Centrifuge modelling of embankment failure on soils with different degrees of consolidation

Modélisation par centrifugeuse de l'effondrement d'un remblai sur des sols présentant différents degrés de consolidation

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ABSTRACT: This paper reports the results of a series of centrifuge modelling of embankment failure on reconstituted saturated soils. The soils were prepared and subjected to loading under 1g conditions. The duration of loading was varied to achieve different degrees of consolidation of the soils. Embankment failures on these soils were modelled in a centrifuge by increasing its angular speed. The critical angular speed at which the embankment collapses was recorded and used to calculate the critical height of prototype embankment. The embankment stability was estimated. The test results show that the higher the degree of consolidation of the soil is, the shallower the critical slip surface underneath the embankment, and the higher the critical angular speed. The critical height of prototype embankment varies approximately linearly with the degree of consolidation of the soil.

RÉSUMÉ : Cet article présente les résultats d'une série de simulations centrifuges sur la déstabilisation d'un remblai situé sur un sol saturé reconstitué. Le sol saturé a été préparé et ensuite chargé sous une condition de gravité de 1g. De plus, on fait varier le temps du chargement afin d'obtenir de différents degrés de consolidation. La déstabilisation du remblai sur sol saturé est simulée à l'aide d'une centrifugeuse en augmentant la vitesse angulaire de cette dernière. La vitesse angulaire critique lors de la déstabilisation du remblai est enregistrée et utilisée pour calculer la hauteur critique du remblai prototype. La stabilité du remblai a été également évaluée. Les résultats des essais montrent que plus le degré de consolidation du sol saturé est élevé, moins la surface critique de glissement sous le remblai est profonde et plus la vitesse angulaire critique est élevée. La hauteur critique du remblai prototype varie approximativement de façon linéaire avec le degré de consolidation du sol.

KEYWORDS: centrifuge modelling; embankemnt failure; degrees of consolidation; reconstituted saturated soils.

1 INTRODUCTION

Construction of an embankment on soft soil is frequently encountered in engineering practice. The soft soil consolidation will occur under the weight of the embankment. During consolidation, the undrained shear strength of soil increases with the compression of the soil and the dissipation of excess pore pressure. Therefore, the stability of the embankment varies with the degree of consolidation of the soil. In this sense, the degree of consolidation of the soil plays an important role in evaluating the stability of the embankment (Li & Row 2001, Rujikiatkamjorn & Indraratna 2009, Zhu et al. 2017, Stark et al. 2018).

Geotechnical centrifuge modelling technique can be utilised to generate a stress field in a small-scale model similar to that in a full-scale prototype. In this way, the strength behavior and the failure performance of prototype can be reproduced in the model. A number of centrifuge model tests have been carried out to investigate the performance of embankment construction on soft soil. Most of the studies have focused on the effects of reinforcements and vertical drains on soft soil improvement and embankment behaviour (Sharma & Bolton 1996, Mandal & Joshi 1996, Kitazume & Maruyama 2007, Chen & Yu 2011, Ye et al. 2015, Reshma et al. 2019, Shen et al. 2019, Chen et al. 2020). Only a limited number of studies have paid attention to the stability of the embankment. Almeida et al. (1985) reported two centrifuge model tests of staged-constructed embankments built on an untreated clay foundation and on a clay foundation strengthened with granular columns. The embankment was constructed during flight in five stages. Both foundations had an overconsolidated crust overlaying the normally consolidated clay. The pore pressures at selected positions in the foundations were measured during the test, and they were used to estimate the stability of the embankments by the effective stress analyses. The results showed that the safety factor of embankment on the foundation strengthened with granular columns was larger than that on the untreated foundation at any stage of embankment construction. This was due to the rapid dissipation of pore pressure in the soils around the granular columns. Sharma & Bolton (2001) investigated the behaviour of the stage-constructed embankment on clay foundations with and without wick drains using both centrifuge model tests and finite element analyses. Reasonably good agreement was obtained between the results of the tests and analyses. They found that the degree of consolidation of the clay foundation with wick drains was higher than that of the clay foundation without wick drains during the embankment construction. This resulted in a significant increase in the undrained shear strength of the clay foundation with wick drains and an improvement of the stability of the embankment.

