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Evolution of Landslide Dam Breach Mechanisms Observed in Centrifuge Tests: From Progressive Erosion to Sliding and Fluidized Failure

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1. Introduction

If a river is blocked by deposition of landslide material, it's called a landslide dam (LD). LDs are almost exclusively located in mountainous areas in a relatively narrow river valley and spread worldwide. Due to the potential energy stored in the lake created by its blockage, which is mostly located in an elevated area, it poses a threat to lives, infrastructure, and the environment. It's necessary to study in order to mitigate the threat. However, many LDs have a short lifetime, i.e., more than 60% LDs failed within two months, and are located in a rugged topography and harsh climate, which makes the in-situ study challenging.

One popular method for assessing slope stability and landslide phenomena is the laboratory shear test. Many studies have investigated the stress–strain behavior to investigate the failure process. By collecting samples near the sliding surface, triaxial or ring shear tests are conducted test (e.g., Rabbi et al., 2019; Wang & Sassa, 2002). Although the stress-strain relations obtained by these laboratory approaches are valuable for characterizing shear behavior, they often fail to capture the influence of environmental factors, such as internal erosion, surface erosion, and overtopping. To address these limitations, physical modeling has been widely adopted (e.g., Fu et al., 2025; Luo et al., 2025; Takayama et al., 2021; J. Zhang et al., 2021), including flume tests, which have gained popularity due to their cost-effectiveness, versatility, and suitability for investigating coupled geotechnical and hydraulic processes.

Although flume tests are convenient and widely used, most LD failures conducted in flumes are due to overtopping, surface erosion, or shallow sliding failure. It can be caused by the flume test stress level being relatively low compared to that in the prototype, thereby changing the failure type.

To address the stress level issue in the flume test, the centrifuge test can be used to replicate the prototype's stress level in a small-scale model. However, the use of a centrifuge to investigate the failure process of LDs remains limited, with most studies focusing on overtopping.

In contrast, the use of a centrifuge to investigate the slope failure or landslide is focused on sliding failure, including deep-seated failure (e.g., Cho et al., 2024; Ng et al., 2023; Wang et al., 2025; Zhang et al., 2024). However, the loading condition for slope failure/landslide is different from that for LD; in slope failure, overtopping is rare.

Until now, studies of LD failure have not examined overtopping, surface erosion, and deep-seated failure in a single study, making it difficult to understand how conditions govern the evolution of the failure process from one failure to another. In this study, 25 centrifuge tests were conducted to investigate a wide range of failure processes within a single framework under various conditions, including initial dry density, soil type, soil particles' mean diameter, LD downstream slope length, LD upstream slope length, and influx discharge rate.

2. Materials and Methods

Twenty-six LD test cases were prepared using the wet-tamping method under various conditions: i) soil type used are silica No. 7 and 8, tephra, masado, and mix of masado-halloysite soil, b) the mean diamter are ranging from 0.05 mm to 0.4 mm, c) the dry densities ranging from 1.022 g/cm^3 to 1.842 g/cm^3, d) the downstream slope are from 15 to 20 cm, e) the upstream slope are from 15 to 17 cm. Three to six sensors were installed to monitor PWPs inside the LD bodies (**Figure 1**). The sample was then mounted on a geotechnical centrifuge at the Disaster Prevention Research Institute (DPRI), Kyoto University. The centrifuge acceleration gradually increased until reaching 50g. Then the valve was opened to allow water to flow into the upstream lake. The increase in upstream water level and PWPs inside LD was recorded. The test was terminated whenever one of the three conditions was met first, i.e., 1) the LD failed, 2) the reservoir was empty, or 3) the disposed water reached the test area.

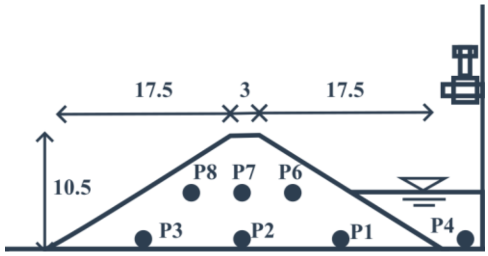

Figure 1. LD dimension and sensor placements.

3. Results

To categorize the failure mode, several failure characteristics are examined, such as i) the influence zone of the failure, ii) the erosion process, iii) sliding velocity, iv) vertical strain on each mode. The effects of soil type, mean diameter, inflow discharge rate, and LD geometry are also investigated. However, in this extended abstract, we only introduce the failure process.

During the tests, all the models experienced a similar process that can be divided into three stages: i) wetting, ii) failure, and iii) equilibrium stages. The wetting stage starts when the water infiltrates the LD body. The second stage is the failure stage. The failure can involve initial downstream toe failure, main failure, or both. After the main failure leading to the breach, the final stage is the equilibrium stage.

