Centrifuge model tests on the dynamic response of slopes subjected to water storage at the toe area

J., Xu ⁱ⁾, R., Uzuoka ⁱⁱ⁾ and K., Ueda ⁱⁱⁱ⁾

i) Ph. D Student, Department of Civil and Earth Resources Engineering, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan.

ii) Professor, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan.

iii) Assistant Professor, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan.

ABSTRACT

Stability of slopes where water was accumulated at the toe area during dynamic events were studied in this paper. The soil below and right above water level tended to be contractile and loose due to water storage at the toe of slope, and the slope behaviors became different compared with those without water storage. Several model tests in a geotechnical centrifuge were carried out in this paper to examine the effects of water accumulation at slope toe, relative density of soil, and shaking intensity of dynamic events on the slope stability. The compression of the soil below the water level and localized failure at the toe region subjected slopes to more shearing during shaking and potentially large movements. For the unsaturated slopes with high suction, total collapse was not possible even in model where intense shaking was excited. Successive shaking with increasing intensities could cause more cracks on the surface of the slope, and the deep and wide cracks were mainly on the upper middle part of the slope. Cracks concentrated at areas near the water level. Seepage and capillary flow are two factors that need further attention in the study of the dynamic response of unsaturated slopes with water storage at toe.

Keywords: slope stability, water storage, dynamic response, unsaturated slopes

1 INTRODUCTION

Slope stability under earthquakes were widely studied and most of the related research were focused on the saturated slopes by means of different methods, such as physical model experiments or numerical computation. As to unsaturated slopes, the change of suction during shaking influences the strength of soil and thus the stability of slope, which differ themselves greatly from saturated slopes. The fluctuation of reservoir water level imposes great risks to the stability of the slope and landslides are likely to take place in certain reservoir areas (Wang et al., 2007; Sun et al., 2016). Field monitoring methods (Fujita, 1977; Kilburn and Petley, 2003; Qi et al., 2006; Pinyol et al., 2012; Wang et al., 2014) were usually applied by a lot of researchers to predict the slope stability, and few physical experiments (Miao et al., 2016; Xiong et al., 2019) were carried out to simulate the real events or predict slope behaviors. However, these studies focused on the effects of the water level on the static stability of slopes and dynamic response of these slopes were not thoroughly studied. In this paper, the influences of water at the toe of slopes during shaking were studied using centrifuge modelling technology. Parameters such as the height of water level, relative density, intensity of shaking, and successive shaking were also studied to clarify their influences on the overall stability of slopes.

2 GEOTECHNICAL CENTRIFUGE AND SHAKE TABLE

The centrifuge model tests were carried out on the shake table in Kyoto University centrifuge, which has an effective radius of 2.5 m and a maximum capacity of 24 G-ton. The shake table is integrated with the swing basket of the centrifuge and has a maximum force capacity of 14.7 kN, a maximum acceleration of 10 g, and maximum amplitudes of ± 2.5 mm in model scale.

Since soil is highly stress dependent and the geotechnical centrifuge can provide an accelerated field of N times Earth's gravity for a model scaled down by $1/N$, results from the tests can be extrapolated to a prototype situation. This is the basic scaling law of centrifuge modelling, that stress similarity is achieved at homologous points by accelerating a model of scale N to N times Earth's gravity. The centrifuge scaling factors were summarized in Table 1.

Table 1. Centrifuge scaling factors.

Parameter	Prototype-model ratio
Length	N
Density	1
Time (dynamic)	N
Time (diffusion)	N^2
Frequency	$1/N$
Stress	1

5 TEST RESULTS

5.1 Deformation of slopes

In the first three tests, a high speed camera was fixed above the container and the tests were filmed. For the last test, the camera was moved to the front so that the plan view photos were not available. Photos of slopes models in first four tests were shown in Fig. 2.

