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Review

Depositing Characteristics of Landslide Dams and Advances in the Model Test for Seepage Failure

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Abstract

Landslide dam is one of the main types of barrier dams, whose structure is loose and stability is poor. Once seepage failure occurs, it will threaten the life and property safety of downstream people. The particle composition and depositing characteristics of the dam are key influence factors in evaluating the seepage safety of landslide dams, which are also the primary considerations to carry out model tests. Based on previous studies, combined with the results of field investigations and indoor model tests, the depositing characteristics of landslide dams and advances in model tests for seepage failure are summarized, and the existing problems are discussed. Results show that the depositing characteristics of the landslide dam are related to the lithology of landslides, sliding path, bank slope structure, etc. The failure modes and processes of landslide dams are varied from depositing characteristics, particle size compositions to hydraulic conditions. For the landslide dams with high permeability zones, their failure can be attributed to the progressive cycle of piping and downstream dam slope collapse. While designing a model test, experimenters should not only consider the dynamic flow similarity but also determine the particle size distribution of the dam soils according to the relationship between particle size and particle movement. Finally, it is proved that the grading entropy can comprehensively reflect the gradation characteristics of the landslide dam as well as the change in gradation in the fine particle erosion process, which can be used to predict the permeability and internal stability of dam particles. Combined with other information, the failure mode and process of landslide dam can be predicted. The research results can provide references for the experimental research of landslide dam.

Keywords: landslide dam, particle composition, depositing characteristics, seepage failure, model test

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Introduction

Barrier dam is one kind of dam body with a loose structure, which is formed by rockfall, landslide or debris flow blocking the river channel caused by the earthquake, rainfall, or volcanic eruption under special geological and geomorphic conditions [1-3] (Fig. 1). According to statistics, the number of landslide dams accounts for more than 90% of the total amount of all barrier dams [4]. Landslide dam is the rapid deposition of landslide bodies. Since there is no impermeable wall in the dam body and no relevant drainage facilities to stabilize the water level in front of the dam, as the rise of water level in front of the dam and the continuous increase of water head, the landslide dam is susceptible to be eroded and damaged by seepage, which will threaten the safety and stability of the dam [3, 5, 6].

According to the literature, in 1933, several landslide dams were formed in the upper reaches of the Minjiang River owing to the Diexi earthquake. Thousands of people were killed in the flood due to the collapse of the dam body [7]. On May 12, 2008, the Wenchuan earthquake occurred in Sichuan, China. It resulted in the formation of more than 200 landslide dams, including more than 30 high-risk dams. Those dams threatened a total population of 1.3 million [6, 8-10]. In 2009, a barrier lake failed in Meishankou, Kaohsiung County, Taiwan, which caused flooding of downstream villages and trapped more than 2000 people [11]. In 2018, a landslide occurred in Baige Village of Jinsha River in China and a landslide dam was formed. The height of the dam was 61 m and the flood peak discharge was 31000 m^3/s, which forced 25000 people downstream to evacuate urgently [12]. The failure of these landslide dams was mostly related to the seepage deformation of the dam body.

One of the key factors controlling the failure mode and process of the dam is the depositing structure and permeability of the landslide dam, which is strongly affected by the particle composition and depositing state of the landslide dam [13-15]. Meanwhile, there are great differences in the spatial shape, internal structure and particle depositing state of this natural depositing body, which is significantly different from the artificial earth rockfill dam formed by the same depositing of loose particles. Since the landslide dam formed naturally has not been strictly designed and compacted, the dam slope is generally the natural repose angle of the soil, and the material composition and density of the dam may be highly nonuniform [16, 17].

For example, the deposition characteristics of the Donghekou landslide dam were analyzed using multi-channel analysis of the surface wave, and it was found that the shear wave velocity of the surface soil in the longitudinal direction of the dam body was small, only 180-270 m/s [18], indicating that many rock debris abound in this area [19]. However, the shear wave velocity in some areas of the dam is as high as 300-360 m/s, indicating that many block stones abound in this area [18]. This distribution characteristic has been verified by a field sieving test [20]. The distribution of coarse and fine particles in the dam depend on many factors, which are not only related to the rock mass properties , but also related to the sliding speed of the slope, geometric characteristics of the blocked river and other factors [21]. Therefore, the internal deposition structure of landslide dam is usually random, nonuniform and invisible, which make it difficult to study the safety and stability of landslide dam and prevent secondary disasters.

