Experimental investigation of failure modes and breaching characteristics of natural dams

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ABSTRACT
The failure mode and breaching time of a natural dam are affected by many factors. To comprehensively analyse the effects of these factors on dam failure modes, 159 runs of laboratory experiments were performed with 11 channel bed slopes, 4 dam geometric shapes, 3 construction materials, and 8 inflow rates. Through these experiments, two types of failure modes were identified. The results show that for lower permeability coefficients of the dam material, the overtopping failure mode will more likely occur. When the permeability coefficient and angle between the downstream slope and the horizontal plane are both high, slope failure occurs. When other conditions are unchanged, an increase in the channel bed slope and a decrease in the inflow discharge will result in slope failure. As the channel bed slope increases, the failure mode will change from the overtopping failure mode to the slope failure mode and back to the overtopping failure mode. A new parameter, \( C_{ig} \) (an abbreviation corresponding to channel, inflow, and geometric) is defined to reflect the influences of these factors on breaching time. Under the two types of failure modes, breaching time is an exponential function of the lake volume and is a power function of \( C_{ig} \).

KEYWORDS
Natural dam; failure mode; breaching time

INTRODUCTION
Natural dams are often formed due to earthquakes, rainfall, and snow melting, which cause soil or rock to slip and block valleys or rivers (Costa and Schuster 1988; Casagli et al. 2003). The dam material is loose, underconsolidated, and prone to rapid collapse, which result in the release of a large quantity of hammed water in a short period of time, producing turbulent floods with catastrophic consequences (Korup 2002; Miller and Cruden 2002; Knight and Abril 2004; Dai et al. 2005; Davies et al. 2007). For example, on 25 August 1933, an earthquake of magnitude 7.5 occurred in Diexi, Sichuan, forming 12 natural dams (the largest of them was 160 m high) and blocking the Minjiang River. With continued inflow, the water level of the three natural dams along the mainstream of the Minjiang River continuously increased and subsequently breached, which resulted in turbulent flooding and more than 2500 deaths in the downstream area (Chai et al. 2000). In 1941, a moraine lake outburst in Lake Cohup, Huaraz, Peru, submerged one-third of the city, and approximately 6000 people lost their lives (Lliboutry et al. 1972). On 8 August 2010, a serious debris flow disaster...
occurred across Zhouqu County, flooding the houses and streets and killing 1765 people. After investigation and analysis, experts found that many natural dams piled up in steep channels (approximately 13°); water collected in the gullies under heavy rainfall conditions, causing the dam burst and the subsequent debris flow (Ma and Qi 1997; Hu et al. 2010; Yu et al. 2010; Zhao and Cui 2010; Tang et al. 2011; Cui et al. 2013).

The non-uniform and discontinuous dam material and the inconsistent water flow particularly complicate the failure process, and there are different failure modes such as the overtopping failure mode and slope failure mode. To analyse the failure modes, processes, and mechanisms, the IMPACT project conducted five groups of large in situ tests, analysed the failure modes and processes of different dam materials, and emphasized the importance of soil properties in the failure process. However, other scholars did not pay sufficient attention to this topic in their past studies (Høeg et al. 2004; Morris et al. 2008). Because it was complicated to operate large in situ tests, many scholars used flume tests to simulate dam failures to analyse the breaching discharge and change in breach size of the overtopping failure mode, and they introduced formulas to predict these parameters (Rozov 2003; Yan et al. 2009; Xi et al. 2010; Cao et al. 2011; Pickert et al. 2011; Zhu et al. 2011; Javadi and Mahdi 2014; Zhang and Yu 2014). Most tests focused on the failure process and changes in the breaching discharge but failed to study the prerequisites for different failure modes to occur and did not analyse the effect of the controlling factors on the failure modes. For example, large in situ tests demonstrated different failure modes by controlling the dam material, but there was a single controlling factor selected (Høeg et al. 2004; Morris et al. 2008). Some scholars studied the breaching discharge process of the overtopping failure mode with a slow or relatively horizontal slope using flume tests, but they did not study the breaching characteristics or trends in the variations in parameters (such as breaching time) for other failure modes (Yan et al. 2009; Xi et al. 2010; Cao et al. 2011; Pickert et al. 2011; Zhu et al. 2011; Javadi and Mahdi 2014; Zhang and Yu 2014).

The failure modes affect the breaching parameters. Kuang (1993) and Awal et al. (2008) analysed the peak discharges under different failure modes and concluded that the overtopping failure mode had the smallest peak discharge, followed by the slope failure mode. Therefore, if we can predict the failure mode of a natural dam in advance according to the geometry, material, and inflow conditions of the dam, we can more reasonably predict the breaching parameters, such as the breaching discharge. Moreover, although several scholars have attempted to establish a method to assess the stability of natural dams using historical disaster data (Casagli and Ermini 1999; Ermini and Casagli 2003; Korup 2004), only few have analysed the relationships between these controlling factors and the failure modes.

