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Formation conditions of outburst debris flow triggered by overtopped natural dam failure

Abstract Natural dams formed by landslides may produce disastrous debris flows after dam outburst. However, studies on the critical conditions required for the formation of outburst debris flow resulting from natural dam failure are still at an early stage. In this paper, we present the results of a series of laboratory tests that assessed three different materials, five different flume bed slope angles (2°, 7°, 9°, 10°, and 13°), two in-flow rates, and four types of dam geometric shapes. The results showed that the unit weight of downstream fluid increased with increasing bed channel slope. Additionally, a critical flume bed angle was found for debris flow formation. Furthermore, the combination of lake volume and flume bed angle was found to influence the formation of debris flow. A nonlinear trend was observed between the unit weights of debris flow and the uniformity coefficients of solid material. Based on the theory of stream power, a critical condition for debris flow formation from natural dam failure was established. Based on two case studies, the results indicate that the condition that was established for debris flow formation following natural dam failure agrees well with reality.

Keywords Natural dam · Debris flow · Overtopping · Critical condition

Introduction

Excessive rainfall and earthquakes often cause landslides of slightly liquefied matter, which can fall into river channels and choke the river. This is called a natural dam (Takahashi 2007). More than 50 % of natural dams break by overtopping, and 85 % fail within 1 yr of formation (Costa and Schuster 1988). Hazardous flooding may result when a dam breaks. For example, the Tangjiashan landslide dam (volume of 2×10^7 m^3) was the largest of 260 natural dams after the Wenchuan earthquake. Twenty-seven days after its formation, the dam breached, with a peak flow of 6500 m^3/s, forming a flash flood downstream (Liu et al., 2010). Natural dams usually have enormous volumes, long lengths, and small downstream and upstream slopes. A large-scale natural dam often is made of loose, easily erodible materials that are incorporated into the overflowing flood, which may also lead to a debris flow downstream (Schuster 2000). For example, a landslide dam on the Bairaman River of Papua New Guinea broke in 1986, releasing a debris flow flood consisting of an estimated 4×10^7 m^3 of water and 8×10^7 m^3 of rock and soil debris (King et al. 1989). High velocity debris flows that contain large particles such as boulders have large damage capacity.

Different from outburst floods from natural dam failure, the outburst debris flows often bury downstream infrastructures for days or months while flood only causes inundation during it occurs. Moreover, debris flow carries larger energy than flood and lead to significantly more severe impact damage than flood. Since debris flow and flood have very different extend and pattern of damage, it is essential to evaluate whether a debris flow or flood will be formed timely before natural dam failure so that targeted measures can be made to minimize the casualties and property loss. Therefore, a clear understanding on the formation condition of outburst debris flow due to natural dam failure is certainly necessary for disaster prevention and mitigation. To analyze and establish the formation condition of outburst debris flow, it should firstly confirm which factors (such as character of dam materials, channel slopes, and dam geometric shapes) have directly influence on the formation of outburst debris flow. Flume tests are commonly used to model dam failure and debris flow initiation in riverbeds. Previous studies have focused on the process of break development, the mechanism of failure, the creation of dam breach simulation models (Butler et al. 1991; Hanisch 2002; Zech et al., 2008; Pickert et al. 2011; Rozov 2003; Cao et al., 2011a, b; Dou et al. 2014), the calculation of the peak flow of a flood and on the simulation, and prediction of flood routing (Singh and Quiroga, 1987; Fread 1988; Walder and O'Connor, 1997; Macchione 2008; Belikov et al. 2010; Ma and Fu 2012; Fan et al. 2012). But until now, there has been no test focus on the relationship between natural dam failure and debris flow formation. Various attempts have been made by many researchers to study the peak discharge and motion of debris flow induced by the failure of natural dams (Takahashi and Nakagawa, 1993; Mizuyama et al., 2006; Horiuchi et al. 2010). However, these studies have not revealed whether dam length, lake volume, dam materials, or channel slope are connected with outburst debris flow. Therefore, the main factors on the formation of outburst debris flow are still unclear.

Some researchers have studied the critical conditions required for the formation of debris flow due to rainfall and have established quantitative relationships regarding the conditions (Takahashi, 2007). However, the critical conditions required for the formation of debris flow due to natural dam destruction are different from those for debris flow due to channel bed erosion following severe rainfall. First, natural dams are made of loose, easily erodible materials, whose consolidation degree is lower than the materials lining the channel bed. Second, the dynamic water condition is different. Outburst flow due to natural dam breach possesses large volume and high velocity; this can easily sweep erodible soils into the outburst flow. Water flow due to rainfall on the channel bed leads to the accumulation of materials, and the debris is entrained to form debris flow. Surface flow caused by rainfall has a smaller volume and slower velocity than outburst flow (Schuster, 2000). Additionally, the initiation process of debris flow due to rainfall is longer than that for outburst debris flow. Third, the initiation of debris flow due to rainfall requires a larger bed channel slope than the initiation of outburst debris flow. For example, Takahashi (1980) conducted a number of tests on this topic and deemed that 14° is the critical channel gradient for debris flow initiation. However, Wang and Zhang (1989) stated that debris flow caused by natural dam failure usually requires a smaller channel slope. The critical conditions that lead to the formation of debris flow due to natural dam breach have been short of quantitative analyses.

This paper presents a series of flume tests to study crucial influences on the formation of outburst debris flow. In our tests, we chose four factors that might have influence on the formation of outburst debris flow, which included materials, flume bed slope angles, in-flow rates, and dam geometric shapes. Then, after reviewing the results from the tests, we screened out the main factors which have mostly influenced the formation of outburst debris flow and established the formation conditions of outburst debris flow. Therefore, the objectives of this paper are to better understand the controlling factors of debris flow formation from natural dams and to establish the critical conditions required for such debris flow by considering the main controlling factors. Using data from the Chayuan gully natural dam and the Tangjiashan natural dam, the unit weights of the outburst fluids were calculated to determine whether debris flow formed and to verify the established conditions.

