Influence of dam geometry on the breaching process of landslide dams

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Abstract. The breaching process of landslide dams is influenced by many factors. In this study, several laboratory experiments on the overtopping of landslide dam were conducted to investigate the specific effects of dam geometry on the breaching process of landslide dams. According to the test results, geometric parameters of the dam, including dam height, crest width, and downstream slope, had considerable effects on the breaching process. The breaching process was divided into three stages: (1) breach initiation stage, (2) breach development stage, and (3) attenuating and reequilibrium stage. Dam height reflected the volume of impoundment and affected the breach development stage. With the increase of the dam height, the peak discharge increased, and its time of arrival was delayed. The dam crest width affected the breach initiation stage. The peak discharge increased significantly, and its arrival time was shortened by the decrease in the dam crest width. Downstream slope reflected the dam stability and affected the breach initiation and breach development stages. With the decrease of the downstream slope, the peak discharge decreased, and its time of arrival was delayed considerably.

1. Introduction
Landslide dams are natural dams formed by the lateral blockages of natural rivers triggered by landslides, debris flows, volcanic eruptions, and so on (Casagli et al., 2003; Peng et al., 2019). As a type of natural hazard, landslide dams are widely distributed in mountainous areas.
worldwide as the required conditions are not difficult to attain (Shen et al., 2020). As landslide dams are formed by rapid deposition in the natural process, the materials are not compacted or remodeled by humans, and they tend to be irregularly shaped (Peng and Zhang, 2012). After the formation of a landslide dam, the water level in the upstream area gradually rises, thereby forming a barrier lake. In many cases, flooding occurs after landslide dam failures cause damages downstream of the dammed river sections. For instance, in 1933, the Diexi landslide dam burst and washed away a large number of villages and farmland along the river and caused more than 2,500 deaths (Chai et al., 2000).

Flume tests are commonly used to study the breaching process and mechanism of landslide dams (e.g., Davies et al., 2007; Zhao et al., 2015; Zhao et al., 2019; Zhou et al., 2019). Chen et al. (2015) used flume tests to simulate earthquake- and rainfall-induced landslide dam failures for various dam shapes and materials and found that dam shape affects the life span of dams and their corresponding failure modes. Considerable progress has also been made in the study of the breaching process and mechanism of landslide dams. However, existing research is more focused on the breaching process of artificial dams than on that of landslide dams in relation to dam morphology. Given the devastating consequences of landslide dam failures, it is important to study the influence of dam geometry on the breaching process of landslide dams.

2. Experimental setup

2.1 Experimental apparatus
In this study, the experiments were conducted in a tailored flume, as shown in figure 1. The experimental apparatus consisted of three parts: the flow supply device, the flume test section, and the tail bay. The length, width, and height of the flume channel were 5.0, 0.4, and 0.4 m, respectively. The slope of the flume bottom was 1°. The bottom of the flume was a steel structure. Both sides of the flume were made of transparent acrylic sheets. The experimental phenomena in the flume could be observed and recorded directly through the transparent glass. The flow supply device measured 2.0 m × 2.0 m × 1.0 m (length × width × height) and was placed in the front section of the flume channel. During the experiments, the inflow was supplied by the flow supply device at a constant flow rate and was accurately controlled with an electromagnetic flow meter. The inflow rate $Q_{in}$ used in the experiments was 1.0 L/s. The tail bay measured 1.0 m × 1.0 m × 0.5 m (length × width × height) and was used to collect the water and sediments from the flume channel.

