Centrifuge modelling of slope stabilized by piles

La modélisation par centrifuge de la pente stabilisée par des pieux

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ABSTRACT: Pile spacing ratio and bending stiffness are two decisive factors for slope stabilization using piles. Their influnces are examined through centrifuge modelling. The failing slope is modelled by a soil layer sliding above a stationary layer. Two pile spacings and two pile bending stiffnesses were considered. Five centrifuge tests are presented in this study. Four failure modes are shown and their relations to pile spacing and stiffness are discussed. Local soil failure in the downslope soil trends to happen when the pile stiffness is high and pile spacing ratio is small. Soil fails by flowing around the piles for high pile stiffness and large spacing ratio. Overtop movement above the stabilized part of the soil is concerned when the pile stiffness is very low. This soil deformation is accompanied by bending failure in the pile when the spacing ratio is small.

RÉSUMÉ : Le rapport d'espacement des pieux et la rigidité à la flexion sont deux facteurs décisifs pour la stabilisation de la pente à l'aide de pieux. Leurs influnces ont été examinées par modélisation de centrifuge. La pente à rupture a été modélisée par une couche de sol glissant au-dessus d'une couche stationnaire. Deux espacements de pieux et deux rigidités de flexion de pieux ont été considérés. Cinq essais de centrifuge sont présentés dans cette étude. Quatre modes de rupture avec leurs relations sont discutées. Une dégradation locale du sol dans les tendances du sol descendant se produit lorsque la rigidité du pieu est élevée et le rapport d'espacement des pieux est faible. Le sol deforme à rupture en s'écoulant autour des pieux lors de la rigidité du piux élevée, mais avec un grand rapport d'espacement. Le mouvement au-dessus de la partie stabilisée du sol est plus d'attention lorsque la rigidité du pieu est très faible. Cette déformation du sol s'accompagne d'une rupture de flexion dans le pieu lorsque le rapport d'espacement est faible.

KEYWORDS: Centrifuge modelling, slope, pile, spacing ratio, bending stiffness

1 INTRODUCTION

Piles arranged in rows are widely used for slope stabilization. For this purpose, the piles are installed through the sliding mass into the stable ground. Each pile behaves as a single vertical beam, which interacts with adjacent piles giving rise to the well-known arching effect. The essence of pile stabilization is to transfer the shear force from the failing soil mass to the stable ground beneath.

The analysis of slope stabilized by piles has been performed using various methods. In analytical methods, the stability of the slope and the calculation of the pile response are usually analyzed independently. First, conventional slope stability analysis is utilized to evaluate the total shear force needed to increase the safety factor of the slope to the desired value. Second, the pile response is calculated regarding the pile as passive piles under lateral soil movement (Ito and Matsui 1975, Viggiani 1981, Poulos 1995, Cai and Ugai 2011, Ashour and Ardalan 2012, He et al. 2015). Several failure modes, depending on the geometry of the problem, the yield moment of the pile section and the strength of the stable and sliding soil, were proposed by Viggiani (1981) and Poulos (1995). The application of numerical method on this problem can be divided into coupled and uncoupled analyses. Coupled analysis (Won et al. 2005, Wei and Cheng 2009, Liang and Yamin 2010) combines the aforementioned two aspects and usually adopts the strength reduction method or external loading to trigger the failure. The idea of uncoupled analysis (Liang and Zeng 2002, Jeong et al. 2003, Martin and Chen 2005, Kourkoulis et al. 2010, Kanagasabai et al. 2011) is to conduct the above second part in analytical methods using numerical methods. The slope instability is replaced by lateral soil movement as boundary conditions. Without the restriction of slope geometry, design charts are able to be produced through the study of arching effect or ultimate soil resistance. Laboratory reduced-scale model tests (Chen et al. 1997, Guo et al. 2006, Qin and Guo 2013, Tang et al. 2014, Li et al. 2016) and centrifuge model test (Hayward et al. 2000, Yoon and Ellis 2009, Wang and Zhang 2013) were also used to solve this problem. Hayward et al. (2000) and Wang and Zhang (2014) performed centrifuge tests on uniform slopes reinforced by piles, which has brought further understanding into the mechanism of pile reinforcement. But in the view to improve the application of this remedial technique, a better understanding of pile response under slope movement is more realistic when applying the test results into practice. Yoon and Ellis (2009) adopted an identifiable weak slip surface in the centrifuge tests to separate the sliding soil and stable substratum. Tests results show that the soil movement and failure are related to the sliding length ratio and the pile spacing ratio. Pile response along the depth was also analyzed. The shortcoming of their study is that the impact of pile flexibility was not considered, which results in the fact that some widely accepted failure modes (Viggiani 1981, Poulos 1995) were not revealed.

