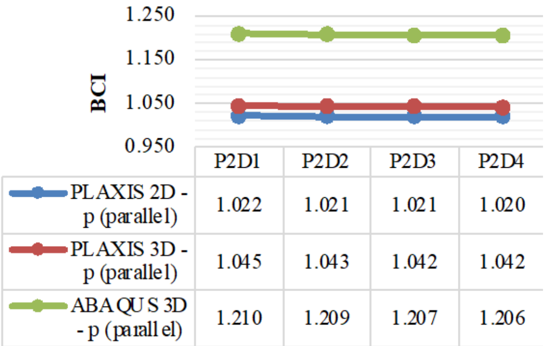


Fig. 2 The slope model BCI (parallel configuration)

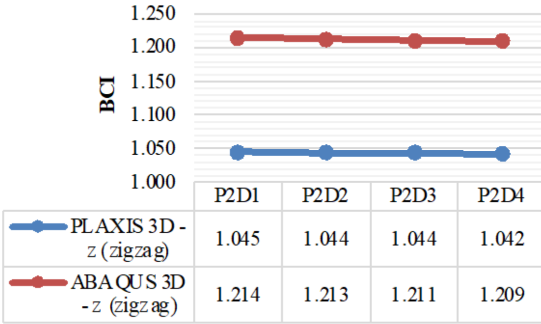


Fig. 3 The slope model BCI (zigzag configuration)

Based on the test results, the q_a plummeted as the pile diameter was reduced. The pile spacing significantly impacted the soil–pile interaction [30]; therefore, the loss of the q_a occurred on the slope model while the spacing area between each pile was wider as its diameter shrank. In every mode of analysis, either 2D FEM or 3D FEM, the slope with the smallest pile diameter on the second row (P2D2 with D1 = 0.6 m) had the highest q_a (Table 5).

Nevertheless, there were differences in the analysis results between the 2D and 3D FEM models using PLAXIS 2D, PLAXIS 3D, and ABAQUS 3D. These differences are principally due to the various calculation techniques each program uses. Double-row pile reinforcement in the parallel pile configuration could increase the slope-q_a on the model with the widest diameter (P2D1) by up to 2.14% (PLAXIS 2D), 4.81% (PLAXIS 3D), and 21.08% (ABAQUS 3D). However, enhancing the slope-q_a with double-row reinforcing piles in a zigzag configuration could raise the slope by up to 4.22% (PLAXIS 3D) and 21.14% (ABAQUS 3D) on the similar slope model with the largest pile diameter.

The second-row pile positioning configuration—parallel to the first row or zigzag—also contributed to the direction of soil flow, leading to different soil arching areas. Further study is required to assess and thoroughly determine every detail of the second-row pile arrangement.

Table 5 The q_a of the slope models

Model	PLAXIS 2D - p (parallel)		PLAXIS 3D - p (parallel)		ABAQUS 3D - p (parallel)		PLAXIS 3D - z (zigzag)		ABAQUS 3D - z (zigzag)	
	q_a (kN/m^2)	Deviation	q_a (kN/m^2)	Deviation	q_a (kN/m^2)	Deviation	q_a (kN/m^2)	Deviation	q_a (kN/m^2)	Deviation
P0D0	42.188	-	43.420	-	30.045	-	43.420	-	30.045	-
P2D1	43.090	2.14%	45.508	4.81%	36.377	21.08%	45.253	4.22%	36.398	21.14%
P2D2	42.982	1.88%	45.376	4.51%	36.314	20.87%	45.190	4.08%	36.366	21.04%
P2D3	42.962	1.83%	45.317	4.37%	36.291	20.79%	45.205	4.11%	36.350	20.99%
P2D4	42.932	1.76%	45.303	4.34%	36.276	20.74%	45.162	4.01%	36.332	20.93%

Although the modeling of the slope using 3D FEM can be performed in an identical approach based on the slope geometry, each program showed varying calculation results and also exhibited different methods of calculation.

