

Influence of dam and erodible bed material composition on landslide dam failure and induced morphological changes: An Experimental Study

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Abstract: Landslide dam failure and induced morphological changes are dependent on the material composition. A bimodal material composition is observed in landslide dams and riverbeds, but its influence on dam failure and morphological changes is poorly understood. In this study, we experimentally investigate landslide dam failure and its effect on local morphology by varying both dam and bed material composition. The results show that the peak discharge and final breach size increase, while the upstream residual water level decreases with increasing fine material (sand) content in the dam material. The effect of the bed material is limited and the whole dam failure process is rather controlled by the dam material. However, erosion surface slope and final erosion depth vary with changes in both dam and bed material. Sediments are deposited unevenly on the erodible bed, resulting in the formation of sandbars after dam failure. Similar topographies are observed with different erodible beds, while the deposition depth and its anisotropy increase with increasing sand content in the dam material. The influence of bimodal material on dam failure and morphological changes is related to the incipient motion and transport of sediments, leading to the formation of armour layer and non-uniform bedform after dam failure. A dam failure pattern is proposed by considering the variation of the erosion surface slope caused by the change in erosion rate and the occurrence of deposition during dam failure. This study improves the understanding of landslide dam failure and induced morphological changes, and further aids the hazard management.

Keywords: landslide dams; grain size distribution; erodible bed; dam failure process; morphological evolution

1. Introduction

Landslide dams are common [catastrophic events](#) in mountainous areas and are formed by the lateral obstruction of the river channel by landslides, rockfalls and debris flows (Costa and Schuster 1988; Casagli et al. 2003). Due to their unconsolidated earth material composition, landslide dams are prone to overtopping failure, resulting in mega-discharge floods after their formation, posing a great threat to people and infrastructure downstream and further altering the local morphology (Korup et al. 2004; Strom et al. 2010). The failure of landslide dams and their impact on the local area are directly related to the material composition of the dams. The material composition of landslide dams plays an important role in the erosion-deposition process during dam failure, which complicates the dam failure process. Thus, different final breach and hydraulic parameters can be observed (Casagli et al. 2003; Shen et al. 2020; Qiu et al. 2023). Meanwhile, the local impact of dam failure is highly dependent on [the material composition of the dam](#). For instance, the downstream flood area affected by the failure of [the Tangjiashan landslide dam](#) is much smaller than that of the second Baige landslide dam due to its coarser material composition, although a larger lake volume was observed in the Tangjiashan landslide dam (Peng et al. 2012; Yang et al. 2022). Therefore, it's crucial to investigate the influence of material composition on dam failure and its impact on the local area.

In contrast to artificial dams, landslide dams are characterized by a more complex grain size distribution (Ermini and Casagli 2003; Shi et al. 2015; Ehteshami-Moinabadi and Nasiri 2019). Studies on the material composition of landslide dams show that dam material is mainly characterized by its poor sorting and multi-modal distribution (Casagli et al. 2003; Zygouri and Koukouvelas 2019; Ruan et al. 2021). These two characteristics show a dominant influence on the dam stability, further complicating the failure pattern of the landslide dams (Takahashi 2007; Chen et al. 2015; Shen et al. 2020). [Several studies have investigated the influence of dam](#)

material composition on the failure mechanism and the evolution of hydraulic parameters based on empirical models (Chang and Zhang 2010; Peng et al. 2014; Zhong et al. 2018), field experiments (Yan et al. 2017; Kang et al. 2020; Zhou et al. 2022) and laboratory flume experiments (Coleman et al. 2002; Morris et al. 2008; Gregoretti et al. 2010; Cao et al. 2011; Walder et al. 2015). In these studies, empirical models such as BREACH, DABA and DB-NHRI are widely used in real case studies. Field experiments are able to investigate the dam failure mechanism due to their more realistic geological settings, but setting up large-scale experiments, controlling the boundary conditions and measuring data during dam failure are still the main challenges in conducting such an experiment. Flume experiments allow parametric analysis and are widely used to analyze parameters change and breach evolution during dam failure. However, the existing flume experiments mainly focused on the failure of dams with uniform, non-cohesive material, and neglected the influence of widely graded material (Shan et al. 2022). In addition, although the non-uniform material is considered in some of the studies (Zhou et al. 2019; Shen et al. 2022), the different diameters are usually considered by using specific diameters (such as d_{50}). This kind of parameter may well represent the material with grain size in a small range, but natural material is often characterized as a mixture of different components of sand and gravel (Wilcock et al. 2001; Almedeij et al. 2006). In this case, two materials with different proportions of sand and gravel may have similar d_{50} , resulting in a much wider grain size distribution. Therefore, it is necessary to include some other parameters (e.g. sand content) to analyze the influence of material composition on the failure of landslide dams and its impact on the local area.

In addition to dam failure, the interaction between the landslide dam and the erodible bed significantly influences the river dynamics. The presence of the erodible bed leads to the more intense erosion-deposition processes that can be observed during dam failure, thus affecting the downstream flood propagation (Cao et al. 2011; Jiang et al. 2019; Zhou et al. 2022). In

1 addition, the dam-break flow can induce intense sediment transport, leading to the changes in
2 the downstream morphology and sediment distribution, and further reshaping the entire valley
3 (Carrivick et al. 2011; Soares-Fraza0 et al. 2012). Therefore, the existence of the erodible bed
4 cannot be ignored.

5 The influence of the erodible bed on the failure of landslide dams has been investigated
6 based on field investigations, as well as flume and field tests. For instance, Chen et al. (2015)
7 pointed out that the riverbed conditions have a significant influence on both the longevity and
8 the failure mode of landslide dams, and a series of sandbars with an armored layer can be
9 observed under the influence of the dam-break flow. Turzewski et al. (2019) suggested that the
10 extreme flood hydraulics induced by the failure of landslide dams control the erosion and
11 deposition of the riverbed downstream. Zhou et al. (2022) pointed out that the erosion-
12 deposition process, which further induces the downstream morphological change is directly
13 related to the dam failure process and the failure mode of the landslide dams. However, studies
14 on the landslide dam failure considering the erodible bed and its influence on morphodynamics
15 are rather limited. In addition, the relationship between landslide dam failure and the evolution
16 of local morphology is still unclear.

17 Since the material composition of both dam and erodible on dam failure and the induced
18 local morphological evolution are rarely considered in the previous research, in this paper, four
19 widely graded materials with bimodal characteristics are considered in both dam and erodible
20 bed of eight flume tests. Based on these flume tests, the dam failure process, hydraulic
21 parameter variation and morphological change are investigated, and further the influence of
22 material composition on them is analyzed. The paper is organized as follows. In Section 2, the
23 experimental setup, the procedures and also the data processing methods are introduced. In
24 Section 3, the dam failure process, hydraulic parameters variation and also the influence of
25 dam and erodible bed material composition on them are analyzed. In Section 4, the

morphological evolution induced by dam failure and its variation with the change of dam and channel bed material composition are analyzed. Finally, the influence of wide-graded material on dam failure and morphological changes, the erosion characteristics and the dam failure process are discussed, and the similarities between experimental results, analytical model and field investigation are also clarified in Section 5.

2. Material and method

2.1. Experimental equipment and setup

The experiments were carried out at Tongji University in China. The flume used in this study had a rectangular geometry with a length of 6 m, a width of 0.4 m and a height of 0.4 m (Fig. 1a and b). The upstream end of the flume was suspended by a steel frame to adjust the flume gradient i ($i = 0.016$ in these experiments). Both the upstream and downstream ends of the flume were connected to a water tank and a pump to recirculate the water throughout the system. An electromagnetic flowmeter was connected to the pipe to record and control the inflow rate during the experiments. Both side walls of the flume were made of organic tempered glass to allow easy access to the longitudinal evolution of the dam during dam failure. The first 1.5 m of the flume bottom was treated as a fixed bed by using an organic tempered glass, and the middle 3.5 m of the flume was filled with sand and gravel mixtures during the experiments (Fig. 1c) to simulate the erodible river bed and to better consider the topography and bed roughness in real scenarios. The fixed bed and the erodible bed had a height of 0.08 m, which was 2 times of the maximum grain size that was used in the experiments. An organic glass was fixed at the end of the erodible bed to prevent the local failure of the bed. In addition, four cameras (GZ-R10BAC, JVC, 1920 x 1080 pixels, 25 Hz) were used throughout the process to measure the dam failure and flow characteristics, and the topography change before and after dam failure was recorded from two different positions by a 3D laser scanner with resolution of 1.2 mm + 10 ppm (ScanStation P40, Leica).

The modelled dam in the experiments had a trapezoidal shape with a height (H_d) of 0.25 m, a bottom width (W_d) of 1.08 m and a top width (W_t) of 0.12 m (Fig. 1c, d and e). The similarity between the experiments and the real cases was ensured by considering the three dimensionless parameters proposed by Peng and Zhang (2012) (H_d/W_d , $V_d^{1/3}/H_d$, $V_l^{1/3}/H_d$, V_d and V_l are the dam volume and lake volume, respectively). The three dimensionless parameters in our experiments were 1.61, 0.22, and 2.58, respectively, which were within the range that proposed by Zhou et al. (2019) based on 80 field cases. In addition, a triangular diversion channel with a depth of 0.05 m and a width of 0.06 m was created at the dam crest. The flume gradient was kept constant at 0.016 in all experiments. The inflow rate of the experiments remained at 0.001 m³/s throughout the test, and a dimensionless hydrodynamic coefficient ($(Q_{in}T_u)^{1/3}/H_d$) proposed by Li et al. (2021) was used here to check the similarity of the experimental inflow rate, where Q_{in} is the inflow rate and T_u is the time scale with $T_u = 1.0$ s. The dimensionless hydrodynamic coefficient in our experiment is 0.40, which is in the range of 0.007–1.176 based on the 70 field cases analyzed by Li et al. (2021).

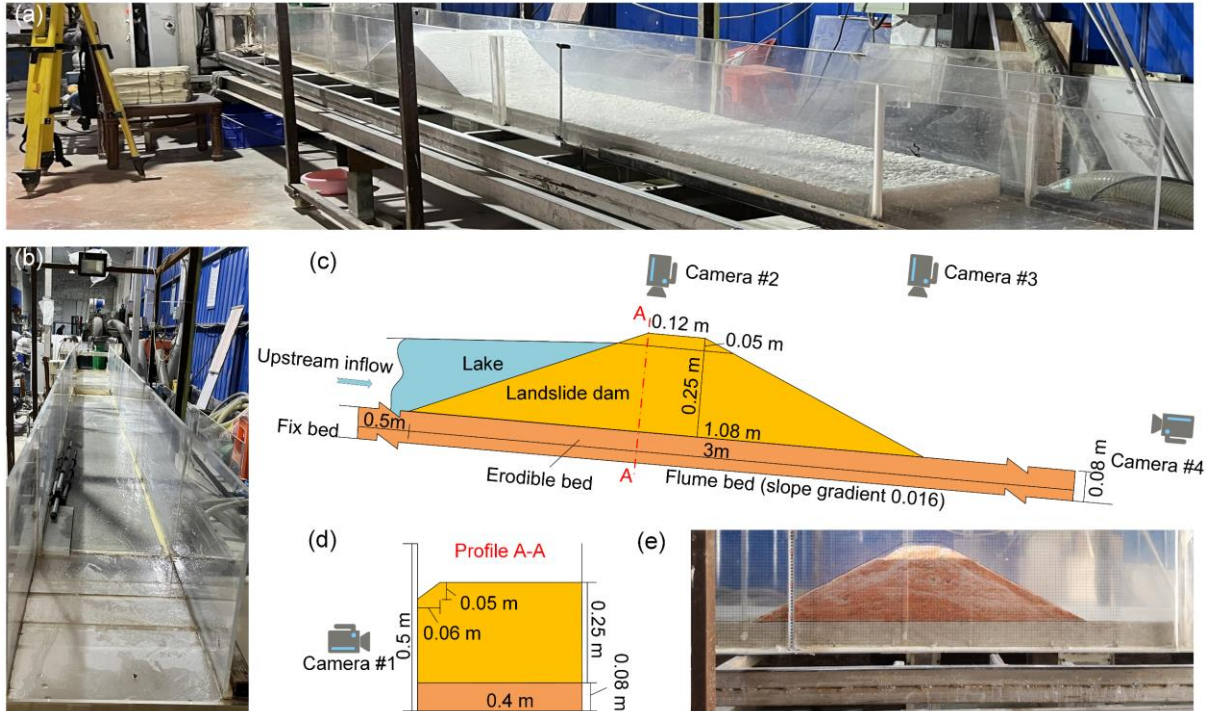


Fig. 1 Experimental flume: (a), (b) Photographs of the flume from different point of view; (c), (d), (e) Geometry of the experimental model and the measurements.