Different sedimentary structures and external hydraulic conditions may lead to different failure forms and processes of landslide dam. The failure forms of landslide dam mainly include overtopping, seepage failure and dam slope instability [3, 5, 22]. Compared with the dam crest overflow failure, the seepage failure is more difficult to find and detect and easy to cover up in the dam crest overflow failure. Some researches showed that piping and internal erosion caused by seepage were one of the main causes of landslide dam failure [23, 24]. The peak discharge caused by seepage failure is more remarkable for higher dams than that caused by overtopping failure [25]. If the seepage failure of landslide dam is ignored, it would be difficult to understand the real cause of dam failure or instability, especially the failure mechanism of landslide dams when seepage failure is associated with overtopping. If the landslide dam was out of danger and reinforced

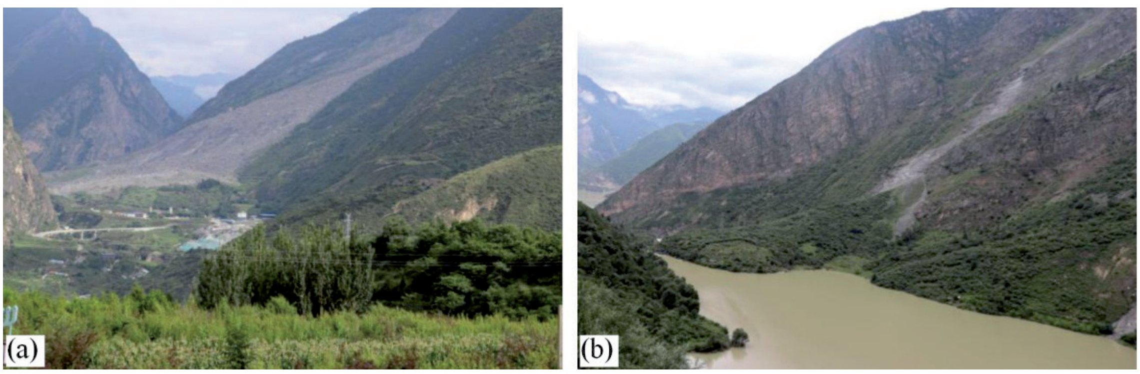

Fig. 1. Photos of site investigation of landslide dams: a) Xinmo landslide in Xinmo Village, b) Dahaizi landslide in Diexi Town.

according to the seepage failure law of the earth rockfill dam, it may be counterproductive. Therefore, it is necessary to have a more comprehensive understanding of the depositing characteristics and seepage stability of landslide dams.

In this paper, based on the particle composition of the landslide dam, combined with the results of field investigation and indoor model test, the natural depositing characteristics of landslide dam and advances in the model test for seepage failure are summarized. At the same time, the paper puts forward some solutions to the problems existing in the current research. The research results may provide a reference for evaluating the seepage stability of landslide dams and provide a basis for reducing the risk of dam-break floods and preventing similar natural disasters.

Depositing Characteristics of Landslide Dam

The depositing characteristics of landslide dams are very complex, which are affected not only by the particle composition of landslide mass, geometric characteristics of the blocked river, but also by the upstream inflow and other factors. Since the depositing characteristics of landslide dams are the basis of the study on seepage stability, they have been studied for a long time.

Particle Composition of Dam Soils

The particle composition of the landslide dam is the most important influence factor of its depositing characteristics. It is very important to obtain the particle size distribution of the deposit for predicting the failure mode and process of the dam. The particle size range of landslide dam soils is wide, ranging from a few millimeters to more than ten meters. And the particle size and gradation will affect the resistance to erosion of the dam.