Based on the above analysis, a series of tests were performed to study the failure modes and breaching characteristics of natural dams at different channel bed slope angles and dam geometric shapes, materials, and inflow rates. These tests were performed in a 15-m-long, 0.3-m-wide, 0.6-m-high flume. We selected 11 different channel bed slope angles to reflect natural dams with different landform conditions. A total of four geometric shapes were selected to study the effect of the dam geometric shape on the failure mode. Additionally, three materials (sand–gravel mixture and naturally graded soils (NSs)) and eight inflow rates were selected. In total, 159 test runs were conducted. According to the experimental results, two types of failure modes of natural dams were analysed, and the effect of each factor on these two failure modes was studied. The occurrence of different failure modes was mainly explained by the seepage of the dam and the slippage driving force. Finally, we explored the relationships between the breaching time and the controlling factors of different failure modes.

**Experimental method**

**Experimental material**

The experimental materials were mainly natural soils and sediment that were manually configured. The natural soils were obtained from a slope near Yingxiu (N31°05'30.24" E103°29'06.94") and
consisted of coarse particles (gravel, sand) and fine particles (clay, silt) (Figure 1(a)). The non-uniformity coefficient of the soil was 1.56, the average particle size was 0.452 mm, the moisture content was approximately 8.3%, and the soil density was 1.85 g/cm³. Because of the limitation of laboratory facilities, large gravels were excluded, and only particles with diameters smaller than 2 cm were retained.

In addition, we purchased gravel, coarse sand (CS), fine sand (FS), and clay materials and divided them into nine particle groups according to size: 2–3, 1–2, 0.5–1, 0.2–0.5, 0.1–0.2, 0.05–0.1, 0.025–0.05, 0.0075–0.025, and <0.0075 cm. According to the experimental requirements, we mixed together particles of different groups and stirred them well. The particles were coloured by size; for example, the gravel was black, the CS was white, and the clay was dark yellow. Therefore, it was easy to observe the structural details of the soil in our experiments (Figure 1(b)).

We configured three different materials: CS with a maximum particle diameter of 3 cm, FS with a maximum particle diameter of 2 cm, and NS with diameters smaller than 2 cm. The $d_{50}$ values of the CS, FS, and NS were 5, 5.8, and 0.52 mm, respectively. Their fine particle contents were 0.7%, 1.872%, and 11.2%, respectively. The moisture content and dry density of these three materials were 7.82% and 1.72 g/cm³, respectively. The grain-size distribution curves are shown in Figure 2.

**Experimental design and process**

The experiments were performed in a flume that was 15 m long, 0.3 m wide, and 0.6 m deep, and the slope angle was adjustable from approximately 0° to 30°. The flume was made from tempered glass with scales on both sides to record the height of the breach bottom at different times during the experiment. The inflow rate was controlled by an electromagnetic flowmeter, the measurement error

![Figure 1. Experimental material: (a) natural soil and (b) different particle size classifications.](image)

![Figure 2. Grain-size distribution curve.](image)
of which was within $\pm 0.01$ L/s. The different dam shapes were produced with different lengths along the river; however, in the experiment, the foot of the upstream slope was set 10 m from the tank. A baffle was arranged at the end of the flume, which was equal in height to the movable riverbed. We set cameras at the top of the dam, on both sides of the dam, in front of the flume, and on both sides of the riverbed to record the entire breaching process. The experimental set-up is shown in Figure 3.

### Experimental parameter settings

We tested four types of dam geometric shapes: the upstream and downstream slope angles ($\alpha$ and $\beta$) of type I were $20^\circ$ and $15^\circ$, respectively; for type II, they were $30^\circ$ and $20^\circ$, respectively; for type III, they were $35^\circ$ and $30^\circ$, respectively; and for type IV, they were both $30^\circ$. The width of the dam crest was $W$ (=30 cm), and the dam height was $H_b$ (=30 cm). We created an initial triangular breach at one side of the dam; the breach had a depth and width of 4 cm (Figure 3). A 5-cm-thick movable riverbed constructed from the same material as the dam was paved downstream of the dam. Considering the effect of different inflow rates and channel bed slope angles on the failure process, the values of the main controlling factors are summarized in Table 1.

![Figure 3. Experimental equipment layout. The length of the dam depends on its upstream and downstream slopes. The sum of the length of the dam and downstream channel is 5 m.](image)

### Table 1. Experiment conditions.

| Inflow rate (L/s) | Channel bed slope (°) | Upstream/downstream slope (°) | Materials |
|------------------|-----------------------|-------------------------------|-----------|
| 0.5              | 1                     | 20/15 (dam type I)            | CS        |
| 1                | 2                     | 30/20 (dam type II)           | NS        |
| 1.5              | 3                     | 35/30 (dam type III)          | FS        |
| 2                | 4                     | 45/45 (dam type IV)           | –         |
| 2.5              | 5                     | –                             | –         |
| 3                | 6                     | –                             | –         |
| 3.5              | 7                     | –                             | –         |
| 4                | 9                     | –                             | –         |
| –                | 10                    | –                             | –         |
| –                | 11                    | –                             | –         |
| –                | 13                    | –                             | –         |
There were 159 experiments conducted by using 11 channel bed slope angles, 8 inflow rates, 4 upstream and downstream slope angles, and 3 types of materials.

