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Centrifuge modeling of C-RHA pile reinforcement for slope stability

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ABSTRACT: Recent studies have demonstrated various slope reinforcement methods for reducing the deformations of slopes and preventing landslides. There has also been an increasing interest in rice husk ash (RHA) as a cement replacement to strengthen the concrete. This research uses C-RHA piles made of cement, sand, and fine RHA. The slope reinforcement system consists of several arrays of precast piles penetrated perpendicular to the slope surface. A series of centrifuge testing was conducted to evaluate the slope stability under self-weight loading after being reinforced by C-RHA piles. Each slope model was prepared with different numbers of C-RHA piles to observe the pile spacing effect. The slope failure process was recorded through cameras during centrifuge spinning, and a surface scanner was used to map the slope deformation and surface elevation change. The test results indicate that slope without piles, with 4 piles, 9 piles, and 16 piles fail at 50g, 48g, 55g, and 65g, respectively. After normalized by the theoretical planar failure wedge volume, the depletions mass is 67.0%, 64.5%, 59.3%, and 48.6%, respectively. Based on the Bishop slice method calculation, C-RHA piles could increase the safety factor and become more effective when the pile spacing decreases. The decreasing number of C-RHA pile spacing will decrease the depletion mass of the slope.

Keywords: Slope stability, centrifuge modeling, C-RHA pile, spacing effect.

1 INTRODUCTION

In this study, mortar piles with rice husk ash (C-RHA pile) have been used for mitigating moderate slope failure. C-RHA pile is expected to increase the slope's resisting force against the driving force by pile-soil interaction. RHA was chosen because of the significant amorphous silica percentage and microporous particle structure, making it a reactive material (Madandoust & Ghavidel, 2013).

Previous researches show that 7.5%-15% of cement replacement with RHA was the optimum mortar mix design to increase the long-term compressive strength (Hu et al., 2020; Salem Al-Ahdal et al., 2018; Sam, 2020). This waste material can be found easily at an economical price in rice-consuming countries worldwide, including China, India, Indonesia, Vietnam, Philippines, Thailand, Japan, and Brazil.

A series of geotechnical centrifuge modeling was conducted to produce identical self-weight stresses in the model and prototype and monitor the C-RHA pile contribution in resisting the driving force. Realistic self-weight induced stresses in the small case model can be conveniently created in the centrifuge test, and the failure mechanism of the model slope will be more similar to the prototype (Timpong et al., 2007). The principle of the centrifuge modeling is that the stress can be approximately replicated by increasing centrifugal acceleration by spinning the model away from a fixed axis to N times Earth's gravity in a scale model

corresponding to the stress in the field.

This research aims to clearly understand the effect of C-RHA pile spacing in reinforcing sandy slopes under the gravitational condition to later contribute to various construction projects' safety and economy. Pile spacing is one major factor that might affect the reinforcement performance aside from the pile diameter, length, and inclination angle.

2 MODEL SETUP AND TEST PROCEDURE

A series of centrifuge modeling was conducted at the Experimental Center of Civil Engineering at National Central University, Taiwan. The instrument is a France manufactured Acutronic type 665-1 consisting of a swinging cradle, a servo-hydraulic electromechanical system, counterweight support tube, clevises, clevis pin, and spherical bearing. The platform radius is 3 m from the center of the payload to the centrifuge axis. The maximum capacity of the centrifuge is 100 g.ton. Thus, the centrifuge can carry 1 ton in 100 g acceleration. The maximum acceleration is 200 g in static tests. The maximum payload weight for the dynamic test is 400 kg, and the maximum acceleration is 80 g.

Specimen were made in a container with inner dimensions of 736 mm × 385 mm × 200 mm (L × H × W). The back aluminum and acrylic parts had a thickness of 15 mm and 20 mm, respectively. The aluminum container was made with one transparent glassy side for observing the slope failure and deformation process

during tests. Some cameras were installed to record video and photos from the side and front of the model. A laser displacement transducer device was used to map the slope surface contour before and after the test.

2.1 Soil and reinforcement material

The models were prepared from 80% silica sand and 20% kaolin clay mixed at 12% water content. The soil properties are presented in Table 1. The mix design for the C-RHA pile slurry is 1 : 2 : 0.1 for cement, sand, and RHA with a 0.45 water-cement ratio. The piles were cast with 10 mm in diameter and 100 mm in length. Unconfined compression strength tests show that the specimen could reach an unconfined compressive strength of 2.20 MPa after being cured for 28 days.

