Research on the erodibility of landslide dam materials based on flume test

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Abstract. Landslide dams are usually formed by river blockages with massive amounts of materials from avalanches, landslides, and debris flows. The breaching of landslide dams may cause mega floods, posing great threats to people and infrastructure downstream. The important role in evaluating the breaching of landslide dams is the erodibility of dam deposits. In this study, ten grain size distribution with different characteristics (e.g. unit weight, fines content, d₅₀) were extracted based on 7 landslide dams. The laboratory flume apparatus, with a length of 5 m and a width of 0.4 m, were used to study the erosion rate of materials under six water flow rates. The test samples were collected, dried, and weighed before and after every single test to calculate the erosion rate. Results indicated that the erosion rate increases with the increase of flow velocity and shear stress. The relationship between erosion rate and flow velocity and shear stress is almost linear. Both the critical incipient velocity and critical shear stress have poor correlations with soil property, which means these two parameters cannot be predicted by one or two influence factors since it is affected by multi-factors. The work can serve as a basis to predict erosion rate of dam materials and analyze the breaching of landslide dams.

1. Introduction
Landslide dams usually formed by river blockages with massive amounts of materials from avalanches, landslides, and debris flows caused by the earthquake, rainfall, and volcanic eruption [1][2][3]. Due to the sudden formation, landslide dams always have inhomogeneous material composition and weak internal structure, raising the possibility of dam breach [4]. The breaching of landslide dams may cause mega-floods, exerting a disastrous effect on people and infrastructure downstream. Examples include the breaching of the 2000 Yigong landslide dam, which had a peak discharge of 120,000 m³/s, and the flood that killed at least 94 people in Northern India [5] or the failure of the 2018 Baige landslide dam, which had a peak outflow rate of 33,900 m³/s, leading the evacuation of 25,000 people [6]. Overtopping failure is the most common cause of landslide dam failure. Peng and Zhang [4] reported 144 landslide dam failure cases with known failure modes, among which 91% (131 cases) failed by overtopping. The process of overtopping failure is the result of the interaction between erodible dam material and water [7]. The erodibility can be defined through the erosion rate and shear stress induced by water [8][9]. It is therefore necessary and important to study the erosion resistance of materials of landslide dams.

In order to quantitatively measure the erodibility of material, many testing methods were developed in the past, such as the rotating cylinder tests [10][11], erosion function apparatus tests [7], hole...
erodibility tests [12], jet erosion tests [13], flume tests [14][15], cylindrical erosion test apparatus tests (CETA) [16], and a list of improved test methods based on the above test apparatus. Although jet erosion tests, CETA tests and flume tests can be used to test the erosion parameters of broadly graded materials, the first two testing methods still have some shortcomings, for instance, the $d_{so}$ of materials measured by the CETA tests should be less than 30 mm; the water flow of the jet erosion tests is perpendicular to the soil surface, while the water flow of overtopping breaching is parallel to the soil surface. Therefore, the flume tests may be a suitable test method.

The erodibility of soils is controlled by soil properties. Briaud [17] summarized the influence factors for erodibility, including soil water content, soil unit weight, soil plasticity index, soil void ratio, soil mean grain size, soil clay minerals. Chang and Zhang [13] found the main control factors of soil erodibility are grain-size distribution, void ratio, fine content and plasticity index based on 27 field jet index tests on the Hongshiyan landslide dam. Briaud [18] presented the critical stress and velocity of coarse-grained soils increase when the percent fines increase, unit weight increase, and water content decrease; while the critical stress and velocity of fine-grained soils increase when the plastic limit increase, percent fine increase and mean grain size decrease. Many researchers have studied erosion characteristics and influence parameters of different soils, but the material of landslide dams is broadly graded with soil particles ranging from clay to pebbles [13]. Therefore, the erodibility of dam materials still need to be studied.

In this paper, the erodibility characteristics of different materials of landslide dam are studied. Firstly, the experimental materials and apparatus are introduced. Then, the erodibility tests are conducted on the materials of ten gradation curves collected from landslide dams. Finally, the erodibility characteristics are analyzed and the key factors (e.g., grain size, fines contents, void ratio) that influence the materials erodibility are investigated. This study can guide the research of the breach process of landslide dams.

2. Experimental method

2.1. Experimental materials

The grain size distribution of landslide dams has a significant effect on the erodibility characteristics. Therefore, ten grain size distribution curves were selected from the Tangjiashan, Xianggangjian, Hsiao Lin, Hongshihe, Donghekou, Yigong and Baige landslide dam, and numbered from A1 to A10 (figure 1(a)). The test materials were prepared from kaolin, silica sand, and gravel according to the required grain composition in the laboratory (figure 1(b)). The main characteristics parameters, such as fines contents, mean grain size, dry density, are shown in table 1.

