International Journal of Civil Engineering and Environmental Science. Volume 3, Issue 1, (2015) 1-17
http://www.cayley-nielson.com/ijcees/

Stability Analysis of Landslide Dams In an Earthquake

Qi-De Lin
College of Engineering, National Chung Cheng University, Chia-Yi County 621, Taiwan (R.O.C.)
E-mail: *qidefor040@yahoo.com.tw*

Abstract

Failure of landslide dams is one of the typical natural hazards in mountainous areas. The landslide dams triggered by an earthquake can be divided into three types according to their material composition: soil-type, rock-type, and rock-soil mixture type. Several field investigations of typical landslide dams in an earthquake disaster region have been carried out and have shown that the transverse section of a landslide dam can be simplified as a broad-based trapezoidal. The particle size distribution, mechanical properties, and morphological characteristics of each type of landslide dam are summarized. Landslide dams have three failure modes: overtopping, abrupt collapse, and progressive failure. A conceptual model of a landslide dam was used for stability analysis, and the GEO-SLOPE software was used for numerical simulation. The simulated results show that the safety factor of landslide dams is increased with increasing cohesion or increasing friction angle of the dam's materials, but is decreased with increasing slope inclination. Finally, the limiting mechanical and geometric parameters for stability evaluation of landslide dams are presented. These limiting parameters can help governments and engineers to formulate prevention and mitigation measures for landslide dams.

Keywords: landslide dam; failure mode; stability analysis; numerical simulation.

1. Introduction

Natural damming of rivers by landslide material blocking river channels causes significant hazards in many countries (Costa and Schuster 1991). Especially during strong earthquakes in mountain regions, rivers are blocked by landslide deposits which form landslide dams (Ripendra 2008; Korup 2011). The stability of landslide dams is of great concern because they pose potential dangers to downstream life and property. Failure of a landslide dam causes extremely dangerous disruptions of water and sediment flux in mountain river regions, and downstream life and property can be seriously threatened by possible extreme dam-break flooding. Landslide dams are ubiquitous and occur frequently in tectonically active mountains with steep narrow valleys (Costa and Schuster 1988). Most of the landslide dams (approximately 90% of 390) examined worldwide were formed by landslides triggered by rainstorms, snowmelts, or earthquakes (Schuster 1986); strong earthquakes are among the prime triggering factors (Keefer 1984; Pierce et al. 1995).

Geomorphic forms and processes affecting landslide dam formation, stability, and failure have been extensively explored (Takahashi et al. 2001; Wang et al. 2009). Schuster and Costa (1986) reported that three factors are generally relevant to failure occurrence: (1) magnitude and rate of inflow to the dammed reservoir; (2) dimensions of the dam; and (3) material characteristics of the dam. Swanson et al. (1986) suggested that landslide volume and drainage basin area are important factors contributing to the stability of a landslide dam. Schuster and Evans (2011) proposed a block size stability diagram for classification for natural rock blockages and the expected life span of their dammed lakes to work out the stability

ISSN 2333-5416 /
March, 2015

conditions for 20 landslide dams in the Indian and Nepalese Himalayas as well as two in China. Dong et al. (2009) used a discriminant model which uses the log-transformed catchment area, dam height, and dam volume as relevant variables to evaluate the stability of landslide dams.

Many landslide dams usually break down rapidly soon after the formation of their lake because they were composed of large volumes of unconsolidated and poorly sorted material (Costa and Schuster 1991). The peak discharges produced by each failure model are extremely different (Awal, Ripendra 2008); therefore, rapid assessment of a landslide dam's possible failure mode is essential for decision-making to reduce associated disasters. In this paper, the material composition, particle size distribution, mechanical properties, and morphological characteristics of the landslide dams induced by the 2008 Wenchuan earthquake are summarized. Failure mode and stability analyses are carried out for different types of landslide dam. The impact of the shear strength of a dam's material and of geometric parameters on the stability of landslide dams is discussed. The limiting mechanical and geometric parameters for landslide dams are presented after extensive sensitivity analysis.

2. Landslide dams induced by the earthquake

On May, 12, 2008, the earthquake occurred in an area of southwestern China characterized by rugged topography, steep high mountains, deep valleys, and complex geologic structure. The strong earthquake triggered numerous landslide dams. By means of field investigation and remote sensing inspection, 257 landslide dams have been identified and located in a cascade distribution layout along the valleys. The stability of landslide dams has been related to their material composition, particle size distribution, morphological features, and other factors.

2.1. Landslide dam types

After several field investigations of typical landslide dams in an earthquake disaster area, it was determined that landslides occur mainly in regions of limestone, sandstone, granite, tuff, and thick lumpy sedimentary rock, resulted in different material compositions for the various landslide dams. Although the material composition of landslide dams is very complex, this study found that they exhibit certain similarities, which depend mainly on rock and soil features and the structural characteristics of the landslide material source.

The composition of landslide dam materials influences the strength, morphological characteristics, and failure mechanisms of a landslide dam. Dams composed of permeable soil or unconsolidated materials are more likely to fail than dams composed of large rock boulders or cohesive clays (Schuster 1993). According to their different material compositions, landslide dams can be divided into four types (Xu et al. 2009):

- Soil-type, mostly consisting of soil and rock fragments with particle size varying from 0.1 mm to 20 mm. In general, soil-type landslide dams are formed mainly by large-scale soil landslides which block rivers due to their rapid sliding velocity.
- Rock-type, mostly consisting of boulders and rock blocks with little soil and few rock fragments; most of the particles are larger than 200 mm. Structural gaps are large, and the dam body is relatively stable.
- Rock-soil mixture type, which consists of soil and rock fragments with a few boulders and large rock blocks. More than 50% of the soil and rock fragments have a particle size between 0.1 mm and 20 mm; the boulders and rock blocks are larger than 200 mm. This is the typical landslide

dam type in an earthquake disaster region.

- Other types, consisting of a large number of trees or other unconsolidated substances.

Through statistical analysis of the material compositions of the 257 landslide dams triggered by an earthquake, the proportions of different types of landslide dam can be determined (Fig. 1).