Experimental methods

Experimental setup

The tests were carried out in a flume measuring 6 m long, 0.3 m wide, and 0.4 m deep. The flume was made of glass with a variable bottom slope, and the Manning roughness was approximately 0.01. Figure 1 shows the experimental setup. A triangle weir, which was used to measure the inflow discharge, was fixed at the bottom of the flume, 0.5 m away from the intake. A plate was set 0.3 m behind the weir to reduce inflow kinetic energy. The dam was located 2 m away from the intake. The tests involved the use of a movable riverbed. The movable riverbed was composed of the same materials as the dam and had a thickness of 5 cm. At the end of the flume, a 5-cm-high plate was set as the boundary condition. A collection pool was used to collect the sediments and water from the riverbed. A 1-m ruler was pasted on the wall of the reservoir to measure the height of the fluid contained within it. As shown in Fig. 1, six digital video cameras were installed above the dam, on the side of the dam, and above the riverbed, weir, and reservoir to record the entire process. Piezometers were installed both upstream of the dam and in the dam itself, as shown in Fig. 1.

Experimental procedure and data

In the tests, three different materials were used: coarse sand (CS), fine sand (FS), and mixed soils (NS) excavated from a slope in Beichuan County, PRC. Figure 2 shows the grain-size distributions of the CS, FS, and FS. The median diameters are 5, 6, and 0.5 mm, respectively, for the CS, FS, and NS samples, and they have a common water content of 7.82 %. The water content was 7.82 % when the dam was built. The dam was built without compacting. The specific gravities of the CS, FS, and NS materials are 2.700, 2.704, and 2.663, respectively. The uniformity coefficients were 25.6, 12, and 18.3, respectively, for the CS, FS, and NS. In lacking some particle groups, the gradation curve of CS presents a stepped shape. The curvature coefficient of the CS is 0.38. The CS was considered a poorly graded material. The order of material grading from best to worst is NS, FS, and CS.

The preliminary designs of the flume bed slope were 2°, 7°, 9°, and 13°. To obtain the critical angle for debris flow formation from natural dam failure, we increased the angle of the flume in step. Four types of dams with trapezoidal profiles were simulated in the flume tests. The initial upstream and downstream slopes of the dams were 20°, 15°, 30°, 20°, 35°, and 30° and 45° and 45°. All of the dams had a common height and width of 0.3 m and a crest width of 0.3 m. The inflow discharges used in the experiments were 1 l/s. In total, 53 experimental runs were conducted, as summarized in Table 1. The values of lake volumes in the table are based on the data measured during the experiments.

During the experiments, the water/sand mixture ran down from the riverbed. To test the unit weights of flow samples at different times, we collected the samples with sample cups. After the lake water overtopped the dam, we collected the water/sand mixture at the end of the flume every 2 s. The sample cup was made of plastic and had a height of 0.25 m and a diameter of 0.15 m. The sample cup had tick marks to know the total volume of the sample. Then, the total weights, solid weights, and water weights of the samples were measured. The video cameras and piezometers were turned on before the tests to begin recording the initial parameters, including the initial pore-water pressure, the initial height of the dam, and so on. In each test, the maximum unit weight data of each sample was used to know whether debris flow formed.

Results

General description

Figure 3 shows the typical temporal advance of the dam breach (the downstream and upstream slope of the dam are 20°and 30°). A steady inflow rate of 1 l/s resulted in the dam overtopping at $t = 0$ s. When the outflow overtopped the channel on the crest, it ran down on the dam face incorporating sediments from the dam body. The accumulated sediment formed a small hillock on the top of the downstream slope at $t = 10$ s. The hillock was formed from the leading portion of the debris flow. The flow entrance of the sediment on the downslope and the hillock become larger at $t = 15$ s. The breach became deeper and wider, and the cross section of breach at this time point was rectangular. The leading portion of the debris flow (hillock) moved to the toe of the dam at $t = 20$ s. A channel was formed from the crest to the dam toe. At $t = 25$ s, the debris flow eroded the channel bed and moved to the end of the flume. The slope of the breach continued to slide, which made the breach wider than it was at $t = 20$ s. The erosion also made the breach deeper than at the time point 5 s prior. At this moment, the cross section of the breach was primarily trapezoidal. The erosion on the channel was weaker than on the downstream slope of the dam. At $t = 30$ s, the erosion and the slide of the breach slope continued. Additionally, the outflow discharge became larger than before, the erosion on the bed channel became stronger, and the entrance of the sediments proceeded downwards quickly. In addition, there was a greater velocity of debris flow through the bed channel than 5 s prior, which increased the tractive shear stress and resulted in a high degree of erosion. The sediment transport reached a state of 'equilibrium', and the breach process ended at $t = 60$ s.

The small hillock stated above is called debris flow head, which is one of debris flow's characters. Figure 3 shows that in the initial phases of dam failure ($t = 0$–25 s), the debris flow head was formed on top of the steep downstream slope although the outflow discharge is small. And the volume of the debris flow head increases as time going on. When the debris flow head moved to the toe of the downstream slope (at the junction of downstream slope and bed channel), the debris flow stopped and deposited due to the