Fan et al. found that the particle composition of Tangjiashan landslide can be divided into gravel soil layer, block rubble layer, nearly layered rock mass, and silty gravel layer from top to bottom, in which there are not only 1~2 m boulders, but also 2 cm gravels [26]. Xu et al. conducted a statistical analysis of 32 landslide dams formed by the Wenchuan earthquake and found that the dam body particle has a large variation in particle size [8]. For some landslide dams, 20-200 mm soil particles accounted for about 50% of the total mass. Fan et al. (2015) classified landslide dams into types of block stone, loose debris, and composition composed of two or three layers of sedimentary according to their composition particles and sedimentological characteristics [27]. Duan and Jiang investigated the Diexi Dahaizi landslide dam and found that a large number of giant rock blocks were enriched on the surface of the dam body, with a maximum particle size up to 20-30 m [7]. Lin et al. made a field investigation of the Yanmenshan landslide dam and found that the dam soils had poor graduation and high content of coarse particles. The median particle diameter D_{50} of dam particle was 415 mm, the coefficient of uniformity C_u was 23.8, and the coefficient of curvature C_c was 4.2 [28].

In July 2020, the authors investigated two landslide dams in Lijiawan Village, Aba Prefecture, and Xinmo Village, Beichuan County, China, which were relatively recently formed and well-preserved. The location of the site investigation is shown in Fig. 2. The Xinmo landslide dam was formed in June 2017 (Fig. 1a), located at a thin bedding ridge with a vertical height of 1200 m on the left bank of Songpinggou, a tributary of the Minjiang River. After the slope collapsed, it slid down at a high speed to the valley and disintegrated to form a debris flow. The main valley of the Xinmo landslide dam was arc-shaped, about 3.2 km long. Its upper part was an exposed bedrock zone of sand-slate, and the middle and lower parts were old landslide deposition. The slope aspect was consistent with the dip of the stratum, which was a typical dip slope [8, 30, 31]. The other landslide dam, the Lijiawan landslide dam, was formed in September 2016 (Fig. 3), which resulted from a high-position and high-speed landslide. The landslide mass could be divided into two parts. The upper part was the residual

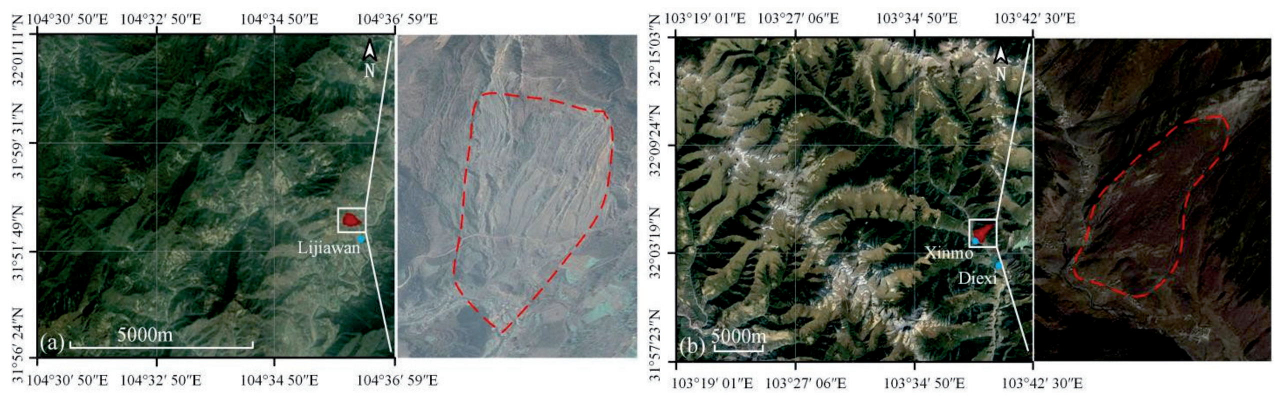

Fig. 2. Location of the site investigation: a) Lijiawan landslide dam, b) Xinmo village landslide dam.