2.2. Material composition and experimental scenarios

The widely graded characteristic of the material of landslide dams can often be characterized by a limited number of dominant grain sizes, as they feature a bimodal or multimodal behavior. This is illustrated with the grain size distribution of dozens of landslide dams in Italy and China shown in Fig. 2 (Casagli et al. 2003; Shan et al. 2022), where a relatively wide range of grain size (from 10^{-7} m to 10 m) was observed in the grain size distribution of most landslide dams. Based on the material composition of 42 landslide dams, Casagli et al. (2013) classified the materials into five groups, including the boulder, gravel, sand, silt and clay fractions. Among these five fractions, sand and gravel are the two dominant fractions (more than 70% of the material in most landslide dams is sand and gravel), and a bimodal or even multimodal is observed within these two fractions (Fig. 2a and b). In addition, the landslide dam material can be divided into two types, including the fine-particle-dominated and coarse-particles-dominated materials (Fig. 3a and b). These two types of materials greatly influence the dam failure and are observed in most of landslide dams. For instance, the material on the surface of the Tangjiashan landslide dam is fine-particle-dominated type, while the coarse-particle-dominated material is observed in the center of the dam (Fig. 3b).

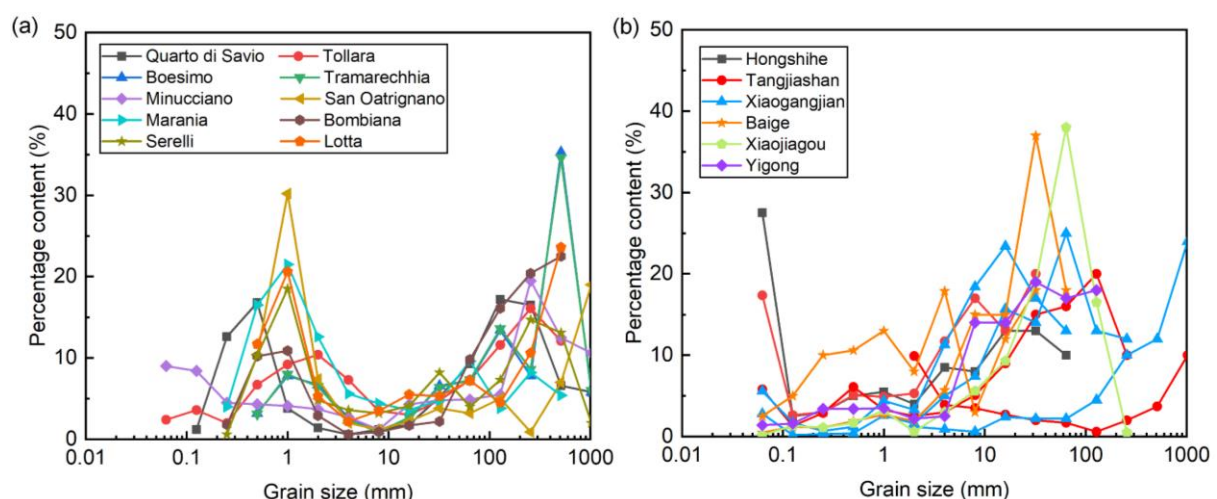


Fig. 2 Grain size distribution of several landslide dams: (a) Ten landslide dams in Italy recorded by Casagli et al. (2003); (b) Six landslide dams in China recorded by Shan et al. (2022).

In our experiments, four synthetic dam materials with different grain compositions were

considered based on one of the grain size distributions of the Tangjiashan landslide dam (G3 in Fig. 4). Due to the limitation of the experimental scale and the characteristics of the dam material composition (Fig. 2), grains with diameters larger than 40 mm and smaller than 0.075 mm were neglected. The grain size distribution of Tangjiashan landslide dam (Fig. 4a) was then divided into two fractions: sand fraction (from 0.075 mm to 2 mm) and gravel fraction (from 2 mm to 40 mm), and the four experimental materials were obtained by varying the percentage content of the sand fraction from 30% to 90% to simulate the different types of materials. All four materials showed a bimodal characteristic (Fig. 4b) and their grain size distributions were within the range of 42 landslide dams recorded by Casagli et al. (2003) (Fig. 4a). Table 1 shows the basic composition and geotechnical properties of the four materials. The median diameter d_{50} for the four materials is 0.730 mm, 0.999 mm, 2.000 mm and 6.563 mm, respectively. It should be noted that although the sand content in G1, G2 and G3 varies, the d_{50} for these three materials is very similar. The parameter C_u of the four materials is greater than 5, indicating that all four materials are well-graded. The parameter C_c shows the uniformity of the materials, and it's unevenly distributed for G1 and G3, while it's evenly distributed for G2 and G4. Therefore, the four materials can well represent dam materials with different characteristics (Shi et al. 2015). The maximum dry density of the four materials, which was obtained by the Proctor compaction test, ranges from 1,980 kg/m³ to 2,400 kg/m³. The angle of repose of the four materials, which represents the friction characteristic of the material, ranges from 31.6° to 37.8° and was obtained by a series of rectangular container tests (Table 1).

Based on the modelled dam and the four materials mentioned above, eight flume experiments were carried out with different material compositions of both the dam and the erodible bed (Table 1). Note that the tests are named by considering the sand content of both the dam and erodible bed materials. For instance, in T90-30, the sand content of dam and erodible bed materials is 90% and 30% respectively. The experiments can then be divided into

two groups. In T90-90, T70-70, T50-50 and T30-30, the dam and the erodible bed were made of the same materials, whereas in T90-30, T70-30 and T50-30, the coarsest material G4 was used as the material of all four erodible beds. Under these circumstances, the influence of the bed material composition on the dam failure and morphological change is obtained by comparing the results of T90-30, T70-30, T50-30 and T30-30, while the influence of the erodible bed material composition can be analyzed by comparing the experimental results of T90-90–T90-30, T70-70–T70-30 and T50-50–T50-30. In addition, the materials used in the experiments were stained with different colors according to their size distribution, so as to observe the sediment transport as well as the erosion and deposition during the dam failure.

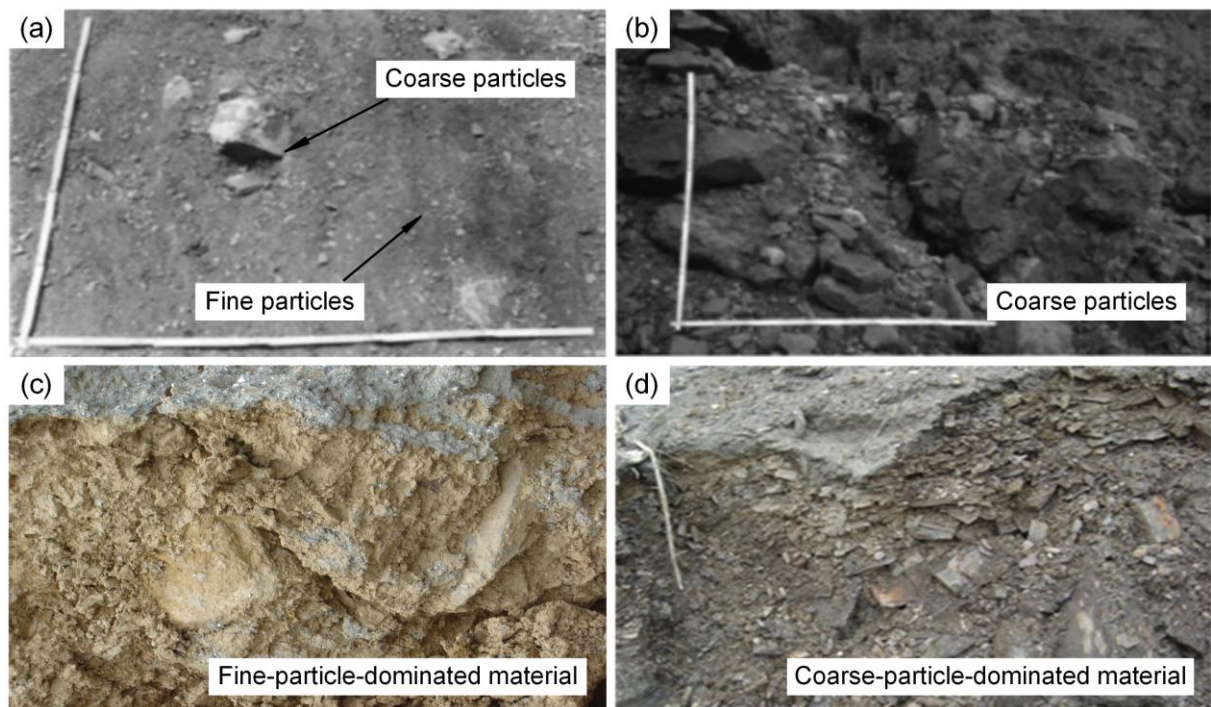


Fig. 3 Classification of landslide dam material. (a) and (b) are the two types of landslide dam material classified by Casagli et al. (2003), (c) and (d) are the material at the surface and middle of the Tangjiashan landslide dam, respectively.

2.3. Experimental procedures and data processing methods

The experiments were carried out as follows: First, the flume was filled up with the graded material with the same degree of compaction ($\rho/\rho_{\text{dmax}} = 0.75$), and then the erodible bed was saturated with a small inflow rate of $0.001 \text{ m}^3/\text{s}$. Second, the modelled dam was filled with the same degree of compaction as the erodible bed, and the 3D laser scanner was used to record

the initial topography of the experiments. The upstream reservoir of the dam was then filled with a constant inflow rate of $0.001 \text{ m}^3/\text{s}$. Dam failure was considered to start when the water overflowed the diversion channel and ended when the local topography became stable. During the whole process, the flow characteristics, the evolution of the breach and the dam were well recorded by using the four cameras. The topography after the experiments was recorded and the final breach was measured at the end of the experiments.

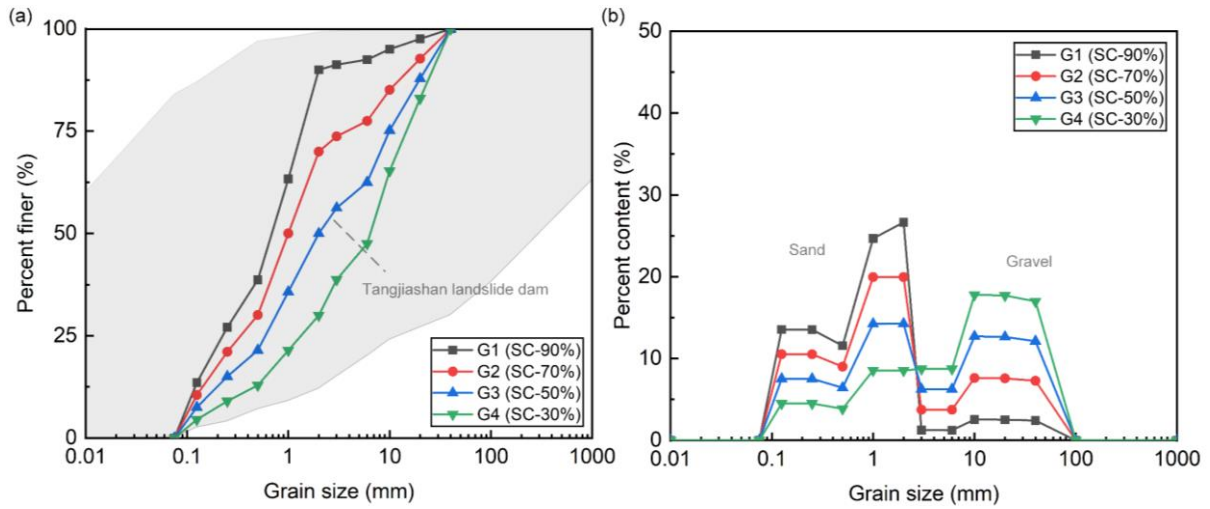


Fig. 4 Grain size distribution of the four experimental materials: (a) Cumulative grain size distribution; (b) Frequency grain size distribution.