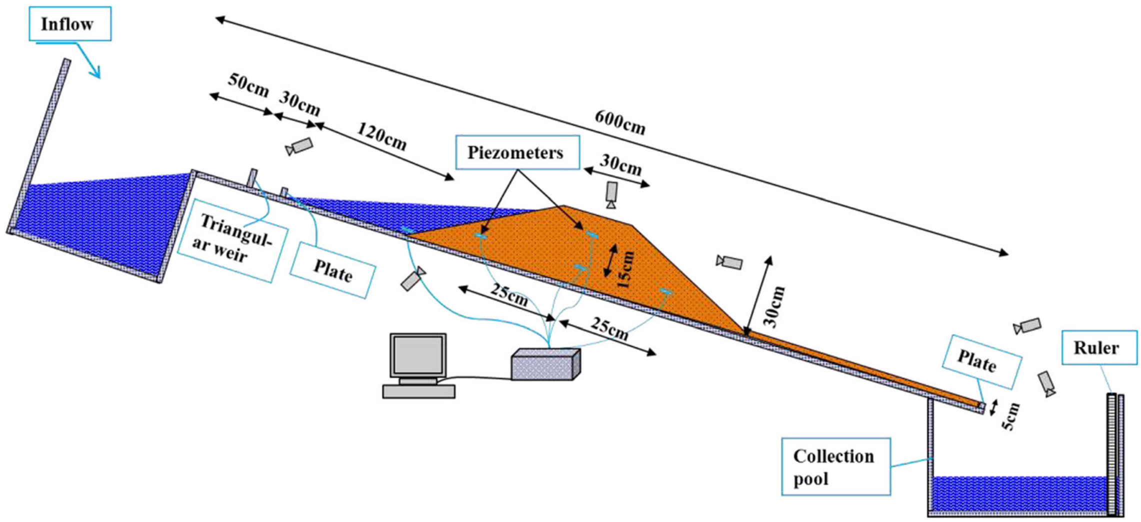

Fig. 1 Experimental setup. Four piezometers are located at the longitudinal and lateral profiles of the dam

sharp decreasing of bed slope. As outflow discharge became larger, the deposits were pushed away. Because of low sediment concentration, the water/solid mixture flowing on the channel was a hyper-concentrated flow rather than debris flow. It was noted that debris flow was not formed due to dam failure if hyper-concentrated observed along the downstream slope at initial stage. As outflow discharge increased (t = 30 s), the peak discharge appeared and the outflow entranced lots of sands and gravels to the downstream channel. The concentration of the water/solid mixture on the channel was high (as shown in the picture) and the solids in the mixture were mainly from dam and channel bed by erosion. At this stage, debris flow was formed in the channel. As water level gradually dropping (t = 60 s), the outflow discharge decreased and the amount of sand and gravel incorporated in the flow reduced. The water/solid mixture in the channel returned to hyper-concentrated flow again.

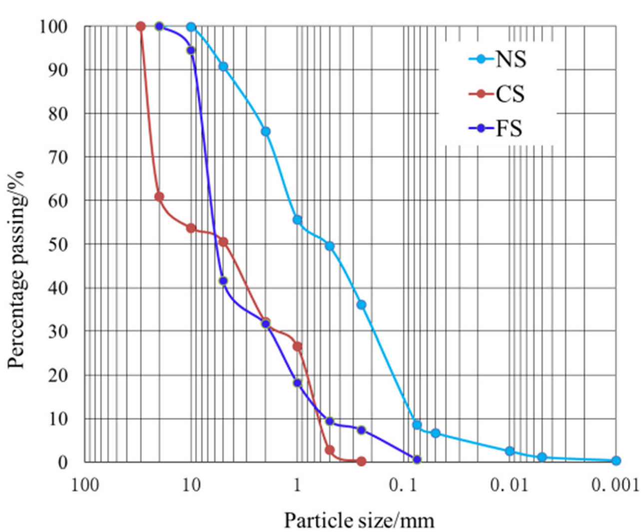

Fig. 2 Particle size distribution of dam materials, including sands (CS and FS) and natural soils (NS)

Hydrographs

Outflow discharge is one of the main parameters that affects debris flow formation following the failure of landslide dams. The flood discharge during this process could be obtained from the water pressure data that was recorded by the piezometer installed upstream of the dam. Figure 4 shows a sketch of the natural dam. The angle of the upstream slope of the dam is θ_1, and the angle of the channel is θ_2. After the lake water overtopped, at time t, the water depth in front of the dam was $h(t)$, and the volume of the lake is as follows:

$$V(t) = \frac{1}{2}h^2(t)[\cot(\theta_1) + \cot(\theta_2 - \theta_1)]d \quad (1)$$

where d is the width of the flume.

At time $t + \triangle t$, the volume of the lake is:

$$V(t + \Delta t) = \frac{1}{2}h^2(t + \Delta t)[\cot(\theta_1) + \cot(\theta_2 - \theta_1)]d \quad (2)$$

Within the time interval $\triangle t$, the outflow discharge is:

$$V(t) - V(t + \Delta t) = \frac{1}{2}[h^2(t) - h^2(t + \Delta t)][\cot(\theta_1) + \cot(\theta_2 - \theta_1)]d \quad (3)$$

Figure 5 shows a sequence of outflow hydrographs that was made during the dam failure process. Figure 5 a, b, c, and d represents the outflow hydrographs for the same dam (which was composed of FS and had upstream and downstream slopes of 30°and 20°, respectively) which corresponded to the 2°, 7°, 9°, and 13° flume beds, respectively. As the figure shows, the curves are not at all smooth and formed undulating patterns throughout the process. This is because during the break the side slope of the breach continuously slid or fell down, and the block always choked the breach. This caused the outflow discharge to decrease. Another reason is that the length of the lake upstream was shortened due to the large channel angle. When inflow arrives in the dam, the water produces fluctuations. Therefore, the water depth in the front of