**Experimental results**

Figure 4 shows two failure modes: the overtopping failure mode and the slope failure mode. For the overtopping failure mode (Figure 4(a)), the continuous inflow caused the water level to rise; when the water reached the breach, the flowing water began to erode the dam along the preset breach, carrying away soil particles and gradually forming a rill. Small collapses occurred on both sides of the breach, and fine particles such as clay with small particle sizes flowed downstream with the water; coarse particles such as gravel were deposited downstream. At this point, only a small amount of soil with small particle sizes was carried away along the surface of the riverbed; next, a slight coarsening phenomenon occurred. With time, the water level continued to decrease, and the water flow increased and formed a gully; simultaneously, collapses and landslides occurred on both sides of the breach, and the breach gradually expanded into a trapezoidal form. With increasing inflow, the previously accumulated coarse particles were gradually carried away, disturbing the soil coarsening in the riverbed and ultimately forming a coarsening layer. Then, the movement of water and sand reached a new balance, which marked the end of the dam outburst.

The other failure mode was caused by dam slope instability, i.e. the slope failure mode (Figure 4(b)), the appearance of which is directly related to soil permeation. As the water level gradually increased, significant seepage occurred in the dam, and the phreatic line was observed to rapidly develop towards the downstream. When the phreatic line developed at the toe of the inner slope and formed a through-going seepage channel, the soil above the phreatic line suddenly lost its stability and rushed downstream. Then, the hammed water was immediately released, overtopped the dam, and rushed downstream. Subsequently, the water flooded to the dam crest and gradually eroded the dam.

Table 2 shows the failure modes of the 159 groups of tests. O denotes the overtopping failure mode, and S denotes the slope failure mode. Table 2 shows that 120 groups failed by the overtopping failure mode, accounting for 75% of the total experiments; the remaining 39 groups failed by the slope failure mode, which account for 25% of the total tests. Table 2 shows that when other factors remained unchanged, the failure mode of natural dams might be affected by a single factor; hence,
Table 2. Failure modes of the dams under different conditions.

| Materials | Channel bed slope (°) | Upstream slope (°) | Downstream slope (°) | Inflow rate (L/s) | Failure mode |
|-----------|-----------------------|-------------------|---------------------|-----------------|--------------|
| FS        | 1                     | 20                | 15                  | 1               | O            |
|           | 1                     | 30                | 20                  | 1               | O            |
|           | 1                     | 30                | 20                  | 1.5             | O            |
|           | 1                     | 30                | 20                  | 2               | O            |
|           | 1                     | 30                | 20                  | 2.5             | O            |
|           | 1                     | 30                | 20                  | 3               | O            |
|           | 1                     | 30                | 20                  | 3.5             | O            |
|           | 1                     | 30                | 20                  | 4               | O            |
|           | 1                     | 35                | 30                  | 1               | O            |
|           | 1                     | 45                | 45                  | 0.5             | S            |
|           | 2                     | 20                | 15                  | 1               | O            |
|           | 2                     | 30                | 20                  | 1.5             | O            |
|           | 2                     | 30                | 20                  | 2               | O            |
|           | 2                     | 30                | 20                  | 2.5             | O            |
|           | 2                     | 30                | 20                  | 3               | O            |
|           | 2                     | 30                | 20                  | 3.5             | O            |
|           | 2                     | 30                | 20                  | 4               | O            |
|           | 2                     | 35                | 30                  | 1               | S            |
|           | 2                     | 45                | 45                  | 1               | S            |
|           | 3                     | 20                | 15                  | 1               | O            |
|           | 3                     | 30                | 20                  | 1               | O            |
|           | 3                     | 30                | 20                  | 1.5             | O            |
|           | 3                     | 30                | 20                  | 2               | O            |
|           | 3                     | 30                | 20                  | 2.5             | O            |
|           | 3                     | 30                | 20                  | 3               | O            |
|           | 3                     | 30                | 20                  | 3.5             | O            |
|           | 3                     | 30                | 20                  | 4               | O            |
|           | 3                     | 35                | 30                  | 1               | S            |
|           | 3                     | 45                | 45                  | 1               | S            |
|           | 4                     | 20                | 15                  | 1               | O            |
|           | 4                     | 30                | 20                  | 1               | S            |
|           | 4                     | 30                | 20                  | 1.5             | O            |
|           | 4                     | 30                | 20                  | 2               | O            |
|           | 4                     | 30                | 20                  | 2.5             | O            |
|           | 4                     | 30                | 20                  | 3               | O            |
|           | 4                     | 30                | 20                  | 3.5             | O            |
|           | 4                     | 30                | 20                  | 4               | O            |
|           | 4                     | 35                | 30                  | 1               | S            |
|           | 4                     | 45                | 45                  | 1               | S            |
|           | 5                     | 20                | 15                  | 1               | O            |
|           | 5                     | 30                | 20                  | 1               | S            |
|           | 5                     | 30                | 20                  | 1.5             | O            |
|           | 5                     | 30                | 20                  | 2               | O            |
|           | 5                     | 30                | 20                  | 2.5             | O            |
|           | 5                     | 30                | 20                  | 3               | O            |
|           | 5                     | 30                | 20                  | 3.5             | O            |
|           | 5                     | 30                | 20                  | 4               | O            |
|           | 5                     | 35                | 30                  | 1               | S            |
|           | 5                     | 45                | 45                  | 1               | S            |
|           | 6                     | 20                | 15                  | 1               | O            |
|           | 6                     | 30                | 20                  | 1               | S            |
|           | 6                     | 30                | 20                  | 1.5             | O            |
|           | 6                     | 30                | 20                  | 2               | O            |
|           | 6                     | 30                | 20                  | 2.5             | O            |
|           | 6                     | 30                | 20                  | 3               | O            |
|           | 6                     | 30                | 20                  | 3.5             | O            |
|           | 6                     | 30                | 20                  | 4               | O            |
|           | 6                     | 35                | 30                  | 1               | S            |
|           | 6                     | 45                | 45                  | 1               | S            |
|           | 7                     | 20                | 15                  | 0.5             | S            |