![Figure 1. Tests materials. (a) grain size distribution; (b) photographs of particles.](image-url)
Table 1. Summary of material properties of test materials.

| Materials | $\rho_d$ (g/cm$^3$)$^a$ | $P$ (%)$^b$ | $e^c$ | $d_{50}$ (mm) | $C_u^d$ | $C_c^e$ | $\phi$ (°)$^f$ |
|-----------|-----------------|-----------|------|--------------|--------|--------|--------|
| A1        | 1.61            | 37.95     | 0.67 | 0.38         | 160.47 | 0.69   | 32     |
| A2        | 1.90            | 5.95      | 0.42 | 8.77         | 19.87  | 2.98   | 39.8   |
| A3        | 1.88            | 17.9      | 0.44 | 4.77         | 474.49 | 5.43   | 25     |
| A4        | 1.82            | 15.53     | 0.49 | 3.89         | 146.96 | 2.64   | 21.8   |
| A5        | 1.71            | 2.68      | 0.58 | 0.87         | 4.50   | 1.72   | 31.3   |
| A6        | 1.76            | 2.59      | 0.53 | 2.09         | 26.78  | 0.80   | 36.8   |
| A7        | 1.71            | 36.03     | 0.58 | 0.95         | 752.92 | 0.14   | 21     |
| A8        | 1.67            | 31.76     | 0.62 | 1.70         | 922.21 | 0.20   | 23     |
| A9        | 1.93            | 2.68      | 0.40 | 10.22        | 38.49  | 5.42   | 47.8   |
| A10       | 1.65            | 55.86     | 0.64 | 0.06         | 116.78 | 0.12   | 19.8   |

$^a$ $\rho_d$ is the dry density.

$^b$ $P$ is the fines contents with particle size less than 0.075 mm.

$^c$ $e$ is the void ratio, $d_{50}$ is the mean grain size.

$^d$ $C_u$ is the uniformity coefficient of the grading curve.

$^e$ $C_c$ is the curvature coefficient of the grading curve.

$^f$ $\phi$ is the angle of response.

2.2. Experimental apparatus

A laboratory flume was built to allow examination of the material erosion rate on test section length at Tongji University. Figure 2 gives a sketch of the flume setup, which includes water inject-pump, upstream water tank, flume, material box, and collection pool. The water injects pump with a water pipe of 305 mm in diameter, and the water pipe was attached to the water tank to provide the required discharge. The upstream water tank was 0.42 m long, 0.68 m wide, and 0.48 m high and provided a smooth entrance flow condition to the flume. The flume with a length of 5 m, a width of 0.4 m, and a height of 0.4 m. The bottom of the flume was made of the steel plate and the sidewalls were made of organic tempered glass. The soil box was 0.24 m long, 0.4 m wide, and 0.04 m deep, and located 2 m away from the intake. At the end of the flume, the water poured freely to the collection pool, and the water level was kept close to zero at the flume end. Two digital video cameras (GZ-R10BAC, JVC, 1920 × 1080 pixel) were installed on the side and top of the flume to record the entire process.

Figure 2. Sketch of the flume setup and its hydrological equipment.

2.3. Experimental design
For each test, the materials of different particle sizes were mixed and dried first, and then added to the soil box. Six inflow rates were applied in tests to obtain erosion parameters. During testing, the sample was scoured for 1 min at a certain water flow. After the test, the residual materials were collected, dried, and weighed. The detailed procedure is summarized as follow:

1. Material preparation. The materials are added to the soil box until it is 2 mm above the elevation of the flume bottom to ensure the sample can be eroded. The materials are uniformly compacted by slightly tapping with a steel plate to obtain the required compactness of 80%. The materials used in each test are weighed and recorded.

2. Data record. Cameras are installed in the top and side of the flume before tests. The videos collected by the cameras are auto-saved during each test.

3. Water injection. The inflow rates are set at 12.96 m³/h, the sample is eroded for 1 min.

4. Residual materials collection. After the test, the residual sample is collected and dried in the oven for 24 hours. Then, the residual materials are weighed.

5. Repeat steps (1) to (5) for inflow rate equal to 25.92 m³/h, 38.88 m³/h, 51.84 m³/h, 64.80 m³/h, and 77.76 m³/h.

3. Data processing method

The apparatus could only record the inflow rate. Therefore, the water flow velocity under a certain inflow rate should be converted. The average flow velocity can be calculated as follow:

\[ v = \frac{Q}{A_w} \]  

Where \( Q \) is the inflow rate, \( A \) is the area of the water cross-section.

\[ A_w = l \times h \]  

Where \( l \) is the flume width (m), equal to 0.4 m. \( h \) is the water depth, during the test, the water depth will fluctuate slightly, average values of the water depth was selected for calculation.