Table 1 Summary of dam experiments

Materials	Bed channel slope (°)	Upstream slope (°)	Downstream slope (°)	Lake volume (l)	Inflow discharge (l)
NS	2	20	15	205.43	0.5
	2	30	20	213.49	
	2	35	30	215.90	
	2	45	45	219.30	
	2	20	15	205.03	1
	2	30	20	213.30	
	2	35	30	215.80	
	2	45	45	219.00	
	7	20	15	42.84	0.5
	7	30	20	50.88	
	7	35	30	53.32	
	7	45	45	56.43	
	7	20	15	42.82	1
	7	30	20	50.79	
	7	35	30	53.29	
	7	45	45	56.69	
	9	20	15	28.30	0.5
	9	30	20	36.36	
	9	35	30	38.77	
	9	20	15	26.45	1
	9	30	20	36.32	
	10	20	15	23.20	0.5
	10	30	20	31.26	
	10	35	30	33.32	
	10	45	45	37.02	
	10	20	15	23.24	1
	10	30	20	31.53	
	10	35	30	33.67	
	10	45	45	37.07	
	13	20	15	12.50	0.5
	13	30	20	20.58	
	13	35	30	23.00	
	13	45	45	26.44	
	13	20	15	12.57	1
	13	30	20	20.63	
	13	35	30	23.04	
	13	45	45	26.35	
FS	2	20	15	213.49	1
	7	20	15	42.83	1
	7	30	20	50.98	
	9	20	15	28.15	1
	9	30	20	36.55	

Table 1 (continued)

Materials	Bed channel slope (°)	Upstream slope (°)	Downstream slope (°)	Lake volume (l)	Inflow discharge (l)
	10	20	15	23.22	1
	10	30	20	31.30	
	10	35	30	33.86	
	13	20	15	12.61	1
	13	30	20	20.66	
	7	20	15	42.67	1
	7	30	20	50.76	
	9	20	15	28.46	1
	9	30	20	36.12	
	10	20	15	22.80	1
	10	30	20	34.92	
	10	35	30	34.86	
	10	45	45	35.68	
	13	20	15	23.02	1
	13	30	20	23.03	

the dam changes over time. Figure 5 a, b, and c shows that the peak discharges increased with increasing flume slopes. However, the peak discharge in Fig. 5 d was lower than that in Fig. 5c. This is mainly because the lake volume at the 9° flume bed is obviously greater than at the 13° one. Additionally, the time between initial outflow discharge and peak discharge at the 9° flume bed was shorter than at the 13° channel. For these reasons, the peak discharge of the 9° flume bed is greater than at the 13° one. This indicates that the peak discharge increases as the bed slope of the flume increases, under a certain limitation in slope angle. If the slope of the bed is larger than the limits, the peak discharge decreases as the slope increases.

Influence of different factors

The judgment index for debris flow formation mostly depends on the unit weight of the water/sand mixture (Kang et al. 2004; Fei and Shu, 2004; Wang et al. 2014). Fei and Shu (2004) summarized a definition of debris flow as proposed by previous researchers. He defined debris flow as a water/solid mixture with a minimum unit weight of 14308N/m^3 on the basis of energy conservation. This means that if the unit weight of a water/solid mixture exceeds 14308N/m^3, the mixture can be called debris flow. Furthermore, the volumetric concentration of solid particle can reach approximately 0.3 when the unit weight of the mixture is 14308N/m^3, which fits better with the field data. Therefore, in this paper, we defined the minimum unit weight of debris flow to be 14308N/m^3. The unit weight data from each test were analyzed statistically. During each test, we collected six or more samples (depending on test time), the samples' unit weights were used to judge the formation of debris flow. The maximum unit weight of each sample was selected in each test to serve as the main indicator for the judgment of debris flow formation. In this test, if the maximum unit weight was less than 14308N/m^3, the flood was not regarded to contain debris flow due to natural dam break. In our tests, the total weights and volumes of all of the samples were obtained. We divided the total weight by the volume to obtain the unit weight of the sample.