deposition of the landslide formed by the "5.12" Wenchuan Earthquake in 2008. It was composed of block stone and debris, mainly the Quaternary Holocene landslide depositing layer, with an average thickness of about 19 m. The lower part was the Silurian Hanjiadian Formation slate and carbonaceous shale intercalated with bioclastic limestone, with a thickness of about 43 m. Due to the strong tectonic action, the rock mass is very broken, the joints and fissures are fully developed, and its strength is low [32]. The water content and density of the soil of two landslide dams were measured in situ (Fig. 4), and the results are listed in Table 1, where XM and LJW represent the Xinmo and Lijiawan landslide dam, respectively. Meanwhile, the area frequency method [33] (Fig. 5) and volume screening method were used to determine the particle size distributions of the dam soils, and the results are shown in Fig. 6. Compared with the soil of the Xinmo village landslide dam, that of Lijiawan landslide dam has a lower natural density and higher water content, with an average value of 1.94 g/cm^3 and 10.28%, respectively. The variation range of soil particle size of the two dam soils is wide, and the maximum particle size reached 3 m. Gap-graded soil is present in some sampling sites, and the inhomogeneity of dam soil is very strong.

Above all, the landslide dam is mainly composed of loose rock and soil mass, and its particle size varies widely. Under the seepage action, fine particles are easy to pass through the skeleton formed by coarse particles and cause internal erosion. Therefore, to study the depositing characteristics and overall permeability of landslide dams, it is necessary to use field prototype tests or large-size model tests to meet the characteristics of wide particle size distribution and large particle size of dam soils.

Dam Depositing Characteristics

The depositing characteristics of a landslide dam are related to the particle composition, the sliding speed of the slope, the river topography, and the slope of the mountain. The pore structure of the dam with different depositing characteristics is considerably different, which is an important factor to influence the global stability of the dam. Especially if continuous rainfall occurs and the water level in front of the dam increases rapidly, it would easy to cause secondary disasters and expand the scope of disaster influence [34-36]. Therefore, it is necessary to have a clear understanding of the depositing characteristics of landslide dams.

In 1932, Heim first proposed the inverse grading structure in the high-speed remote landslide deposition after investigating the Goldau landslide [37]. In a certain period, the inverse grading structure was once considered as a typical characteristic of landslide

Fig. 3. Landslide depositing site in Lijiawan density.

Fig. 4. Water-filling method to measure the density.

Fig. 5. Sampling of area frequency method.

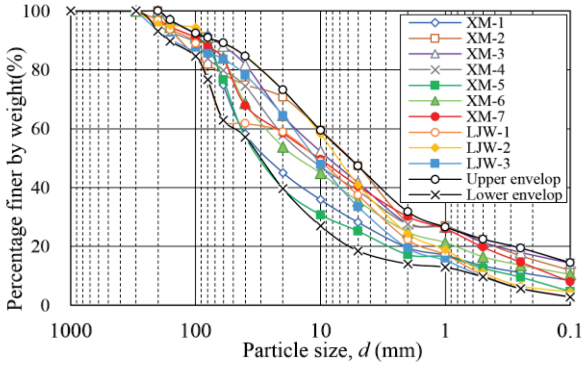

Fig. 6. Soil particle size distributions obtained from field investigation.

Table 1. Water content and dry density of the two dam soils obtained by water-filling method.

Sampling point	Latitude and longitude	Latitude and longitude (kg)	Test pit volume (L)	Natural density (g/cm^3)	Water content (%)	Dry density (g/cm^3)
LJW-1	104°36'24"E,31°58'24"N	31.83	15.62	2.04	12.11	1.82
LJW-2	104°36'25"E,31°58'26"N	37.90	20.95	1.81	10.73	1.63
LJW-3	104°36'27"E,31°58'27"N	31.59	16.00	1.97	8.01	1.83
XM-1	103°39'11"E,32°03'57"N	52.95	23.31	2.27	5.61	2.15
XM-2	103°39'10"E,32°03'55"N	41.92	18.78	2.23	4.76	2.13
XM-3	103°39'10"E,32°03'53"N	46.97	20.97	2.24	5.24	2.13