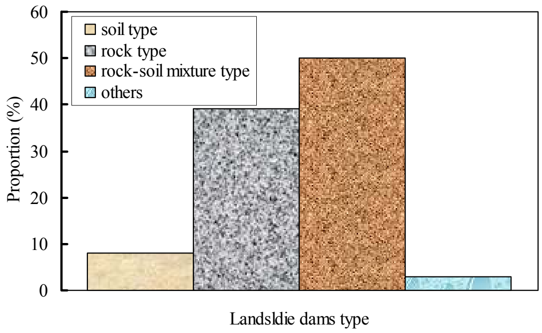


Fig. 1. Proportions of different types of landslide dam induced by an earthquake.

As shown in Fig. 1, the proportions are 8%, 39%, 50%, and 3% for soil-type, rock-type, rock-soil mixture type, and other type of landslide dams. Few soil-type landslide dams exist in an earthquake disaster region because the soil particles are easily carried away by erosion and water flow. If the soil landslide volume is not huge enough, it is hard to form a landslide dam. Most soil-type landslide dams have a huge volume, such as the landslide dam (Fig. 2a), with a volume of approximately 1200×104 m3.

(a) soil-type (b) rock-type

(c) rock-soil mixture type (d) others

Fig. 2. Site photos of landslide dams: (a) soil-type; (b) rock-type; (c) rock-soil mixture type; and (d) others.

Figure 2b shows a typical rock-type landslide dam, in which the material composition is all rock blocks. The proportion of rock-type landslide dams is approximately 39% in this study. The large numbers of rock slides and rock avalanches triggered by the earthquake are the main cause of rock-type landslide dams. These dams are mostly stable, but because of their high permeability, their upper reservoirs contain little water. The largest group of landslide dams (approximately 50%) is of the rock-soil mixture type. Figure 2c shows a typical rock-soil mixture type landslide dam. The landslide surface was originally a massive rock layer, but due to weathering and unloading effects, collisions of landslide material produce fine particles. The material composition is fine-grained soil and rock fragments. During the landslide process, large number of trees or other substances are carried away by the landslide mass. The proportion of the “others” landslide dam type is less than 3%. Figure 2d shows the landslide dam, which consists mainly of rock blocks and trees.

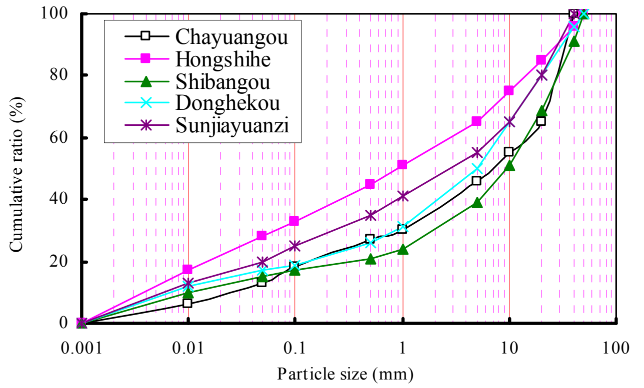
2.2. Particle size distribution

The particle size distributions, mechanical properties, and morphological characteristics are different for the different landslide dam types (Sato and Harp 2009). The geotechnical and hydrogeological properties of the dam materials are influenced by the particle size distribution characteristics and result in different failure modes for the landslide dams. Particle size distribution usually varies with material composition.

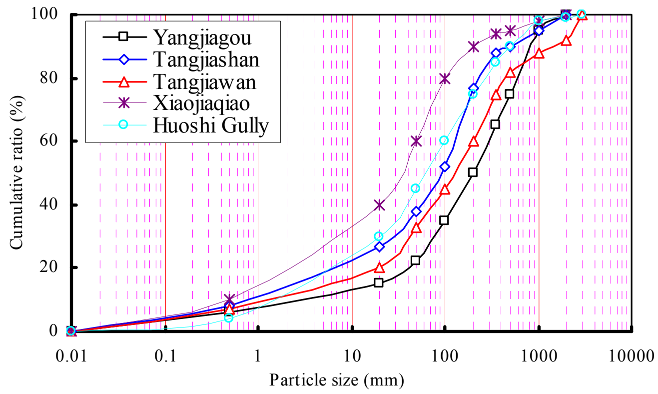
Through field investigation and on the basis of existing research results for earthquake landslide dams (Chen et al. 2011), the particle size distribution characteristics for different landslide dam types were determined. Figure 3 shows the particle size distribution of typical landslide dams belonging to different types.

As shown in Fig. 3a, for the soil-type landslide dam, more than 55% of the soil and rock fragments fall into the particle size range from 0.01 to 20 mm, with a maximum particle size of approximately 40 mm. Taking the landslide dam as an example, the maximum particle size is 50 mm, the proportion of particles larger than 20 mm is approximately 18%, the proportion of particles between 0.01 mm and 20 mm is approximately 62%, and the proportion of fine particles less than 0.01 mm is approximately 20%.

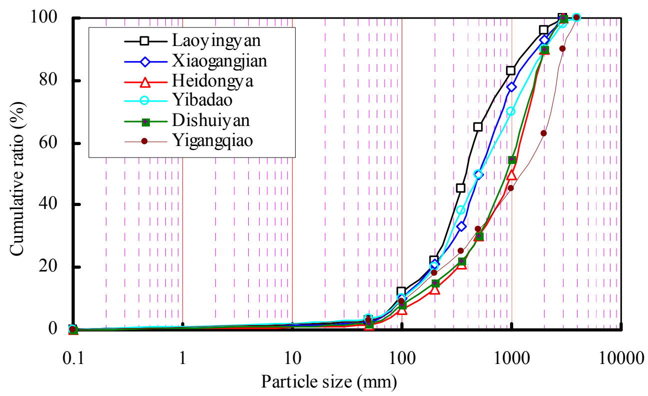
As shown in Fig. 3b, for the rock-soil mixture type landslide dam, more than 50%–80% of the particles fall into the range from 10 to 1000 mm, with a maximum particle size larger than 1000 mm. The particle size distribution is broad, with fine-grained soil and rock blocks, and exhibits good compaction and low permeability. Taking the landslide dam as an example, the maximum particle size is approximately 2000 mm, the proportion of particles larger than 1000 mm is less than 2%, the proportion of rock fragments with particle size between 10 mm and 1000 mm is approximately 66%, the proportion of particles between 0.1 mm and 10 mm is approximately 29%, and the proportion of particles less than 0.1 mm is approximately 3%.



