D204

Study on Progressive Failure on Landslide Dam Subjected to Seepage Flows Using Centrifuge Test

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Abstract

Landslide dams (LDs) are deposited landslide material that blocks a river. They are mostly located in hilly areas and are a potential threat to human lives, infrastructure, and facilities. To mitigate LD, an understanding of its failure mechanisms is needed. This study conducted a series of centrifuge tests to examine the failure mechanisms of LD. The result shows that the continuous settlement and rise of the water level in the upstream lake facilitated the increase in pore water pressure (PWP), leading to progressive failure. When progressive failure happened, high PWP was observed. This study shows that in relatively low density, the increased water table can cause fluidized sliding behavior, leading to a catastrophic failure of the LD.

1. Introduction

When landslide material is deposited on and blocks the river valley, it's called a landslide dam (LD). If LDs are in mountainous areas, they become a potential threat to lives, infrastructure, and the environment. Many studies have been conducted to investigate the failure characteristics of the LD.

Many studies focused on the effect of the soil properties on the hydraulic aspects of the LD breach, such as erosion-deposition, breach mechanism, breach hydrograph (Hu et al., 2024). Most of the above-mentioned studies use flume and or large-scale field tests.

However, most flume-test-based LD failed under surface erosion and overtopping due to the lack of stress level replication in flume tests. Zheng et al. (2024) conducted a study using a small-scale flume test and full-scale field test to understand the failure mechanism of the LD on different scales. They concluded that the small scale can be beneficial in studying the failure process but not in predicting the stress level of the failure. In the flume test, the failure mechanism of the dam also changes when soil size is used in different sizes (Schmocker & Hager, 2009).

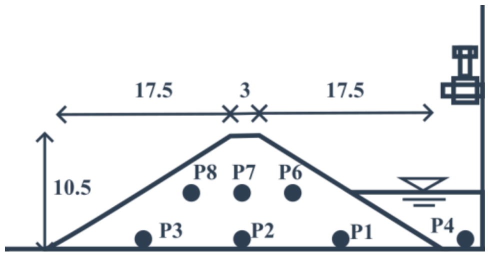
To tackle the stress level issue in the flume test, the centrifuge test can be used to replicate the same stress level of the prototype in a small-scale model. In contrast to the flume test, most centrifuge test studies are focused on geotechnical aspects of slope/dam/LD failure, such as water level-induced failure (Ma & Zhang, 2023), static-liquefaction (Askarinejad et al., 2015), rainfall-induced failure (Ling et al., 2009). Hydraulic aspects of dams/LDs also have been studied, such as overtopping, breach hydrographs, breach process (Mei et al., 2023).

However, it's very rare in the literature to investigate the failure mechanism of LD from the hydro-geotechnical aspects of LD breaching using a centrifuge. The objective of this study is to investigate the influences of soil density on the failure mechanism of LD using a centrifuge. Six centrifuge tests were conducted to examine the failure mechanism and the change of failure mode on LDs.

2. Materials and Methods

Six LD test cases were prepared with dry densities ranging from 1.001 tons/m^3 to 1.441 tons/m^3, representing low and moderate to high soil density. Three and six sensors were installed to monitor PWPs inside the LD bodies on tests 1 – 3, which are P1 – P3, and tests 4 – 6, which are P1 – P6, respectively (**Figure 1**).

After preparing the samples using a wet-tamping method, the sample was mounted to a geotechnical centrifuge at the Disaster Prevention Research Institute (DPRI), Kyoto University. The acceleration of the centrifuge gradually increased until reaching 50g. Then, the valve was opened to allow the influx discharge to fill the upstream lake. The increase of upstream water level and PWPs inside LD were recorded. The test was terminated whenever the LD failed, the reservoir was empty, or the disposed water reached the test area.



(a) (b)

Figure 1. LD dimension and sensors placements.

3. Results

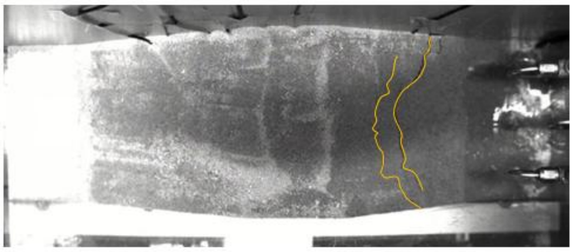
3.1 Failure mechanism

The failure mechanism of two soil groups, i.e., low and moderate to high density, exhibited two different mechanisms. Although both groups experience seepage on the toe, the response to the seepage is different.