(continued)
| Materials | Channel bed slope (°) | Upstream slope (°) | Downstream slope (°) | Inflow rate (L/s) | Failure mode |
|-----------|----------------------|-------------------|----------------------|------------------|--------------|
| 7         | 30                   | 20                |                      | 0.5              | S            |
| 7         | 35                   | 30                |                      | 0.5              | S            |
| 7         | 45                   | 45                |                      | 0.5              | S            |
| 7         | 20                   | 15                |                      | 1                | O            |
| 7         | 30                   | 20                |                      | 1.5              | O            |
| 7         | 30                   | 20                |                      | 2                | O            |
| 7         | 30                   | 20                |                      | 3                | O            |
| 7         | 30                   | 20                |                      | 3.5              | O            |
| 7         | 30                   | 20                |                      | 4                | O            |
| 7         | 35                   | 30                |                      | 1                | O            |
| 7         | 45                   | 45                |                      | 1                | O            |
| 9         | 20                   | 15                |                      | 0.5              | O            |
| 9         | 30                   | 20                |                      | 0.5              | S            |
| 9         | 35                   | 30                |                      | 0.5              | S            |
| 9         | 45                   | 45                |                      | 0.5              | S            |
| 9         | 20                   | 15                |                      | 1                | O            |
| 9         | 30                   | 20                |                      | 1                | O            |
| 9         | 30                   | 20                |                      | 1.5              | O            |
| 9         | 30                   | 20                |                      | 2                | O            |
| 9         | 30                   | 20                |                      | 3                | O            |
| 9         | 30                   | 20                |                      | 3.5              | O            |
| 9         | 30                   | 20                |                      | 4                | O            |
| 9         | 35                   | 30                |                      | 1                | O            |
| 9         | 45                   | 45                |                      | 1                | S            |
| 9         | 20                   | 15                |                      | 2.5              | O            |
| 9         | 35                   | 30                |                      | 2.5              | O            |
| 9         | 45                   | 45                |                      | 2.5              | O            |
| 10        | 20                   | 15                |                      | 0.5              | S            |
| 10        | 30                   | 20                |                      | 0.5              | S            |
| 10        | 35                   | 20                |                      | 0.5              | S            |
| 10        | 45                   | 45                |                      | 0.5              | S            |
| 10        | 20                   | 15                |                      | 1                | O            |
| 10        | 30                   | 20                |                      | 1                | O            |
| 10        | 35                   | 30                |                      | 1                | O            |
| 10        | 45                   | 45                |                      | 1                | O            |
| 11        | 20                   | 15                |                      | 1                | O            |
| 11        | 30                   | 20                |                      | 1.5              | O            |
| 11        | 30                   | 20                |                      | 2                | O            |
| 11        | 30                   | 20                |                      | 2.5              | O            |
| 11        | 30                   | 20                |                      | 3                | O            |
| 11        | 30                   | 20                |                      | 3.5              | O            |
| 11        | 30                   | 20                |                      | 4                | O            |
| 11        | 35                   | 30                |                      | 1                | O            |
| 11        | 45                   | 45                |                      | 1                | O            |
| 13        | 20                   | 15                |                      | 0.5              | S            |
| 13        | 30                   | 20                |                      | 0.5              | S            |
| 13        | 35                   | 30                |                      | 0.5              | S            |
| 13        | 45                   | 45                |                      | 0.5              | S            |
| 13        | 20                   | 15                |                      | 1                | O            |
| 13        | 30                   | 20                |                      | 1                | O            |
| 13        | 30                   | 20                |                      | 1.5              | O            |
| 13        | 30                   | 20                |                      | 2                | O            |
| 13        | 30                   | 20                |                      | 2.5              | O            |
| 13        | 30                   | 20                |                      | 3                | O            |
| 13        | 30                   | 20                |                      | 3.5              | O            |
| 13        | 30                   | 20                |                      | 4                | O            |
| 13        | 35                   | 30                |                      | 1                | O            |
| 13        | 45                   | 45                |                      | 1                | O            |

(continued)
the inflow rate, dam geometric shape, channel bed slope, and dam material are the main controlling factors of the failure modes.