(a) soil-type



(b) rock-soil mixture type



(c) rock-type

Fig. 3. Particle size distribution of landslide dams: (a) soil-type; (b) rock-soil mixture type; and (c) rock-type.

For the rock-type landslide dam, more than 50% of the boulders and blocks fall into the range from 100 mm to 2000 mm, and the maximum particle size is larger than 3000 mm (Fig. 3c). The structure of these landslide dam materials is very loose and permeable, but the stability of such a landslide is very good. Taking landslide dam as an example, the maximum particle size is larger than 3000 mm, the proportion of boulders with particle size larger than 2000 mm is approximately 3%, the proportion of rock blocks with particle size between 100 mm and 2000 mm is approximately 90%, and the proportion of particles less than 100 mm is approximately 7%.

Table 1 summarizes the particle size distribution characteristics of different landslide dam types induced by the earthquake.

Soil-type landslide dams have a higher compaction degree and poor permeability compared to the other two types. However, rock-type landslide dams with many pores, high strength, and good permeability. The particle size distribution of rock-soil mixture type landslide dams is better than the other two types, with good compaction and low permeability.

2.3. Mechanical properties

The safety of a landslide dam depends on the mechanical properties of the materials composing the dam. Because the composition and particle size distribution of landslide dam materials vary widely, their mechanical properties will also be different. The acquisition of mechanical properties data is extremely important for correct interpretation of the stability of landslide dams.

Table 1. Statistical results for particle size distribution for different landslide dam types.

Landslide dam type	Particle size (mm)	Proportion (%)
Soil	>20	15–40
	0.01-20	>55
	<0.01	5–20
Rock-soil mixture	>1000	2–10
	10–1000	50–80
	0.1–10	5–30
	<0.1	5
Rock	>2000	3–40
	100 –2000	>50
	<100	5–10

Although the particle size distributions of the materials in the three types of landslide dam vary widely, each type has a certain regularity, which means that its mechanical properties also have a certain regularity. Table 2 summarizes the mechanical parameters of the three types of landslide dam (Cui et al. 2011; Huang et al. 2012).

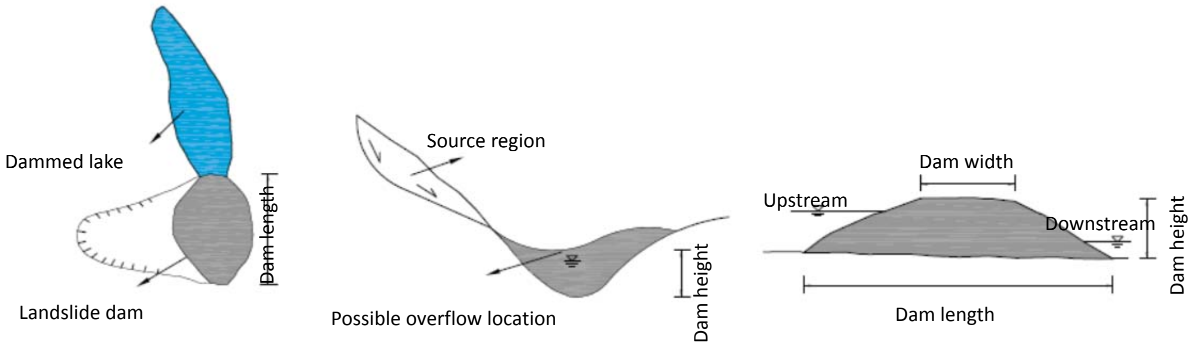
Table 2. Mechanical parameters of different landslide dam types.

Parameter	Soil-type	Rock-soil mixture type	Rock-type
Cohesion (kPa)	20–50	10–30	0–20
Friction angle (°)	20–30	25–32	30–36
Density (g/cm^3)	1.6–2.0	1.8–2.3	2.0–2.5
Permeability coefficient (cm/s)	10^{-3}–10^{-5}	10^{-2}–10^{-4}	10^{-1}–10^{-3}

As shown in Table 2, a rock-type landslide dam consists mainly of boulders and rock blocks, and therefore the friction angle and the density of the dam material are larger than in the other two types of dam. However, the cohesion is the smallest (approximately 0–20 kPa) due to the large content of crushed stone; there are also many internal pores, so the infiltration capacity is large, and the permeability coefficient is approximately 10-1-10-3 cm/s. For the materials in the soil-type landslide dam, the friction angle and density are the smallest because the dam consists mainly of fine-grained soil with low permeability coefficient and high cohesion.

2.4. Morphological characteristics

Morphological features have a great influence on the stability of a landslide dam: the more gently the dam slopes, the more stable is the dam. For this reason, gathering and summarizing the morphological characteristics of landslide dams through post-breach investigations are important from both the scientific and hazard-mitigation viewpoints. Figure 4 shows a sketch of the geomorphometric properties of a landslide dam.



(a) Top view (b) Longitudinal section (c) Cross section

Fig. 4. Sketch of geomorphometric properties of a landslide dam.

As shown in Fig. 4, the river channel is blocked by the landslide deposits, and the water level upstream will rise to form a dammed lake. The morphological characteristics of a landslide dam are influenced by the dam's material composition, water flow conditions, and terrain conditions. Table 3 gives characteristic morphological parameters of some typical dams (Sun et al. 2011; Wang et al. 2012).

As shown in Table 3, the large volume of soil landslides most often results in huge landslide dams, but for rock-type landslide dams, the height is mostly less than 300 m. The geometric dimensions of a landslide dam depend on the volume of landslide deposits. The volume of rock-soil landslide dams varies over a relatively large range; the volume of the landslide dam is approximately 2037×104 m3, but that of the landslide dam is approximately 70 ×104 m3. Because the structural and mechanical properties of each landslide dam's material are different, the geometric shape of a landslide is not the same for each landslide dam type. Table 4 summarizes the range of slope inclinations for different landslide dam types.

As shown in Table 4, the upstream slope inclination is usually larger than the downstream slope. The rock-type landslide dam is similar to a rock-fill dam, and therefore its slope inclination is the largest, as much as 45º, because the frictional coefficient of rock blocks is very large. The soil-type landslide dam is similar to an earth dam, and the lower frictional coefficient of the dam's materials results in a gentle slope inclination. The slope inclination of rock-soil mixture type dams is between the other two types.