This paper reports centrifuge tests of embankment on clay foundations with different degrees of consolidation. The aim of this paper is to investigate the stability of the embankment during the consolidation process of clay foundation. A full description of the centrifuge model is provided. The critical scaling factor was calculated using the critical angular speed of the centrifuge when the model embankment collapsed. The relationship between the critical height of prototype embankment and the degree of consolidation of clay foundation was investigated.

2 CENTRIFUGE MODELLING TESTS

The centrifuge model tests were carried out in the beam centrifuge at Nanjing Hydraulic Research Institute, China. The beam centrifuge has a swinging platform radius of 2.25 m and a carrying capacity of 50 g-t. The platform supports a rectangular model container with internal dimensions of 700 (length) × 350 (width) × 450 (depth) mm. One side of the model container is a transparent wall and a camera was placed in front of it to observe the deformation of the centrifuge model during the test. In order to minimise the friction between the soil and the model container, the inner walls of the model container were coated with silicon grease.

Figure 1 shows the schematic diagram and the photograph of the centrifuge model. The model foundation was founded on a saturated sand layer, which was 30 mm thick and covered with a geotextile to prevent clogging. Noodles were placed on the side surface of the centrifuge model at an interval of 40 mm to visually observe the deformation of the centrifuge model during the test. Three laser displacement sensors (LS1, LS2 and LS3) were installed and used to measure the vertical displacements of the centrifuge model. The measurement position of LS1 was located approximately 1 cm to the left of the slope shoulder of the model embankment. The measurement position of LS2 was located approximately 1 cm to the right of the slope toe of the model embankment.

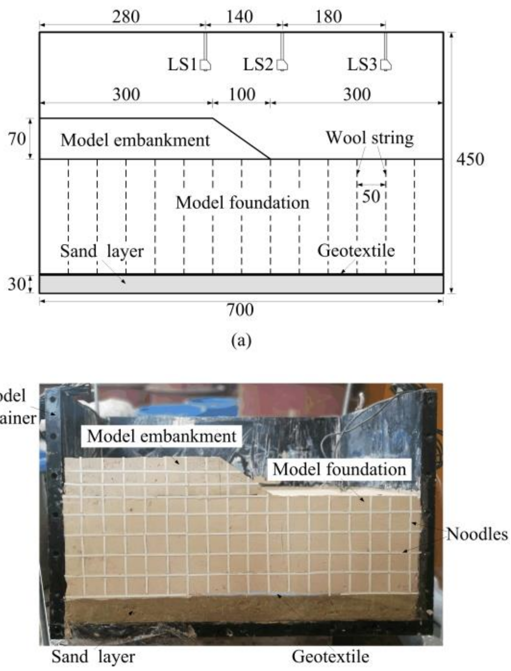

Figure 1. Centrifuge model: (a) schematic diagram (unit: mm); (b) photograph

2.1 *Model embankment*

The model embankment was made of kaolin clay mixed with 25% pure sand by weight and had the water content of 30% (ratio of the mass of water to the mass of soil). The properties of kaolin clay and sand are listed in Table 1. The model embankment had the height of 70 mm, the slope inclination of 35°, the density of 1.8 g/cm^3, the cohesion of 22.57 kPa and the internal friction angle of 5.89°. A wooden frame was used to make the model embankment, as shown in Figure 2. The wood frame comprised four hardwood boards. In order to prevent the soil from adhering to the wooden frame, each board was wrapped by plastic film. Two binding belts were tightly fastened to reinforce the wooden frame. In addition, a narrow groove was cut on the inner side surface of the hardwood board. The inclined plane of the narrow grooves was equal to the slope inclination of the model embankment. In this way, the soil block could be easily cut into a slope along the narrow grooves using a wood plate.

2.2 *Model foundation*

The model foundation was made of kaolin clay with properties as listed in Table 1. A slurry was prepared by mixing the kaolin clay with water at a water content of 125% (twice the liquid limit). The slurry was then poured slowly into the model container over the saturated sand layer covered with geotextile and preloaded to a pre-consolidation pressure of 33 kPa under 1g condition. The final height was 200 mm.