2.2 Test configuration

The model consists of slopes with a height of 200 mm, and a base foundation with a thickness of 50 mm. the slope inclination angle was set to 70°. The variation of C-RHA pile numbers was 4 piles, 9 piles, and 16 piles. The specification of models prepared for this study is listed in Table 2. Fig. 1 shows the layout of the model and the piles configuration. The pile spacing and tension crack properties are normalized by slope height.

2.3 Model preparation

The mixed soil materials were compacted into five layers with a thickness of 40 mm each. Horizontal supports were used to create a 70° slope inclination angle. After the compaction, the horizontal supports were removed, and precast piles were penetrated perpendicular to the slope surface. The precast piles were prepared 28 days prior to the penetration.

2.4 Test procedure

After the slope model was ready, the container was mounted to the centrifuge platform. A surface scanner was used to map the model contour before the test. The scanner consists of laser displacement transducers (LDT) attached to a moving arm powered by a motor. The arm was positioned on top of the container and moved in the length direction. The arm needs to be moved manually in the width direction to obtain several elevation lines. Later, the deformed soil volume could be calculated by comparing the model's elevation before and after the test, as shown in Fig. 2.

The gravitational acceleration gradually increased in the centrifuge test until the slope failed (gravity condition). The failure process was recorded through cameras installed on the front, side, and top of the slope. The data was acquired and transmitted from the centrifuge chamber to the control room.

After finishing the centrifuge test, the post-test surface contour was recorded. The undrained shear strength of the model was then estimated by using Torvane, a handheld vane shear device. This study used a small vane for stiffer soils with a 2.5 multiplier factor.

Table 1. Soil property.

Properties	Mixed soil	Silica sand	Kaolin clay
Specific gravity, G_s	2.70	2.65	2.72
Max. dry unit weight, $\gamma_{d,max}$ (kN/m ³)	18.87	16.19	14.52
Min. dry unit weight, $\gamma_{d,min}$ (kN/m ³)	-	14.03	-
Optimum water content (%)	9.50	-	28.20
Plastic limit, PL (%)	-	-	29.80
Liquid limit, LL (%)	-	-	53.40
Plastic index, PI	-	-	23.60
Cohesion, c (kN/m ²)	13.20	-	-
Friction angle, ϕ	21°	-	-

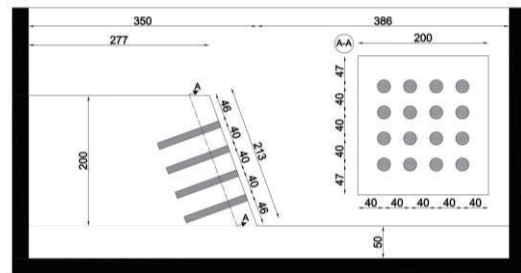


Fig. 1 Model layout for test C-4.

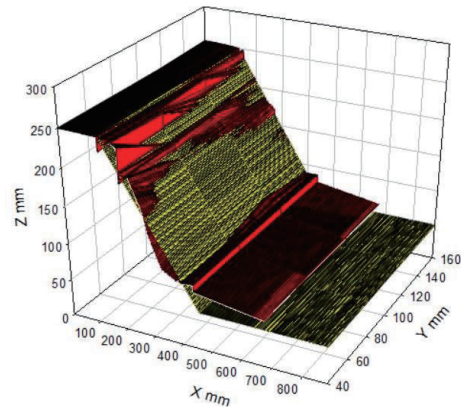


Fig. 2 Comparison of model's elevation before and after test.

The test was conducted based on ASTM D8121-19 with one shear strength test point representing an area of 50 mm × 50 mm. After the Torvane test, the soil was taken to check the post-test water content.

3 TEST RESULTS AND DISCUSSION

3.1 Centrifuge test results

The summary of the test results is presented in Table 2. The planar failure surface was assumed from the most significant tension crack to the slope toe. The presence of the tension crack can decrease the stability of a slope. It was found that Test C-0 and Test C-4 had identical failure behavior. The soil movement was smooth, and the circular failure can be seen clearly (Fig.). On the other hand, Test C-9 and Test C-16's soil movement was very rough and failed suddenly because of the brittle C-RHA pile behavior contribution on the slope. Three piles were broken in Test C-4, nine piles were broken in Test C-9, and 11 piles were broken in Test C-16.