4.2 Factor of Safety (FS) of Slope

The efficacy of pile reinforcement on the slope was assessed using the 2D and 3D PLAXIS, as ABAQUS 3D could not fully analyze the slope stability. The value of the FS for each model was determined from the results of the FEM model considering its significance while assessing the degree of slope stability. To examine the influence of the second row reinforcing pile addition, the unreinforced slope model with identical slope geometry and loaded conditions as the actual slope at the National Road section at 39+900 km, Baturiti, Tabanan, Bali was also analyzed using 2D and 3D FEM as a comparison of the slope stability. In this study, 3D FEM was analyzed under two configurations (parallel and zigzag) of the placement of the second-row pile, as shown in Table 6.

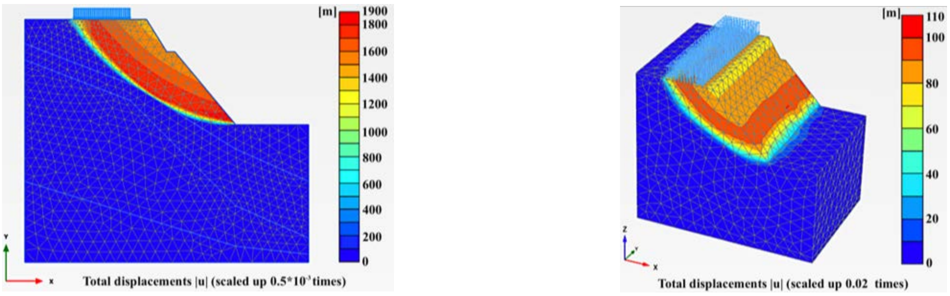
Table 6 The q_a of the slope models

Model	PLAXIS 2D - p (parallel)		PLAXIS 3D - p (parallel)		PLAXIS 3D - z (zigzag)	
	FS	Devia-tion (%)	FS	Devia-tion (%)	FS	Devia-tion (%)
P0D0	1.73	-	2.06	-	2.06	-
P2D1	2.30	33.06	2.74	32.82	2.75	33.20
P2D2	2.29	32.48	2.68	29.91	2.69	30.25
P2D3	2.27	31.67	2.65	28.21	2.67	29.28
P2D4	2.26	30.86	2.61	26.56	2.65	28.41

There were slight differences in the enhancements between 2D and 3D FEM according to the analysis results for both the parallel or zigzag pile configuration on the slope. In comparison to the slope in its 2D unreinforced model (FS = 1.73), the slope with two rows of reinforcing piles had an increased FS of up to 2.39, as per the analysis of the 2D FEM model. As the pile diameter was increased, the FS at the P2D1 slope model with the biggest diameter increased rapidly by 33.06%. In addition, the P2D1 slope model achieved the highest FS at 2.74 (32.82%), which is greater than that of the unreinforced slope (2.06), referring to the 3D FEM. Furthermore, with an FS value of 2.75 (model P2D1), the increase in the FS of the slope with a zigzag configuration on the second-row pile arrangement was up to 33.20%. The stability of the slope was strengthened as the pile obstructed greater in size despite various analyses using 2D and 3D FEM.

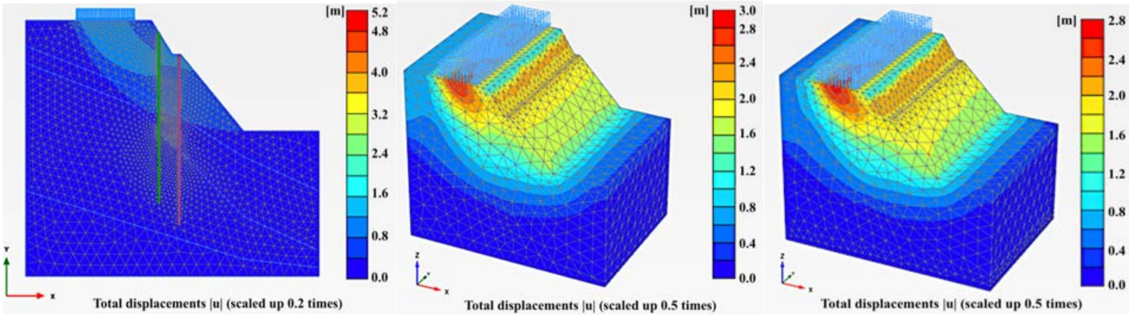
If the slope model applied the largest pile diameter, this condition would have caused narrower pile spacing. The soil–pile interaction was affected by the pile spacing. Pile spacing would directly affect the arching area, and this circumstance might optimize the likelihood of soil arching, which might reduce the rate of soil flow between the piles [30]. Additionally, pile spacing is required to be meticulously calculated during construction. The cost of a slope reinforced with piles is influenced by pile spacing; costs will rise as pile spacing (S/D) decreases, even though the slope and pile will be stable with the narrow pile spacing [25, 31]. The pile spacing was narrower, and additional piles were placed on the site. Consequently, for practical reasons, installing the reinforcing pile on site should have pile spacing of at least 3d–5d, which is the most efficient and bearable to the construction cost.