deposition, which showed that the grain size gradually decreased with the increase in dam depth. In general, the structure is the result of the vertical separation of particles with different sizes in the process of particle movement, and this sorting phenomenon is common in particle flow [38]. The sorting process of the particle flow made large particles gather at the front edge and close to the surface, while the small particles were migrated to the tail and bottom, thus an inverse grading structure was presented. Zhang et al. [39] conducted a detailed investigation on the Donghekou landslide dam and analyzed the particle size distribution characteristics of the landslide dam in the movement direction and vertical direction. It is revealed that the inverse granular structure in the deposition is the result of the combined effect of geometric and mechanical effects. Wang et al. analyzed the particle composition characteristics of three typical high-speed remote landslides, including Xiejiadianzi, Niuquangou, and Wenjiagou landslide caused by the 2008 Wenchuan earthquake [40]. The inverse granular structure was quantified, and its characteristics in the dam body and formation mechanism were discussed.

However, not all high-speed remote landslide deposits presented an inverse grading structure, and not an inverse grading structure presented in the whole thickness range. Shi et al. classified the depositing process of landslide dams into three types: slowly sliding type, over-river type, and repeated cover type (Fig. 7) [41]. If the sliding bank slope was relatively gentle and the opposite bank slope was steeper, the sliding speed of the landslide was slower, a slowly sliding landslide dam would form. For this type of landslide dam, except relatively more coarse particles presented at the top of the dam and more fine particles appeared at the rear edge of the landslide, the particle distribution characteristics of the dam were found to remain generally consistent with that of the original landslide (Fig. 7a). If the opposite bank of the landslide was relatively flat, the landslide would slide down and continue to climb along the gentle slope on the opposite bank under the action of dynamic force until the energy was exhausted. This kind of landslide dam was called an over-river type landslide dam (Fig. 7b). There were many fine particles at the back edge of the landslide dam, and the largest particles slid out of the river or climbed up to the opposite bank. On the whole, the particle size gradually decreased from front to back. If the opposite bank was steep, the landslide volume was large and the sliding speed was very fast. After sliding, it climbed up along the slope on the opposite bank and then turned back, a repeated cover type landslide dam would form (Fig. 7c). This kind of landslide was very broken because of the collision between particles. Many fine particles and broken rock mass were formed on the surface and trailing edge of the landslide dam, and even large particles appeared in the middle.

Some scholars use indoor sliding tests to explore the depositing process of landslides. Zhang et al. conducted a sliding test by changing sliding slopes and soil gradations [42]. It was found that due to the collision and friction between particles during the sliding process, an obvious sorting phenomenon appeared in the deposit. The coarse particles were distributed on the front and surface of the sediment, while the fine particles were distributed on the back and bottom of the sediment. As the proportion of coarse particles increased, the fine-grained sediment shrunk to the center of the rear

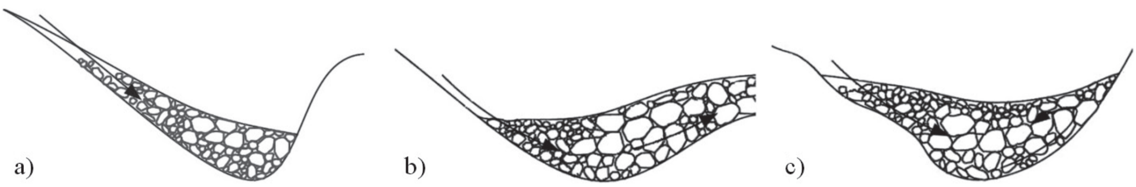

Fig. 7. Simplified diagram of three depositing modes of landslide dam [41]: a) slowly sliding type, and b) over-river type, c) repeated cover type.

