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STABILITY ANALYSIS ON LANDSLIDE DAM UNDER SURGE ACTION BASED ON LARGE-SCALE EXPERIMENTS

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The rapid rise and fall of the water level in the upstream reservoir area of a landslide dam may trigger slope sliding into the reservoir, leading to huge surge wave. The stability of landslide dams under the action of landslide surge is seldom studied and of the target in this paper. Landslide dam model tests with the height of 80 cm and width of 317 cm were performed in a water flume with a full length of 42 m. Models are made up in accordance with the grain gradation curve of the Donghekou, Xiaogangjian and Tangjiashan landslide dam, which are dominated by fine, coarse and mixed particles, respectively. The tests are performed under different reservoir water level and wave height. It is found from the tests: (1) the dam stability is controlled by the relationship of the dam height and the actual water level which is determined by the reservoir water level and the wave height. If the actual water level is lower than the dam height, the surge wave would result in a stable eroded surface; otherwise, the landslide dam would be breached by the wave action with obviously higher speed. (2) The erosion of the landslide dam dominated by fine particles is relatively easier and will breached with curve shape under the action of waves. The landslide dam dominated by coarse particles is relatively more stable. The wave-acted dam breaching process of the landslide dam dominated by mixed particles is similar to that without the action of wave action, but the dam breaching of the former is much faster. (3) The wave action on landslide dam would not incur liquefaction due to relatively loose structure. The pore water pressure would vibrate during the wave action period and drop rapidly when the dam starts to breach.

Keywords: landslide dam, dam breach, model test, dam stability, landslide surge

1 Introduction

The 2008 Ms 8.0 Wenchuan earthquake triggered as large as 257 landslide dams (Cui et al., 2009). The aftershocks and the rapid rise and fall of the water level in the upstream reservoir area of a landslide dam may trigger side slope sliding into the reservoir. For example, at least 20 landslides, avalanches and debris flows occurred and slid into the reservoir of the Tangjiashan landslide dam. Large surge is very likely to be induced by a reservoir landslide, which may bring hazard to the stability of the landslide dam. However, the research on the stability of landslide dam under the action of landslide surge is little. Risley et al. (2006) calculated the overtopping wave volume of Usio landslide dam in Pakistan. Some studies on landslide surge on man-made dam are found: Xu et al. (2015) studied the effect of landslide surge on the dam under the conditions of different landslide water entry area, landslide height and distance from the water entry point to the dam site. Lin et al. (2015) established an ISPH model to simulate the process of landslide surge climbing over the dam. This study may be reference of the dynamic stability of landslide dam. However, due the large differences on the dam structure and materials of these two types of dams. The results may not be directily applied to landslide dams.

This paper aims to analyze the stability of landslide dam with different materials under surge action based on large-scale experiments. First, the test layout, devices and the landslide dam materials will be introduced. Then, the results, including the failure mode, erosion rate and pore water pressure, during the action of the surge waves are illustrated. Finally, conclusions on the experimental studies are drawn.

2 Experimental design

2.1 Test device

The experiment was carried out in the wave flume experiment system of Tongji University. The system mainly includes wave flow flume, wave maker system and data processing system. The flume length is 42m, width is 0.80m, height is 1.25m. The wave making system used in the experiment adopts the wave current control system and data acquisition system. The measurement system of pore water pressure consists of pore water pressure gauge and dynamic strain gauge. During the test, the deformation and displacement of the dam are monitored by high definition camera.

2.2 Dam material

The different dam material may have a great influence on the dam stability under the wave action. The dam model in this paper is made up in accordance with the grain gradation curve of the Donghekou landslide dam (Shi, et al., 2014), Tangjiashan landslide dam and Xiaogangjian landslide dam (Chang, et al., 2011), as shown in Fig. 1. Generally, the dam materials of the Donghekou, Xiaogangjian and Tangjiashan landslide dam are dominated by fine, coarse and mixed particles, respectively.