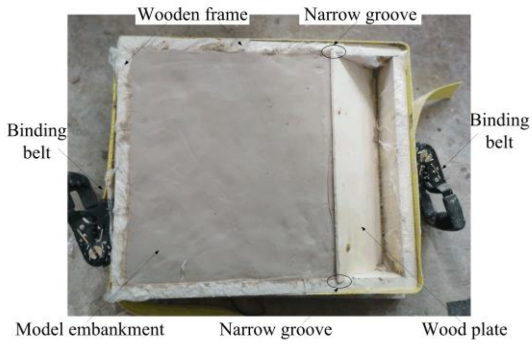

Figure 2. Wooden frame for making the model embankment

Table 1. Properties of the soils used in tests

Soil type	Parameter	Value
Kaolin clay	Specific gravity G_s	2.6
	Liquid limit w_L (%)	62.5
	Plastic limit w_p (%)	27.5
	Plasticity index I_p	35
Pure sand	Specific gravity G_s	2.65
	Particle sizes d_{10}, d_{50}, d_{60} (mm)	0.121, 0.168, 0.181
	Maximum dry density ρ_{dmax} (g/cm^3)	1.57
	Minimum dry density ρ_{dmin} (g/cm^3)	1.37
	Coefficient of uniformity C_u	1.5
	Coefficient of curvature C_c	1.0

To accelerate the consolidation of soil, wool strings were installed in the model foundation as the vertical drains. A guide plate was employed to ensure that the wool strings were vertically inserted into the model foundation. Figure 3 shows the photograph of the guide plate. The guide plate has a thickness of 60 mm and the spacing of drill holes is 50 mm. The wool strings were inserted into the whole model foundation through the holes using a stainless steel needle. Figure 4 shows the top view of the model foundation after the installation of wool strings. The dashed blue grid with the same spacing of holes in the guide plate was used to check the positions of the wool strings. It was found that the majority of wool stings were installed at the expected positions, with only a few of them had a deviation (marked by the circles in Figure 4).

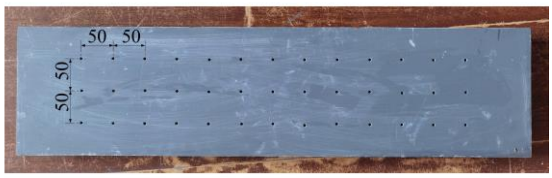

Figure 3. Photograph of guide plate (unit: mm)

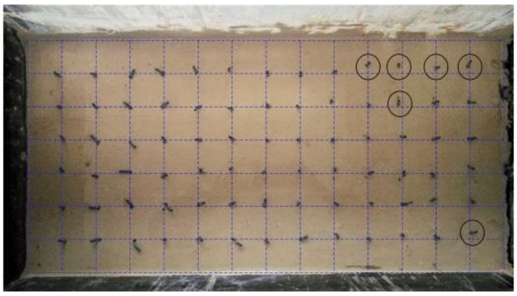

Figure 4. Top view of the model foundation after the installation of wool strings

After completing the installation of the wool strings, the model foundation was consolidated at 47.5 kPa under 1g condition. Figure 5 shows the settlement of the model foundation surface measured by the linear variable differential transformer during the consolidation process. The degree of consolidation of the model foundation, U, is defined in terms of the settlement of model foundation surface as follows:

$$U = \frac{S_t}{S_f} \times 100\% \tag{1}$$

where S_t is the settlement of the model foundation surface at a particular instant time, and S_f is the final settlement of the model foundation surface when the model foundation is fully consolidated. In this study, three degrees of consolidation of the model foundation, 0%, 40.6%, and 100%, were considered. Once the targeted degree of consolidation was reached, the consolidation was judged to be complete.