Table 3. Characteristic morphological parameters of typical landslide dams.

Landslide dam		Length (m)	Width (m)	Height (m)	Volume (10^4 m^3)	Upstream slope (º)	Downstream slope (º)
	A	300	70	20–100	130	30	28
	B	300	300	45	200	33	32
Rock-type	C	80	120	45	60	35	27
	D	60	90	30	40	40	35
	E	60	60	37	26	34	32
	F	803	611	82–124	2037	25	23
Rock-soil	G	55–160	50–150	50–60	70	27	20
mixture	H	220	200	60–80	82.4	30	20
type	I	260	390	67	240	35	30
	J	600	300	25–35	400	30	27
	K	400	450	15–40	200	28	25
Soil-type	L	500	350	50	1200	26	20
	M	800	450	75	1500	22	20

Table 4. Slope inclinations for different landslide dam types.

Landslide dam type	Upstream slope (º)	Downstream slope (º)
Rock	40–30	35–25
Rock-soil mixture	35–25	30–20
Soil	30–20	25–18

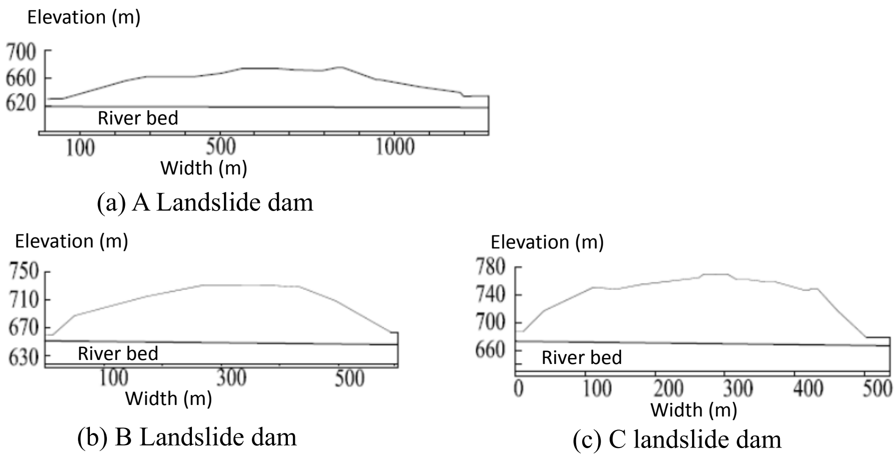


Fig. 5. Typical cross sections of landslide dams: (a) soil-type; (b) rock-soil mixture type; and (c) rock-type.

Figure 5 shows typical cross sections of various landslide dams; although stacking in a landslide dam is irregular in shape, its transverse section is approximately trapezoidal, with large bottom and crest width and lower height.

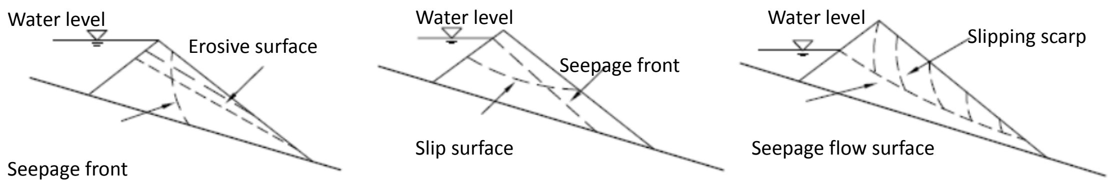
A rapid assessment of landslide-dam stability is essential because catastrophic disasters frequently occur soon after the formation of a landslide dam. Understanding the classification, characteristics, and dimensions of the dam is crucial for distinguishing probable dam-failure modes. Stability and possible failure modes of landslide dams were determined under different situations as described in the following sections.

3. Failure mode and stability analysis method

This section presents the results of field investigation and theoretical analysis together with a discussion of potential failure modes for landslide dams. According to the actual status of landslide dams triggered by the earthquake, a simplified numerical model is presented. Finally, a stability analysis method for landslide dams is introduced.

3.1. Failure modes of landslide dams

The water storage capacity upstream of a landslide dam can be very large, and dam failure can potentially cause downstream flooding, resulting in a great disaster. Stability analysis of landslide dams is very important for hazard prevention and mitigation. In most cases, the stability of landslide dams is not very good because the dam structure is loose and has not been subjected to any treatment measures. A landslide dam with a loose structure under high pore-water pressure is susceptible to slope failure. Landslide dams will fail in different modes depending on their material properties: erosive destruction due to overtopping, abrupt collapse of the dam body, or progressive failure (Takahashi and Nakagawa 1994), as shown in Fig. 6.



(a) Overtopping (b) Abrupt collapse (c) Progressive failure

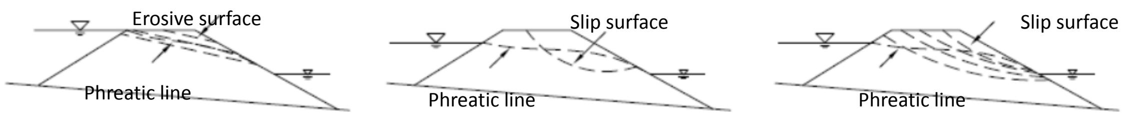
Fig. 6. Failure modes of landslide dams (modified from Takahashi and Nakagawa 1994).

The failure modes of a landslide dam are influenced by the permeability, the shear strength of the dam materials, and the level of impounded water behind the dam. Based on field investigation reports of actual landslide dam failure modes, it seems that 67% of failure cases were due to overtopping, 7.5% to sliding collapse, 6% to progressive failure, and 15% to intentional destruction (Keefer 1984). The majority of landslide dam failures are caused by overtopping and abrupt collapse. This study has concentrated on these two failure modes (overtopping and abrupt collapse), and the infiltration rate of landslide dams is hypothesized to be intermediate between these two.

The peak discharge produced by abrupt collapse of a landslide dam is greater than that produced by overtopping, resulting in different degrees of damage to downstream life and property. Therefore, a failure mode analysis of landslide dams under different mechanical properties and morphological characteristics is necessary for the formulation of prevention and mitigation measures.