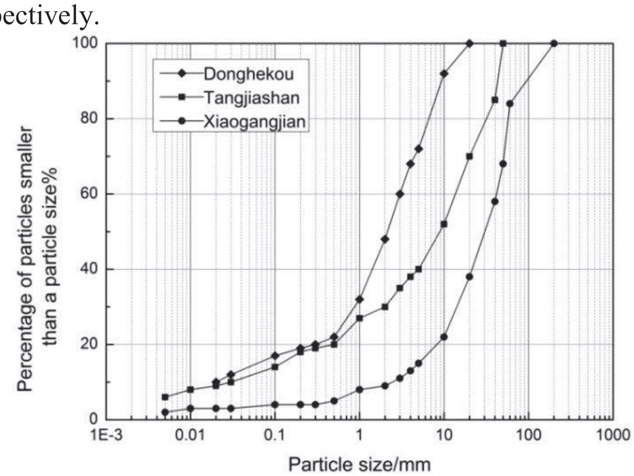
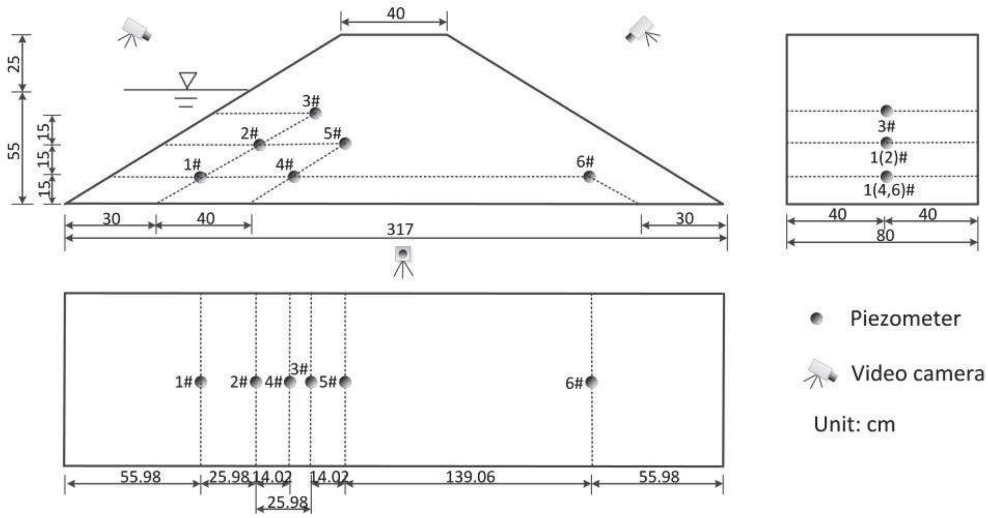


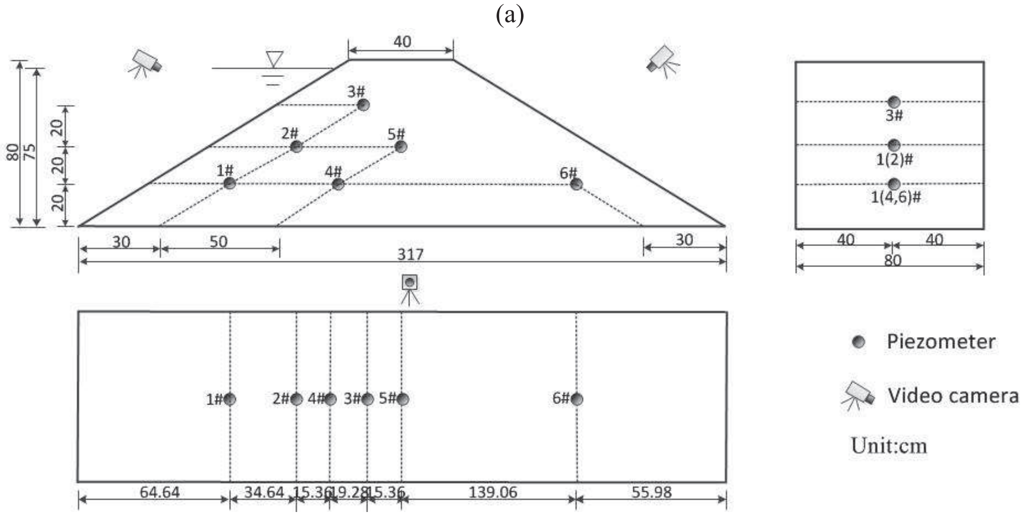
Fig. 1. Grain size distribution curve of landslide dams

2.3 Dam model and test layout

The dam models and test layouts of the first and the last three scenarios are shown in Fig. 2(a) and 2(b), respectively. The only difference between these two figures are the layout of the piezometers, which are placed proportionally to the water level. The dam models in the two figure both have the height of 80 cm, top width of 40 cm and bottom width of 317 cm. Five piezometers are placed in the upstream part of the dam and one is placed in the downstream part of the dam, since the upstream part is close to the reservoir and more easily affect by the changes in the reservoir and the upstream slope. Three cameras are set up in order to monitor the erosion and displacement of the dam during the test.