Table 1 Summary of the flume experiments and the material characteristics

Test	Erodible bed	Material	d_{50} (mm)	S_c	Dam material properties						
					G_c	C_c	C_u	ρ_{dmax} (kg/m ³)	Φ (°)	e	
T90-90	G1	G1	0.730	90%	10%	0.939	8.321	1980	31.6	0.785	
T90-30	G4										
T70-70	G2	G2	0.999	70%	30%	1.356	12.287	2070	33.1	0.707	
T70-30	G4										
T50-50	G3	G3	2.000	50%	50%	0.801	28.916	2210	36.6	0.599	
T50-30	G4										
T30-30	G4	G4	6.562	30%	70%	1.451	28.144	2400	37.8	0.472	
T30-30	G4										

Note: d_{50} (mm) is the median diameter. S_c and G_c are the sand content and gravel content. $C_u = d_{60}/d_{10}$ and $C_c = d_{30}^2/(d_{60} * d_{10})$ are the uniformity coefficient and curvature coefficient of the materials. ρ_{dmax} (kg/m³) is the maximum dry density of the materials. ϕ (°) is the angle of repose and e is the void ratio.

For data processing, the whole dam failure process and the upstream water level change were obtained from the recorded videos. The discharge during dam failure was obtained based

on the change of water level in the upstream and was calculated as follow:

$$Q_t = Q_{in} - \frac{V(H_t) - V(H_{t-\Delta t})}{\Delta t} \quad (1)$$

where Q_t is the discharge at time t , Q_{in} is the upstream inflow rate. H_t is the water level in the upstream at time t . $V(H_t)$ is the water volume in the upstream at time t . The final breach geometry and the topography were obtained by analyzing the 3D scan data which was recorded after the breaching of the dam. In order to ensure the accuracy of the results, the 3D scan data are analyzed as follows: First, the 3D scan data of the dam and the erodible bed, which were scanned from two different positions, were extracted from the point cloud data. Then, the data from two different positions were merged based on several control points. Finally, the point clouds were disposed by using a MATLAB (The MathWorks, version R2018a) code to obtain the final topography of the channel bed in the downstream of the dam.

3. Experimental results of the dam failure

3.1. General description of dam failure process

All the modelled dams in our experiments behaved as overtopping failures, and similar characteristics of the overtopping failure process were observed. Therefore, one of the tests (T30-30) is used here to illustrate the dam failure process (Fig. 5), the variation of discharge and upstream water level (Fig. 6). After the water flowed through the diversion channel, the upstream water level gradually increased due to the relatively small outflow discharge compared to the inflow rate (Fig. 6). Meanwhile, the failure of the dam began. Surface erosion was first observed on the downstream slope of the dam, while the dam crest was eroded by retrogressive erosion until the point A in the upstream of the dam crest was eroded (Fig. 5b and c). The erosion of point A resulted in the decrease of the dam height, and a rapid decrease in the upstream water level, while an increase in discharge was observed. This larger discharge increased the erodibility of the water, resulting in the variation of the erosion surface and in a rapid alteration of the dam geometry (Fig. 5d and e). The discharge increased rapidly to its

maximum value and subsequently declined until the upstream water level reached a constant value, indicating the evolution into a steady-flow over the remaining dam (Fig. 6). During this period, frequent lateral slope failures occurred, which increased the breach width and further influenced the variation of water level and discharge. In addition, the gradient of the erosion surface decreased and intense deposition was observed near the downstream dam toe (Fig. 5e and f). Due to the significant erosion and deposition processes, a residual dam with a relatively gentle slope was formed, as well as an armor layer (which consisting mainly of coarse grains) was observed on the surface of the residual dam after dam failure.

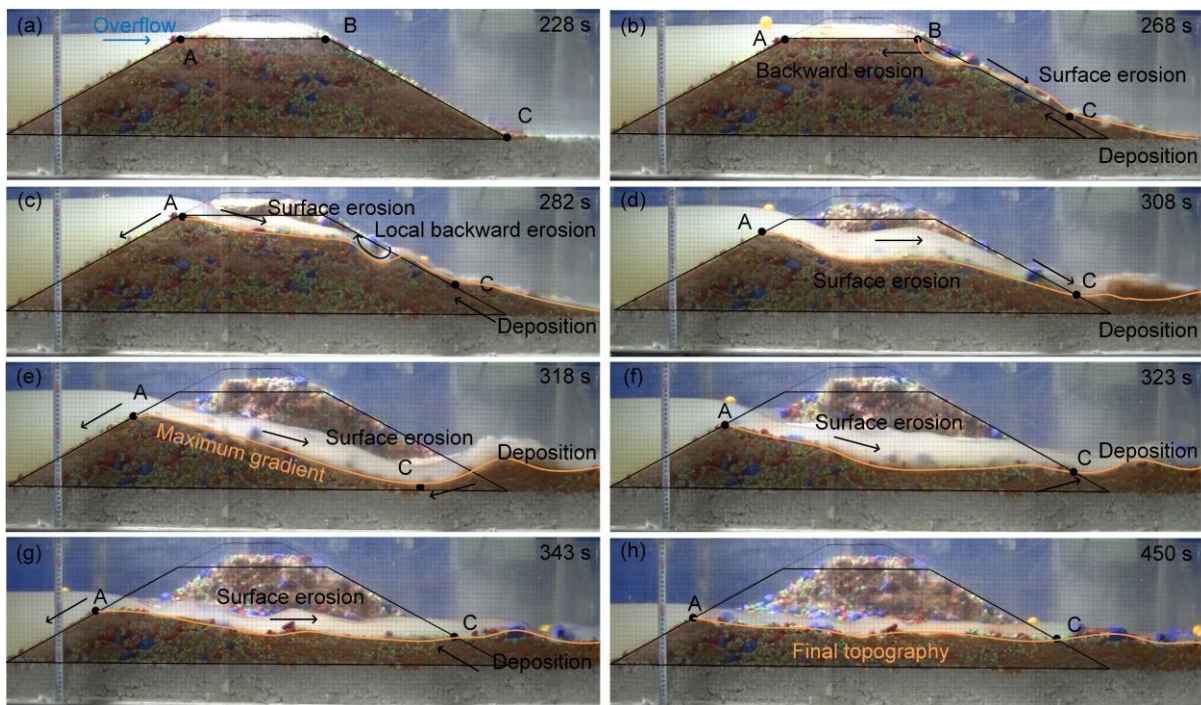


Fig. 5 Dam failure process (Take T30-30 as an example): (a) $t = 228$ s; (b) $t = 268$ s; (c) $t = 282$ s; (d) $t = 308$ s; (e) $t = 318$ s; (f) $t = 323$ s; (g) $t = 343$ s and (h) $t = 450$ s.

The dam failure process was characterized by the variation of discharge and the erosion characteristics during dam failure and can be further divided into the following four stages based on these two factors: the initiation stage, the acceleration stage, the attenuation stage and the recovery stage. The initiation stage started from the beginning of dam breaching and ended with the erosion of the upstream dam crest (point A in Fig. 5). The surface erosion accompanied by the retrogressive erosion of the dam crest were mainly observed. The discharge in this stage

was relatively small due to the constant dam height. The acceleration stage starts with the erosion of the point A (Fig. 5) and is followed with the attenuation stage, which ends with the equilibrium between discharge and inflow rate. In these two stages, rapid surface erosion is mainly observed, while the discharge increased during the acceleration stage and it decreased in the attenuation stage. Finally, the recovery stage, which corresponds to the end of dam failure, is characterized by the balance between the inflow rate and the discharge. In this stage, the long-term evolution of the final topography of the residual dam and the downstream erodible bed was observed.

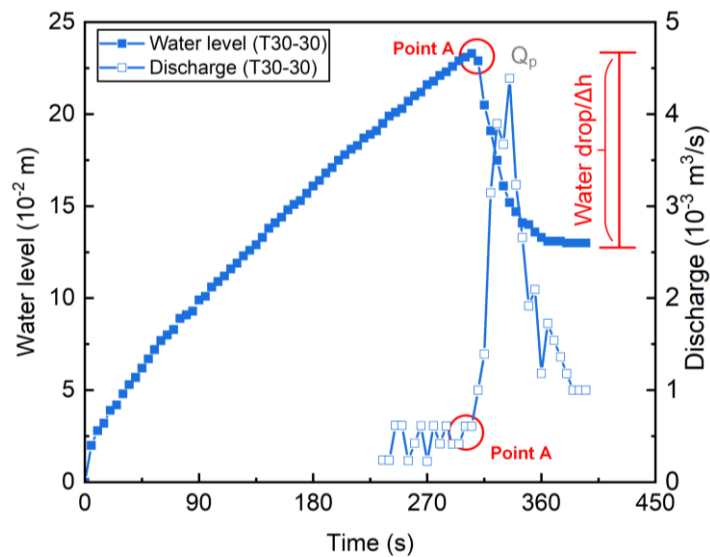


Fig. 6 Evolution of discharge and upstream water level during dam failure.

3.2. Influence of dam material composition on the dam failure

3.2.1. Dam failure parameters

The influence of material composition on three key dam failure parameters is analyzed in this paper, including the change of upstream water level, the peak discharge variation and the dam failure duration (Costa and Schuster 1988; Walder and O'Connor 1997; Peng and Zhang 2012). Note that the dam failure duration is divided into two parts according to the failure stages of landslide dams: the first the one is the time for the initiation stage (T_{in}), and then the time for the acceleration and attenuation stages (T_b). Fig. 7 shows the variation of the upstream water level, peak discharge and the above-mentioned dam failure duration with different dam

material composition (T90-30, T70-30, T50-30 and T30-30, as blue line in Fig. 7). Both the upstream water drop and the peak discharge increase with increasing sand content in the dam materials (Fig. 7a and b). The peak discharge of the tests with different sand content varies within $4.50\text{--}5.46 \times 10^{-3} \text{ m}^3/\text{s}$. The water drop is 0.11 m for T30-30 and it increases to 0.18 m for T90-30. The variation of these two parameters is directly related to the sand content: for higher sand contents, a lower residual dam is observed with a relatively low upstream water level. This is because sand is more easily entrained by the flow, resulting in a more obvious erosion of the dam and a larger volume of water released during dam failure. Moreover, the increase of released water volume further induces the increase of the peak discharge during dam failure. However, the difference in peak discharge with different dam material composition is relatively small compared to the change in released water volume. This is because the breaching of the dam with higher sand content has a relatively shorter time duration in the initiation stage, but a longer duration in the acceleration and attenuation stages (Fig. 7c and d). Since the variation of discharge and water level occurs mainly in the acceleration and attenuation stages, a longer duration in these two stages indicates that a smaller water release rate is observed, resulting in a smaller peak discharge during the dam failure. As shown in Fig. 7c and d, the duration decreases in the initiation stage, while it increases in the acceleration and attenuation stages from 77–103 s for T30-30–T90-30 with increasing sand content in the dam materials.