Table 2. Pile configuration and test results.

Model	Number of piles	Pile spacing (Normalized by the slope height)	Gravity level when the slope failed (g)	Water content after test (%)	Slope shear strength from Torvane test (kPa)	Tension crack width/depth/distance (Normalized by the slope height)
Test C-0	0	-	50	8-13	16-26	0.015 / 0.33 / 0.32
Test C-4	4	0.34	48	9.5-11.5	14-26	0.011 / 0.27 / 0.30
Test C-9	9	0.25	55	10-11.5	12-24	0.016 / 0.35 / 0.33
Test C-16	16	0.2	75	9-11.5	16-28	0.011 / 0.16 / 0.56

The water content range for all tests is 8%-13%. The water content was decreased from the upper part of the slope surface and accumulated on the lower layer, especially near the toe of the slope. The water content significantly impacted the shear strength and caused Test C-4 (Fig.) not to stand a higher gravity level than Test C-0. The water content was shown to be accumulated in the failure zone. The shear strength obtained was around 16-26 kPa for Test C-0 and 14-26 kPa for Test C-4. In test C-4, shear strength around the slope surface was low because the water content decreased below the optimum.

3.2 Pile spacing effect and depleted slope mass

After being subjected to a certain gravity level, the C-RHA piles also fail through the circular failure of the slope. There is a clear relation between pile spacing and gravity level when the first crack, second crack, and slope failure occur, as represented in Fig. . The slope will restrain a more significant driving force by reducing the pile spacing. The outmost tension crack position also drew away from the crest, and the position of the failure plane became more deep-seated as the pile spacing

reduced (Fig.). However, no clear correlation exists between the crack depth, width, and pile spacing.

Although the slope material strength was low, the C-RHA piles significantly increased the resisting force. All the piles were broken during the test (Fig.) except in Test C-16, where only 68.75% were broken. The slope height in the prototype related to the gravity level when the failure occurred is 10 m, 9.6 m, 11 m, and 15 m for Test C-0, Test C-4, Test C-9, and Test C-16, respectively. Lin et al. (2013) stated that even though the vertical spacing effect is insignificant, the horizontal spacing highly affects the slope strength increment.

The depleted mass is the displaced material volume, which overlies the rupture surface but underlies the original ground surface (Cooper, 2007). The depleted mass is shown in Fig. as the soil mass located above the red dash line and below the black dash line. The depleted mass presented in the paper is already normalized by the volume of the theoretical planar failure wedge. The theoretical failure angle (θ) for the volume calculation is calculated from the slope angle (β) and soil internal friction angle (ϕ) by using Eq (1).

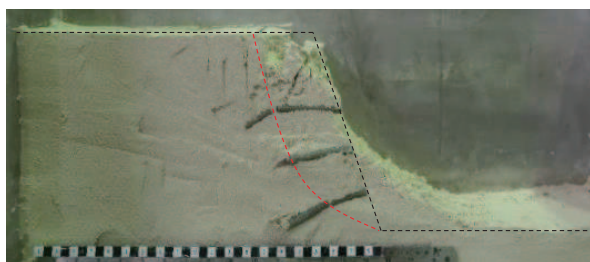


Fig. 3 Broken piles at Test C-9 after centrifuge test (side view).

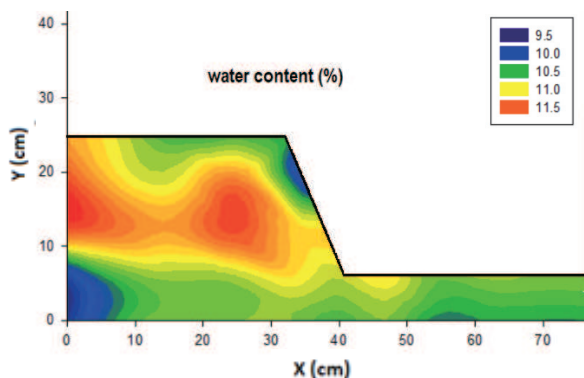


Fig. 4 Water content of Test C-4 after centrifuge test.