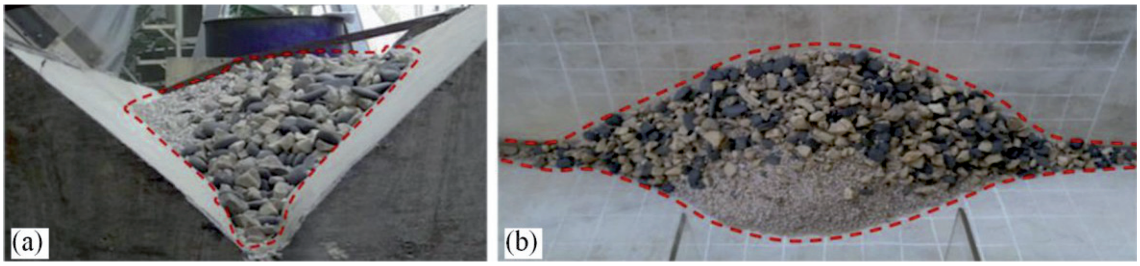

Fig. 8. Geometric characteristics of deposit in a sliding test [42]: a) side view, and b) top view.

edge, and the outline of the sediment became flatter and nonuniform, which was closer to the opposite bank of the valley (Fig. 8). Liao et al. used three types of cemented blocks of coarse-grained gravel, medium-grained gravel, and fine sand to simulate rock masses with different fracture distributions and strengths and conducted the sliding test [43]. The results showed that the rock mass would be broken during sliding. The back part of the sliding mass had a lower speed, the minimum height of the deposit was close to the depositing center, and the front side of deposition at the opposite bank was high. There was a strong positive correlation between the maximum dam height and the landslide volume.

In summary, many factors can affect the depositing of landslide dams. For example, for the same sliding body, different lengths and surface roughness of the slideway, and different sliding speeds would cause the horizontal shape and vertical depositing characteristics of the landslide dam to be different. The distribution of particles in the landslide dam is very nonuniform, and the characteristics of particle gradation at different positions are quite different. Therefore, to study the resistance to seepage failure of the special deposit, it is necessary to carry out large-scale model tests for specific depositing modes and unfavorable conditions.

Experimental Study on Seepage Failure of Landslide Dam

The landslide dam had not been designed and artificially compacted and there was no special filter particle in it. Its particle composition and density may be extremely nonuniform. The dam soil was usually under-consolidated and loose and the slope of the dam was usually at a natural repose angle. Hence, it is more likely to suffer seepage erosion. Previous studies showed that piping and internal erosion caused by seepage are the main causes of the landslide dam failure [44-47]. If the seepage failure of landslide dam is ignored, some failure mechanisms will be concealed, and it will be difficult to find out the real cause of dam failure or instability [12]. Therefore, what kind of seepage failure may occur in landslide dams and influence factors of occurrence and development of seepage failure are worthy of attention and research.

Seepage Failure Mode and Process of Landslide Dam

Casagli et al. used the sedimentary facies analysis method to classify landslide dam particles into the matrix-supported type and particle-supported type [33]. The particle of particle-supported dam bodies is mainly coarse particles with low compactness, which may have some strongly permeable zones. It is easy to cause internal erosion and eventually lead to dam instability [3]. For example, the Allpacoma landslide dam in Bolivia collapsed due to internal erosion. There was a piping channel with a diameter of 1.5 m inside the dam. The seepage stability characteristics of landslide dams such as Xiaojiaqiao, Tangjiashan, and Hongshihe are also directly affected by the strong permeability zones [3, 47, 48]. Thus, many scholars had induced internal erosion by setting artificial piping channels inside the dam to study the seepage failure characteristics of landslide dams.

Wang et al. laid a 0.3m wide gravel and pebble artificial piping channel at the bottom of the model dam to study the failure characteristics of the landslide dam [11]. The test is based on the following assumptions: (1) The structural characteristics of random deposition in the Hata landslide dam can be reflected by the deposition structure of the local strong permeability zone. (2) The loose structure of landslide dam is consistent with the uncompacted dam model structure of artificial natural deposition. (3) The dam always carries seepage deformation at the highest safe water level, and the water level does not exceed the dam crest elevation.