**Effect of different factors on the failure modes**

**Effect of the materials**

Morris et al. (2008) focused on the physical properties and conditions of the dam materials, which directly affect the failure modes and breaching characteristics. Different materials have different permeabilities. The experimental phenomena show that the positions of the phreatic line can indirectly reflect the seepage state of the dam.

Figure 5 shows the variation in the phreatic line before the dam outburst in an experiment with a type II dam that was constructed of FS material and had a channel bed slope angle of $9^\circ$ and an inflow rate of 0.5 L/s. As shown in Figure 5, the phreatic line in the longitudinal section developed towards the toe of the inner slope, and it developed most quickly along the bottom of the dam. The development in the vertical direction was mainly caused by the increase in water level with continuous inflow. In the experimental process, when $t = 61$ s, the dam lost its stability in the inner slope immediately as the phreatic line developed at the toe of the inner slope. The development of the phreatic line directly affected the soil moisture. The soil was first unsaturated; through the permeation process, the soil below the phreatic line became saturated with water. Next, the phreatic line formed the boundary between the saturated and unsaturated states. The abrupt increase in moisture

| Materials | Channel bed slope (°) | Upstream slope (°) | Downstream slope (°) | Inflow rate (L/s) | Failure mode |
|-----------|----------------------|-------------------|---------------------|-----------------|--------------|
| NS        | 2                    | 30                | 20                  | 0.5             | O            |
|           | 2                    | 20                | 15                  | 1               | O            |
|           | 2                    | 30                | 20                  | 1               | O            |
|           | 2                    | 35                | 30                  | 1               | O            |
|           | 2                    | 45                | 45                  | 1               | O            |
|           | 7                    | 20                | 15                  | 0.5             | O            |
|           | 7                    | 30                | 20                  | 0.5             | O            |
|           | 7                    | 35                | 30                  | 0.5             | O            |
|           | 7                    | 45                | 45                  | 0.5             | O            |
|           | 7                    | 20                | 15                  | 1               | O            |
|           | 7                    | 30                | 20                  | 1               | O            |
|           | 7                    | 35                | 30                  | 1               | O            |
|           | 7                    | 45                | 45                  | 1               | O            |
|           | 9                    | 20                | 15                  | 0.5             | O            |
|           | 9                    | 20                | 15                  | 1               | O            |
|           | 9                    | 30                | 20                  | 1               | O            |
|           | 13                   | 20                | 15                  | 0.5             | O            |
|           | 13                   | 30                | 20                  | 0.5             | O            |
|           | 13                   | 20                | 15                  | 1               | O            |
|           | 13                   | 30                | 20                  | 1               | O            |
|           | 13                   | 35                | 30                  | 1               | O            |
|           | 13                   | 45                | 45                  | 1               | O            |
| CS        | 7                    | 20                | 15                  | 0.5             | S            |
|           | 7                    | 30                | 20                  | 0.5             | S            |
|           | 7                    | 20                | 15                  | 1               | O            |
|           | 7                    | 30                | 20                  | 1               | O            |
|           | 10                   | 30                | 20                  | 1               | O            |
|           | 10                   | 35                | 30                  | 1               | O            |
|           | 10                   | 45                | 45                  | 1               | O            |
|           | 13                   | 20                | 15                  | 0.5             | S            |
|           | 13                   | 30                | 20                  | 0.5             | S            |
|           | 13                   | 30                | 20                  | 1               | O            |
|           | 13                   | 35                | 30                  | 1               | O            |
|           | 13                   | 45                | 45                  | 1               | O            |
remarkably reduced the strength of the soil, and the shearing force that resisted the downward sliding was also reduced. Because the phreatic line controls the high-impact area, the soil above the phreatic line easily slid along the line; then, instability occurred. Under identical conditions, the development of the phreatic line in the dam constructed with CS material occurred more slowly than that in the FS material, but the phreatic line also developed at the foot of the downstream slope in the CS material. In contrast, the phreatic line in the NS material slowly developed and could not form a seepage channel in the downstream slope; therefore, there was no instability on the surface of the downstream slope (Figure 6).