3.2. Numerical model

The shape of a landslide was assumed triangular by Takahashi and Nakagawa (1994), but field investigation has shown that a simplification of the transverse section of a landslide dam as a broad-based trapezoidal is more suitable. Here, the landslide dam is assumed to be a homogeneous body without drainage facilities in the downstream slope, and the original riverbed contact surface is simplified as a bedrock surface (Fig. 7).



(a) Overtopping (b) Abrupt collapse (c) Progressive failure

Fig. 7. Three types of collapse of a landslide dam.

Two types of failure modes are considered in this paper: overtopping and abrupt collapse. The size and shape of different landslide dams for numerical simulation under different conditions were assumed identical. The dam width is 100 m, the dam height is 50 m, and the water depth is 50 m upstream and 5 m downstream. Table 5 shows the range of values of the characteristic parameters for different landslide dams.

Table 5. Characteristic parameter settings for different landslide dams used for numerical simulation.

Landslide dam type	Upstream slope (°)	Downstream slope (°)	Cohesion (kPa)	Friction angle (°)
Soil	30–20	25–18	20–50	20–30
Rock-soil mixture	35–25	30–20	10–30	25–32
Rock	40–30	35–25	0–20	30–36

As shown in Table 5, the characteristic parameter settings used for numerical simulation are based on the mechanical properties and morphological characteristics of different landslide dam types. There are two types of parameters for sensitivity analysis of landslide dam stability: the shear strength of the dam material and the geometric parameters of the landslide dam.

3.3. Numerical method

In this research, the GEO-SLOPE commercial software package was used for stability analysis of landslide dams. Using also the finite element method and limit equilibrium theory, the stability of landslide dams under different condition was analyzed. A two-dimensional problem is considered here. Seepage was simulated by the finite element method, after which the phreatic line and the pore-water pressure for the landslide dam could be determined. The simplified Janbu method was used for slope stability analysis, from which the geometry of the limit slip surface and the safety factor of the landslide dam under different conditions could be obtained. The pore-water pressure was considered as a force on the sliding surface.

On the basis of several numerical simulations of the stability problem for landslide dams under different conditions, the overtopping and abrupt-collapse failure modes can be summarized for different landslide dam types. According to limit equilibrium theory, if the safety factor of a landslide dam is greater than 1.0, failure will not occur, but overtopping may sometimes occur. If the safety factor of the landslide dam is less than 1.0, a typical instantaneous slip failure can be expected to occur. When the safety factor is equal to 1.0, this situation is defined as the limiting state, and the corresponding slope inclination and mechanical parameters are called the limiting slope inclination and the limiting mechanical parameters.

4. Results and discussion

This section describes extensive sensitivity analyses of the mechanical parameters of dam materials and the geometric parameters of landslide dams. The impact of the shear strength of dam material and of geometric parameters is discussed. In addition, limiting values of shear strength and slope inclination are presented for landslide dams in the earthquake disaster region.

4.1. Impact of shear strength

To analyze the influence of cohesion and friction angle on the stability of a landslide dam, a rock-type landslide dam is considered. The inclination of the upstream and downstream slopes is kept constant at 25°, the density is 2.3 g/cm3, and the permeability coefficient is 10-3 cm/s. The sensitivity analysis of the shear strength of dam material considered two conditions: (1) cohesion is constant at 0 kPa, friction angle is varied from 30° to 36°; (2) friction angle is constant at 30°, but cohesion is varied from 0 kPa to 20 kPa. The stability of the downstream slope was analyzed for each case. Figure 8 shows the results for sensitivity analysis of the impact of shear strength on the stability of the landslide dam.

As shown in Fig. 8, the safety factor of a landslide dam is increased with increasing cohesion or increased friction angle of the dam materials, but the impact of friction angle on stability is greater than that of cohesion. For a rock-type landslide dam, the cohesion of the dam material is always small, and therefore the stability of the landslide dam depends mostly on the friction coefficient of the dam material; a larger friction angle means greater stability.

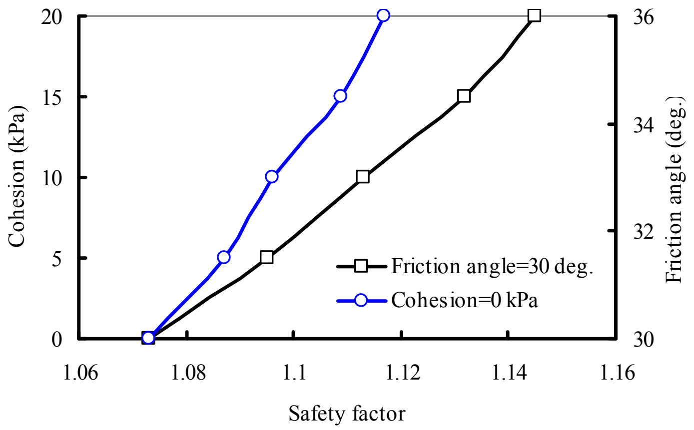


Fig. 8. Results of sensitivity analysis of shear strength impact on stability of a landslide dam.

4.2. Impact of slope inclination

The stability of a landslide dam is influenced by the inclination of the landslide dam slope. A larger slope inclination means a more dangerous dam. To analyze the influence of slope inclination on the stability of a landslide dam, two conditions are considered here: (1) the inclination of the downstream slope is held constant at 25°, but the inclination of the upstream slope is varied from 22° to 35°; (2) the inclination of the upstream slope is held constant at 25°, but the inclination of the downstream slope is varied from 20° to 30°. The mechanical parameters for different landslide dam types are: for soil-type dams, cohesion is 20 kPa, friction angle is 20°, density is 1.9 g/cm3, and permeability coefficient is 10-5 cm/s; for rock-soil mixture type dams, cohesion is 10 kPa, friction angle is 25°, density is 2.1 g/cm3, and permeability coefficient is 10-4 cm/s; and for rock- type dams, cohesion is 0 kPa, friction angle is 30°, density is 2.3 g/cm3, and permeability coefficient is 10-3 cm/s. Figure 8 shows the results for sensitivity analysis of slope inclination impact on the safety factor of landslide dams and the development of dangerous slip surfaces for different landslide types.