3.2.2. Dam failure process and the final breach

The difference in the dam failure process with different material composition is characterized by the variation of the erosion surface slope during the dam failure. Since the dam geometry and the dam failure parameters mainly vary in the acceleration and attenuation stages, therefore, only the erosion surface slope variation of these two stages is analyzed in this paper. In addition, note that the slope of the erosion surface is measured based on the position of two control points, in this way, the erosion surface slope analyzed in this paper refers to its

average value. As shown in Fig. 8, the similar variation of the erosion surface slope is observed with different dam material composition (Fig. 8a). The slope of the erosion surface first increases to a maximum value, and then decreases until the final topography is observed. For finer material, a larger maximum slope of the erosion surface is observed but then the final topography shows a smaller surface slope. As shown in Fig. 8a, the maximum erosion surface slope is 0.42 and 0.44 for T90-30 and T70-30, respectively, which are much larger than that of 0.24 and 0.26 for T50-30 and T30-30. However, the difference in the maximum slope of erosion surface between T90-30 and T70-30 is quite small, and it is even larger in T70-30 than in T90-30. This is because the variation of the erosion surface during dam failure is also influenced by the lateral slope failure. For example, the higher sand content in T90-30 leads to the easier failure of the lateral slope, which results in the change of the erosion surface slope and further changes the dam failure process.

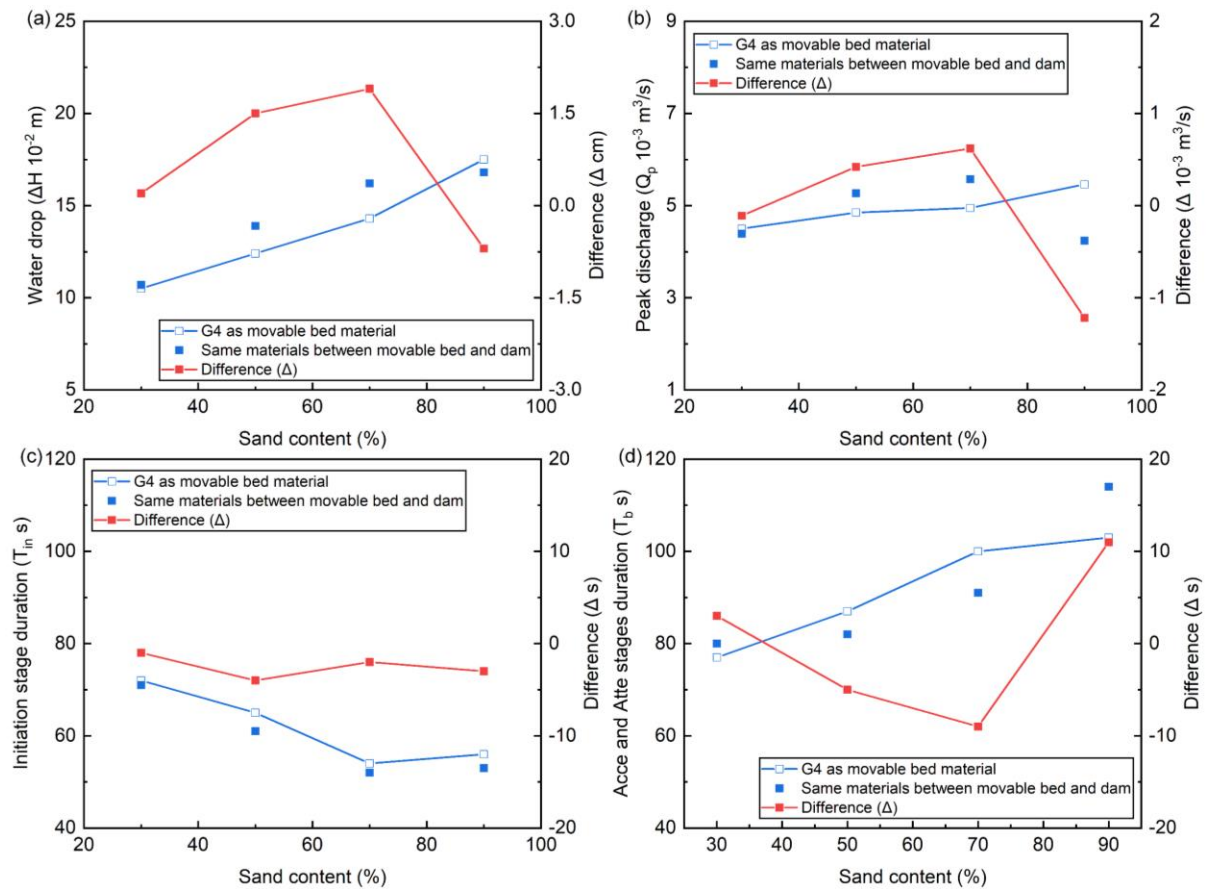


Fig. 7 Relationship between sand content of the dam/erodible bed materials and the dam failure parameters: (a) water drop; (b) peak discharge; (c) initiation stage duration; (d) acceleration

and attenuation stages duration.

The final breach cross-sections analyzed in this section are located in the downstream dam crest (as A-A shown in Fig. 9a). With different dam material compositions, the final breach has a trapezoidal shape in all tests. In T90-30 and T70-30, where the sand content of the dam materials is 90% and 70%, respectively, undercutting erosion is observed (Fig. 9a). This is caused by the difference in material composition between the dam and the erodible bed. In the case of the coarsest material G4 with sand content of 30% as considered in the erodible bed of T90-30–T30-30, stronger erosion resistance is observed on the erodible bed, resulting in the undercutting erosion of the lateral slope at the bottom of the dam. However, the influence of undercutting erosion is relatively small and is thus ignored in calculating the lateral slope of the final breach.

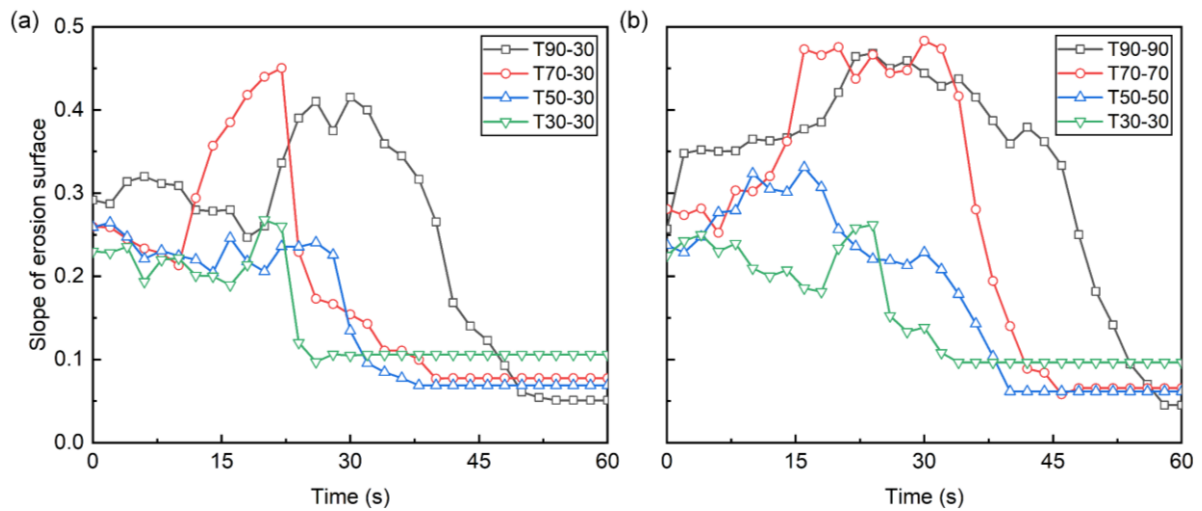


Fig. 8 Variation of the average slope of the erosion surface during dam failure: (a) tests with same erodible bed; (b) The same material is considered in dam and bed material in each test.

Furthermore, three dimensionless parameters are proposed to analyze the breach variation associated with material changes, including the dimensionless final breach depth (H_b/H_d), width (W_b/W_d), and lateral slope (S). In these parameters, H_b , H_d , W_b and W_d are breach depth, dam height, breach bottom width and dam width, respectively, and these three parameters can well represent the breach degree after dam failure. The effects of dam material composition on the three dimensionless breach parameters are shown in Fig. 9b. Both the breach depth and top

width increase, while the lateral slope decreases with increasing sand content in the dam material. The change in breach depth is mainly controlled by the erosion resistance of the materials. The finer the material, the lower the erosion resistance is observed, resulting in a larger breach depth. The width and the lateral slope of the breach are controlled by the angle of repose of the materials and their water content. The coarser the material, the larger the angle of repose is observed (Table 1), resulting in a more stable breach with a larger lateral slope and smaller width (Shen et al. 2022). In addition, as the sand content of the materials decreases, a higher water content is observed due to seepage in the dam prior to failure, leading to an unsaturated state of the dam materials. This unsaturated state prevents the failure of the lateral slope, which further increases the stability of the breach and a larger lateral slope is observed (Fig. 9b). It should be noted that the lateral slope for T30-30 is much large than that for the others. This may be induced by the material composition of the dam, which further influence the seepage in the dam before and during the dam failure, thus, changing the stability of the lateral slope.

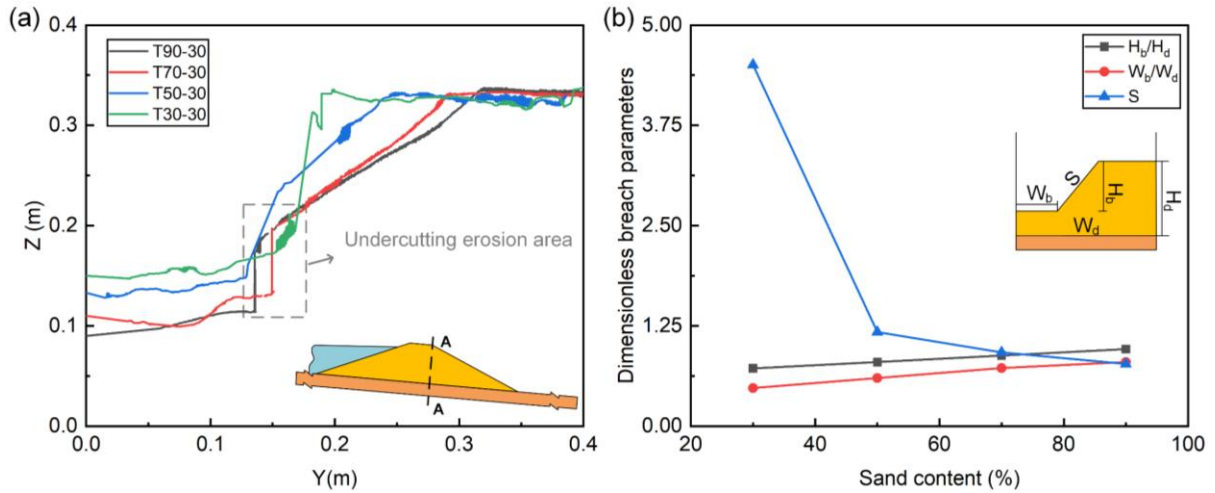


Fig. 9 Breach characteristics with different dam material compositions: (a) refers to the breach at A-A cross section and (b) is the influence of dam material composition on dimensionless breach parameters (H_b/H_d and W_b/W_d are the ratio of breach depth and dam height and the ratio of breach bottom width and dam width, respectively; S is the lateral slope of the breach).