The relative pile stiffness can be increased by either increasing the thickness of the sliding soil layer or reducing the pile stiffness. In this study, the pile spacing and the pile material are investigated. Moreover, the failure modes are described and their dependence on the pile spacing and pile stiffness is discussed.

2 CENTRIFUGE MODELLING

As illustrated in Figure 1, a 45-degree slope reinforced by a row of discrte piles was modelled. The slope consisted of two layers: a sliding soil layer, which was modelled by medium sand with a relative density of 1.53 and a water content of 11.5%, and a stationary layer underneath modelled by wood. The unstable soil layer was prepared through two steps: First, the premixed soil sample was compacted to the required density via moist tamping. Divided horizontal sublayers with thickness of 2.5cm were found out to be adequate to produce a uniform density distribution in the soil. Second, the compacted soil was trimmed to the dimensions of the model.

A slip surface with low friction was prescribed between the unstable and stable layers. It was implemented by a three layer system which was comprised of a 2mm thick rubber sheet with smooth surface, sprayed silicon oil layer and a 1mm thick aluminum sheet. The aluminum sheet was fixed on the wood structure. A centrifuge test with no piles was performed to validate this system.

The piles were installed during the soil compaction in order to ensure a tight soil-pile contact. The pile top and toe lined up with the ground surface and the bottom of the wooden structure, respectively. The total length of the model pile was 24 cm with an embedded length of 11 cm. To install the piles, the rubber and aluminum sheets were perforated at the pile locations. The perforated areas were extended in both the downslope and upslope directions to enable the relative movement between the pile and the rubber and aluminum sheets.

Two different kinds of model piles with bending stiffness of 17.8 $MNmm^2$ and 1.53 $MNmm^2$ were used to represent relative rigid and flexible piles, respectively. The stiff piles were manufactured from 10mm diameter aluminum tube with a wall thickness of 1 mm whereas the flexible piles were made of 10mm diameter plastic tube with 3mm wall thickness. The corresponding prototype diameter for both piles at 50g is 500mm. The prototype bending stiffness at the same target g-level is 111 MNm2 for aluminum pile and 9.54 MNm2 for plastic pile, which correspond to the stiffness level of bored concrete pile and steel tube pile, respectively, according to reported studies (Smethurst and Powrie 2007, Lirer 2012).

The only trigger factor of the soil sliding was gravity. G-up test procedure, which continuously increased the gravity-induced stress field, was employed. The increase of stress in the model slope corresponds to the increase of prototype slope height. The g-up test procedure was terminated when the soil movement reached the limit or the target g-level, which was 50 g, was reached. The increase of centrifugal acceleration was conducted at a low rate of 0.1 rpm per second by a computer program.

In-flight photography both from the side and the top was used to monitor the movements of the pile-slope system. PIV analysis (White et al. 2003) was employed to quantitatively study the soil deformation.

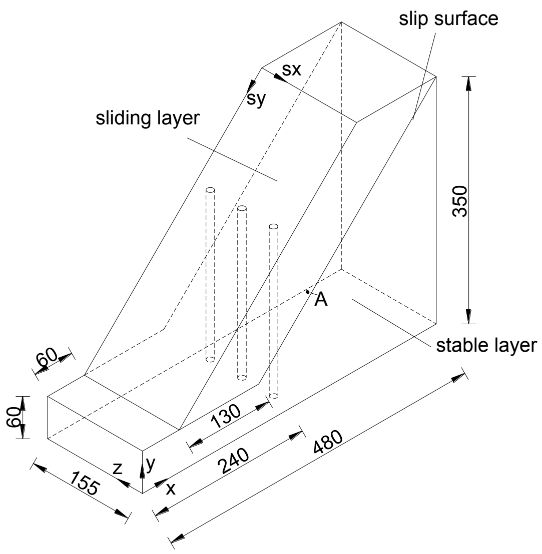

Figure 1. Geometry of the centrifuge model. (Unit: mm)

3 TEST RESULTS AND ANALYSIS

Five centrifuge tests (Table 1) are presented in this paper. Different pile configurations were adopted to investigate the effect of pile spacing and bending stiffness. Four failure modes are observed and their relations to pile stiffness and pile spacing are discussed.