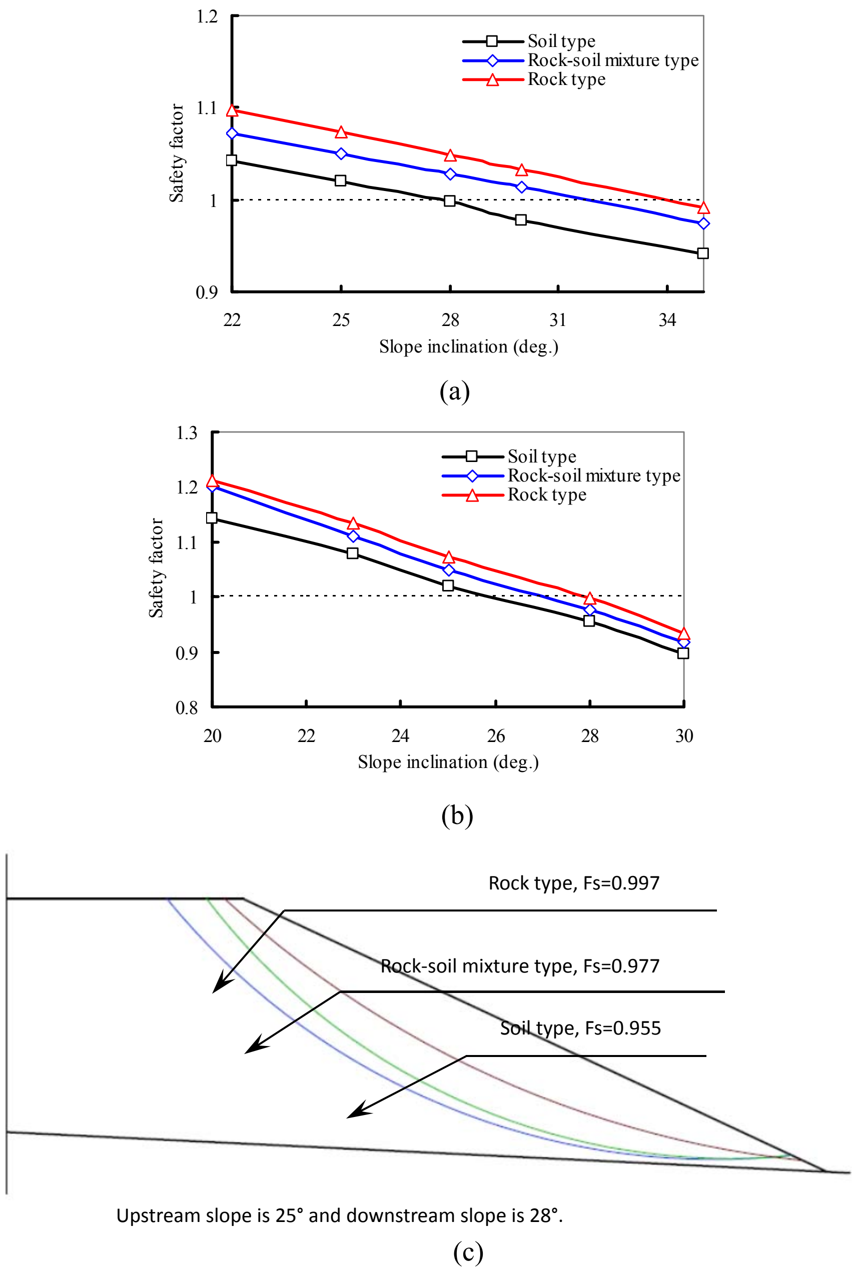


Fig. 9. Impact of slope inclination and landslide type: (a) upstream slope inclination is constant; (b) downstream slope inclination is constant, and (c) dangerous slip surfaces for different landslide dam types.

As shown in Figs. 9a and 9b, the safety factor of a landslide dam is decreased with increasing slope inclination. When the inclination of the downstream slope is kept constant, the stability of the upstream slope is influenced by its slope inclination, and therefore the limiting upstream slope inclination can be determined for each landslide dam type, and similarly for the downstream slope. Because the water-pore pressure field distribution in the upstream slope is not the same as in the downstream slope, the impact of slope inclination on the stability of the downstream slope is greater than for the upstream slope. The stability of soil-type landslide dams is the worst, and that of rock-type landslide dams is the best. The computed results reflect actual experience with landslide dams in the Wenchuan earthquake region; various failure patterns have occurred in soil-type landslide dams, and some of these were completely destroyed after one rainy season. However, most of the rock-type landslide dams remain intact after several rainy seasons. As shown in Fig. 9c, for different types of landslide dam under the same geometric conditions, the failure of soil-type landslide dams shows a deep-slip characteristic, but the rock type of landslide dam shows a shallow-slip characteristic.

When other parameters are fixed, the corresponding slope inclination when a landslide dam is at the limiting state (safety factor of 1.0) can be determined. Table 6 shows the limiting slope inclinations for different landslide dam types.