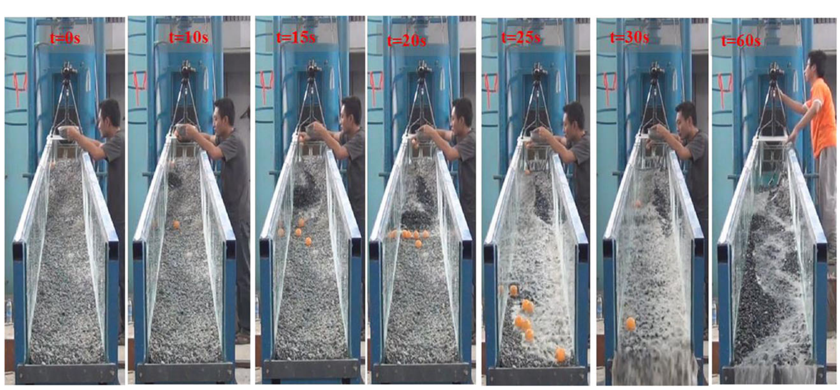

Fig. 3 Advance of natural dam erosion at different times

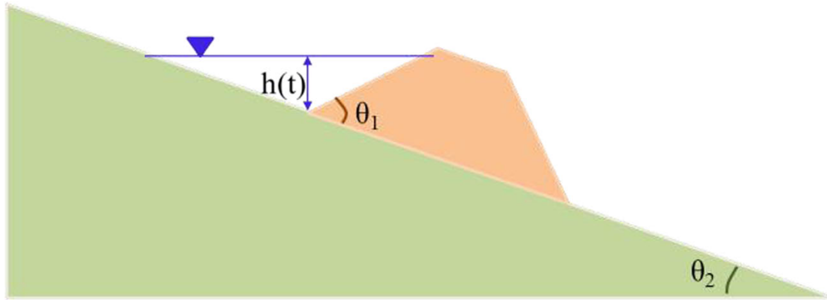

Fig. 4 Sketch of the natural dam and channel

Figure 6 shows the relationships between the unit weights, bed slopes, lake volumes, and uniformity coefficients of the materials. The unit weights of the fluid were greater than 14308N/m^3 when the bed slopes were 10° and 13°; in the cases of the bed slopes at 2°, 7°, and 9°, the unit weights of the water/sand mixture were less than 14308N/m^3 (Fig. 6a). The results indicate that 10° is the minimum bed slope for debris flow formation. Additionally, they demonstrate that the unit weight of the water/sand mixture increases as the bed slope increases in this angle range (2°–13°). According to the principles of energy conversion, the kinetic energy (converted from potential energy) of the outflow on a steep bed channel is larger than the kinetic energy of the outflow on a gentle bed channel. This means that the velocity of the outflow on a steep bed channel is faster than that on a gentle bed channel. In other words, outburst flow can carry more soil when it occurs on a steeper bed channel, which adds to the unit weight of the flow and is conducive to the formation of debris flow. This is the reason that a greater bed channel slope can more easily produce debris flow. Figure 6a also shows the relationship between lake volume and the unit weight of a mixture. The points at the bottom right corner correspond to the parameters at a 2° bed slope. Combined with Table 1, this indicates that the unit weights of a mixture are greater than 14308N/m^3 when a lake volume is smaller than 18 L. However, this does not imply that smaller lakes more easily form debris flow. Because lake volumes are related to bed slopes, the greater the bed slopes, the smaller the lake volumes. This reflects that bed slope, and not lake volume, is a key factor in debris flow formation. The uniformity coefficient Cu reflects the uniformity of the particles.

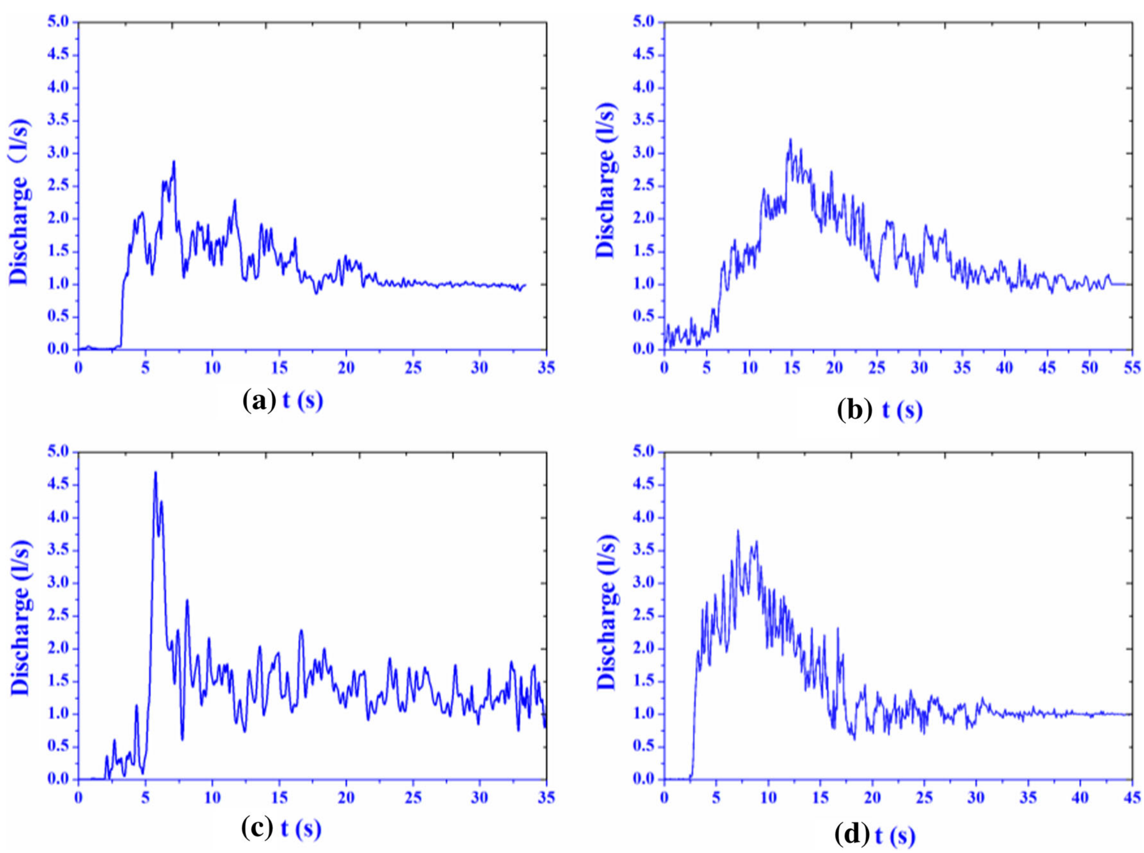

Fig. 5 Stage hydrographs of a dam with the same material and geometry but at different bed slopes. **a** Channel bed slope of 2°. **b** Channel bed slope of 7°. **c** Channel bed slope of 9°. **d** Channel bed slope of 13°