3.3. Influence of erodible bed material composition on the dam failure

3.3.1. Dam failure parameters

The blue solid points in Fig. 7 show the upstream water drop, peak discharge and the dam failure duration of T90-90, T70-70, T50-50 and T30-30, where the same dam and erodible bed materials are considered. Comparing the results between T90-90–T90-30, T70-70–T70-30 and T50-50–T50-30, as the difference (red line) between each two tests shown in Fig. 7, it can be observed that the dam failure with different erodible bed material composition is also controlled by the dam material composition. Both the upstream water drop and the peak discharge increase with increasing sand content in the bed material when the dam material has a sand content of 50% and 70% (Fig. 7a and b). For instance, the water drop increases from 0.14 m to 0.16 m and the peak discharge increases from $4.95 \cdot 10^{-3} \text{ m}^3/\text{s}$ to $5.57 \cdot 10^{-3} \text{ m}^3/\text{s}$ when the sand content of the dam material is 70%. Conversely, for the test considering the finest material (90% of sand content), the upstream water drop and the peak discharge decrease from 0.18 m to 0.17 m and from $5.46 \cdot 10^{-3} \text{ m}^3/\text{s}$ to $4.24 \cdot 10^{-3} \text{ m}^3/\text{s}$ respectively with increasing sand content of the erodible bed. This phenomenon can be explained by the interaction between the dam and erodible bed. The finer material composition of the erodible bed leads to an increase erosion of both the dam and the erodible bed, thus achieving a shorter failure duration (Fig. 7d), resulting in an increase in both the upstream water drop and the peak discharge. However, when considering the finer material of both the dam and the erodible bed, a strong bed erosion is observed and a larger volume of sediment is eroded during dam failure (Fig. 10), resulting in a longer failure duration (Fig. 7d), and in the decrease of both the water drop and peak discharge. This explanation is further supported by the variation of the dam failure duration of the experiments (Fig. 7c and d). The duration in the initiation stage is similar between T90-90–T90-30, T70-70–T70-30 and T50-50–T50-30. However, in the acceleration and attenuation stages, the duration decreases when the sand content is 50% and 70%, and it increases when 90% sand content is considered (Fig. 7d).

3.3.2. Dam failure process and the final breach

Compared to the T90-30, T70-30, T50-30 where the coarser erodible bed is considered, a similar variation of the erosion surface slope and its maximum value is observed in T90-90, T70-70 and T50-50 (Fig. 8). The slope of the erosion surface also first increases to its maximum value and then decreases until the final topography is observed. However, a longer period where the maximum erosion surface slope occurs is observed in T90-90, T70-70 and T50-50, and the slope decreases more slowly than that of T90-30, T70-30, T50-30 (Fig.8a and b). This variation of erosion surface slope is related to the erosion and deposition of the erodible bed. As shown in Fig. 10, the erosion of the erodible bed is more severe when a finer erodible bed is considered. The erosion of the bed at the downstream dam toe slows down the decrease of the erosion surface slope during dam failure. Therefore, a longer period with larger erosion surface slope is observed, which ultimately leads to the variation of the failure process and the failure parameters. In addition, the variation of erosion surface slope during dam failure of T90-90, T70-70, T50-50 and T30-30 is totally different with each other, which further verify that the dam failure is influenced by the material composition of both the dam and the erodible bed.

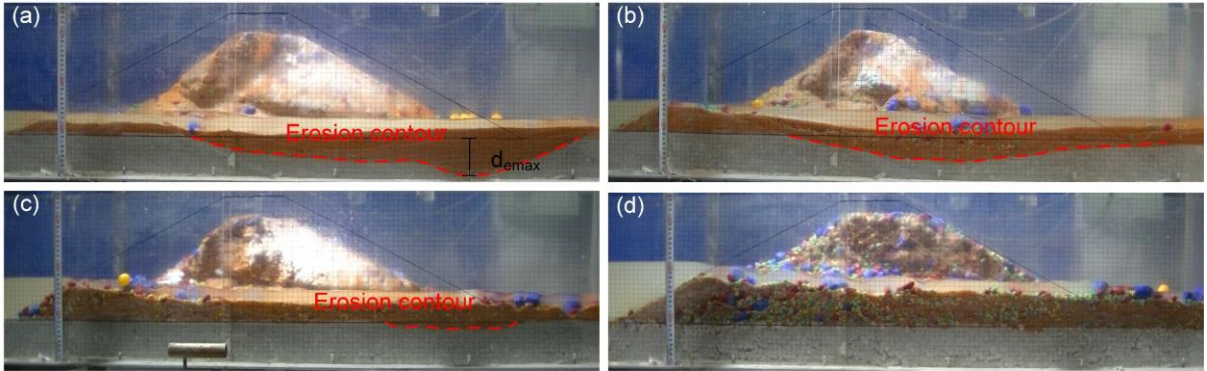


Fig. 10 Erosion characteristic of the erodible bed. (a) T90-90; (b) T70-70; (c) T50-50; (d) T30-30 (Note: $d_{\max}$ is the maximum erosion depth in the erodible bed).

The final breach cross-sections with the same dam material but different erodible bed material are shown in Fig. 11. The final breaches show little variation with different bed material, especially the final breach depth. Since the magnitude of the outburst flood caused by the dam failure is mainly influenced by the final breach depth (Yang et al. 2022), the influence of the erodible bed material composition on the breach geometry can be ignored. However, it

should be noted that the breach evolution during dam failure is quite different in different scenarios even though the final breach geometry is almost the same. As shown in Fig. 10, the erosion and deposition during the dam failure are more intense when considering a finer erodible bed. This stronger erosion and deposition process further induced the change of the peak discharge, upstream water level and the dam failure duration (Fig. 7).

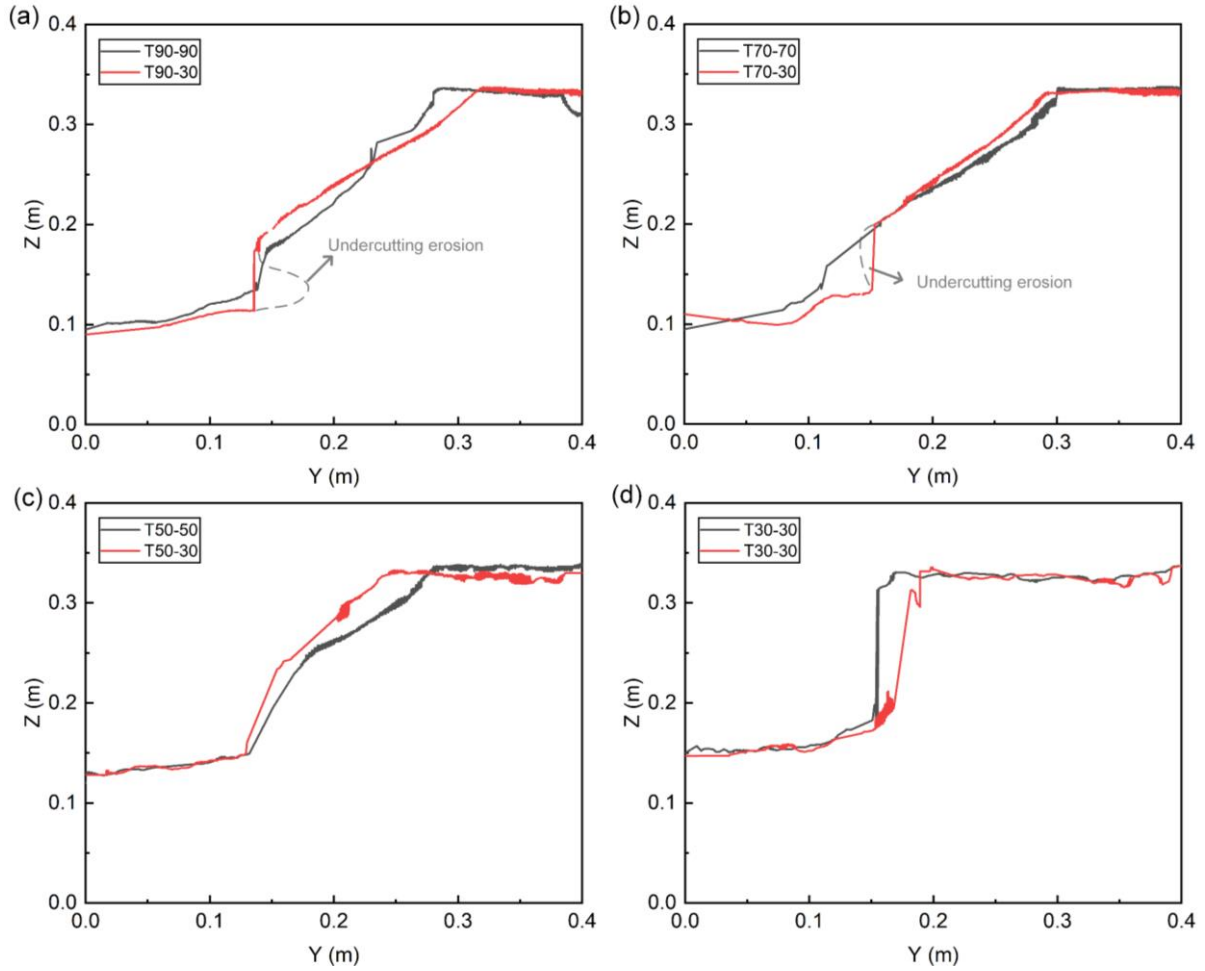


Fig. 11 Comparison of final breach cross-sections with the same dam material but the different bed materials: (a) T90-90–T90-30; (b) T70-70–T70-30; (c) T50-50–T50-30 and (d) T30-30–T30-30.

4. Experimental results of the downstream morphological changes

4.1. Generation description of the downstream morphological changes

The downstream topographies before and after the dam failure are used to analyze the distribution of erosion and deposition on the erodible bed. The topography variation of the eight tests is shown in Fig. 12. It can be seen that the variation of erosion-deposition distribution is

similar in all of the tests. The deposition of sediment in all of the tests mainly occurs downstream near the dam. The deposition height decreases with increasing distance from the dam site, until a relatively small erosion volume is observed at the downstream of the erodible bed. In addition, an uneven distribution of the erosion and deposition depth is observed in the direction that is perpendicular to the flume. This heterogeneous distribution of erosion and deposition changes the flow direction, further leading to the formation of a meandering channel on the erodible bed. The material composition shows significant influence on the erosion and deposition of the erodible bed in the downstream of the dam. With the same erodible bed material (Fig.12e–h), the deposition depth near the dam downstream increases with decreasing sand content in the dam material, and different topographies of the erodible bed are observed. However, with the same dam material but different erodible bed materials (as a comparison between Fig. 12a and e, Fig. 12b and f, Fig. 12c and g), the distribution of erosion-deposition and their final topographies show high consistency with each other.

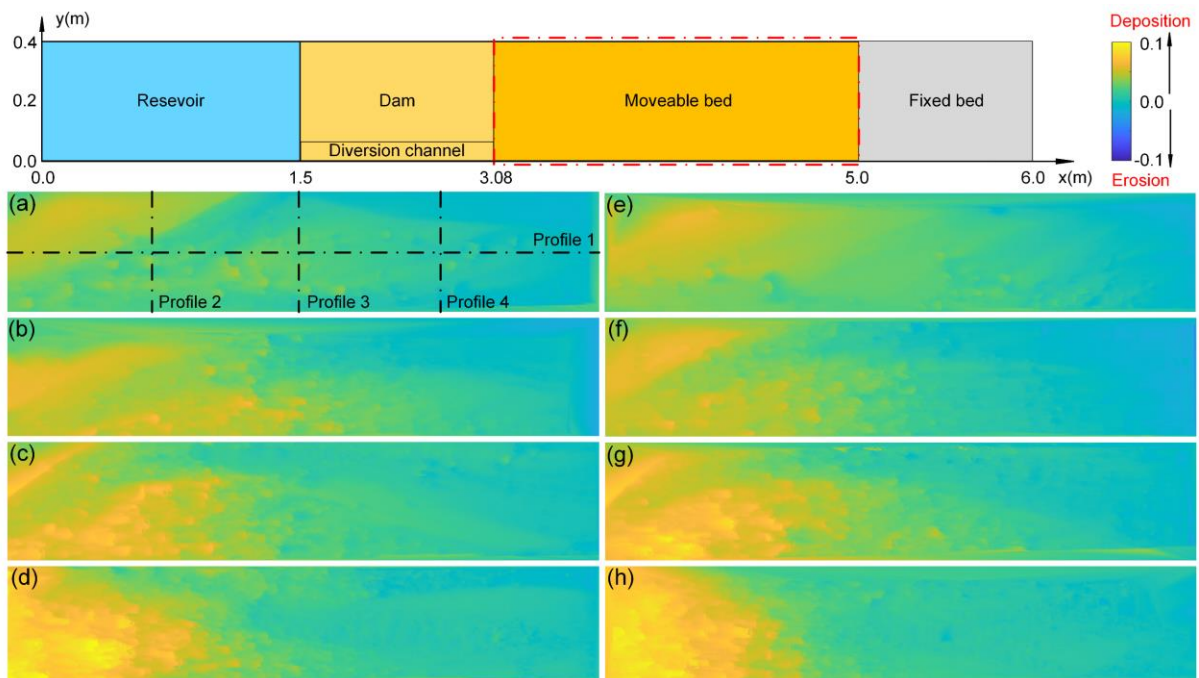


Fig. 12 Variation of the erodible bed topography: (a) T90-90; (b) T70-70; (c) T50-50; (d) T30-30; (e) T90-30; (f) T70-30; (g) T50-30 and (h) T30-30.