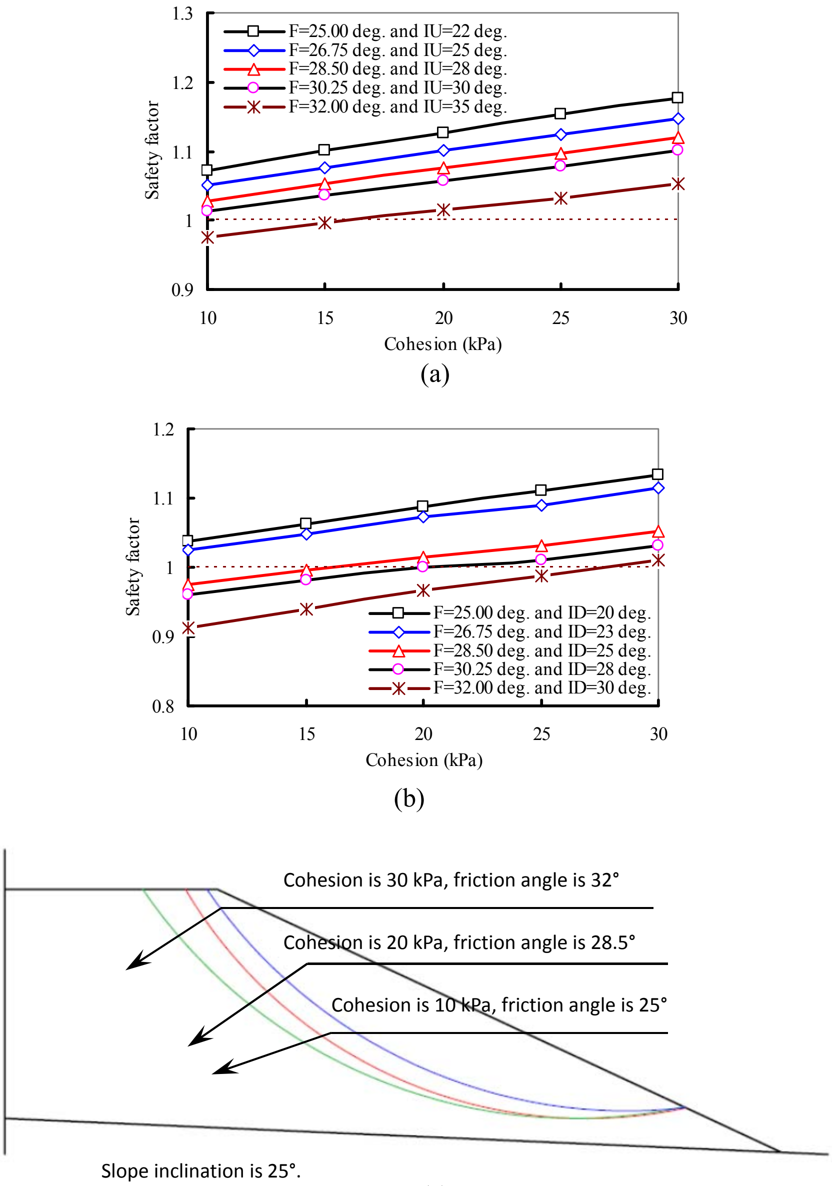
Table 6. Limiting slope inclinations for different landslide dam types.

Landslide dam type	Downstream slope (°)	Limiting upstream slope (°)	Upstream slope (°)	Limiting downstream slope (°)
Soil	25	27	25	26
Rock-soil mixture	25	31	25	27
Rock	25	34	25	28

As shown in Table 6, when the downstream slope inclination is 25°, the limiting inclinations of the upstream slope are 27°, 31°, and 34° respectively for the soil, rock-soil mixture, and rock types of landslide dam. The same definition is used for the downstream slope. If the slope is steeper than the limiting slope inclination, deep slip will occur in the soil-type landslide dam and collapse will occur in the rock-type landslide dam; such an instantaneous slip failure will result in a huge disaster. However, if the slope inclination is not greater than the limiting value, although the landslide dam will remain in a stable state, overtopping will occur if the water flow is large enough and the level rises higher than the dam top.

4.3. Limiting mechanical and geometric parameters

The stability of a landslide dam is influenced by the shear strength of the dam material and the geometric parameters of the landslide dam. Through sensitivity analyses of parameters which impact on landslide stability, certain limiting mechanical and geometric parameters can be determined. Landslide dams will fail under different parameter conditions, but the limiting parameters can be obtained through sensitivity analysis. These limiting parameters are very important for quick stability evaluation of landslide dams. Here, a rock-soil mixture type landslide dam has been selected as an example. Figure 10 shows the results of a sensitivity analysis of the impact of mechanical and geometrical parameters on the stability of landslide dams.



(c)

Fig. 10. Sensitivity analysis results for stability of a rock-soil mixture type landslide dam: (a) stability of downstream slope; (b) stability of upstream slope; and (c) dangerous slip surfaces under different shear strength values (F is the friction angle of the dam material, IU is the inclination of the upstream slope, and ID is the inclination of the downstream slope).

As shown in Figs. 10a and 10b, the safety factor of a landslide dam is increased with increasing cohesion. The impact of slope inclination on the stability of the landslide dam is greater than that of the friction angle of the dam material. If the slope inclination of the landslide dam is large enough, the dam will be prone to failure. As shown in Fig. 10c, for landslide dams under the same geometric conditions, the failure depth is decreased with increasing shear strength of the dam material. Greater shear strength of the dam material will result in deep slippage of the landslide dam, while lesser shear strength will result in shallow collapse. For the rock-soil mixture type landslide dam, because the stability is always very good and the permeability is poor, overtopping is a common failure mode. Abrupt collapse or progressive failure happens more often to soil-type landslide dams.

The stability of a landslide dam depends on the shear resistance of the dam material. Here, the Mohr-Coulomb criteria are used to determine the limiting slope inclination and shear-strength parameters for landslide dams. Shear resistance can be described by the cohesion and the friction angle, $\tau = c + \sigma \tan\varphi$. Table 7 shows the limiting mechanical and geometric parameters for landslide dams triggered by the earthquake.

Table 7. Limiting mechanical and geometric parameters for landslide dams triggered by earthquake.

Landslide dam type	Limiting slope inclination		Limiting shear strength	
	Upstream slope (°)	Downstream slope (°)	Cohesion (kPa)	Friction angle (°)
Soil	27	26	41.5	27.5
Rock-soil mixture type	31	29	30.0	31.5
Rock type	35	31	20.5	35.0

As shown in Table 7, the limiting inclinations for upstream slope and downstream slope are 27° and 26°, 31° and 29°, and 35° and 31° respectively for soil, rock-soil mixture, and rock types of landslide dam. If the slope inclination is greater than these limiting values, the landslide dam will be prone to failure. The limiting inclination of the rock-type landslide dam is the largest, and that of the soil type is the smallest. The limiting shear-strength parameter is determined by stability analysis and the Mohr-Coulomb criteria. When the slope inclination of a landslide dam is in the range shown in Table 4, if the cohesion and the friction angle are larger than 41.5 kPa and 27.5° respectively, the landslide dam will be stable. However, if the shear-strength parameter is less than the limiting mechanical parameters, failure of the landslide dam can be expected, and further stability analysis should be carried out. These limiting parameters can help governments and engineers to formulate prevention and mitigation measures for landslide dams.