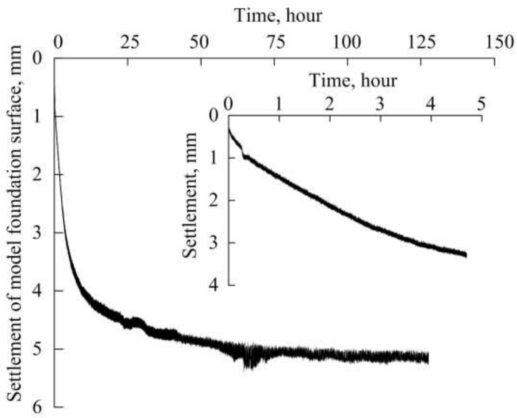

Figure 5. Settlement of model fundation surface during consolidation process

The undrained strength of the model foundation was estimated by a cone penetrometer with 30º cone tip. In the process of penetration, the cone penetrometer was maintained perpendicular to the surface of model foundation and manually penetrated into the model foundation with a rate of 2 cm/s. The measured data were recorded when the penetration depth reached 50 mm, 100 mm, 140 mm and 180 mm. The cone penetration test was repeated four times at different penetration positions on the surface of model foundation. Figure 6 shows the undrained shear strength profiles of model foundations with different degrees of consolidation. It can be seen that both the undrained shear strength at the model foundation surface and the rate of increase in the undrained shear strength with depth increase with the increase in the degree of consolidation. When the degrees of consolidation varied from 0% and 100%, the stress ratio of the undrained shear strength to the consolidation stress increased from 0.144 (at the surface of model foundation) to 0.185 (at the bottom of the model foundation). This range is lower than the suggested value of 0.22 for normally consolidated clay (Larsson 1980, Mayne 1980, Ladd 1991). This could be because the data recording was manually operated during the penetration process. The penetration rate could be less than 2 cm/s when recording the data.

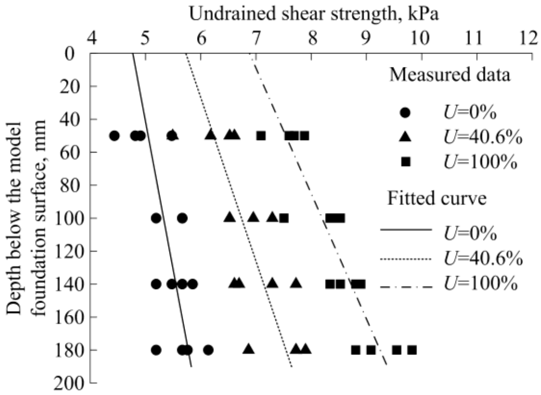

Figure 6. Undrained shear strength profiles with depth measured from model foundations with different degrees of consolidation

2.3 *Test procedure*

In the centrifuge model test, the stress field of model is distorted compared with prototype due to the linearly increasing centrifugal acceleration along the centrifuge radius. To minimise the effect of the distortion on the accuracy of the centrifuge test results, the model embankment was set up at an optimum location suggested by Lei et al. (2020). The middle point of the slope surface of the model embankment was on the central axis of the centrifuge arm. The cross section of the model embankment was placed on the radial plane passing through the axis of rotation of the centrifuge.

Collapse of the model embankment was caused by increasing the angular speed of centrifuge. The deformation of the centrifuge model was evaluated by observations of noodles deformation through the transparent window and the measured vertical displacements using the laser displacement sensors.

3 TEST RESULTS AND DISCUSSION

Figure 7 shows the embankment failure on the foundation with degree of consolidation $U = 0\%$. A deep-seated failure occurred and the critical slip surface almost reached the bottom of the model foundation. Figure 8 shows the critical slip surfaces obtained by inspecting the deformations of noodles. The gray dotted grid is formed by the noodles before the model embankment failure. Obviously, an increase in the degree of consolidation caused the critical slip surface beneath the model embankment to become shallower.

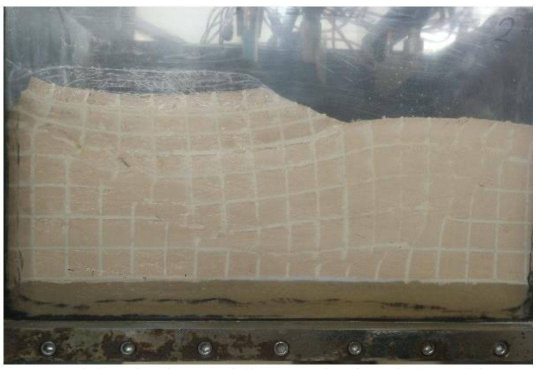

Figure 7. Model embankment failure on the foundation with degree of

consolidation $U = 0\%$

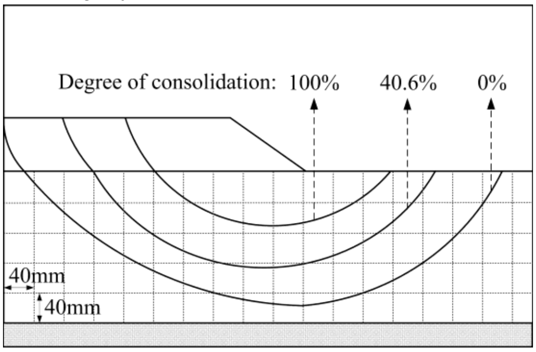

Figure 8. Critical slip surfaces of the centrifuge model with different degrees of consolidation