Figure 7 shows the relationships between the permeability coefficient and the failure modes. For the NS material with a smaller permeability coefficient, the failure mode was the overtopping failure mode when the other factors were changed. For the FS and CS materials with larger permeability coefficients, the failure mode changed when the other experimental conditions changed. For example, when the channel bed slope angle of the FS material was 13°, both the overtopping failure mode and slope failure mode occurred, each under different inflow conditions. Figure 7 shows that the slope failure mode occurred when the sum of the channel bed slope and downstream slope angle (γ) was high. When both the permeability coefficient and γ were high, the overtopping failure mode might also occur. In this case, when the channel bed slope angle was relatively high, the water storage time decreased, and when the downstream slope was relatively low, the seepage path lengthened.

Figure 6. Phreatic lines in the dams constructed with different materials.
Effect of the geometric shapes of the dam and slopes of the channel bed

Figure 8 shows the failure modes at different channel bed slopes. When the channel bed slope angle was lower \( (1^\circ - 3^\circ) \) or higher \( (7^\circ - 9^\circ) \) and \( \gamma \) was just less than 40\(^\circ\), the overtopping failure mode was predominant. The slope failure mode mainly occurred when the channel bed slope angle was 4\(^\circ\)–6\(^\circ\). When \( \gamma \) was greater than 40\(^\circ\), the slope failure mode easily occurred. In this case, the occurrence of the slope failure mode was less affected by the channel bed slope.

The failure modes are mainly affected by the seepage of the dam and the slippage driving force. The effect of seepage on the failure modes mainly includes two aspects: whether the seepage channel can be formed and the speed of the seepage velocity (seepage intensity). Before the water level reaches the top of the dam, if a seepage channel can form (such as in the FS material for dam type II with an inflow rate of 1 L/s and channel bed slope angle of 1\(^\circ\)–6\(^\circ\)), the slippage driving force, seepage velocity, and seepage force increase as the channel bed slope increases. The combined effect of seepage on both sides reduces the stability of the dam. When the channel bed slope is increased (such as in the FS material for dam type II with an inflow rate of 1 L/s and channel bed slope angle of 7\(^\circ\)–13\(^\circ\)), the lake volume decreases, the water rises to the crest of the dam more quickly, and a seepage path does not form; therefore, it is difficult for slope failure to occur (Takahashi 2007). When \( \gamma \) is

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**Figure 7.** Relationship between the permeability coefficient and the failure modes.

**Figure 8.** Relationship between the channel bed slope and the failure modes.
greater than 40°, the slippage driving force is relatively high; simultaneously, if the channel bed slope is low, a seepage channel can form. In this case, the slope failure mode is likely to be triggered. If the channel bed slope increases, the slope failure mode also easily occurs due to a high slippage driving force, although there is no seepage channel.

Figure 9 shows the relationship between the failure modes and the downstream slope. No slope failure occurred when the downstream slope was 15°, indicating that a natural dam would mainly be destroyed by the overtopping failure mode when the downstream slope angle is low. The slope failure mode mainly occurs when the downstream slope angles are 30° and 45°. Meanwhile, γ was almost greater than 30°, indicating that an increase in the downstream slope angle and γ is favourable to the occurrence of the slope failure mode. The main reason for this behaviour is the shortening of the seepage path when the downstream slope angle increases; a shortened seepage path is beneficial to the formation of a seepage channel inside the dam. Moreover, a large γ strengthens the slippage driving force and induces slope instability.

**Effect of the inflow rate**

Different inflow rates cause different failure modes. Figure 10 shows the breaching surface morphology under two inflow rate conditions (1 and 0.5 L/s); dam type II was used here and constructed with FS material, and the channel bed slope angle was 7°. Figure 10(a) shows the initial surface morphology of the dam, Figure 10(b,c) shows the final surface morphology after the breach with inflow rates of 1 and 0.5 L/s, respectively. When the inflow rate was 1 L/s, the dam was destroyed by the overtopping failure mode. The water overflowed the preset breach along the side of the dam and continued to deepen and widen the breach because of the large inflow rate; thus, the height of one side of the dam was significantly reduced, whereas the side without the initial breach had a smaller height reduction. When the inflow rate was 0.5 L/s, the dam surface underwent a complete instability; then, the crest elevation was reduced. However, water outflowed not only at the breach but also across the entire crest section of the dam. The crest elevation was basically unchanged after the dam breached.

Figure 11 shows that when the inflow rate was greater than 1.5 L/s, overtopping was the main failure mode. The slope failure mode occurred when the inflow rate was small (0.5 L/s). When the inflow rate was 1 L/s, both the overtopping failure mode and slope failure mode likely occurred. The results show that with an increase in inflow rate, the failure mode changes from the slope failure mode to the overtopping failure mode. The main reason for this switch is that the inflow rate affects
the storage time of the barrier lake, and a small inflow rate increases the storage time; thus, a through-going seepage path in the dam is more easily formed, increasing the probability of occurrence of the slope failure mode. Meanwhile, a seepage path is more difficult to form with a large inflow rate, inducing the overtopping failure mode.
Breaching time of different failure modes

The breaching time is the time from the beginning to the end of the breach. The breaching time is related to the lake volume and erosional extent of the dam (Xu and Zhang 2009; Peng and Zhang 2012). Figure 12 shows the relationship between the breaching time and the lake volume. The breaching time in both failure modes increased with the lake volume. As determined from a series of analyses, the relationship between the breaching time \((T_f)\) in these two failure modes and the lake volume is expressed in the following function:

\[
T_f = a \ln(V_w) + b
\]

For the overtopping failure mode, \(a = 172.3\) and \(b = -694.5\); for the slope failure mode, \(a = 89.4\) and \(b = -336.4\).