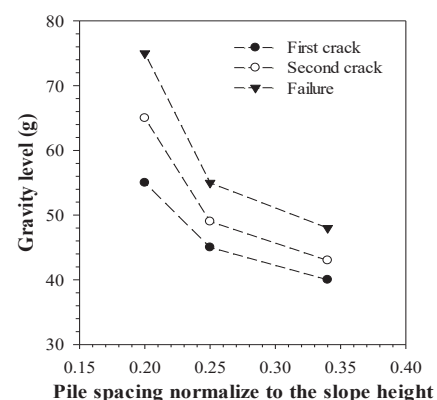


Fig. 5 Pile spacing effect on the slope stabilization.

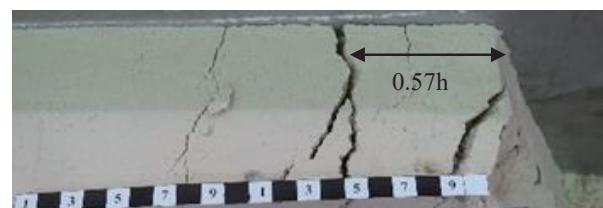


Fig. 6 Tension cracks on Test C-16 (top view).

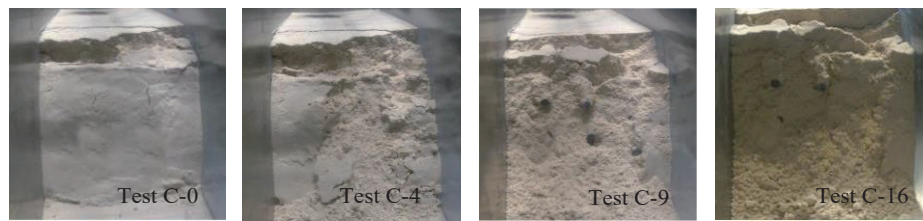


Fig. 3 Slope surface condition after the test (front view).

$$\theta = \frac{\beta + \phi}{2} \quad (1)$$

The normalized depletions mass volume for Test C-0, Test C-4, Test C-9, and Test C-16 is 67.0 %, 64.5 %, 59.3 %, and 48.6 %, respectively.

Fig. 7 and 8 show that decreasing pile spacing will reduce the depleted slope mass. In the case of soil nailing, the nails are supposed to be at a distance of 1-2 m in the vertical and horizontal direction (Villalobos & Villalobos, 2021). However, the test results show that C-RHA pile reinforcement could perform well at 0.2H (3 m for Test C-16) pile spacing.

3.3 Slope stability number

Taylor (1948) proposed a parameter to evaluate slope stability based on the internal friction angle and cohesion acting over the failure plane. The Stability number expressed the factors affecting soil slope stability. Fig. 8 shows the stability number of each model. The stability number for Test C-0, Test C-4, Test C-9, and Test C-16 is 0.149, 0.128, 0.112, and 0.082, respectively.

According to Taylor's chart, all models fall into zone A. Slopes in zone A with a slope angle greater than 53° will have a failure plane pass through the slope's toe with the lowest point at the slope toe (Steward et al., 2011). With increasing g level, the stability number will decrease because the allowable height increases while the cohesion does not change.

4 CONCLUSIONS

Four centrifuge models with and without C-RHA

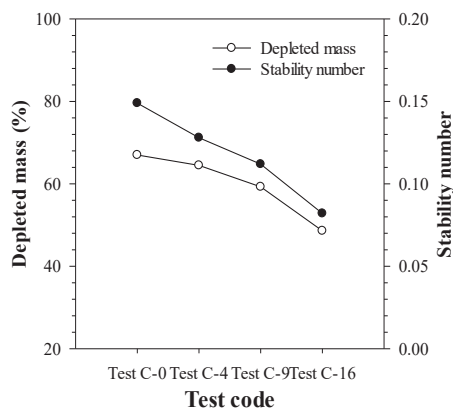


Fig. 4 Depleted mass and stability number of the models.

piles reinforcement has been tested under gravitational condition. From test results, it can be concluded that:

- (1) Water content plays an essential role in affecting the slope's shear strength. The slope in the Test C-4 model only can stand up to 48 g, while Test C-0 could achieve a higher gravity level of 50 g due to the water content distribution of Test C-4 dropping below the optimum content at the slope surface.
- (2) Reducing the pile spacing will result in drawing the tension crack position away from the crest, and the position of the failure plane tends to be deep-seated.
- (3) The slope stability number and depleted mass will decrease with smaller pile spacing. However, the pile should not be too narrow to avoid problems in the construction method and reduce the economic value.

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