In test 1, massive soil movements didn't occur and the cracks only took place at 2 to 4 cm above the water level. In test 2, due to the lowered water level at the slope bottom, the cracks near the water level were less than those in test 1, even though cracks at the upper part of the slope showed up before shaking during the spin-up process. Shaking-caused cracks only took place in the soil that was near the water level, and the upper part still had good stability,

In test 3, cracks caused by shaking took place at positions closer to the water level and the apertures of them were larger than those in test 1. This was because of the lower stiffness of the slope and the lateral soil displacement was much more. And the cracks at the crest were enlarged and developed, which was not seen in tests 1 and 2. Even though there were some clear cracks on the surface of the upper slope in test 3 during spin-up and before shaking, the shaking-caused cracks were in different locations on the upper slope as well as near water level. This was different from the tests 1 and 2. It also showed that the suction in the soil near water was lowest, and the suction in the middle part of the slope between the cracks was uniformly distributed.

Fig. 2. Photos of slope models in the first four tests.

In test 4, the shaking was so intense that even the upper slope far away from the water level generated cracks as deep as 6 cm in model scale, as shown in Fig. 2 (d), which was not seen in other three tests. Because

of the existing suction in the upper soil, the soil blocks were still stable and no massive soil movement was observed. For the soil few centimeters above the water level, though unsaturated, the water moved upward due to the capillary forces and the soil began settling and moving at very high speed during the intense shaking. The lower slope collapsed, and the settlements and lateral displacements were apparent especially for the soil in the lower section. The soil accumulated at the corner of the container. Failure was associated with long travel distances of soil at lower part of the slope.

5.2 Response of accelerations

Input motions of each test were shown in Figs. 4 and 4. In tests 1, 2, and 3, the slopes were only subjected to shaking with an amplitude of 0.8 m/s^2 in prototype scale and the slope in test 4 was subjected to shaking with an amplitude of 6 m/s^2 . In tests 5 and 6, the slopes were shaken twice and the amplitudes of the two shakes were about 2 m/s^2 and 4 m/s^2 .

Fig. 5 showed the response of accelerations at various depths of slope models in tests 1, 2, 3, and 4. In tests 1 and 2 the amount of accelerometers were more than those in tests 3 and 4. The geometry and relative density of both tests were the same, the response of accelerations differed though.

In test 1, the amplitudes of five accelerations especially A1, A2, and A5 were larger than input motions except for A3, whose amplitude didn't differ much. In test 2, however, A4, A5, and A6 showed larger amplitude increases instead of A1, A2, and A3 with A1 having problematic lowest accelerations.

Some accelerometers at the bottom of the slope in each test tilted during shaking, and readings were not zero even after shakes ended. In test 4, the readings of A1 were the most tilted suggesting large lateral displacements of soil at the base and the A2 located deep below the surface didn't tilt meaning the deep soil did not have large movement during shaking.

Fig. 3. Input motions in tests: same shaking (a) in tests 1, 2, and 3; and intense shaking (b) in test 4.

Fig. 4. Input motions in tests 5 and 6: first shaking (a) and

second shaking (b).

Fig. 5. Accelerations in slopes in tests 1, 2, 3, and 4.

5.3 Response of excess pore water pressures (EPWP)

In test 1, the water pressures at the base increased especially P1 and P2. No EPWP developed at the upper slope, except for the P10 where little suction increased (in Fig. 6). Due to the insufficient infiltration of the water at the toe area, the pore water pressures within the slope were very small and the shaking was not intense enough to cause large increases in pore water pressures.

In test 2, because of the low water level at the slope base, excess pore water pressured in didn't develop much. EPWP in P1 rose to 1 kPa, water pressures were negative (suction) but only last to a very limited value (less than 2 kPa) and disappeared at the end of shaking. The suction recorded was not likely to reflect the real conditions in slopes because of the limitation of the transducers used in the tests.

In test 3, all four transducers showed increase in EPWP and the dissipation began first in P1 and then P3. EPWP in P2 and P4 still showed a rising trend even after shaking. The relative density of the slope in test 3 was the lowest in all tests, and the all the transducers recorded increasing pore water pressures during shaking. Even though all transducers were in the same level and the depths were the same, the increase in pore water pressures were different, but it showed an increasing trend.