To further compare the topography variation of the erodible bed with different dam and

bed material compositions, the height of the bed along the four cross-sections mentioned in Fig. 12a is analyzed (Fig. 13 and 14). Deposition depth and position are highly dependent on the dam material composition. As shown in Fig. 13a, the deposition depth varies with the distance from the dam for different dam material compositions. At 3 m–3.5 m, the largest deposition depth is observed in T30-30 with the coarsest dam material, while it is observed at T70-30 or T50-30 in 3.5 m–4 m and at T90-30 in 4 m–4.5 m. This is because the largest sediment transport distance is observed in T90-30 due to the finer material and the larger discharge during dam failure, while the smallest is observed in T30-30. Therefore, the sediments are deposited widely along the erodible bed with finer dam material, resulting in the smaller deposition depth near the dam and larger one at the downstream of the erodible bed in T90-30 compared to that in T30-30. Sediment deposition along the profile perpendicular to the flume also varies with the composition of dam material. The dam material is mainly deposited on the right bank of the flume when the finest dam material is considered. As the sand content of the dam material decreases, the sediment is gradually deposited from the right to the left bank (Fig. 13b). This variation in sediment deposition shows less pronounced with increasing distance from the dam, and no variation of erodible bed depth is observed at profile 4 (Fig. 13c and d).

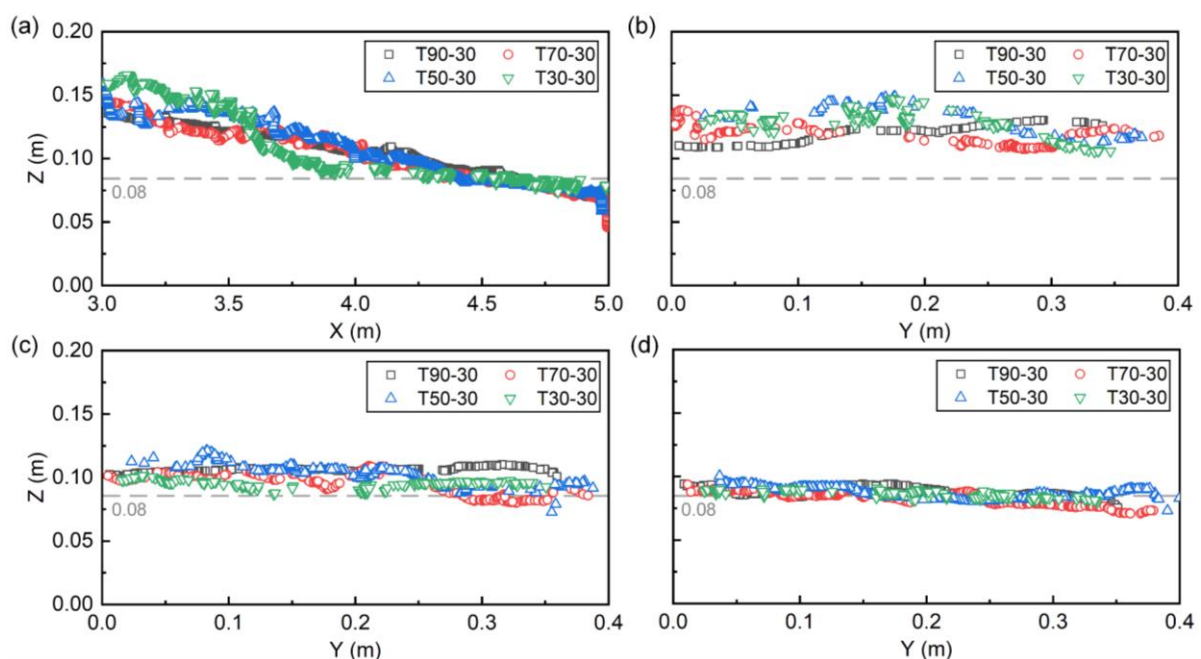


Fig. 13 The erodible bed elevation along four profiles of T90-30, T70-30, T50-30 and T30-30: (a) Profile 1; (b) Profile 2; (c) Profile 3 and (d) Profile 4.

Since the final topography is similar between T90-90 and T90-30, T70-70 and T70-30, T50-50 and T50-30, the influence of erodible bed material composition on the final topography is analyzed based on the difference in bed elevation between each two tests (Fig. 14). The erodible bed elevation of the tests with coarser bed material is greater than that of the test with finer bed material (Fig. 14a), indicating that the deposition depth increases with decreasing sand content in the erodible bed. In addition, the influence of the bed material composition on the final topography is also controlled by the dam material composition. As shown in Fig. 14b, c and d, the largest difference is always observed between T90-90 and T90-30 with the finest dam material composition. This is because a larger erosion volume of erodible bed is observed when considering the finer material in the dam (Fig. 10). This intense interaction between the dam and the erodible bed leads to the variation of erosion and deposition on the downstream bed, resulting in the change of the final topography.

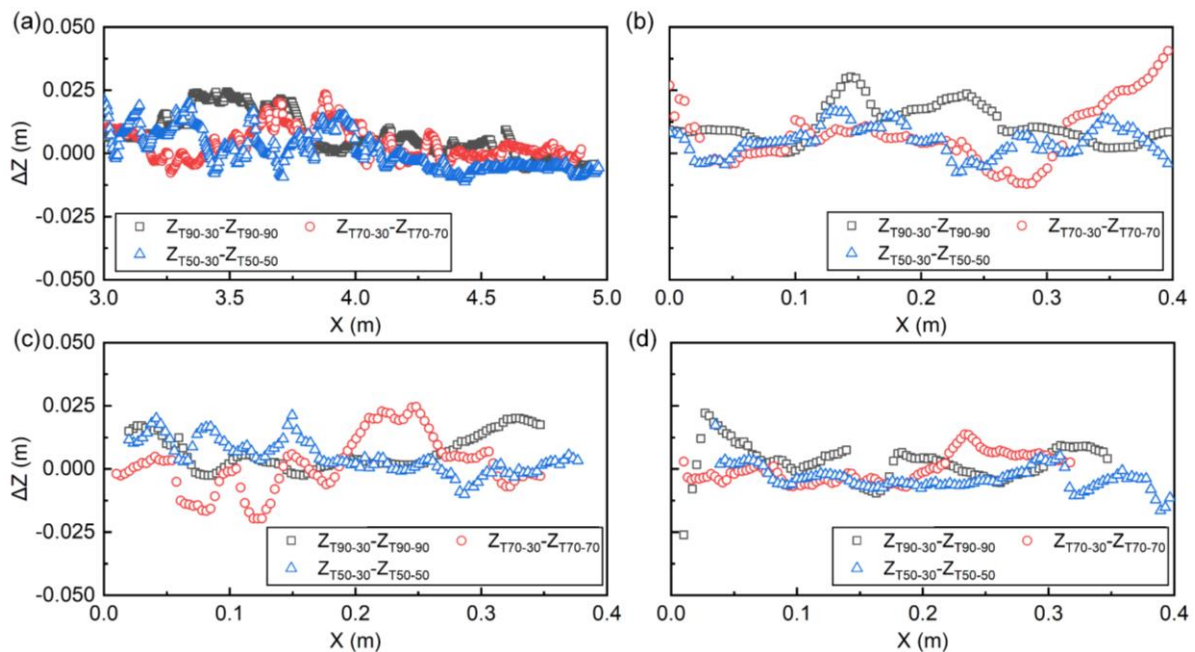


Fig. 14 The difference of the erodible bed elevation between T90-90 – T90-30, T70-70 – T70-30 and T50-50 – T50-30 along four profiles: (a) Profile 1; (b) Profile 2; (c) Profile 3 and (d) Profile 4.

4.2. Surface grain size distribution

The final topography of the tests with the same dam material but different erodible bed material is consistent. Therefore, only the sediment distribution of two areas on the erodible bed of T90-90, T70-70, T50-50 and T30-30 is analyzed, as shown in Fig. 15.

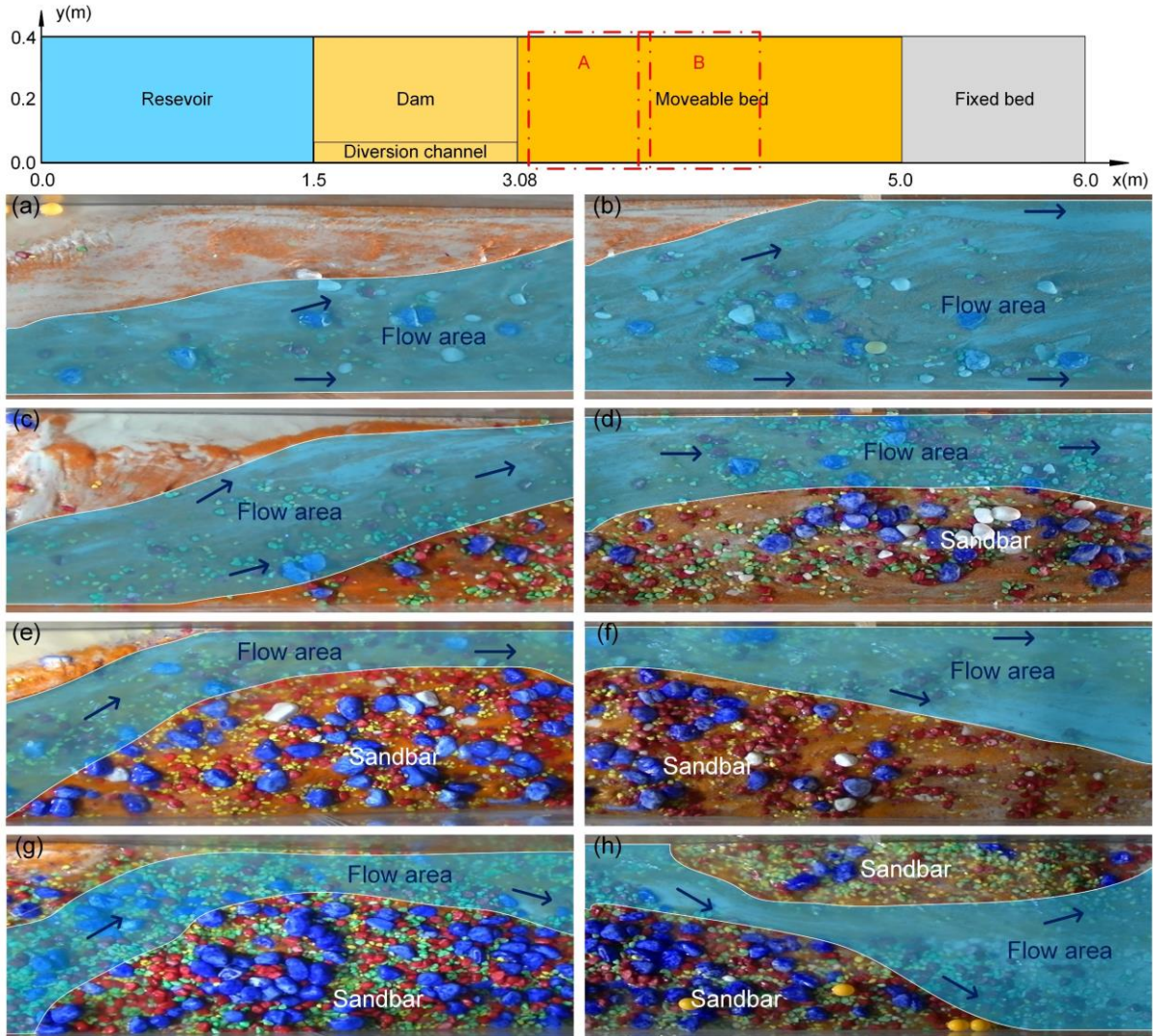


Fig. 15 Flow direction and sediment distribution after dam failure: (a) and (b) T90-90; (c) and (d) T70-70; (e) and (f) T50-50; (g) and (h) T30-30. ((a), (c), (e) and (g) are from area A range from 3.1–3.7 m in the downstream of the dam toe; (b), (d), (f) and (h) are from area B range from 3.6–4.2 m).