(a)



(b)

Fig. 2. The model dam and the test layout: (a) the first three scenarios with water level of 55 cm; (b) the last three scenarios with water level of 75 cm.

2.4 Test scenarios

Six scenarios were set up in the tests, as shown in Table 1. The First three scenarios have the same water level of 55 cm and the same dam material of Donghekou, but different in wave height of 5, 10 and 20 cm, respectively. The last three scenarios have the same water depth of 75 cm and the same wave height of 5 cm, but different dam materials of Donghekou, Tangjiashan and Xiaogangjian, respectively. The waves in the six scenarios are all sine waves with the period of 2 s.

Table 1. Test scenarios

Scenario	Dam material	Water depth（cm）	Wave height (cm)	Period（s）	Wave form
1	Donghekou	55	5	2	Sine wave
2	Donghekou	55	10	2	Sine wave
3	Donghekou	55	20	2	Sine wave
4	Donghekou	75	5	2	Sine wave
5	Xiaogangjian	75	5	2	Sine wave
6	Tangjiashan	75	5	2	Sine wave

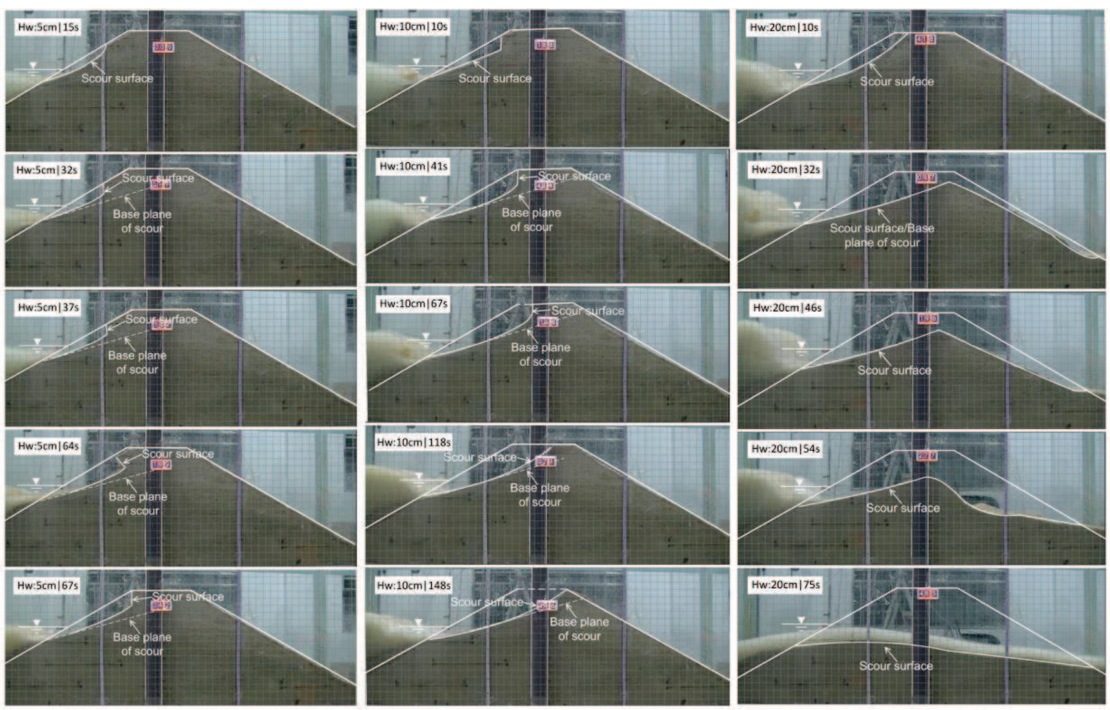
3 Test results

3.1 Erosion characteristics

In scenario 1 with relatively low wave height of 5 cm, the waves erode the upstream dam slope and gradually forms a scour datum plane, as shown in the dashed line in Fig. 3(a) and Fig. 4(a). The subsequent erosion processes are developed on the basis of this datum. In the process of wave erosion, the upstream dam slope will continue to suffer from local instability. Finally, as the wave climbing height is not enough to cause further erosion of the dam, the upstream dam slope will form a stable erosion surface with the angle of 18.4°.