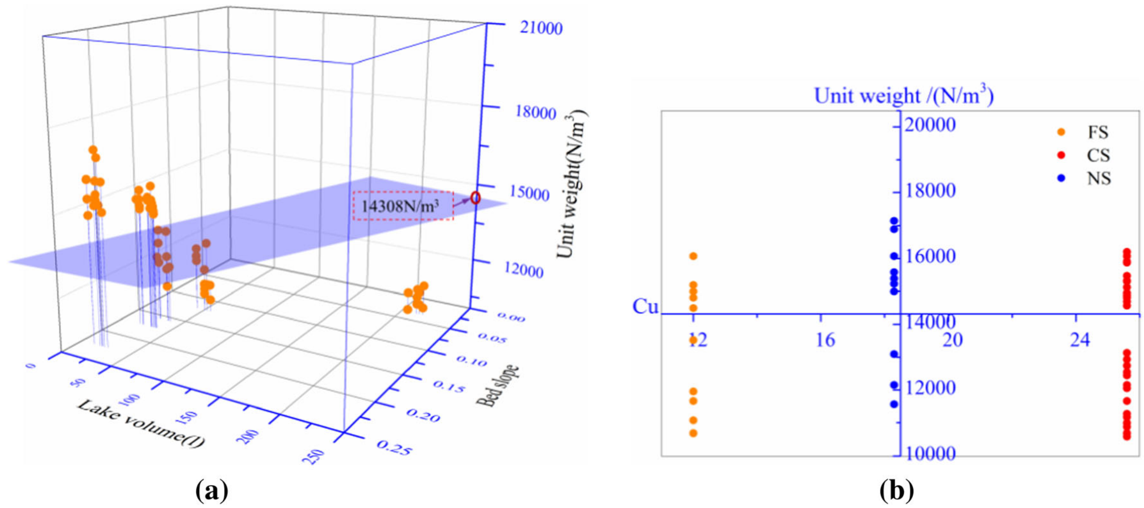

Fig. 6 **a** Relationships between unit weights of fluid, flume bed slopes, and lake volume. **b** Relationships between unit weights of fluid and a uniformity coefficient. The ordinate value of the intersection of the horizontal axis and the longitudinal axis is $\gamma_m = 14308 N/m^3$

As shown in Fig. 6b, the unit weight of the mixture of water and NS is larger than those of the other mixtures (water and CS; water and FS). As stated above, the size distribution of solid particle of CS is worse than that of NS. Additionally, the uniformity coefficient of NF is larger than that of FS, such that the graduation of NS is better than that of FS. As shown in Fig. 2, we can also observe that the fine fraction of NS is greater than the other two materials; as such, it is easily carried in water and acts as matrix component. This, the fine concentration in the fluid outburst from the dam made of NS is larger than those made from the other two materials. Iverson (1997) considered that an increased fine concentration in fluid leads to an increase in its effective Newtonian viscosity, which increases the shear stress of the fluid. This results in a greater degree of soil erosion and facilitates the formation of debris flow. The figures also show that the geometrical shape of a dam and its inflow rates have little effect on debris flow formation in such conditions. The geometrical shape of a dam only affects the unit weight of water/sand mixtures downstream of the slope of the dam. When water/sand mixture flows into a channel, the slope of the channel directly influences its unit weight. Even if debris flow occurs on the downstream slope of a dam, leading to sediment-laden flows on the channel, this is still not considered to be a condition of debris flow formation. Thus, the slope of the channel is the determining factor for the formation of debris flow, not the downstream slope of the dam (geometrical shape of the dam).

Critical conditions for debris flow formation

When a natural dam bursts, the overflow entrains rocks, sands, and soils from the dam and the channel bed, which may result in a debris flow downstream (see Fig. 7). As stated above, formation condition of outburst debris flow is mainly influenced by the slope of channel bed, materials, outflow discharge (lake volume is one factor on discharge).

The mechanism of debris flow formation is based on water flow picking up particles and dragging them downstream (Takahashi 2007). In this process, the particles require energy to initiate movement, which is provided by the water flow. Bagnold (1966) revealed that stream power represents the energy of water flow, which is a function of unit width flow discharge and bed slope. Wang and Zhang (1989) explored the minimum stream power for channel debris flow initiation. In Wang's paper, the conception and method of stream power are referenced.

Bagnold established the bed load initiation condition with stream power as

$$\frac{\gamma_s - \gamma_w}{\gamma_s} q_s = k(W_o - W_c) \tag{4}$$

where k is a dimensionless constant, γ_s and γ_w are the weights of particles and water, q_s is the sediment transport rate of unit width, W_o is the stream power, $W_o = \gamma_w q_w J$, q_w is the discharge of water flow per unit width, J is the bed slope, and W_c is the critical stream power for the initiation of particle movement.

Then, in multiplying the width of the river channel B on both sides of Eq. (4), it becomes

$$\frac{\gamma_s - \gamma_w}{\gamma_s} Q_s = k(W_{o1} - W_{c1}) \tag{5}$$

where $Q_s = q_s B$, $W_{o1} = W_o B$, $W_{c1} = W_c B$, and B is the width of the channel.

During the failure of a natural dam, the outflow discharge may vary. However, there is only one peak discharge, which has the strongest erosive force. As shown in Fig. 3, the debris flow can occur on the channel bed if only outflow discharge increases to a certain value, which may be the peak discharge. We suppose that if a debris flow does not occur at the peak discharge, it will not form during the process. Thus, peak discharge should be considered as the critical condition. Based on the assumption that the outburst water flows throughout the whole width of the river channel, we get

$$\frac{\gamma_s - \gamma_w}{\gamma_s} Q_s = k_1\left(\gamma_w Q_p J - W_{c1} B\right) \tag{6}$$

where k_1 is the constant for the peak discharge.

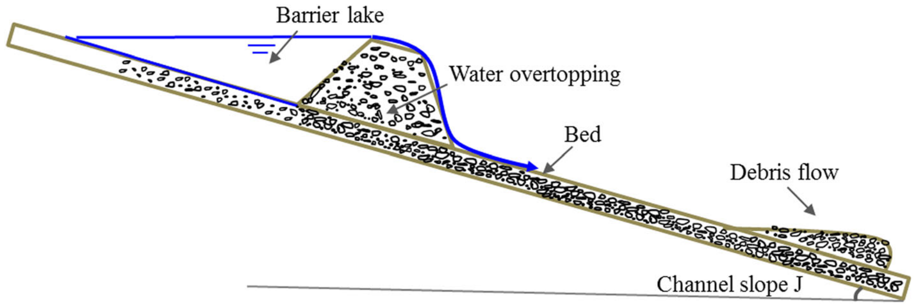

Fig. 7 Schematic diagram of the outburst debris flow due to the failure of a natural dam