Figures 9-11 show the measured data including the angular speed and vertical displacements during the test. Unfortunately, during the test of degree of consolidation $U = 40.6\%$, the laser displacement sensor used to measure the vertical displacement of the shoulder of model embankment was damaged, leading to the absence of this data section. In the vertical displacement curve graphs, a positive value indicates the upheaval of the measurement position, while a negative value indicates the subsidence of the measurement position. It was found that the vertical displacement curve of the toe of model embankment (i.e. the vertical displacement measured by LS2) occurred a sudden change during the test, as indicated by the circles in Figures 9-11. When the sliding mass started to slip along the critical slip surface, a rotational movement around the toe of embankment occurred at the same time. Subsequently, the measurement position of LS2 moved from the left side to the right side of the toe of the model embankment. In addition, the sudden change become unobvious for the model embankment on the foundation

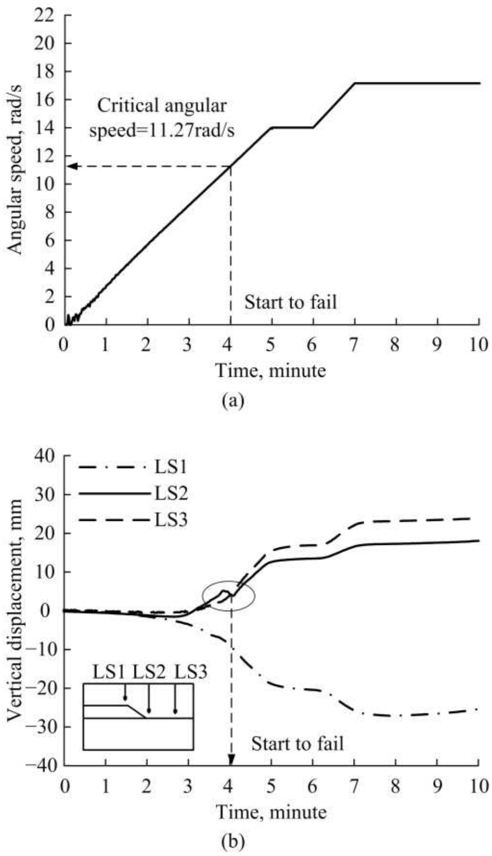

Figure 9. Measured data for embankment on clay foundation with degree of consolidation $U = 0\%$: (a) angular speed of centrifuge; (b) vertical displacements.

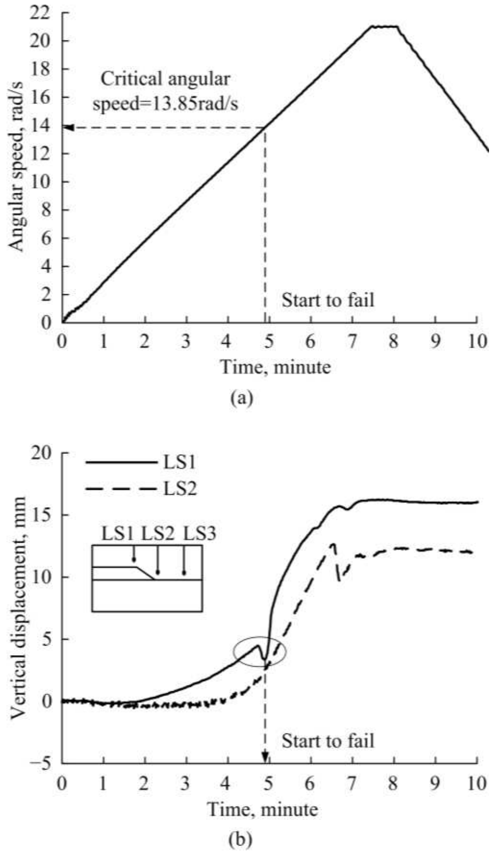

Figure 10. Measured data for embankment on clay foundation with degree of consolidation $U = 40.6\%$: (a) angular speed of centrifuge; (b) vertical displacements.