In scenario 2 with relatively higher wave height of 10 cm, the erosion become faster with larger climbing height. Despite of the existing of a stable erosion surface like the Scenario 1, the surface is have flatter angle of 15.0°, even reach the downstream dam slope.

In scenario 3 with the highest wave height of 20 cm, the waves do not only erode the upstream dam slope, but also climb over the dam crest, causing erosion of the dam crest and downstream dam slope. After that, the dam begin to breach and finished at 75 s after the action of water wave.



(a) (b) (c)

Fig. 3. The snapshots of the first three scenarios with different wave heights: (a) Scenario 1 with 5 cm; (b) Scenario 2 with 10 cm; (c) Scenario 3 with 20 cm

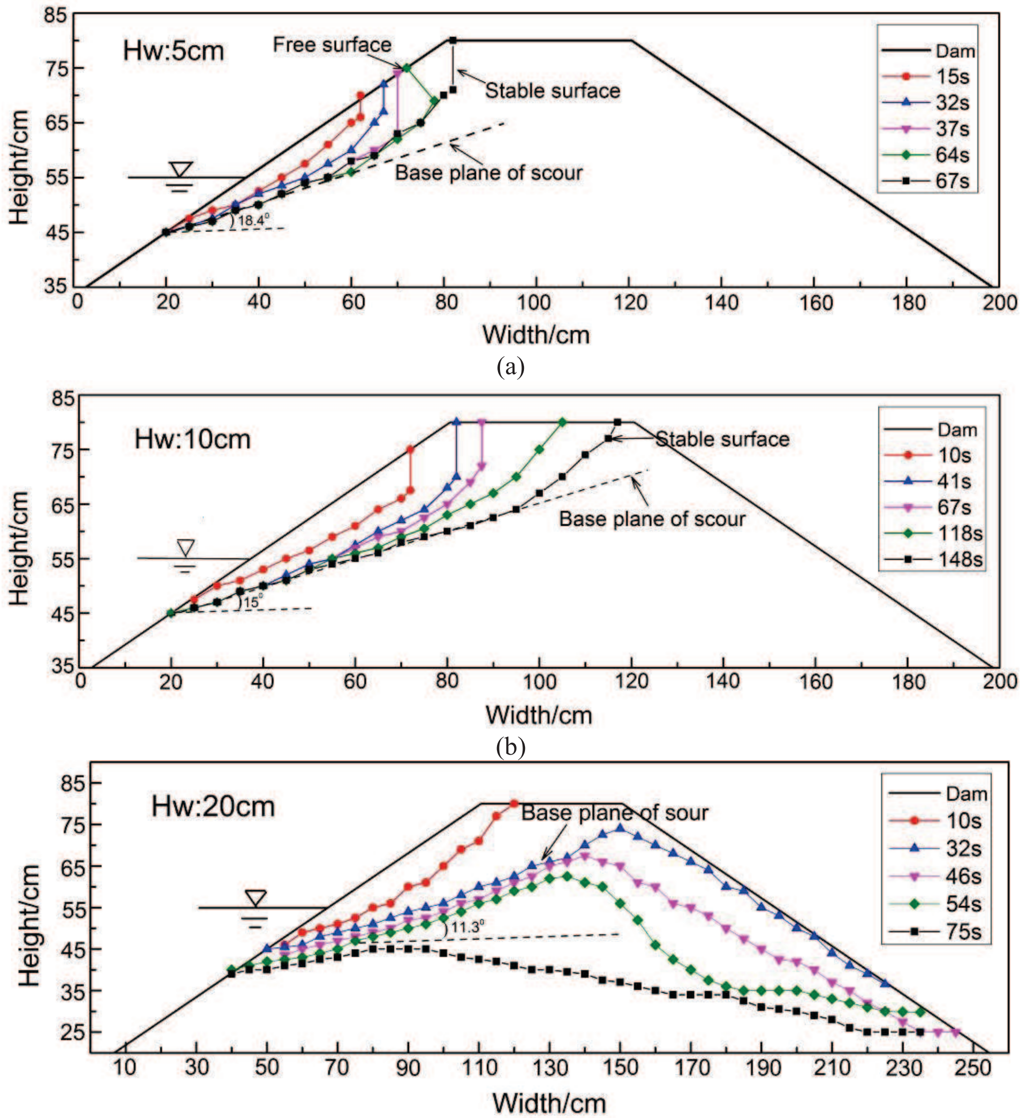
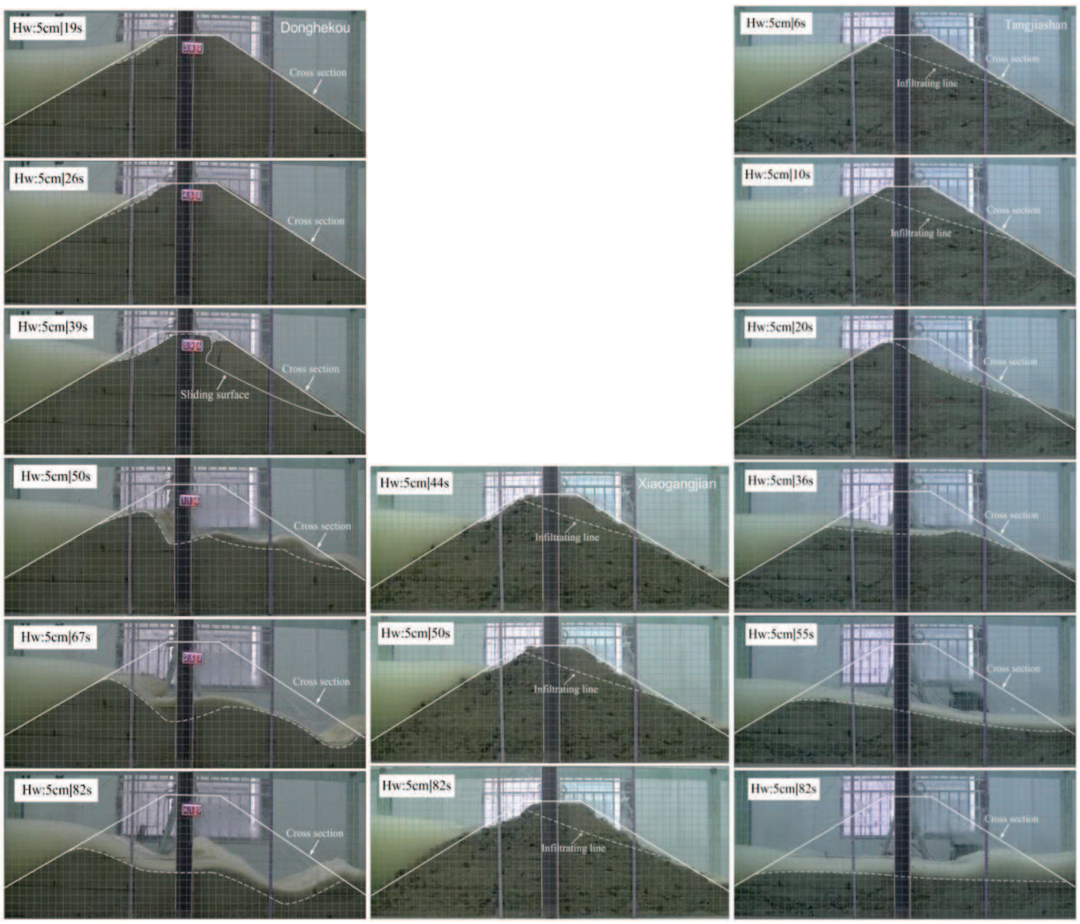


Fig. 4 Schematic diagram of dam erosion with different wave heights: (a) Scenario 1 with 5 cm; (b) Scenario 2 with 10 cm; (c) Scenario 3 with 20 cm

Comparing to Scenario 1 with reservoir water level of 55 cm, Scenario 4 has higher reservoir water level of 75 cm. The water wave climb over the dam crest and cause initial erosion at the bottom of the downstream slope, as shown in Figs. 5(a) and 6(a). Gradually, the erosion reach the dam crest at 32 s after the wave action. The dam starts to breach at around 41 s and finishes at around 82 s after the wave action. The breaching of the landslide dam under wave action is much faster than without the wave.