Supposing that the downstream fluid has a uniform volume concentration in all directions, the following formula is produced

$$\gamma_m = \gamma_w + \left(1 - \frac{\gamma_w}{\gamma_s}\right)s \tag{7}$$

where γ_m is the weight of the fluid in the channel and s is the ratio of solid mass to total volume. Thus, we can obtain the following:

$$Q_s = \frac{Q_p\gamma_s(\gamma_m - \gamma_w)}{g(\gamma_s - \gamma_m)} \tag{8}$$

and

$$\frac{Q_p(\gamma_m - \gamma_w)(\gamma_s - \gamma_w)}{g(\gamma_s - \gamma_m)} = k_1(\gamma_w Q_p J - W_{c1}B) \tag{9}$$

Bagnold indicated that W_c is proportional to the particle diameter to the 1.5th power. For mixed soils with different particle sizes, Gessler (1972) adopted d_{50} as the characteristic value of the total particles and used a coefficient to reflect the nonuniformity of the mixed soils. W_{c1} can be obtained from the following relationship

$$\begin{aligned} W_{c1} &= a\frac{\gamma_w}{g}\left(\frac{\gamma_s - \gamma_w}{\gamma_w} g d_{50}\right)^{1.5} \\ &= a\gamma_w g^{0.5} d_{50}^{1.5}\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)^{1.5} \end{aligned} \tag{10}$$

where a is is a dimensionless coefficient and d_{50} is the median diameter of the mixed soils. Thus, Eq. (9) becomes

$$\frac{Q_p(\gamma_m - \gamma_w)(\gamma_s - \gamma_w)}{g(\gamma_s - \gamma_m)} = k_1\gamma_w Q_p J - k_2\gamma_w g^{0.5} d_{50}^{1.5}\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)^{1.5} B \tag{11}$$

where k_2 is a constant. The data from our tests yielded the best approximation values of the constants $k_1 = 0.45$ and $k_2 = 0.07$.

The specific gravity, the median particle diameter, the geometrical size of the lake, and the slope of the bed channel can all be obtained by field investigations and laboratory testing after a natural dam appears. Then, the unit weight of the fluid can be calculated with Eq. (11), which serves as the judgment index of debris flow formation. The peak discharge Q_p in Eq. (11) can be quickly obtained with the method proposed by Froehlich (Froehlich, 1995).

Case studies

Two case studies are presented below to illustrate the applicability of the above-defined critical condition for debris flow formation. One is the Chayuan gully natural dam that was formed after the Wenchuan earthquake, which failed in 2009 and caused debris flow downstream. The other is the Tangjiashan natural dam, which failed in 2008 without causing debris flow.

The Chayuan gully natural dam was induced by the Ms 8.0 Whenchuan earthquake and has a length of 17.6 m, a width of 10.1 m, and a lake volume of 2060 m^3. A set of parameters that correspond to the Chayuan gully natural dam, which have been obtained by field investigation, are listed in Table 2 (Li et al. 2011).

Using these parameters in Table 3, the calculated peak discharge during dam failure is 27.25 m^3/s.

With Table 3, Eq. (11) becomes the following:

$$\frac{1650Q_p(\gamma_m - 9800)}{25970 - \gamma_m} = 1014.3Q_p - 1454 \tag{12}$$

The Tangjiashan natural dam is the largest and most dangerous landslide dam that was formed during the Wenchuan earthquake. The dam is composed of rocks, sands, and soils, with a height of 90–120 m, a dam volume of 24.3 million m^3, and a lake volume of 238 million m^3. The parameters (Liu et al. 2010) of the dam are listed in Table 3.

Table 2 The variables of the Chayuan gully natural dam

Case	Lake volume (m^3)	Depth of water behind the dam (m)	Median diameter (m)	Bed slope	Width of the channel (m)	Specific gravity of particles
Chayuan gully natural dam	2060	3.5	0.1	23 %	10.1	2.65

Table 3 The variables of the Tangjiashan natural dam

Case	Lake volume (m^3)	Depth of water behind the dam (m)	Median diameter (m)	Bed slope	Width of the channel (m)	Specific gravity of particles	Observed peak discharge (m^3)
Tangjiashan natural dam	2.38×10^8	79	0.008	0.6 %	611	2.75	6500

With Eq. (11), the following relationship is obtained:

$$\frac{1750Q_p(\gamma_m - 9800)}{26950 - \gamma_m} = 1014.3Q_p - 2178 \quad (13)$$

Figure 8 shows the relationships between γ_m, and Q_p. The curve $\gamma_m - Q_p$ is given by the Eqs. (12) and (13). The values on curve $\gamma_m - Q_p$ above line γ_m = 14,308 N/m^3 are the thresholds for debris flow formation. The flow whose value less than 14,308 N/m^3 (below the line) is sediment-laden flow, otherwise the flow is debris flow. The figure indicates that flood flow has important effects on the formation of debris flow when the slope of a bed channel at a fixed value. For example, the outflow should exceed 4 m^3/s when the slope is 23 % (equal to the slope of Chayuan gully) for debris flow formation. The slope of the bed channel of the Chayuan gully natural dam is 23 %, with a peak discharge of 27.25 m^3/s, which is greater than the minimum value of 4 m^3/s. Thus, in this case, debris flow will occur, which is consistent with the actual situation. From Fig. 8, it is revealed that outburst debris flow cannot be formed from the failure of the Tangjiashan natural dam, which has a peak discharge of 6500 m^3/s and a channel bed slope of 0.6 %. This is consistent with the real situation (Cui et al. 2012).

Discussion

An experimental investigation is presented on the formation criteria of outburst debris flow due to erosion of natural dam. In our tests, all the dams are failed by overtopping, followed by breaching due to outflowing water. During the experiments, debris flow is transformed from a hyper-concentrated sediment transport event caused by failure of the natural dam and surface erosion of channel bed due to high hydraulic load. There was no sudden sliding collapse of dam occurred in any of our tests. The formation criteria of outburst debris flow in our paper are only applicable for the overtopping failure mode of natural dams. It is unclear how the failure modes of natural dams affect the formation of outburst debris flow. It is an interesting research and we will do studies on it in the future.