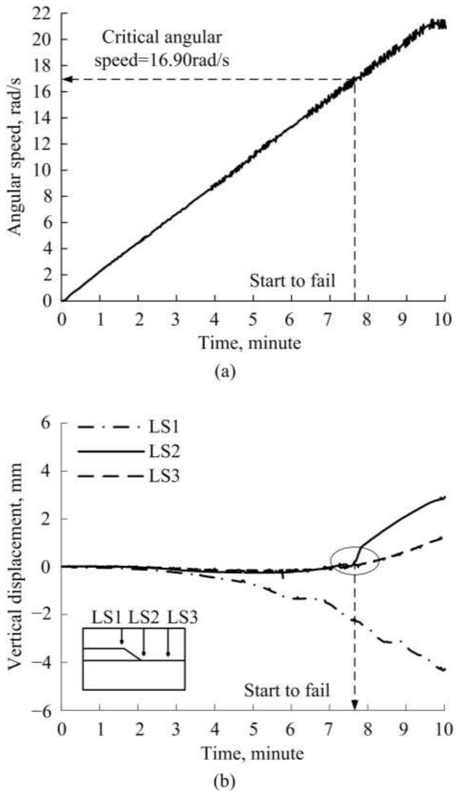

Figure 11. Measured data for embankment on clay foundation with degree of consolidation $U = 100\%$: (a) angular speed of centrifuge; (b) vertical displacements.

with degree of consolidation U = 100%. This is because the increase in the undrained shear strength made the rotational movement of the sliding mass become slight. Therefore, the model started to fail upon a sudden change occurred at the toe of the model embankment. The corresponding angular speed is the critical angular speed.

According to the relationship between the angular speed and the scaling factor given by Taylor (1995), the critical scaling factor can be calculated by $N_{cr} = \omega_{cr}^2 R_e/g$, where ω_{cr} is the critical angular speed, R_e = 2.0 m is the effective radius of the centrifuge, and g = 9.81 m/s^2 is the gravitational acceleration. The product of the critical scaling factor and the height of the model embankment gives the critical height (Chen 1975) of the corresponding prototype embankment. Table 2 lists the calculated critical scaling factors and critical heights of the corresponding prototype embankment. Figure 12 shows the calculated critical height of prototype embankment against the degrees of consolidation of model foundation. It can be seen that the critical height of the prototype embankment increases approximately linearly with the increase in the degree of consolidation.

Table 2. Calculated critical scaling factors and critical heights of prototype embankment

Degree of consolidation (%)	0	40.6	100
Critical scaling factor	25.89	39.11	58.23
Critical height of prototype embankment (m)	1.81	2.74	4.08

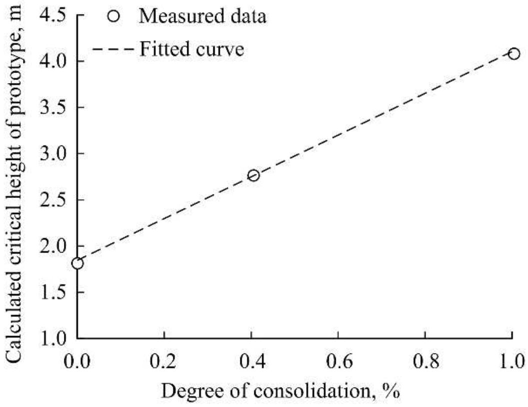

Figure 12. Calculated critical height of prototype embankment against the degree of consolidation of model foundation.

4 CONCLUSIONS

Three centrifuge model tests of embankment on the clay foundations with different degrees of consolidation are reported. Deep-seated slip surfaces underneath the embankment and the rotational movements of the soils around the toe of the embankment were recorded. The critical height of the embankment was calculated. The result shows that the critical height of the embankment increases approximately linearly with the degree of consolidation of clay foundation. It should be noted that the undrained shear strength profiles of the clay foundations were underestimated in this study. Additional research is therefore required to investigate the behaviour of embankment during the consolidation process of soft soil.

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