The zigzag pile configuration to the first row raises the FS of the slope, which also contributes to the stabilization of the slope further. The placement of the second row reinforcing piles affected the direction of soil flow; however, additional research needs to be performed to determine the most effective spot for these piles to achieve the optimum rate of slope reinforcement. Further research is needed to focus on the arching area, including determining whether the space between the first and second rows of piles will assist in effectively catching soil flow, and widening the arching area and the newest flow direction while installing a double-row pile.



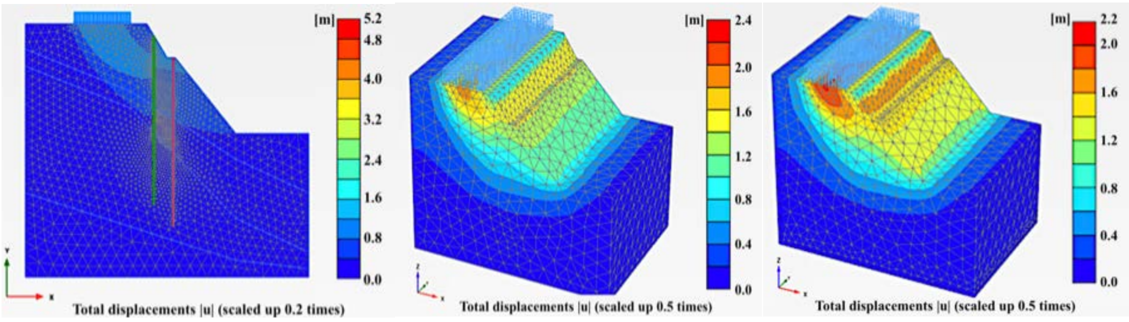
(a) 2D FEM (b) 3D FEM

Fig. 4 The unreinforced slope failure



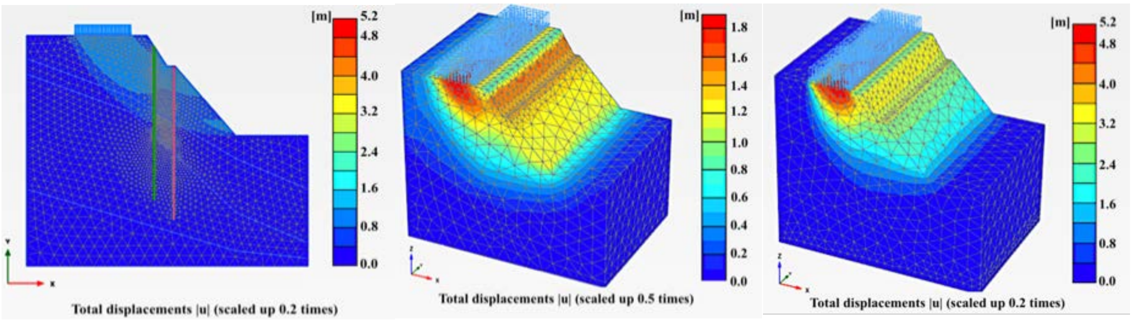
Parallel 2D FEM Parallel 3D FEM Zigzag 3D FEM