5. Conclusions

Landslide dams are a typical geological phenomenon triggered by earthquakes in mountainous river regions. Most landslide dams have been assessed as unstable because they formed spontaneously as a result of rainstorms, snowmelts, or earthquakes within a short time. They usually break down rapidly soon after the formation of their impounded lake, creating a dangerous threat to downstream life and property as a result of possible extreme dam-break flooding. Therefore, a reasonable assessment of landslide-dam stability is essential.

The strong earthquake triggered numerous landslide dams. 257 landslide dams from this event have been used to analyze the particle size distributions, mechanical properties, and morphological characteristics of landslide dams. These dams belong mainly to two types: the rock type and the rock-soil mixture type. The particle size distributions, mechanical properties, and morphological characteristics exhibit differences for different landslide-dam types. The range of mechanical parameters and morphological characteristics of landslide dams have been summarized after extensive field investigations. Landslide dams have three failure modes: overtopping, abrupt collapse, and progressive failure.

A simplified numerical model has been developed to analyze the stability of landslide dams using the GEO-SLOPE commercial software package. The simulated results show that the safety factor of a landslide dam is increased with increasing cohesion or increasing friction angle of the dam materials, but that the impact of friction angle on dam stability is greater than that of cohesion. A larger slope inclination indicates that a landslide dam is more dangerous. Finally, the limiting mechanical and geometric parameters for stability evaluation of landslide dams have been presented here. These limiting parameters can help governments and engineers to formulate prevention and mitigation measures for landslide dams.

References

[1] Chai HJ, Liu HC, Zhang ZY, Xu ZW (2000) The distribution, causes and effects of damming landslides in china. Journal of Chengdu University of technology 27(3): 302-307 (in Chinese)

[2] Chen XQ, Cui P, Li Y, Zhao WY (2011) Emergency response to the Tangjiashan landslide-dammed lake resulting from the 2008 Wenchuan Earthquake, China. Landslides 8: 91–98

[3] Cui P, Han YS, Chao D, Chen XQ (2011) Formation and Treatment of Landslide Dams Emplaced During the 2008Wenchuan Earthquake, Sichuan, China. In: Evans, S.G., Hermanns, R.L., Strom, A.L., Scarascia Mugnozza, G. (Eds.), Natural and artificial rockslide dams. Lecture Series in Earth Sciences. Springer, Berlin, 295-321

[4] Costa JE, Schuster R.L (1988) The formation and failure of natural dams. Geological Society of America Bulletin 100(7): 1054–1068

[5] Costa JE, Schuster RL (1991) Documented historical landslide dams from around the world. US Geological Survey Open-File Report: 91–239, 486

[6] Dong JJ, Tung YH, Chen CC, Liao JJ, Pan YW (2009) Discriminant analysis of the geomorphic characteristics and stability of landslide dams. Geomorphology 110(3-4): 162–171

[7] Huang Y, Chen W, Liu JY (2012) Secondary geological hazard analysis in Beichuan after the Wenchuan earthquake and recommendations for reconstruction. Environ Earth Sci 66: 1001–1009

[8] Keefer DK (1984) Landslides caused by earthquakes. Geological Society of America Bulletin 95(4): 406–421

[9] Korup O (2011) Rockslide and Rock Avalanche Dams in the Southern Alps, New Zealand. In: Evans, S.G., Hermanns, R.L., Strom, A.L., Scarascia Mugnozza, G. (Eds.), Natural and artificial rockslide dams. Lecture Series in Earth Sciences. Springer, Berlin, 123-145

[10] Pierce MW, Thornton CI, Abt SR (1995) Predicting peak outflow from breached embankment dam. Journal of Hydrologic Engineering 15(5): 338–349

[11] Ripendra A (2008) Study on landslide dam failure due to sliding and overtopping. Dissertation, Kyoto University

[12] Sato HP, Harp EL (2009) Interpretation of earthquake-induced landslides triggered by the 12 May 2008, M7.9 Wenchuan earthquake in the Beichuan area, Sichuan Province, China using satellite imagery and Google Earth. Landslides 6:153–159

[13] Sun P, Zhang YS, Shi JS, Chen LW (2011) Analysis on the Dynamical Process of Donghekou Rockslide-Debris Flow Triggered by 5.12 Wenchuan Earthquake. J. Mt. Sci. 8: 140–148

[14] Schuster RL, Costa JE (1986) A perspective on landslide dams. In: Schuster, R.L. (Ed.), Landslide Dam: Processes Risk and Mitigation. American Society of Civil Engineers, 1–20

[15] Schuster RL (1993) Landslide dams—a worldwide phenomenon. In: Proceedings annual symposium of the Japanese Landslide Society, Kansai Branch, 27 April, Osaka: 1–23

[16] Schuster RL, Evans SG (2011) Engineering Measures for the Hazard Reduction of Landslide Dams. In: Evans, S.G., Hermanns, R.L., Strom, A.L., Scarascia Mugnozza, G. (Eds.), Natural and artificial rockslide dams. Lecture Series in Earth Sciences. Springer, Berlin, 77-100

[17] Swanson FJ, Oyagi N, Tominaga M (1986) Landslide dam in Japan. In: Schuster, R.L. (Ed.), Landslide Dam: Processes Risk and Mitigation. Geotechnical Special Publication, 3. American Society of Civil Engineers, 131–

145.

[18] Takahashi T, Nakagawa H (1994) Flood/debris flow hydrograph due to collapse of a natural dam by overtopping. Journal of Hydroscience and Hydraulic Engineering, JSCE 12(2): 41-49

[19] Takahashi T, Chigira M, Nakagawa H, Onda Y, Maki N, Aguirre-Pe J, Jáuregui E (2001) Flood and sediment disasters caused by the 1999 heavy rainfall in Venezuela. Research Report of Natural Disasters, 1-141

[20] Wang FW, Cheng QG, Lynn H, Masakatsu M, Wang HB, Yan CG (2009) Preliminary investigation of some large landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China. Landslides 6:47–54

[21] Wang ZY, Cui P, Yu GA, Zhang K (2012) Stability of landslide dams and development of knickpoints. Environ Earth Sci 65:1067–1080

[22] Xu Q, Fan XM, Huang RQ (2009) Landslide dams triggered by the Wenchuan Earthquake, Sichuan Province, south west China. Bull Eng Geol Environ 68: 373–386