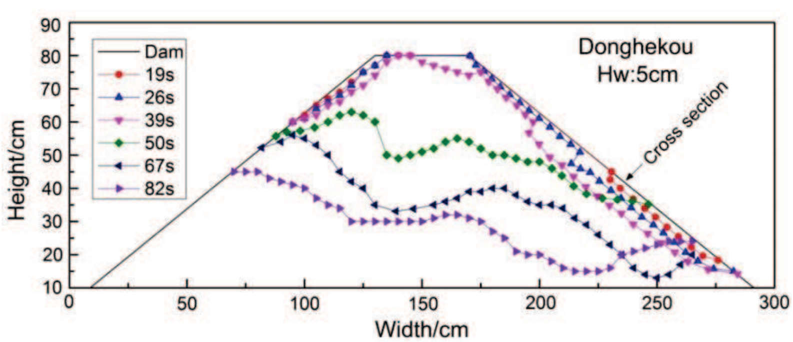
With coarser particles of the Xiaogangjian landslide dam materials, Scenario 5 is more stable than that with finer particles. Erosion only occurs on the upstream slope and part of the dam crest. The seepage in this scenario is much larger than Scenario 4 due to high permeability of coarser particles. Part of the wave energy is diminished by the infiltration into the pores among the large particles.

In Scenario 6 with the Tangjiashan landslide dam materials, the erosion process is more or less like the regular dam breaching without the surge action. Water flow erodes the downstream slope firstly and then the dam crest. When the erosion reach the upstream slope, the landslide dam starts to breach with a high speed. However, the erosion rate with wave action is obviously faster than that of the dam breaching without wave action.

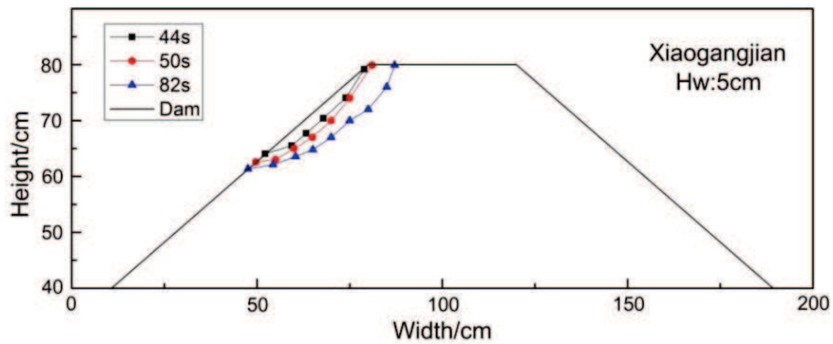


(a) (b) (c)

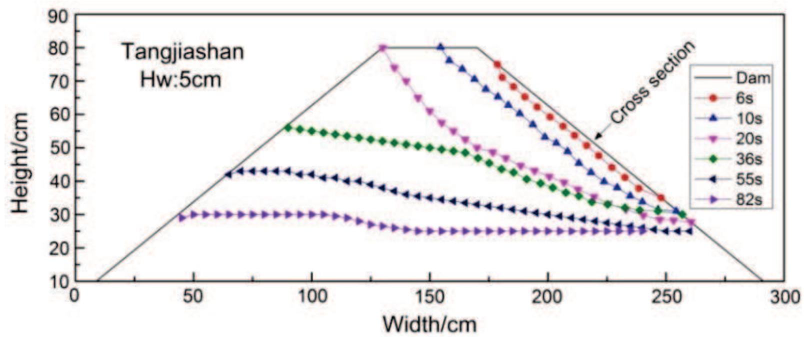
Fig. 5. The snapshots of the last three scenarios with different landslide dam materials: (a) Scenario 4 with Donghekou landslide dam materials; (b) Scenario 5 with Xiaogangjian landslide dam materials; (c) Scenario 6 with Tangjiashan landslide dam materials



(a)



(b)