The erosion rate \( E \) at a given flow rate \( Q \) is

\[ E = \frac{H}{t} \]  

Where \( H \) is the material sample eroded in a time \( t \). \( t \) equals 60 sec in each test, the length \( H \) can be calculated as follow:

\[ H = \frac{m_b - m_e}{A_s} \]  

Where \( m_b, m_e \) are the quality of dried material samples before and after test, \( A_s \) is the surface area of the material sample, and equals 0.096 m².

The shear stress can be estimated from the measured flow velocity and hydraulic radius [19].

\[ \tau = \frac{\rho_w g n^2 v^2}{h^{5/3}} \]  

Where \( \rho_w \) is the density of water \( (1000 \text{ kg/m}^3) \), \( g \) is the acceleration due to gravity, \( n \) is the Manning coefficient, \( v \) is the average flow velocity, \( h \) is the water depth.

The Manning coefficient is related to the mean grain size \( d_{s0} \) with the following suggested equations [20]:

\[ n = \frac{d_{s0}^{1/6}}{A_n} \]  

Where \( A_n \) is an empirical coefficient, and equals 16 for laboratory test [20].
4. Results and discussion

4.1. Relationship between erosion rate and flow velocity and shear stress

Three important parameters involved in soil erodibility are the erosion rate, flow velocity, and shear stress. The erosion rate versus flow velocity and shear stress for material samples M1-M5 and M6-M10 are shown in figure 3,4. The erodibility of samples M1-M10 shows the erosion rate increases with the increase of flow velocity and shear stress. The relationship between erosion rate and flow velocity and shear stress are almost linear.

The critical incipient velocity $v_c$ and critical shear stress $\tau_c$ can be obtained by extrapolation of the erosion rate versus flow velocity and shear stress curve back to zero erosion rate for the material sample. The $v_c$ defined as the minimum flow velocity to initiate erosion of material samples, and the $\tau_c$ defined as the minimum hydraulic shear stress necessary to initiate erosion of material samples. Table 2 shows the critical incipient velocity and critical shear stress for different materials.

![Figure 3](image1.png)

**Figure 3.** Erosion rate curves for material samples M1 to M5. (a) Erosion rate versus flow velocity; (b) Erosion rate versus shear stress.

![Figure 4](image2.png)

**Figure 4.** Erosion rate curves for material samples M6 to M10. (a) Erosion rate versus flow velocity; (b) Erosion rate versus shear stress

| Materials | A1   | A2   | A3   | A4   | A5   | A6   | A7   | A8   | A9   | A10  |
|-----------|------|------|------|------|------|------|------|------|------|------|
| $v_c$ (m/s) | 0.248 | 0.070 | 0.193 | 0.225 | 0.255 | 0.166 | 0.197 | 0.160 | 0.235 | 0.224 |
| $\tau_c$ (N/m²) | 0.582 | 0.949 | 0.434 | 1.130 | 0.193 | 0.112 | 0.394 | 0.860 | 0.551 | 0.720 |

4.2. Correlation between material erodibility and material properties

In order to analyze the relationship between erodibility and soil property parameters, the correlations between critical incipient velocity and critical shear stress and soil parameters should be found. Figure
5 shows the correlation between critical incipient velocity and soil property. The critical incipient velocity has a moderate correlation with the $d_{50}$, curvature coefficient, bulk density, and void ratio, and almost no correlation with uniformity coefficient and fine percentage. The relationship between critical shear stress and soil property is shown in figure 6. The critical shear stress has a moderate correlation with uniformity coefficient, but almost no correlation with $d_{50}$, fine percentage, curvature coefficient, bulk density, and void ratio. This indicates that both the critical incipient velocity and critical shear stress of the wide gradation material are not determined by the minimum particle size. The reason for these findings may be that the existence of coarse particles may protect fine particles from scouring.

Although some regularity is found in single factor analysis, the correlations of erodibility and soil property parameters are poor and tend to indicate that a simple correlation equation is not exist. It is likely that the correlation between erodibility and soil property would involve many parameters. Therefore, more test if different materials are needed in the future to find the correlation and establish multiple regression equations.

![Figure 5](image)

**Figure 5.** Correlation between critical incipient velocity and soil property. (a) critical incipient velocity and $d_{50}$; (b) critical incipient velocity and uniformity coefficient; (c) critical incipient velocity and fine percentage; (d) critical incipient velocity and curvature coefficient; (e) critical incipient velocity and bulk density; (f) critical incipient velocity and void ratio.
Figure 6. Correlation between critical shear stress and soil property. (a) critical shear stress and d_{50}; (b) critical shear stress and uniformity coefficient; (c) critical shear stress and fine percentage; (d) critical shear stress and curvature coefficient; (e) critical shear stress and bulk density; (f) critical shear stress and void ratio.