The sediment distribution shows great difference with different material composition. In T90-90, where the finest material is considered, the coarse grains are widely distributed along the flow direction due to the higher sand content in the dam material (Fig. 15a and b). As the sand content in the dam material decreases, the sediment transport rate for the coarse material decreases and the gravel are deposited immediately downstream of the breach. In this

circumstance, the flow direction is changed due to the deposition of the coarse gravels, further resulting in the formation of a sandbar on the erodible bed (Fig. 15c, d, e and f). In T30-30, where the coarsest material is considered, coarse grains are deposited very close to the downstream dam toe due to the smaller discharge of the outburst flood and limited sediment transport rate for gravels. This creates a sandbar and changes the direction of the flow. However, unlike T2 and T3, another sandbar with finer sediment composition is observed on the opposite bank of the flume, changing the flow direction once again, and finally a meandering channel is observed on the erodible bed.

5. Discussion

5.1. The influence of the wide-graded material on dam failure and morphological changes

5.1.1. Dam failure

The wide-graded material has an impact on the erosion the dam. After dam failure, an armour layer consisting mainly of coarse gravel is observed on the erosion surface. This armour layer prevents the further erosion of the dam, resulting in the formation of a residual dam. This phenomenon is related to the incipient motion of the sediment particles. Dividing the wide-graded material into sand and gravel fractions, the incipient motion of each fraction can be determined as follow:

$$f = \vartheta_i - \vartheta_{ci} \quad (2)$$

where ϑ_i and ϑ_{ci} are the dimensionless shear stress (Shields number) and the critical dimensionless shear stress in each fraction of the material, respectively. These two parameters can be calculated as follows (Eguiazarov 1965):

$$\vartheta_i = \frac{n^2 u^2}{(s - 1) d_{50,i} h^{\frac{1}{3}}} \quad (3)$$

$$\vartheta_{ci} = \begin{cases} \vartheta_c \left[\frac{\log 19}{\log \left(\frac{19d_{50,i}}{d_{50}} \right)} \right]^2 & \frac{d_{50,i}}{d_{50}} \geq 0.4 \\ \vartheta_c \frac{d_{50}}{d_{50,i}} & \frac{d_{50,i}}{d_{50}} < 0.4 \end{cases} \quad (4)$$

where n is the Manning coefficient, u and h are the flow velocity and flow depth, respectively. $s = \rho_s/\rho_w$ refers to the ratio of grain density and water density. $\vartheta_c = 0.06$ is the critical dimensionless shear stress of the whole material, d_{50} and $d_{50,i}$ are the median diameters of the whole material and of each fraction. The sediments start to move when ϑ_i is equal to ϑ_{ci} , then equation (2) under this condition can be expressed as:

$$\frac{n^2 u^2}{(s-1)d_{50,i} h^{\frac{1}{3}}} = \vartheta_{ci} \quad (5)$$

Leaving the hydraulic parameters on the left-hand side, the equation can be further rewritten as:

$$\frac{u^2}{h^{\frac{1}{3}}} = \frac{\vartheta_{ci}(s-1)d_{50,i}}{n^2} = F_m \quad (6)$$

where F_m represents the boundary condition under which the sediments start to move, and its value of the four materials which are considered in the experiments are calculated and analyzed in Table 2.

Table 2 Erosion related parameters of the four materials

Material	d_{50}	n	$d_{50,i}$ (mm)		ϑ_{ci}		F_m	
	(mm)	(s/m ^{1/3})	Sand	Gravel	Sand	Gravel	Sand	Gravel
G1	0.730	0.019			0.067	0.017	0.196	0.738
G2	0.999	0.020			0.085	0.020	0.224	0.748
G3	2.000	0.022	0.620	9.000	0.193	0.026	0.402	0.793
G4	6.562	0.027			0.631	0.049	0.885	0.992

Note: d_{50} and $d_{50,i}$ (mm) are the median diameter of the entire material and of the each fraction, respectively; ϑ_{ci} is the dimensionless critical shear stress in each fraction of the material. n (s/m^{1/3}) is the Manning coefficient and is calculated as $n = \frac{d_{50}^{1/6}}{A_n}$ ($A_n = 16$, Wu, 2013); F_m represents the boundary condition under which the sediments start to move.

As shown in Table 2, the F_m of the sand particles is always smaller than that of the gravel

particles, and both the F_m of the sand and gravel particles increase as the sand content in the material decreases from G1 to G4. In addition, compared with the F_m of the gravel particles, the F_m of the sand particles varies greatly with the change in sand content, and similar F_m between the sand and gravel particles is observed when the coarsest material is considered. The variation of F_m indicates that the sand particles are always more easily washed away under the same flow conditions. Therefore, the sand particles are washed away while the gravel particles are left behind when a relatively small discharge is observed at the end of the dam failure, resulting in the formation of the armour layer that prevents the further erosion of the dam. The incipient motion of the sand particles also depends on the sand content in the material composition. With similar F_m of the gravel particles, the incipient motion of the sand particles becomes more difficult with decreasing of the sand content in the material, resulting in a decrease in the sediment transport rate during dam failure. Therefore, a breach with smaller depth and a residual dam with higher height is observed after dam failure, as shown in Fig. 9.

5.1.2. Morphological changes

The variation of the sediment distribution on the erodible bed is related to the difference in the travel distance of sand and gravel particles. Assuming that the sediments are transported as a sliding motion on the surface of the bed and at the same velocity as the flow, the forces acting on a particle include the submerged weight force G_f , the uplift force F_f and the friction force F_r , and can be expressed as flows:

$$G_f = \frac{\pi}{6}(\rho_s - \rho_w)gd^3 \quad (7)$$

$$F_f = \frac{\pi}{8}C_L\rho_w u^2 d^2 \quad (8)$$

$$F_r = \mu G_f \cos\theta - \mu F_f \quad (9)$$

where ρ_s and ρ_w are the particle and water densities, respectively. d is the particle diameter. C_L is the lift coefficient. u is the flow velocity and θ is the bed slope. μ is the friction

coefficient. According to the kinetic energy theorem:

$$(G_f \sin\theta - F_r)L = -\frac{1}{2}mu^2 \quad (10)$$

where L is the distance that a particle can be transported by the flow. Then it can be expressed as:

$$L = \frac{\rho_s u^2}{2\mu \left((\rho_s - \rho_w)g \cos\theta - \frac{3}{4} \frac{C_L \rho_w u^2}{d} \right) - 2(\rho_s - \rho_w)g \sin\theta} \quad (11)$$

As shown in equation (11), the travel distance of the sediments is determined by the flow velocity, the bed slope and the particle diameter. Under the same flow and bed conditions, the travel distance decreases with increasing the particle diameter. Therefore, gravel particles are deposited closer to the dam than sand particles. This difference in travel distance between the sand and gravel particles leads to the unevenly distribution of sediment deposition on the erodible bed, thus, changing the variation of the downstream morphology. This also explains the difference in final topography between the tests with different material compositions.

5.2. Erosion characteristics and the dam failure pattern

The experimental results of dam failure indicates that the erosion surface slope first increases until it reaches the maximum value, and then gradually decreases until the final topography is observed during dam failure in all of the tests (Fig. 8). This kind of variation is not consistent with the results of previous studies. For instance, Coleman et al. (2002) and Zhong et al. (2018) suggested that the erosion surface slope decreases all the time during the dam failure (Fig. 16a), while in the models proposed by Chang and Zhang (2010) and Zhou et al. (2019), the erosion rate remains constant along the longitudinal cross section of the dam, thus a constant erosion surface slope is considered in their model (Fig. 16b). Since the variation of erosion surface slope represents the difference of erosion rate at different positions during dam failure, so the variation of erosion rate is analyzed here to explain the variation of erosion

surface slope during dam failure.

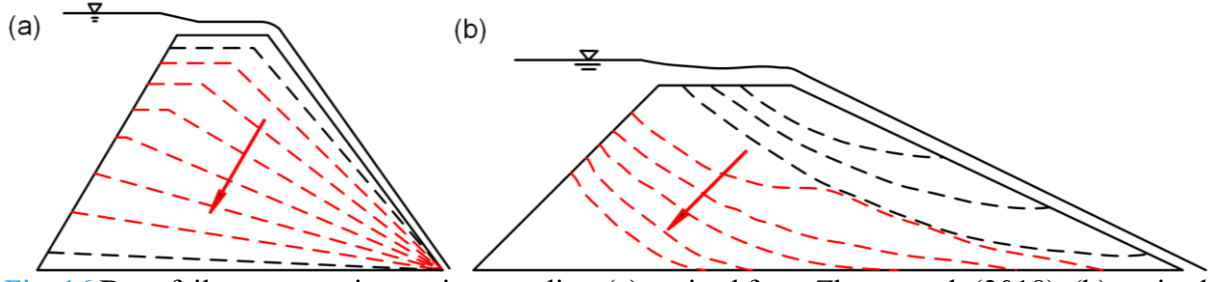


Fig. 16 Dam failure pattern in previous studies. (a) revised from Zhong et al. (2018), (b) revised from Zhou et al. (2019).

Several erosion models have been proposed in previous research (Fraccarolo and Capart 2002; Medina et al. 2008; Iverson and Ouyang 2015; Kang and Chan 2017). However, it's difficult to obtain the relevant parameters to calculate the erosion rate during dam failure with these models. Therefore, in this paper, only the variation of erosion rate during dam failure is analyzed qualitatively. Following Graf (1984), the erosion rate is calculated as follow:

$$E = k_d(\tau - \tau_c) \quad (12)$$

where E is the erosion rate, k_d is a constant coefficient corresponding to the erodibility of the material, τ_c is the critical shear stress and depends on the material composition. τ is the shear stress at the interface between the soil and the flow, and it can be calculated as follow:

$$\tau = \frac{\rho_w g n^2 u_b^2}{h^{1/3}} \quad (13)$$

where ρ_w is the water density, g is the gravity acceleration, n is the Manning coefficient, u_b is the effective velocity acting on the grain, and h is the water depth. The coefficient of erodibility k_d , the critical shear stress τ_c and the Manning coefficient n remain with a given material. Therefore, the erosion rate during the dam failure then can be written as a function of flow depth velocity as follow:

$$E = f\left(\frac{u_b}{h}\right) \quad (14)$$

Based on Equation (14), the erosion rate at each point during the dam failure can be determined when the flow velocity and flow depth are known. The variation of flow velocity

during dam failure can be divided into two phases: the acceleration phase and the deceleration phase. In the first phase, the water flow over the inclined erosion surface, and the acceleration of the flow can be expressed by the kinetic energy theorem as follow:

$$V_B^2 = V_A^2 + 2(g\sin\theta - \mu g\cos\theta)L \quad (15)$$

where V_B and V_A are flow velocities at two positions along the erosion surface. L is the distance between these two points and θ is the slope of the erosion surface. However, in the second phase, the decrease of the flow velocity is determined by the change of the flow direction. In these two phases, a relatively constant water depth is observed on the erosion surface in all tests, while it increases greatly when the change of the flow direction is observed.