![Figure 1. Experimental apparatus.](image-url)
2.2 Dam model

Dams with different geometric shapes and characteristics were simulated in the flume tests to investigate the influence of dam geometry on the breaching process of landslide dams. The characteristic dimensions of typical landslide dams are summarized in Table 1 (Chang and Zhang, 2010). As dam breaching starts in the downstream slope, the influence of the upstream slope could be ignored herein (Yang and Cao, 2015). The dam length was equal to the flume width and remained the same in the experiments. Thus, three geometric parameters were selected to represent the geometrical characteristics of landslide dams in the tests: dam height, dam crest width, and downstream slope. All the geometric dimensions of the model dams in this study are summarized in Table 2. Different dam heights $H$ (18, 24, and 30 cm), dam crest widths $C$ (0, 12, and 24 cm), and downstream slopes $S_d$ (1:1.5, 1:2, and 1:2.5) were set in the tests. An initial triangular breach was set at the side of the dam whose depth, top width, and side slope were 5 cm, 8 cm, and 1:1.6, respectively, as shown in figure 2. The dam was located 210 cm away from the front section of the flume channel. Geometric scaling laws must be satisfied in preparing dam models. Herein, the dam geometry and barrier lake volume were carefully considered. They were described by three dimensionless numbers, namely, ratio of height to width ($H/B$), dam shape coefficient ($V_d^{1/3}/H$), and lake shape coefficient ($V_l^{1/3}/H$), where $H$, $B$, $V_d$, and $V_l$ are the dam height, dam bottom width, dam volume, and dammed lake volume, respectively (Peng and Zhang, 2012). All the three dimensionless numbers of the model dams in this study were evaluated against those of 80 real landslide dams, and they were found to fall within the reasonable range of values (Zhou et al., 2019).

| Table 1. Characteristic dimensions of typical landslide dams. |
|---------------------------------------------------------------|
| Real landslide dam       | Dam height $H$ (m) | Dam crest width $C$ (m) | $H/C$ | Upstream slope $S_u$ | Downstream slope $S_d$ |
|--------------------------|---------------------|------------------------|-------|----------------------|------------------------|
| Tangjiashan              | 82–124              | 300                    | 0.27–0.41 | 1:2.75–1:3.08     | 1:1.19–1:1.43        |
| Laoyingyan               | 130                 | 240                    | 0.54  | -                    | 1:1.88                |
| Xiaogangjian             | 70                  | 24                     | 2.92  | 1:2.75               | 1:1.73                |
| Yangjiagou               | 50–60               | 160                    | 0.31–0.38 | 1:2.75     | 1:2.75–1:3.73        |

| Table 2. Summary of flume test conditions. |
|--------------------------------------------|
| Test No. | Dam height $H$ (cm) | Dam crest width $C$ (cm) | $H/C$ | Upstream slope $S_u$ | Downstream slope $S_d$ | Dam bottom width $B$ (cm) | Dam length $L$ (cm) |
|---------|---------------------|------------------------|-------|----------------------|------------------------|------------------------|-------------------|

3
Four digital video cameras were installed above the dam, on the side of the dam, at the end of the flume, and on the side of the barrier lake to record the panoramic experiment (figure 2). All the dam breaching status, breach developments, and dam section evolutions were observed and recorded during the breaching process. The outflow discharge $Q_{out}$ during the breaching process was calculated from the water depth upstream of the dam. The cameras used in the experiment were GZ-R10BAC produced by JVC, which could provide high-quality videos of the breaching process.

![Figure 2](image_url)

**Figure 2.** Landslide dam model and measurements.

### 2.3 Dam material

The typical grain size distribution of the Tangjiashan landslide dam in China was selected to prepare the dam material, as shown in figure 3(a). The Tangjiashan landslide dam was the largest one induced by the Wenchuan earthquake in 2008, and it is mainly composed of marl, sandstone, siliceous rock, and mudstone (Chang and Zhang, 2010). The grain size of a real landslide dam may vary by several orders of magnitude, and some large particles may be several meters in diameter. Thus, the grain gradation curve of the dam model representing the average level was selected from the sieving test results. This type of method has been adopted by numerous researchers (e.g., Xu et al., 2015; Zhou et al., 2015; Wang et al., 2018).