The scrupulous investigation of the video footage during the test and failure characteristics of the models are conducted, resulting in that failure modes can be classified into seven failure types: A) overtopping prior to failure,

B) deep-seated failure prior to overtopping, C) overtopping, D) sliding failure accompanied by overtopping without breaching, E) only sliding failure without breaching, F) progressive erosion, G) No failure. The final state during failure of the first two failure types (Type A and B) is a fluidized state, while the rest failed in a non-fluidized state.

All of the LDs experienced failures, whether minor or major, leading to breaches or not, except for the test with a very low inflow discharge rate ($1.53e^{-3}$ l/s), which was insufficient to raise the pore water pressure within the LD body to a critical level and the inflow rate was equal to the seepage rate, allowing the system to maintain a water balance and preventing the upstream reservoir from overtopping.

The progressive erosion failure tends to occur in models with a mean diameter smaller than 0.13 mm and built using Silica Nos. 7 and 8 (**Figure 2**a). The higher the mean diameter, the more likely the failure type is sliding failure (**Figure 2**b).

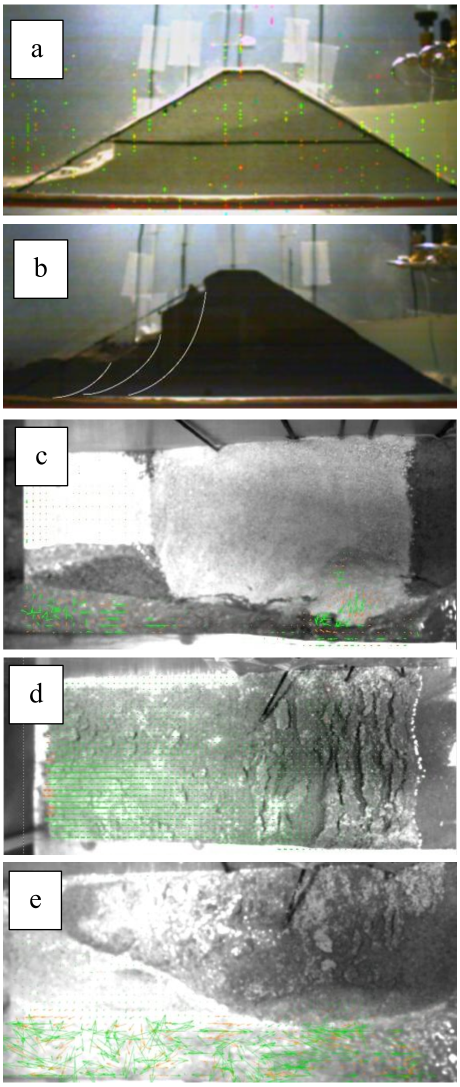

Figure 2. Failure process during the test: a) Silica-based model ($D_{10} \leq 0.13$ mm), b) Masado-based model ($D_{10} = 0.4$ mm), c) erosion process in a non-fluidized failure, d) failure in a fluidized state prior to overtopping, e) failure in a fluidized state after overtopping.

The results also indicate that a decrease in the initial dry density shifts the failure mode from non-fluidized to fluidized. In a non-fluidized failure, when overtopping occurs, the erosion process begins longitudinally, creating a diversion channel. Once it reaches the downstream toe, vertical and lateral erosion (or failure) occur almost simultaneously (**Figure 2**c). The LD's crest height decreases mostly due to surface erosion or lateral failure. In contrast, when the failure occurs in a fluidized state, the lowering LD crest is caused by sliding failure, i.e., no significant erosion (longitudinal, vertical, and lateral erosion) is observed (**Figure 2**d).

A shorter slope length slightly increases the rate of settlement within the LD body, primarily due to the shorter pore-water-escape path. This geometric change alters the failure mode from failure in a fluidized state prior to overtopping to overtopping followed by failure in a fluidized state (**Figure 2**e). The same phenomenon is encountered when the influx discharge rate is slightly increased. In this condition, overtopping occurs before the PWP reaches a critical condition, so water overtops before failure. However, during overtopping, the loss of confining pressure triggers the failure in a fluidized state.

4. Conclusion

This study aims to investigate the effects of geometry, influx discharge, soil types, mean diameter, and initial dry density on the evolution of failures in LD. We show that changes in soil type and an increase in the mean diameter shift the failure mode from progressive erosion to deep-seated failure. A decrease in initial dry density shifts the failure from a non-fluidized state to a fluidized state. A slight increase in the influx discharge rate and a decrease in the slope length can change the failure mode from fluidization prior to overtopping to overtopping prior to fluidization.

5. References

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