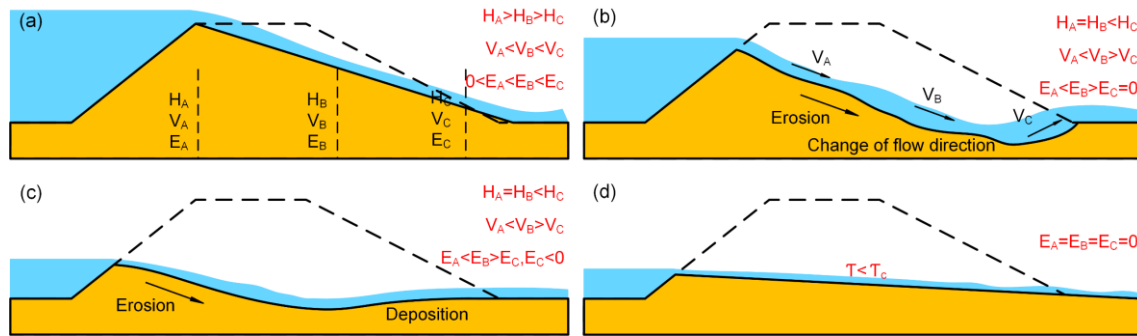


Fig. 17 Erosion characteristics and the variation of erosion surface.

Based on the variation of the flow velocity and water depth, the erosion rate during dam failure is analyzed and a new dam failure pattern is proposed. The initiation stage of dam failure in this paper is similar to that proposed by Coleman et al. (2002) and Zhou et al. (2019). After the initiation stage, differ from the proposed patterns, the flow velocity increases along the erosion surface after the upstream dam crest is eroded, while the water depth is almost constant along the erosion surface. Therefore, the erosion rate increases along the erosion surface, resulting in the increase of the erosion surface slope (Fig. 17a). When the maximum slope of the erosion surface is observed (Fig. 17b), the flow velocity decreases while the flow depth increases greatly due to the change of the flow direction at the downstream dam toe, thus, a smaller erosion rate is observed in this position. Furthermore, deposition occurs at the downstream dam toe with the decreases of the discharge during dam failure. The slope of the

erosion surface then decreases with the erosion in the upstream of the dam and the deposition in the downstream of the dam (Fig. 17c). When the discharge remains constant, the shear stress of the flow is smaller than the critical shear stress of the soil, the particles are unable to be eroded. In the end, the erosion rate on the erosion surface decreases to zero and the final topography can be observed (Fig. 17d).

5.3. Comparison between experimental results and natural landslide dam failure

Although this study considers a simplification of the landslide dam conditions, the results of the experiments are consistent with the observation of natural landslide dams (Fig. 18). Firstly, all of the modelled dams failed mainly by overtopping, although the sand content of the dam material varies considerably between the laboratory tests. Overtopping is also the main failure mode observed in the field. As reported by Peng et al. (2012), 91% of the 144 cases of landslide dams failed by overtopping. Secondly, natural landslide dams usually have a partial failure characteristic, which means that after dam failure, there are residual dams that can further level up the river channel. It should be clear that in some cases the existence of residual dams is induced by the rocks that contribute to the formation of the dam and cannot be washed away when the dam fails. For instance, the Tangjiashan landslide dam, where the dam base is mainly composed of unfractured rocks from the original strata (Xiong et al. 2022). Therefore, the bottom of this kind of landslide dam cannot be eroded away and the residual dam is observed. However, the erosion resistance of the dam material and the deposition observed at the downstream toe of the dam cannot be ignored. These two factors contribute to the change in morphology of both the dam site and the downstream channel. For instance, after the failure of the Hsiaolin landslide dam, an uplift of the riverbed was observed even though it consisted of more than 70% of silt or sand ($d < 2 \text{ mm}$) (Li et al., 2011). A third element concerns the sandbars that were observed on the erodible bed after dam failure, which further changes the flow direction and leads to the formation of a meandering river channel. This phenomenon is

consistent with the field observations of the river channel after dam failure (Fig. 18). For instance, Jiang et al. (2021) recorded 38 sandbars in the field formed by four landslide dam failures, including the eight sandbars caused by the failure of the Tangjiashan landslide dam. The same phenomenon can also be observed in the flume experiment of Chen et al. (2015) and the full-scale field experiment of Yoshino et al. (2011).

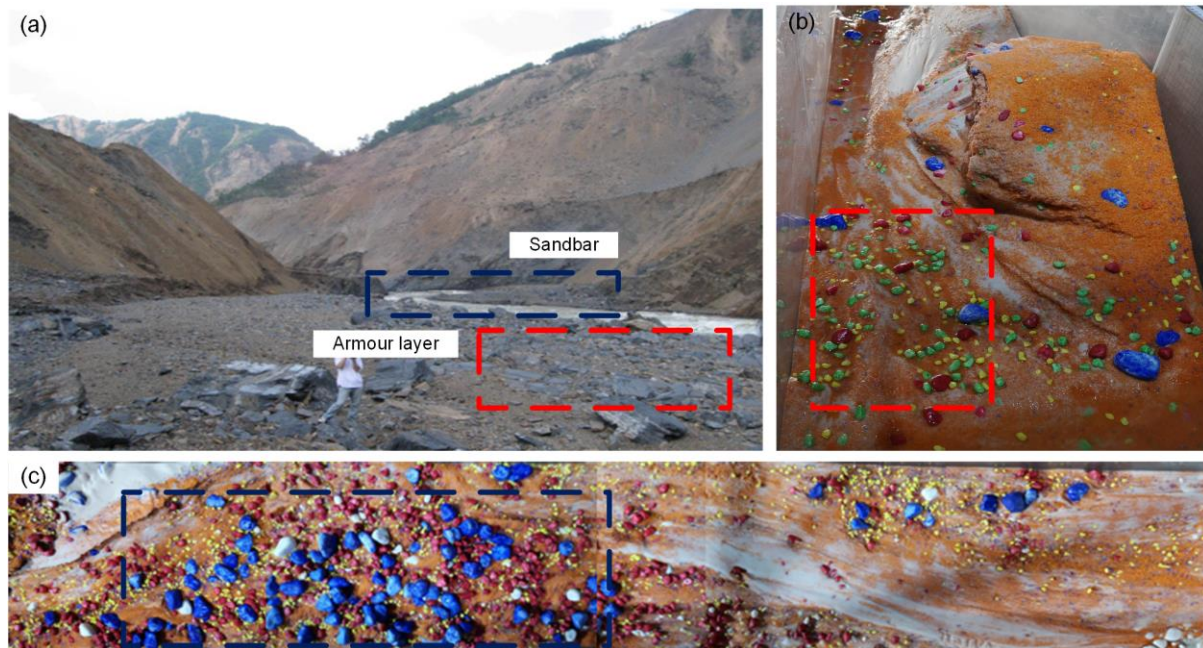


Fig. 18 Comparison between the experimental results and the landslide dam failure in real scenario

5.4. Limitations

The influence of the material composition of both the dam and the erodible bed on the dam failure and the induced morphological changes are analyzed. However, the experiments in this paper have some limitations. Firstly, only four materials and eight tests were considered, and more tests with different material compositions should be conducted. However, several dam failure experiments are conducted with the same equipment and method in our group (Shen et al., 2022; Shi et al., 2022), which ensures that the experimental results presented here are reliable. Secondly, the material distribution of natural landslide dams varies from the top to the bottom. For instance, the finer material is observed at the top of the dam while the coarser material is observed at the bottom. This uneven distribution characteristic greatly influences

the erosion of the dam, and different dam failure process can be observed. In this paper, the material is uniformly distributed throughout the dam, which is quite different from the real cases. However, this paper provides some insights for future research on landslide dams, especially the influence of material composition on dam failure. In addition, these simplified experiments can be easily applied to develop and verify some numerical tools for simulating the failure of landslide dams and the induced morphological changes. [Thirdly, previous research indicates that the cohesive material has great influence on the erosion pattern and the dam failure process \(Shen et al. 2022\). Since the topography change is strongly related to the dam failure, thus, the cohesive material must have an influence on the morphological changes in the downstream of the dam. In our experiments, grains that are smaller than 0.075 mm are ignored in the material composition, so the materials in our experiments are non-cohesive materials. However, it's worth investigating the influence of cohesive material on dam failure and morphological changes in the future.](#)

6. Conclusion

In this paper, the bi-modal characteristic of the landslide dam materials is first considered in experimental study of dam failure and morphological changes. The influence of material composition on dam failure and the induced morphological changes are analyzed based on eight flume tests with considering different sand content in both the dam and the erodible bed.

The main conclusions are as follows:

(1) Experimental dams fail mainly by overtopping. The similar dam failure processes are observed with different material composition. [Based on the erosion characteristics and the variation of hydraulic parameters during dam failure](#), the dam failure is further divided into four stages, including the initiation stage, the acceleration stage, the attenuation stage and the recovery stage. Among these four stages, the acceleration and attenuation stages mainly control the breach development and the change of hydraulic parameters.

(2) The peak discharge increases from $4.50 \cdot 10^{-3} \text{ m}^3/\text{s}$ to $5.46 \cdot 10^{-3} \text{ m}^3/\text{s}$ while the residual water level decreases from 0.18 m to 0.11 m with increasing the sand content from 30% to 90% in the dam material. The difference in the dam failure process is characterized by the variation of the erosion surface slope. A larger maximum slope (0.44 and 0.24 with sand content of 90% and 30% respectively), while the final topography with a smaller slope is observed when the finer dam material is considered. A trapezoidal breach is observed after dam failure. The final breach depth and top width increase while the lateral slope of the breach decreases with increasing sand content in the dam material.

(3) The influence of bed material on the peak discharge and the residual water level is also influenced by the dam material composition. For the dam composed of material with a sand content of 90%, the peak discharge decreases from $5.46 \cdot 10^{-3} \text{ m}^3/\text{s}$ to $4.24 \cdot 10^{-3} \text{ m}^3/\text{s}$ and the residual water level increases from 0.17 m to 0.18 m as the sand content in the erodible bed material increases from 30% to 90%. The opposite conclusion is obtained for dams composed of coarser material (50% and 70% of sand). In addition, a finer erodible bed is able to slow down the decrease of the erosion surface slope during dam failure while similar final breaches are observed with different erodible beds. The main reason of these phenomena is the finer material leads to the more intense erosion and deposition of the erodible bed.

(4) The deposition depth of the final topography increases with increasing sand content in the dam material. The sediment deposition is unevenly distributed on the erodible bed, and it becomes more pronounced with decreasing sand content in the dam material. The influence of the erodible bed material on the final topography is rather limited, and similar final topographies are observed. Sandbars are observed due to the difference in the travel distance between sand and gravel particles during dam failure. The formation of sandbars further changes the flow direction, resulting in the formation of a meandering river channel.

(5) The influence of wide-graded material on dam failure is related to the incipient motion

of sediments, which results in the formation of an armour layer after dam failure. The armour layer prevents the further erosion of the dam and results in the existence of residual dam during dam failure. A new dam failure pattern is proposed by considering the first increase and then decrease of the erosion surface slope caused by the variation of the erosion rate and the occurrence of deposition during dam failure, and appears more suitable to describe landslide dam failure.

This research shows that the dam failure and the induced morphological changes are significantly influenced by the material composition of both the dam and the erodible bed. The experimental results can provide better understanding of the failure mechanism of landslide dams, and help for hazard management.

Acknowledgments

We acknowledge funding from the Natural Science Foundation of China (No. 41731283 No. 42307196 and No. 42007252) and the China Postdoctoral Science Foundation (2023M733029).

Statements and declarations

Competing interests: The authors declare no competing interests.

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