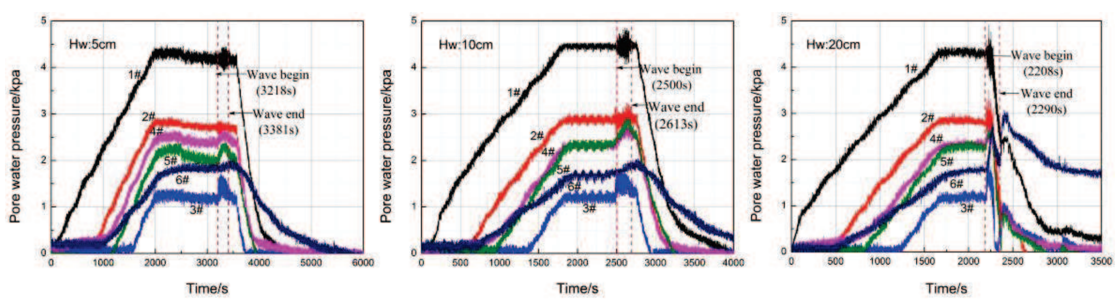


(c)

Fig. 6. Schematic diagram of dam erosion with different landslide dam materials: (a) Scenario 4 with Donghekou landslide dam materials; (b) Scenario 5 with Xiaogangjian landslide dam materials; (c) Scenario 6 with Tangjiashan landslide dam materials

3.2 Pore water pressure

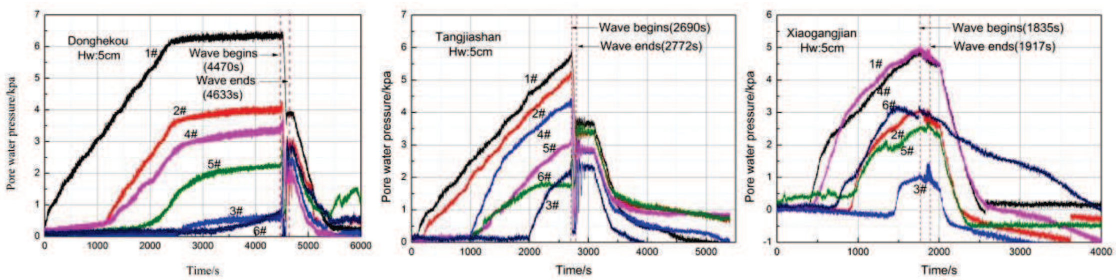
In the first three scenarios as shown in Fig. 7, the water pressures increase gradually during the water filling stage. The rise rate of the #6 gauge is smaller since it locates in the downstream part. The water pressures remain stable after the water level reach 55 cm. The water pressures vibrate during wave action periods. Generally, the changes of the water pressure are higher with large wave heights from Scenarios 1-3. There is sharp drop of the water pressure in Scenario 3 because of the dam breaching. Note the decrease of the water pressure at the end of the tests is because of the artificial removing of the dam materials.



(a) (b) (c)

Fig. 7. Water pressures in the first three scenarios with different wave heights: (a) Scenario 1 with 5 cm; (b) Scenario 2 with 10 cm; (c) Scenario 3 with 20 cm

Fig. 8 shows the water pressures of the last three scenarios. The water pressure in Scenario 4 and 6 drop rapidly soon after the action of water waves due to the dam breaching. The water pressure decease gradually in Scenario 5 with coarse particles (Fig. 8c). The reason is that the dam is not breached and the relatively large seepage leads to drop of reservoir water level.



(a) (b) (c)

Fig. 8. Water pressures in the last three scenarios with different landslide dam materials: (a) Scenario 4 with Donghekou landslide dam materials; (b) Scenario 6 with Tangjiashan landslide dam materials; (c) Scenario 5 with Xiaogangjian landslide dam materials

4 Conclusion

This paper conducts stability analysis on landslide dam under surge action based on large-scale experiments. The following conclusions could be drawn:

(1) The dam stability is controlled by the relationship of the dam height and the actual water level which is determined by the reservoir water level and the wave height. If the actual water level is lower than the dam height, the surge wave would result in a stable eroded surface; otherwise, the landslide dam would be breached by the wave action with obviously higher speed.

(2) The erosion of the landslide dam dominated by fine particles is relatively easier and will breached with curve shape under the action of waves. The landslide dam dominated by coarse particles is relatively more stable. The wave-acted dam breaching process of the landslide dam dominated by mixed particles is similar to that without the action of wave action, but the dam breaching of the former is much faster.

(3) The wave action on landslide dam would not incur liquefaction due to relatively loose structure. The pore water pressure would vibrate during the wave action period and drop rapidly when the dam starts to breach.

Acknowledgments

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