(a) P2D3 (D2 = 0.6 m)



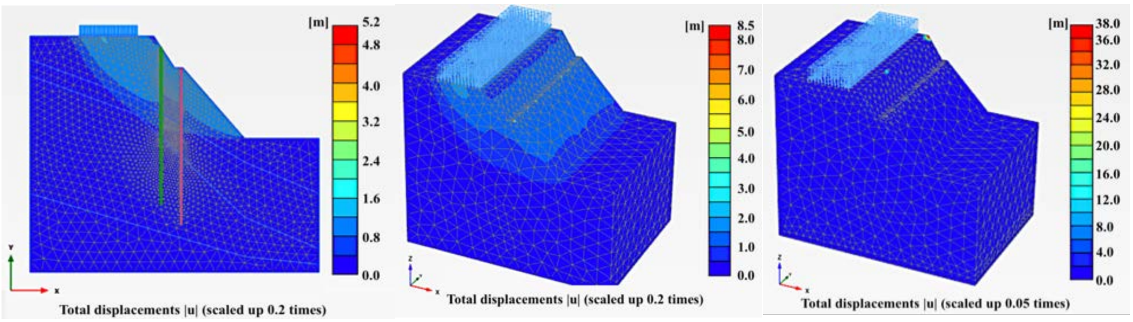
Parallel 2D FEM Parallel 3D FEM Zigzag 3D FEM

(b) P2D2 (D2 = 0.5 m)



Parallel 2D FEM Parallel 3D FEM Zigzag 3D FEM

(c) P2D3 (D2 = 0.4 m)



Parallel 2D FEM Parallel 3D FEM Zigzag 3D FEM

(d) P2D4 (D2 = 0.3 m)

Fig. 5 The slope failure with double-row pile

Based on the results of the FEM analysis results, the double-row pile reinforcing technique could be used as an alternative method to mitigate the landslide on the slope at the National Road section, particularly at 39+900 km, Baturiti, Tabanan, Bali. In addition, the slope models, with or without the reinforced pile, assisted visibility toward the rotational landslide zone at the slope's toe. The top to middle slope of the model with external loads, however, showed the location of the landslide zone. Right under the load was found to be the highest displacement for each model. There was a deeper failure zone as the pile diameter reduced.

5. CONCLUSION

Using 2D and 3D FEM modeling, the strengthening slopes with pile reinforcement indicated that pile reinforcement could enhance the slope-q_a and FS. Installing the double reinforcement improved the FS. On the other hand, as the diameter of the second-row reinforcement pile expands, the q_a and FS decline. FS was improved against the slope without a pile based on the results obtained from the FEM analysis. According to the 2D and 3D FEM analysis, the variation of the pile diameter (D1) = 0.6 m was identified as the largest FS on the slope model. Due to the differences in second-row pile configuration between the parallel and zigzag arrangements to the first row, the zigzag arrangement raised the FS of the slope, which further aids in the stabilization of the slope. The second row of the reinforcing piles placement impacted the direction of soil flow. Still, more investigation is required to identify the best location for these piles to achieve the most efficient rate of slope reinforcement while expanding the arching area and the newest flow direction when installing a double-row pile that could assist in effectively catching soil flow.

However, the slight decline in slope-q_a and FS was determined under an allowed condition with a maximum of 100 mm soil settlement under standardized traffic loads. Thus, further investigation is required to assess the slope under ultimate conditions. In addition, based on the results of the analysis, the double-row pile reinforcing technique could be used as an alternative method to mitigate the landslide on the slope at the National Road section, particularly at 39+900 km, Baturiti, Tabanan, Bali.

6. ACKNOWLEDGMENTS

This research was performed while the University of Brawijaya financially supported the authors through The Professor Research Grant Funding Program. The authors genuinely appreciated the University of Brawijaya and all the people who assisted and supported them. Without outstanding support, completing this study would not have been feasible. We are also grateful for the suggestions from the reviewers, which significantly improved the manuscript. We are appreciative of the generous contribution of their time and knowledge.

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