In the current study, pebbles and quartz sand of various sizes were mixed in different proportions to prepare the dam models. As shown in figure 3(b), the pebbles and quartz sand were sieved into 10 different ranges of particle size: 20–40, 10–20, 6–10, 4–6, 2–4, 1–2, 0.5–1, 0.18–0.5, 0.125–0.18, and ≤0.125 mm. First, the percentage content of each grain size group

|   | 18 | 24 | 0.75 | 1:2 | 1:1.5 | 87 | 40 |
|---|----|----|------|-----|-------|----|----|
| 2 | 24 | 24 | 1    | 1:2 | 1:1.5 | 108| 40 |
| 3 | 30 | 24 | 1.25 | 1:2 | 1:1.5 | 129| 40 |
| 4 | 24 | 12 | 2    | 1:2 | 1:1.5 | 96 | 40 |
| 5 | 24 | 0  | -    | 1:2 | 1:1.5 | 84 | 40 |
| 6 | 24 | 24 | 1    | 1:2 | 1:2   | 120| 40 |
| 7 | 24 | 24 | 1    | 1:2 | 1:2.5 | 132| 40 |
was determined on the basis of the grain gradation curve. Second, the total weight of the dam model was calculated, and the corresponding grain size group was obtained. Finally, the composition was fully mixed to ensure that the dam materials were homogeneous.

![Grain Gradation Curve](a)

![Pebbles and Silica Sand](b)

**Figure 3.** Experimental materials: (a) grain gradation curve; (b) pebbles and silica sand.

### 2.4 Test procedure

The detailed test procedure in this study is as follows:

1. The dam outline and transparent grid on the flume wall were drawn according to the shape and size of the predesigned dam. Herein, the dam was built in three layers by using a density control method. The dry density of the dam was 1.78 g/cm³, which was within the acceptable range.

2. Four cameras were arranged outside the flume. The flow supply device was turned on, and the water flow was controlled with an inflow rate of 1.0 L/s. Meanwhile, all cameras were set to record the experiment.

3. When the dam either became fully damaged or remained stable, the flow supply device and measurements were stopped, and the test was terminated.

4. The residual dam from the flume was removed, and a new dam was rebuilt for the next group of tests.

### 3. Experimental results

As shown in table 2, the seven tests were divided into three groups according to dam geometric shapes and characteristics: different dam heights (Tests 1–3), different dam crest widths (Tests 2, 4, and 5), and different downstream slopes (Tests 2, 6, and 7). In the succeeding discussions, \( t = 0 \) denotes the moment when the inflow began overflowing the initial breach.
3.1 General features

The dam breaching processes were found to be similar between different tests. The dams with different geometric dimensions all failed by overtopping. The breaching process of Test 2 is shown in figure 4. The experimental results revealed that dam breaching began with the initial breach. Next, a scarp was observed on the downstream slope and its geomorphologic feature was similar to a waterfall (see \( t = 52 \) s in figure 4). As the overflow constantly eroded the downstream slope, the scarp collapsed and began to move upstream (see \( t = 92 \) s in figure 4). Later, the erosion extended toward the upstream slope (see \( t = 123 \) s in figure 4). A lateral collapse occurred at the entrance of the breach, and the breach entrance expanded (see \( t = 134 \) s in figure 4). The enlarged breach entrance allowed a large amount of water to be released from the reservoir. Then, the longitudinal section surface of the dam changed drastically with a wave-like type (see \( t = 155 \) s in figure 4). During the breaching process, the outflow discharge increased and then decreased. An armored layer was created on the breach surface as the outflow discharge decreased because the low outflow discharge could only transport fine materials. The dam height remained constant because the armored layer protected the sediments that could not be washed away (see \( t = 210 \) s in figure 4). At the end of the test, the outflow discharge was reduced to the inflow rate.