5. Conclusion
A flume test apparatus is presented and used to analyze the erodibility of landslide dam materials. The erosion rate, critical incipient velocity and critical shear stress of materials with ten different grain size distribution curves are studied using the flume apparatus. The relationship between erosion rate and flow velocity and shear stress is almost linear. With the increase of flow velocity and shear stress, the erosion rate increases.

Both the critical incipient velocity and critical shear stress have poor correlations with soil property parameters. Thus, the critical incipient velocity and critical shear stress of landslide dam materials cannot be predicted by any single parameter since it is usually affected by multiple factors.

References
[1] Costa J and Schuster RL 1988 The formation and failure of natural dams Geological Society of America Bulletin 100 (7) 1054-68
[2] Korup O 2002 Recent research on landslide dams-a literature review with special attention to New Zealand Progress in Physical Geography 26 (2) 206-35
[3] Peng M and Zhang LM 2012 Breaching parameters of landslide dams Landslides 9(1) 13-31
[4] Zhang J, Guo ZX, Cao SY and Yang FG 2012 Experimental study on scour and erosion of blocked dam Water Science and Engineering 5(2) 219-29
[5] Turzewski MD, Huntington KW and Leveque RJ 2019 The Geomorphic Impact of Outburst Floods: Integrating Observations and Numerical Simulations of the 2000 Yigong Flood, Eastern Himalaya Journal of Geophysical Research: Earth Surface 124(5) 1056-79
[6] Zhang LM, Xiao T, He J and Chen C 2019 Erosion-based analysis of breaching of Baige landslide dams on the Jinsha River, China, in 2018 Landslides 16(10) 1965-79
[7] Briand JL, Ting FCK, Chen HC, Cao Y, Han SW and Kwak KW 2001 Erosion function apparatus for scour rate predictions Journal of Geotechnical and Geoenvironmental Engineering 127(2) 105-13
[8] Graf WH 1984 Hydraulics of sediment transport (Colorado: Water Resources Publications)
[9] Amos CL, Umgiesser G, Ferrarin C, Thompson CEL, Whitehouse RJS, Sutherland TF and Bergamasco A 2010 The erosion rates of cohesive sediments in Venice lagoon, Italy.
Continental Shelf Research 30(8) 859-70

[10] Moore WL and Masch FD 1962 Experiments on the scour resistance of cohesive sediments Journal of Geophysical Research 67(4) 1437-46

[11] Chapuis RP and Gatien T 1986 An improved rotating cylinder technique for quantitative measurements of the scour resistance of clays Canadian Geotechnical Journal 23(1) 83-7

[12] Wan CF and Fell R 2004 Investigation of Rate of Erosion of Soils in Embankment Dams Journal of Geotechnical & Geoenvironmental Engineering 130(4) 373-80

[13] Chang DS, Zhang LM, Xu Y and Huang RQ 2011 Field testing of erodibility of two landslide dams triggered by the 12 May Wenchuan earthquake Landslides 8(3) 321-32

[14] Ravens TM and Sindelar M Flume Test Section Length and Sediment Erodibility Journal of Hydraulic Engineering 134(10) 1503-06

[15] Criswell DT, Fox GA Abdul-Sahib T, Miller RB and Daly E 2013 Flume Experiments to Determine the Erodibility of Gravel Streambank Soils (2013 ASABE Annual International Meeting Kansas City, Missouri)

[16] Yu S, Chen ZY, Chen SS, Ma LQ, Li XN, Sha PJ and Wang L 2021 A New Measurement Method of the Erodibility of Soil Geotechnical Testing Journal 44(1) 2018005

[17] Briaud JL, Ting F, Chen HC, Rao G and Wei G 1999 SRICOS: Prediction of Scour Rate in Cohesive Soils at Bridge Piers Journal of Geotechnical & Geoenvironmental Engineering 125(4) 237-46

[18] Briaud JL, Govindasamy AV and Shafii I 2017 Erosion Charts for Selected Geomaterials Journal of geotechnical and geoenvironmental engineering 143(10) 04017072

[19] Zhou G, Zhou MJ, Shrestha MS, Song D, Clarence EC, Cui Kahlil Fredrick E, Peng M, Shi ZM, ZhuXH and Chen H 2019 Experimental investigation on the longitudinal evolution of landslide dam breaching and outburst floods Geomorphology 334(1) 29-43

[20] Wu WM 2013 Simplified physically based model of earthen embankment breaching Journal of Hydraulic Engineering 139 (8) 837-51