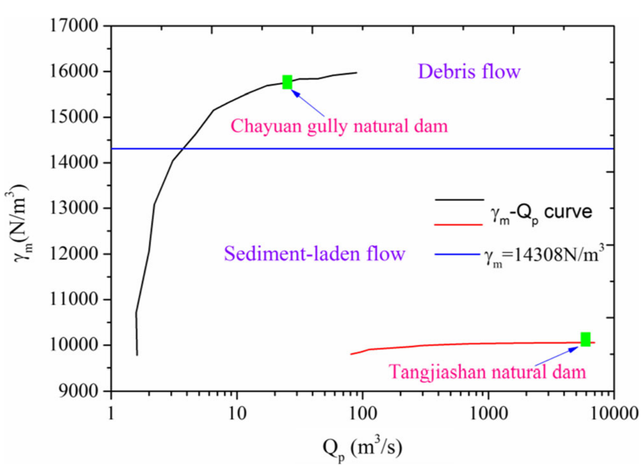

Fig. 8 The relationships of $\gamma_m - Q_p$ of the Chayuan gully natural dam and Tangjiashan natural dam. Debris flow above the line γ_m = 14,308 N/m^3 and sediment-laden flow below the line

All of the tests conducted in this study were aimed at exploring the general law that governs outburst debris flow following the breach of a natural dam. These were exploratory tests, not simulated tests. Thus, we scaled our models based on a prototype. In theory, it is best to design tests that can be scaled to a prototype. However, this is a difficult problem to solve. First, the data that are available regarding outburst debris flow due to natural dam breach are incomplete. We were not able to find a historical case of outburst debris flow due to natural dam breach in the published literature that included information on the gradation of material, the density of particles, the water depth behind the dam at failure time, the bed channel slope, the geometry of the dam, the volume of the lake, the peak discharge, the inlet inflow rate, and the strength parameters. Second, even if all of these parameters had been obtained, it is still hard to satisfy gravity similarity (Froude number) in laboratory tests. For example, in the case of the Bairaman river landslide dam (which formed debris flow when the dam breached), which has a height of 200 m and an outburst debris flow velocity of 5.6 m/s, if we set the scale factor $\lambda = 1/400$, the velocity modeled in the laboratory should be 0.28 m/s, which is considered to be small (unlike the outburst flood, which swept past the soil at a high velocity in the field tests). This is a difficult issue to address in laboratory tests because the formation of debris flow requires a large bed channel slope, resulting in fast debris flow. Furthermore, supposing the inflow rate of the Bairaman river is 200 m^3/s (there is no record in the literature), the inflow discharge used in laboratory tests should be 0.0625 l/s, which may be smaller than the seepage, resulting in no lake formation.

In the field, natural dam breaching is mainly a dam erosion process caused by outflow. The formation of debris flow is also related to erosion; as such, erosion due to flow is important, and the process should be close to the real situation. Although a small flow depth leads to a small Froude number, the small flow depth has no major effect on general erosion (Schmocker and Hager, 2009). Therefore, small discharges of 1 and 0.5 l/s are acceptable for the tests.

Figure 6b shows the materials that have influence on the formation of debris flow. Although the gradation curve of a material can indicate whether the material is good or poor, we need a parameter to quantitatively reflect the gradation; we choose Cu as this parameter. For continuously graded materials, such as NS and FS, coefficient of nonuniformity Cu can reflect the gradation of the material. For discontinuously graded material, such as CS, Cu must be combined with a curvature coefficient to reflect the material's gradation. Therefore, Fig. 6b cannot indicate the difficulty of forming debris flow when the value of Cu is large. Additionally, the figure does not indicate whether the unit weight of FS is equal to that of CS. For example, the minimum unit weight of the water/FS mixture is lighter than that of the water/CS mixture. Based on a large number of tests, the unit weight value was found to generally range between 10,000 and 16,100 N/m^3, although differences in this value existed in some locations

The critical condition model (Eq. (11)) based on Bagnold's theory still imposes some limitations, including the following: (1) The weight of the particles and debris flow are assumed to be the same everywhere, which is not in accord with reality. This assumption is used for mathematical simplicity. (2) In the model, some parameters were simplified, for example, we substituted the different diameters of the soil particles with d_{50}. (3) The parameters that were used in the tests require future calibration with additional prototype data. The parameters that were obtained by testing were limited; if the testing omitted relevant factors, such as soil water content, the parameters may change. Although we propose a novel concept regarding how to establish the critical conditions of outburst debris flow, only the parameters base on the prototypes used with the model can be considered to be correct. Due to a lack of such data, there was difficulty in completing this work; however, in the future, such data may become abundant.

Conclusions

Using flume tests to simulate dam failure, we investigated what factors influence the generation of debris flow. A method of predicting outburst debris flow following natural dam failure was established. Our conclusions include the following:

The unit weight of fluid downstream increased as the bed channel slope increased. This demonstrated that a large bed channel slope could produce debris flow easily. Lake volume had an effect on debris flow formation, which should be considered in combination with the bed channel slope. Compared with materials, in-flow rates, and dam geometric shapes, the slope of the channel is more sensitive for the formation of debris flow.

The conditions for the formation of outburst debris flow following natural dam failure have been established. This predictive method is based on the law of stream power. The unit weight of outburst flow is used to judge if the debris flow is formed and could be calculated with bed slope, width of the channel, peak discharge, and the median diameter of the mixed soils. The parameters of the conditions could be easily obtained, and the prediction conditions have features of clear concept, simple calculation. Based on the parameters of Chayuan gully natural dam and Tangjiashan natural dams, the relationships between γ_{m} and Q_{p} are obtained. The results showed that the conditions were demonstrated to correspond to real situations.

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