![Figure 4. Breaching process of dam in Test 2.](image)

The longitudinal evolution process of the dams in this study is shown in figure 5. From the hydrograph and longitudinal dam profiles, the breaching process of the dams could be generalized as three distinct stages. Stage I (breach initiation) involved the overflow until the erosion of the upstream slope. In Stage I, the outflow discharge was small, and the breach changed slowly. The breach lateral collapse occurred intermittently, and the volume was small. Stage II (breach development) started from the erosion of the upstream slope and lasted until the erosion stopped at the entrance of the breach. In Stage II, the outflow discharge increased rapidly and reached the peak. The breach developed in the lateral and vertical directions simultaneously. The breach lateral collapse occurred frequently, and the average volume was larger than that in Stage I. When Stage III (attenuating and reequilibrium stage) started, the
outflow discharge became too small to cause considerable vertical and lateral erosion, and an armored layer gradually formed. The residual dam remained stable, and the breach reached its final dimensions. When the outflow discharge was equal to the inflow rate, the whole breach process ended. As the breaching characteristics of the three stages were distinct, clearly defining these three stages could facilitate the illustration of the breaching process, especially when making a quantitative comparison of different tests (table 3).

Table 3. Results of flume tests employing different dam geometries.

| Test no. | Stage I duration (s) | Stage II duration (s) | Stage III duration (s) | Breaching duration (s) | Peak discharge (L/s) | Arrival time of peak (s) |
|----------|----------------------|-----------------------|------------------------|------------------------|----------------------|-------------------------|
| 1        | 121                  | 54                    | 87                     | 262                    | 1.97                 | 135                     |
| 2        | 123                  | 82                    | 75                     | 280                    | 3.01                 | 155                     |
| 3        | 136                  | 104                   | 67                     | 307                    | 3.66                 | 165                     |
| 4        | 93                   | 81                    | 62                     | 236                    | 3.46                 | 115                     |
| 5        | 61                   | 67                    | 37                     | 165                    | 4.19                 | 80                      |
| 6        | 177                  | 109                   | 57                     | 343                    | 2.62                 | 190                     |

Figure 5. Longitudinal evolution processes of dams in Tests 1–7.
Influence of dam height

The dams of Tests 1–3 had dam heights of 18, 24, and 30 cm, respectively. The outflow discharge hydrographs for Tests 1–3 are shown in figure 6. Each hydrograph went from a low flow discharge at Stage I to the outburst at Stage II. Then, the outflow discharge decreased gradually at Stage III. Table 3 indicates that the dam height affected the peak outflow discharge and changed the breaching duration in Tests 1–3. Apparently, the peak discharge increased with an increase in the dam height. The peak discharge of the dam measuring 18 cm high in Test 1 was 1.97 L/s. When the dam height increased to 24 cm in Test 2 and 30 cm in Test 3, the peak discharge increased by approximately 53% and 86% of those in Test 1, respectively. The reason was that the dam height reflects the volume of impoundment and potential impact force of water flow. In this work, the arrival time of the peak discharge was delayed slightly by the large dam height. With an increase in the dam height, the durations of Stages I and III were similar in Tests 1–3, whereas that of Stage II lasted much longer, as shown in table 3. Hence, the dam height changed the breaching duration mainly by affecting the breach development stage (Stage II). Figure 5 also shows that the breach deepened substantially and sharply when the dam height was high. The experimental results indicated that the higher dam height could increase the risks and dangers of the dam breaching process.

| 7  | 293 | 125 | 38 | 456 | 2.19 | 270 |

3.2 Influence of dam height

Figure 6. Outflow discharge hydrographs for Tests 1–3.

Figure 7. Outflow discharge hydrographs for Tests 2, 4, and 5.

Figure 8. Outflow discharge hydrographs for Tests 2, 6, and 7.