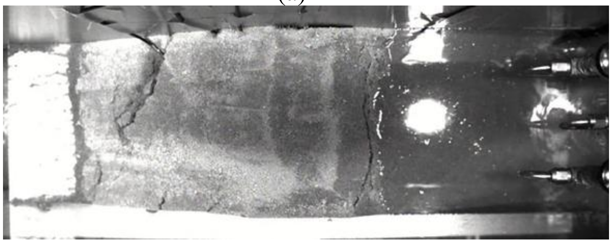
The low-density group responded to the seepage by a progressive failure leading to the breach, except for test 1. Due to the high influx discharge, test 1 experienced minor failure and overtopping.

The moderate to high-density group responded to the seepage with minor failure at the toe (tests 3 and 5). However, in test 5, the minor failure escalated upstream. Although the influx discharge was relatively high, the LD remained stable.

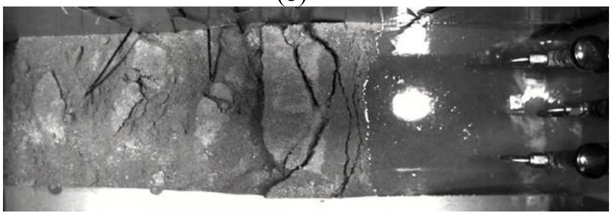
Here, we only show the result of test 4, representing the low-density group. The failure mechanism of test 4 is shown in **Figure 2**. Due to LD's low density, settlement occurred during the spin-up of the centrifuge acceleration, resulting in a crack in the upstream slope. Another crack at the upstream slope developed when the upstream level increased **Figure 2**(a).



(a)



(b)



(c)

Figure 2. The failure mechanism of LD is rising at the upstream level.

The water table inside LD continuously increased with the rise of the upstream level. Due to the reduction of the strength, some cracks developed **Figure 2**(b). The cracks eventually failed, triggering the retrogressive failure **Figure 2**(c). This failure led to the LD breaching.

3.2 Pore water pressure

PWPs of test 4 during the test are shown in **Figure 3**. After the upstream lake was filled with water, the LD experienced a settlement. Sensors P2 and P3 responded to the settlement with a sudden increase of PWPs. Gradually, the excess PWPs were dissipated, and the PWPs continuously increased along with the settlement. The seepage and the development of the cracks took place, but the PWP sensors didn’t respond to it until progressive failure, leading to a breach.

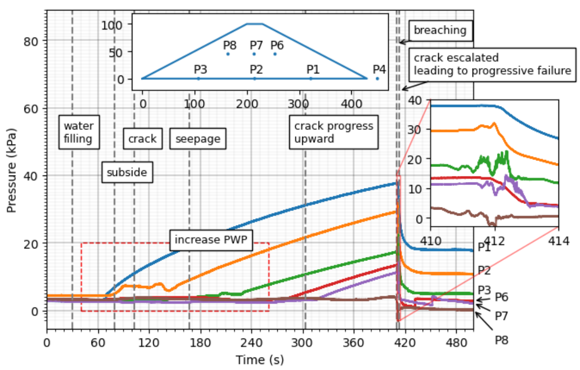


Figure 3. PWPs during the test.

Right after the breach, the PWPs suddenly dropped. During the breach, the PWPs were observed to fluctuate. This fluctuation in PWPs seems to be caused by the sudden change in the volume of void in the LD due to rapid failure. The rapid contraction of the soil prevented the pore water from dissipating quickly, leading to the partially undrained condition.

The trapped pore water developed a rapid increase in PWPs, which were recorded by the sensors as sudden fluctuations. The increase in PWPs resulted in reduced soil strength. The soil becomes fluidized, leading to retrogressive failure in the LDs and the breach.

4. Conclusion

A centrifuge test was conducted at DPRI, Kyoto University. The test successfully replicated the failure of the landslide dam due to retrogressive failure. In relatively low density, the LD undergoes settlement, leading to rapid increases in PWPs. After the dissipation process, the continuous increase in the water table and settlement tend to develop high PWP, resulting in a significant decrease in soil strength.

A significant increase in PWPs triggered the retrogressive failure, leading to the LD breach. During the retrogressive failure, the fluidization of the sliding material was observed.

5. References

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