Natural dam failure is the process of dam material erosion. The stream power is considered to be positively correlated with the erosion rate. The stream power is often expressed as the product of the unit weight of water \((\gamma_w q_{\text{inu}} J_b/J_y)\), the inflow rate of a single channel width, and the channel bed slope. A new parameter \(C_{ig}\), which is an abbreviation of channel, inflow, and geometric, is used here to reflect the influence of stream power, downstream slope, and upstream slope on breaching time. We define \(C_{ig}\) as a failure susceptibility parameter:

\[
C_{ig} = \gamma_w q_{\text{inu}} J_b/J_y
\]

\(q_{\text{inu}}\) is the inflow rate of a single width, \(\gamma_w q_{\text{inu}} J_c\) is the channel bed slope, \(\gamma_w q_{\text{inu}} J_c\) is the downstream slope angle, and \(\gamma_w q_{\text{inu}} J_c\) is the upstream slope angle. \(\gamma_w q_{\text{inu}} J_c\) is the stream power of the inflow rate, and its physical meaning is the potential energy per unit length of a single-width inflow rate. \(T_f = c W_{d}^d\) reflects the positive effect of the downstream slope on erosion and the effect of the upstream slope on the lake volume. Figure 13 shows the relationship between the breaching time and \(C_{ig}\), where the breaching time in different failure modes decreases with an increase in \(C_{ig}\). Under identical conditions, the overtopping failure mode has a longer breaching time than the slope failure mode. Using a power exponential function to fit the experimental data, we observed that the experimental data were generally close to the fitting curve, showing a good fit. Thus, the function form between the breaching time and \(C_{ig}\) is only slightly related to the failure mode and must satisfy the following functional relationship:

\[
T_f = c C_{ig}^d
\]

where \(c\) and \(d\) are parameters.
For the overtopping failure mode, $c = 40.26$ and $d = -0.74$; for the slope failure mode, $c = 16.98$ and $d = -0.91$. Thus, the overtopping failure mode has greater functional parameters than the slope failure mode.

Froehlich (1995) studied the historical failure incidents and concluded that the breaching time is directly related to the lake volume and dam height, but he ignored the effect of erosion on the breaching time. Based on the work of Froehlich, we consider the effect of water erosion on the breaching time; however, erosion is related to both water flow and material properties. The effects of the material properties on erosion were not considered in Equation (3).

Conclusions

We studied the failure modes and breaching characteristics of dams using numerous flume tests with different channel bed slopes and dam geometric shapes, materials, and inflow rates. We analysed the relationships between the breaching time and different parameters. The conclusions are as follows.

The seepage of the dam and the slippage driving force determine the occurrence of the overtopping failure mode and slope failure mode. For natural dams with small permeability coefficients, seepage paths are not easily formed in the dam during the water storage stage, so the overtopping failure mode plays a leading role. For natural dams with large permeability coefficients, the slope failure mode often occurs when $\gamma$ is large. Both the water storage time and slippage driving force are affected by the channel bed slope. With an increase in channel bed slope, the failure mode changes from the overtopping failure mode to the slope failure mode and back to the overtopping failure mode. The slippage driving force is enhanced by an increase in channel bed slope and causes the slope failure mode to occur. An increase in inflow rate can reduce the water storage time; a shorter water storage time is not conducive to the formation of a seepage path, and under these conditions, it is more difficult for the slope failure mode to occur. The slope failure mode has a shorter breaching time than the overtopping failure mode when all other conditions remain fixed. The breaching time and lake volume have an exponential function, whose form is hardly related to the failure modes. The parameter $C_{ig}$ is introduced to reflect the effect of the channel bed slope, dam geometric shape, and inflow rate on natural dam outburst. Under the two types of failure modes studied here, the breaching time can be described by an exponential function of $C_{ig}$, and the overtopping failure mode has greater functional parameters than those of the slope failure mode.

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**References**

Awal R, Nakagawa H, Kawaike K, Baba Y, Zhang H. 2008. Experimental study on prediction of failure mode of landslide dams. ICSE. 2008:655–660.

Cao Z, Yue Z, Fender G. 2011. Landslide dam failure and flood hydraulics. Part I: experimental investigation. Nat Hazards. 59(2):1003–1019.

Casagli N, Ermini L. 1999. Geomorphic analysis of landslide dams in the Northern Apennine. Trans-Jpn Geomorphol Union. 20(3):219–249.