Fig. 6. EPWP during shaking in model tests.

In test 4, the EPWP in P1 was dramatically higher than those developed in other three tests while P3 didn't develop any EPWP. P2 and P4 showed different patterns of changing pore water pressures during the test. EPWP in P2 increased from 7 s and became stabilized until 12 s, while EPWP in P4 showed the opposite trend at this time interval and then rise to a value larger than that of P2 at the end of shaking. Except for P1, P2, P3, and P4 were placed on the inclined base and the readings of them were relatively

low and only small changes occurred, which was because the water didn't infiltrate into the soil at a larger depth.

5.4 Displacement

Soil displacement during shaking was obtained from the image analysis of the photos taken by a high speed camera in front of the container. The image analyses were carried out with an image processing software called Dipp Motion. The tracking markers were placed between the front window of the container and the soil while making the specimen by hammer compaction layer by layer. And the calibration markers were also used to calibrate and ensure the accuracy of the analysis results. To check the reliability of the analysis results, the displacement of the calibration markers was used to compare with that of the container; if the two matched each other and had the same amplitude, the analysis was regarded to be accurate. In this way, the analysis results of the tracking markers were ensured to be accurate.

Image analysis results of the soil displacement in slopes in tests 5 and 6 were shown in Figs. 7 and 8, and discussed below. Since only one high speed camera was mounted in front of the container to record the shaking events in tests 5 and 6, the top view of the slopes in flight were not available. However, photos of the slopes in tests 5 and 6 after shaking was taken, and shown in Figs. 9 and 10. The input motions in tests 5 and 6 were recorded in Fig. 4 (a) and (b); the first shaking was initiated when the centrifugal acceleration reached 50 g and the second shaking continued as the first one ended.

Fig. 7. Displacements of model slope in test 5: first shaking (a) and second shaking (b).

In the first shaking, the slope didn't generate much

displacement on the upper part, but the soil movements below the water level were mainly horizontal, which could be seen in Figs. 7 (a) and 8 (a). This was because the soft soil below water level tended to move easily during shaking.

Fig. 8. Displacement of model slope in test 6: first shaking (a) and second shaking (b).

Fig. 9. Top view of the model slope in test 5 after the second shaking.

Fig. 10. Top view of the model slope in test 6 after the second shaking.

Horizontal displacement of the soil on the lower part made the soil on the upper part unstable and displacement occurred. When the second shaking with a much larger intensity than the first one came, the displacement of soil especially on the lower part was much larger, leaving cracks on the surface of the upper slope. The displacement in Fig. 8 (a) were larger than that in Fig. 7 (a) especially in the area near the water level, and the maximum displacement after the first

shaking in both slopes were 0.98 mm and 3.2 mm in model scale.

When the second shaking came, the displacement continued to develop and the soil below water had the largest movements in both tests (Figs. 7 (b) and 8 (b)). Soil slid and accumulated at the bottom of the slopes after the shaking ended. The cracks in the slope in test 5 after shaking were relatively shallow. The largest depths of the cracks in slope in test 6 were about 1 cm in model scale. From the top views in Figs. 9 and 10, the characteristics of the shaking-induced cracks could be seen clearly. The cracks in slope in test 5 concentrated on the surface of the soil within 10 cm above the water level, and the middle part of the slope didn't have clear cracks except one crack on the top. However, cracks in the slope in test 6 distributed on the whole slope surface with one obvious and deep crack on the upper middle part of the slope. The wide and deep crack was induced by the large soil movements in the lower part of the slope. Cracks were also found on the surface of the middle part of the slope, which were quite different from those in the slope in test 5.

With a larger soil relative intensity, the slope in test 5 didn't generate as much displacement as in the slope in test 6. The outline of the slope in test 6 was almost 1 cm in model scale lower compared to its original outline before shaking, and had more cracks on soil above the water level after the second shaking than the slope in test 5. The direction of the tensors around the water level was almost parallel to the inclined base while the direction of the tensors at the toe area in the slopes were almost horizontal. The largest displacement in the slope in test 6 was 29.1 mm, while the largest displacement in the slope in test 5 was only 10.9 mm in model scale.