Table 1. Pile configurations for all the tests.

Test code	Pile material	Pile spacing ratio
NP	-	-
A3P	Aluminum	5.17
A4P	Aluminum	3.88
P3P	Plastic	5.17
P4P	Plastic	3.88

3 .1 *Soil movement without pile reinforcement*

A test without pile reinforcement was performed to validate the system. A uniform soil movement in the unstable layer was produced, which enabled the pile-soil interaction to be studied in a generic way.

Figure 2 shows the soil displacement in the sliding layer before massive movement which began at 2.7g. The toe area, where the slip surface was bended to be horizontal, was the only anti-sliding part in the unstable layer. When the sliding force in the soil exceeded a certain level, the toe area started to move horizontally and therefore a uniform soil movement for the inclined part was produced (see Figure 3).

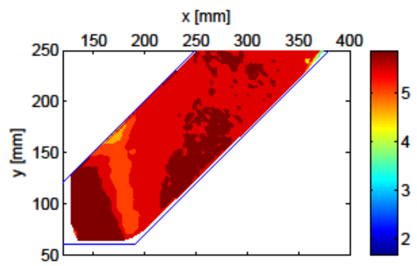

Figure 2. Soil displacement at 2.7g for test NP. (Unit: mm)

Figure 3. Massive soil movement.

3 .2 *Soil movement with pile reinforcement*

The overall movement of the unstable layer was generated by the sliding between the rubber sheet and the aluminum sheet. For test NP, the movement of the soil layer was limited by the model container. For the tests with piles, which penetrated through all the layers, the soil movement was limited by the perforated area in the rubber sheet. In this study, limit of 35mm was predetermined.

Displacement of a single point A which locates at the coordinates (270, 150, 0) (see Figure 1) can be used to determine whether the unstable layer has reached its movement limit or not. Figure 4 shows the total soil displacement of point A for all the tests. For test NP, the displacement reached 5.9 mm at a very early loading stage of 2.7 g and its movement afterwards could not be captured due to the high velocity. In other tests, the movement was well captured because the piles took over part of the moving force.

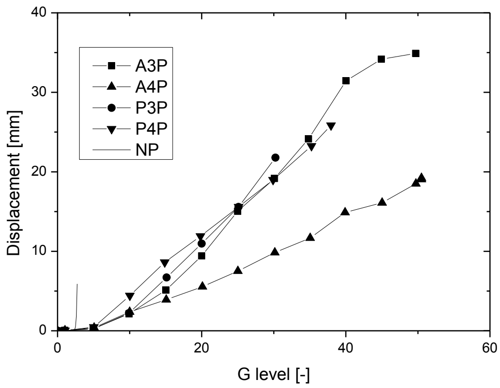

Figure 4. Total soil displacement at point A.

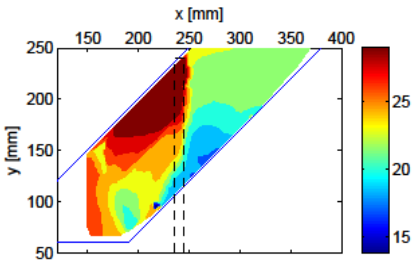

Figure 5. Total soil displacement at 50g for test A4P. (Unit: mm)

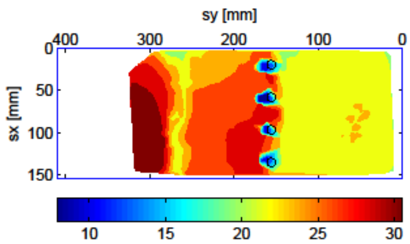

Figure 6. Surface displacement at 50g for test A4P. (Unit: mm)

The total displacement field from the side view at 50g of test A4P is plotted in Figure 5. The side view can be reasonably considered as soil movement through out the longitudinal direction (z-axis in Figure 1) for test NP because of the plain strain model. However, the installation of the piles may result in variations along the longitudinal direction. So for the tests with piles, the side view only represents the movement of a cross sectional plane in the middle of two adjacent piles. The dashed lines in Figure 5 show the location of the pile row. It can be seen that the upslope soil was well stabilized while the downslope part experienced a local failure. Surface displacement (Figure 6) also confirms the big difference between the upslope and downslope soil movement. Soil arching across the piles is well detected on the ground surface, which points out that soil arching was fully mobilized along the pile depth.