Casagli N, Ermini L, Rosati G. 2003. Determining grain size distribution of the material composing landslide dams in the Northern Apennines: sampling and processing methods. Engin Geol. 69(1–2):83–97.

Chai HJ, Liu HC, Zhang ZY, Xu ZW. 2000. The distribution, causes and effects of damming landslides in China. J Chengdu Univ Technol. 27(3):302–307.

Costa JE, Schuster RL. 1988. The formation and failure of natural dams. Geol Soc of Am Bull. 100(7):1054–1068.

Cui P, Zhou GGD, Zhu XH, Zhang JQ. 2013. Scale amplification of natural debris flows caused by cascading landslide dam failures. Geomorphology. 182(427):173–189.

Dai FC, Lee CF, Deng JH, Tham LG. 2005. The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, southwestern China. Geomorphology. 65(3):205–221.

Davies TR, Manville V, Kunz M, Donadini L. 2007. Modeling landslide dambreak flood magnitudes: case study. J Hydr Eng. 133(7):713–720.

Ermini L, Casagli N. 2003. Prediction of the behaviour of landslide dams using a geomorphological dimensionless index. Earth Surf Proc Landf. 28:31–47.

Froehlich DC. 1995. Peak outflow from breached embankment dam. J Water Resour Plan and Manag. 121(1):90–97.

Höeg K, Lovoll A, Vaskinn KA. 2004. Stability and breaching of embankment dams: field tests on 6 meter high dams. Int J Hydr Dams. 5:88–93.

Hu KH, Ge YG, Cui P, Guo XJ, Yang W. 2010. Preliminary analysis of extra-large-scale debris flow disaster in Zhouqu County of Gansu Province. J Mount Sci. 28(5):628–634.

Javadi N, Mahdi TF. 2014. Experimental investigation into rockfill dam failure initiation by overtopping. Nat Hazards. 74(2):623–637.

Knight D, Abril B. 2004. Stabilising the Paute river in Ecuador. Prd Inst Civ Engineers Civ Eng. 157(1):32–38.

Korup K. 2004. Geomorphometric characteristics of New Zealand landslide dams. Eng Geol. 73:13–35.

Korup O. 2002. Recent research on landslide dams – a literature review with special attention to New Zealand. Prg Phys Geog. 26(2):206–235.

Kuang S. 1993. Formation mechanisms and prediction models of debris flow due to natural dam failures. J Sed Res. 4:42–57.

Lliboutry L, Morales Arno B, Pautre A, Schneider B. 1972. Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Study of moraines and mass. J Olc/Acioloi Voi. 1972:239–254.

Ma DT, Qi L. 1997. Study on comprehensive controlling of debris-flow hazards in Sanyanyu gully. Bull Soil Water Cons. 17:26–31.

Miller BGN, Cruden DM. 2002. The Eureka River landslide and dam, Peace River Lowlands, Alberta. Can Geotechn J. 39(4):863–878.

Morris M, Hanson G, Hassan M. 2008. Improving the accuracy of breach modelling: why are we not progressing faster? J Flood Risk Man. 1(3):150–161.

Peng M, Zhang LM. 2012. Breaching parameters of landslide dams. Landslides. 9(1):13–31.

Pickert G, Weibrecht V, Bieberstein A. 2011. Breaching of overtopped river embankments controlled by apparent cohesion. J Hydr Res. 49:143–156.
Rozov AL. 2003. Modeling of washout of dams. J Hydr Res. 41:565–577.
Takahashi T. 2007. Debris flow mechanics, prediction and countermeasures. London: Taylor& Francis.
Tang C, Rengers N, Van Asch TWJ, Yang YH, Wang GF. 2011. Triggering conditions and depositional characteristics of a disastrous debris-flow event in Zhouqu city, Gansu Province, northwestern of China. Nat Hazard Earth Syst. 11(11):2903–2912.
Xi J, Lin B, Falconer RA, Wang G. 2010. Modeling dam-break flows over mobile beds using a 2D coupled approach. Adv Water Resour. 33(2):171–183.
Xu Y, Zhang LM. 2009. Breaching parameters for earth and rockfill dams. J Geotechn Geoenviron Eng. 135(12):1957–1970.
Yan J, Cao ZX, Liu HH, Chen L. 2009. Experimental study of landslide dam-break flood over erodible bed in open channels. J Hydrodynam Ser. B. 21(1):124–130.
Yu B, Yang YH, Su YC. 2010. Research on the giant debris flow hazards in Zhouqu County of Gansu Province on August 7, 2010. J Eng Geol. 18(4):437–444.
Zhang JH, Yu MH. 2014. Experimental study of flood diversion in the middle and lower Han River, China. Can J Civ Eng. 41(5):381–388.
Zhao YC, Cui CG. 2010. A study of rainstorm process triggering Zhouqu extremely mudslide on 8 August 2010. Torr Rain Disast. 3:015.
Zhu YH, Visser PJ, Vrijling JK, Wang GQ. 2011. Experimental investigation on breaching of embankments. Sci China Technol Sci. 54(1):148–155.