For the slope above the water level, the further the soil was from the water level, the smaller the displacement was; the deeper the soil, the smaller the displacement was. In the upper and deep soil in the slopes in Figs. 7 (b) and 8 (b), the displacement was much smaller than that in the lower parts of the slopes. This was because the capillarity in the soil near the inclined base and far from the water level was not significant, suction in the soil near the base was high and so was the shear strength. Infiltration of water into the soil was mainly few centimeters below the surface, and the loss of suction in the soil resulted in large soil displacement. If the time for water infiltration was longer, the displacement in the deep soil would be larger and the slope would be more mobilized, causing a large sliding area, as well as wider and deeper cracks.

6 CONCLUSIONS

In the centrifuge model tests carried out in this study, the water at the bottom of the slope had a great influence on the slope stability. When slopes were subjected to water storage at the toe area, the soil below

and right above water level tended to be compressible and loose, and the slope behavior became different compared with those without storage.

The compression of the soil below the water level and localized failure at the toe region acted as the main trigger to shear the soil above the water level. Because of widely existing high suctions in the upper part of the slopes, total collapse was not possible even in model where intense shaking was excited. Seepage and capillary flow are two factors that need further attention in the study of the dynamic response of slopes subjected to water storage at toe. Cracks were concentrated at areas near the water level. Increasing the shaking intensity or successive shaking on a slope with a certain height of water at its toe area will not produce total collapse of the slope unless more infiltration time is given before the shaking. A large landslide below certain height of the slope can be caused by a strong shaking and the cracks on the unsaturated part of the slope is deepened as the intensity of the shaking increases.

The shaking in tests in this study was introduced right after designated centrifugal accelerations were achieved and the time for seepage and capillary rise was very limited. In future study, model tests with elongated time for these phenomena are needed.

REFERENCES

- 1) Fujita, H. (1977): Influence of water level fluctuations in a reservoir on slope stability. *Bulletin of the International Association of Engineering Geology*, 16(1), 170-173.
- 2) Kilburn, C. R. and Petley, D. N. (2003): Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy. *Geomorphology*, 54(1), 21-32.
- 3) Miao, F., Wu, Y., Li, L., Tang, H. and Li, Y. (2018): Centrifuge model test on the retrogressive landslide subjected to reservoir water level fluctuation, *Engineering Geology*, 245, 169-179.
- 4) Pinyol, N. M., Corominas, J. and Moya, J. (2012): Canelles landslide: modelling rapid drawdown and fast potential sliding. *Landslides*, 9 (1), 33-51.
- 5) Qi, S., Yan, F., Wang, S. and Xu, R. (2006): Characteristics, mechanism and development tendency of deformation of Maoping landslide after commission of Geheyan reservoir on the Qingjiang River, Hubei Province, China. *Engineering Geology*, 86, 37-51.
- 6) Sun, G. H., Zheng, H., Tang, H. M. and Dai, F. C. (2016): Huangtupo landslide stability under water level fluctuations of the Three Gorges Reservoir. *Landslides* 13 (5), 1167-1179.
- 7) Wang, H., Xu, W., Xu, R., Jiang, Q. H. and Liu, J. H. (2007): Hazard assessment by 3d stability analysis of landslides due to reservoir impounding. *Landslides*, 4 (4), 381-388.
- 8) Wang, J. E., Xiang, W. and Lu, N. (2014): Landsliding triggered by reservoir operation: a general conceptual model with a case study at Three Gorges Reservoir. *Acta Geotech*, 9(5), 771-788.
- 9) Xiong, X., Shi, Z., Xiong, Y., Peng, M., Ma, X. and Zhang, F. (2019): Unsaturated slope stability around the Three Gorges Reservoir under various combinations of rainfall and water level fluctuation. *Engineering Geology*, 261, 1-17.