3 .3 *Influence of pile spacing*

Two pile spacing ratios (pile axis distance / pile diameter) of 5.17 and 3.88 were considered in the tests. As seen in Figure 4, the test A3P has much higher displacement at point A than test A4P and the rubber sheet has reached its movement limit. Figure 7 shows the displacement in the side view at 45 g, at which the movement limit was reached. Even though a reduced displacement can be observed in the upslope area, the entire unstable layer has experienced a large movement. Moreover, compare to test A4P (Figure 5), a certain part of the upslope soil has joined the downslope movement, which indicates the failure mode that soil flows around the piles. The cooresponding curve of the test A3P in figure 4 is used as a reference for a failed reinforcement in the following discussion.

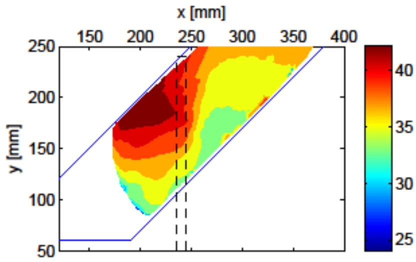

Figure 7. Total soil displacement at 45g for test A3P. (Unit: mm)

3 .4 *Influence of pile stiffness*

Compare the displacement curves of point A in tests P3P and P4P with A3P (Figure 4), both tests failed to prevent the excessive soil movement. But the failing mechanisms are not exactly the same.

The total displacement in the side view of test P4P (Figure 8) shows that only a small part of the upslope soil has been stabilized by the piles while the rest trends to move over that part, i.e., overtop failure mode. All the piles broke at 38g before the limit movement was reached.

The surface displacement (Figure 9) confirms the overtop failure. No distinct displacement between the upslope and downslope can be seen. Moreover, the top part of the piles has even pushed the downslope soil to move forward. It can be concluded that the overall failure of this case is because of big pile deformation and low bending capacity.

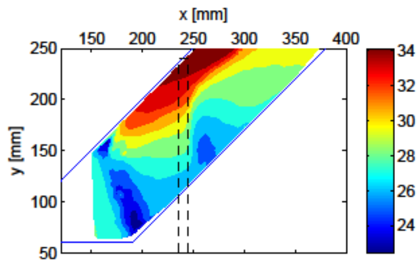

Figure 8. Total soil displacement at 38g for test P4P. (Unit: mm)

Test P3P was terminated by a technique problem at 30g, but it still can be seen from Figure 4 that the soil movement trends to approach the limit at an earlier g-level and a higher velocity than test A3P. Figures 10 is the total displacement in the side view for test P3P at 30g. A more obvious overtop movement above the stabilized soil is observed. The overtop failure in this case is amplified by the flowing soil between the piles due to big spacing.

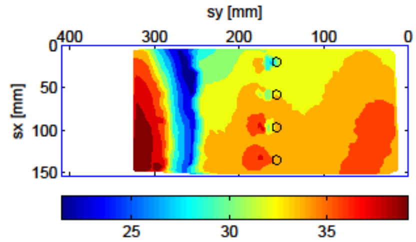

Figure 9. Surface displacement at 38g for test P4P. (Unit: mm)

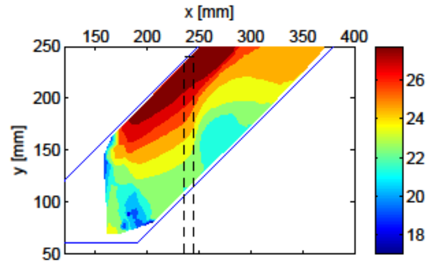

Figure 10. Total soil displacement at 30g for test P3P. (Unit: mm)

4 CONCLUSION

The effect of pile spacing and bending stiffness on slope stabilization using piles were examined in this study. Four failure modes have been revealed:

- Local soil failure in the downslope soil while the upslope soil is stabilized by high stiffness piles arranged in small spacing.
- Soil flows around the piles when high stiffness piles arranged in big spacing.
- Overtop failure (soil moves above a part of soil that is stabilized by the piles) when piles with low stiffness are utilized. This failure can be amplified by big pile spacing.
- Bending failure in the piles. This failure mode can be accompanied by any of the three failure modes above. In this study, it was observed with overtop failure.

5 ACKNOWLEDGEMENTS

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