3.3 Influence of dam crest width

The dams of Tests 2, 4, and 5 had crest widths of 24, 12, and 0 cm, respectively. The longitudinal section of the dams in Tests 2 and 4 was a trapezoid while the longitudinal section of the dam in Test 5 was a triangle. The discharge hydrographs for Tests 2, 4, and 5 are shown in figure 7. The differences in the hydrograph shapes in Tests 2, 4, and 5 were mainly caused by the differences in the dam crest widths. Figure 7 shows that the smaller the dam crest width is, the larger the peak discharge is, and the earlier the arrival time of the peak discharge is. In this study, the peak discharge of the triangular dam without crest in Test 5 was the largest at 4.19 L/s, and its arrival time was the earliest at \( t = 80 \) s. When the dam crest width increased to 12 cm in Test 4 and 24 cm in Test 2, the peak discharge decreased by
approximately 17% and 28%, and the arrival times were prolonged to 1.44 and 1.94 times of that in Test 5, respectively. The primary reason for this discrepancy was that the decrease of the dam crest width caused the breach erosion to extend toward the upstream slope quickly, thereby enhancing the erosion ability of the outflow. Thus, the shape of the discharge hydrograph tended to vary from a broad one to a lanky one with a decrease in the dam crest width (figure 7). The speed of the breach formation was related to the dam crest width, and the dam crest width changed the duration of breaching mainly by affecting the breach initiation stage (Stage I), as shown in figure 5. The experimental results indicated that a small dam crest width could increase the dangers of dam breaching by increasing the peak discharge significantly and shortening its arrival time.

3.4 Influence of downstream slope
The dams of Tests 2, 6, and 7 had downstream slopes of 1:1.5, 1:2, and 1:2.5, respectively. The discharge hydrographs for Tests 2, 6, and 7 are shown in figure 8. An analysis of the discharge hydrographs indicated that the downstream slope of the dams had a considerable effect on the breaching parameters. Figure 8 shows that the smaller the downstream slope is, the smaller the peak discharge is, and the later the arrival time of the peak discharge is. In Test 2, the peak discharge of the dam with the 1:1.5 downstream slope was 3.01 L/s, and its arrival time was at $t = 155$ s. When the downstream slope decreased to 1:2 in Test 6 and 1:2.5 in Test 7, the peak discharges decreased by 13% and 27%, and the arrival times were prolonged to 1.23 and 1.74 times to those in Test 2, respectively. Figure 8 also shows that the style of the discharge hydrograph tended to vary from unimodal to a multimodal one with a decrease in the downstream slope. The reason was that the downstream slope reflected the dam stability and erosion resistance on the downstream surface. When the downstream slope decreased, the supercritical flow on the downstream slope became the subcritical flow gradually, and the headward and deep-cutting erosion rate in the breach decreased substantially. The breach deepened slowly, and the residual dam height increased with a decrease in the downstream slope, as shown in figure 5. Thus, when the downstream slope decreased constantly, Stages I and II in the breaching processes of the dams lasted much longer because of the strong dam stability (table 3). Moreover, the duration of Stage III was shortened, and the entire breaching duration was prolonged with the decrease of the downstream slope. This result indicated that the downstream slope changed the breaching duration mainly by affecting the breach initiation stage (Stage I) and the breach development stage (Stage II). The experimental results indicated that a small downstream slope could significantly reduce the risks and dangers of dam breaching.

4. Conclusions
Through a series of laboratory experiments on landslide dam overtopping, this study investigated the breaching process and influence of dam geometry on breaching parameters. Some key conclusions are drawn as follows:
(1) The breaching process of the landslide dam in this study could be divided into three stages. Stage I referred to the breach initiation stage with slow breach erosion. Stage II was the breach development stage with severe breach erosion. Stage III was the attenuating and reequilibrium stage with the formation of an armored layer; at this stage, breach erosion gradually stopped.

(2) The breaching process was substantially affected by the dam geometric characteristics, including dam height, crest width, and downstream slope. With the increase in the dam height, the volume of the impoundment increased and duration of Stage II prolonged. Meanwhile, the peak discharge increased and its arrival time was delayed.

(3) With the increase in the dam crest width, the headward erosion rate decreased, and the duration of Stage I prolonged. This condition caused the peak discharge to decrease and its arrival time to be delayed.

(4) Downstream slope also significantly influenced the breaching process. With the decrease of the downstream slope, the peak discharge decreased and its arrival time was delayed because a small downstream slope could enhance dam stability and erosion resistance.

This study obtained important preliminary results of the breaching characteristics of landslide dams with different geometries. Nevertheless, other quantitative references involving numerical simulations in engineering should be considered in the future.

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