The soil used to build the dam model was sourced from the Mihata landslide, which occurred on 6 August 2012 in the Mihata district, near Izumo city, Shimane Prefecture, Japan. The soil consists of 35.5% gravel, 37.5% sand, 20.9% silt and 6.1% clay particles. The dry density of the soil is 1210 kg/m^3, the void ratio is 1.257 and the water content is 21.2%. Four groups of parallel tests were carried out to investigate the premonitory factors of landslide dam failure [11].

The whole failure process of landslide dam can be divided into four stages. In the first stage, small deformation of dam occurred due to accumulation of pore water pressure and effective stress in the soil around artificial drainage ditch was reduced. Seepage water appears in the downstream artificial drainage ditch with low turbidity (see Fig. 9b). In the second stage, the turbidity of seepage water and the vertical deformation in the dam increased. The erosion process inside the dam develops into piping erosion. In the third stage, the internal erosion process leads to further deformation of the dam, with evident cracks on the dam crest and their gradual downward development. The turbidity of downstream seepage water increased significantly and the settlement of dam crest increased gradually (see Fig. 9c). In the fourth stage, with the piping channel and crest cracks developed sufficiently, the settlement of the dam crest increased rapidly and the dam collapsed suddenly (see Fig. 9d). During the whole failure process, the settlement of dam crest is time-dependent. At the same time, the self-potential inside the dam, the turbidity of seepage water downstream and the settlement of dam crest have the same change trend. The change in self-potential inside the dam can be regarded as one of the precursor factors for the failure of landslide dam caused by seepage.

Okeke et al. induced internal erosion by embedding pebbles wrapped in plastic nets in the landslide dam model (Fig. 10) [49-51]. It is found that piping failure could be divided into five stages: piping development,

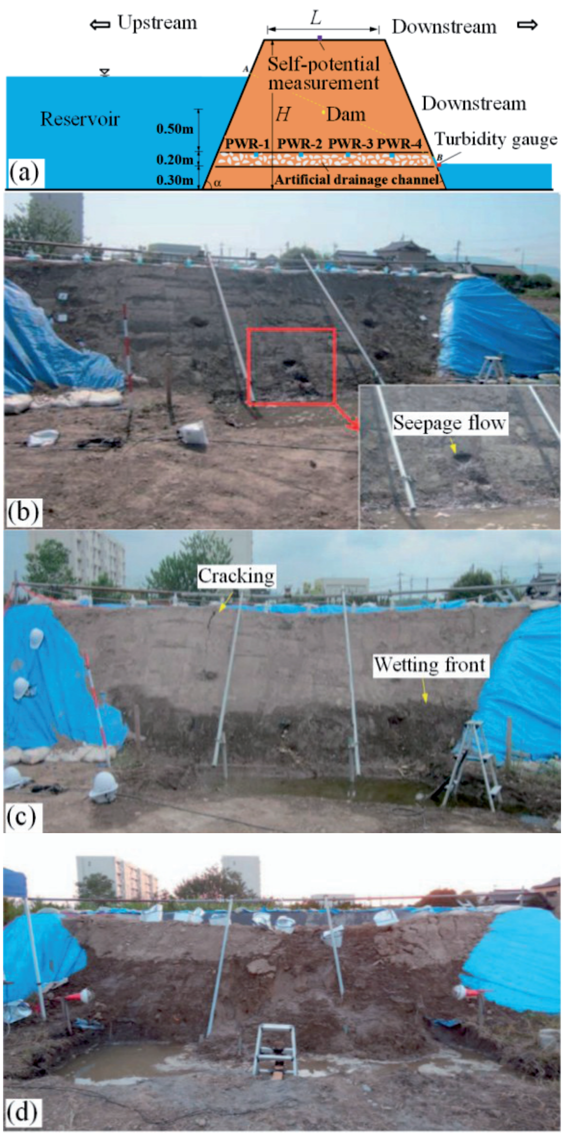

Fig. 9. Field test of seepage failure of landslide dam [11]: a) longitudinal section, b) seepage water at the downstream face, c) emergence and evolution of cracks on the dam crest, and d) settlement of the dam crest and sudden collapse of the dam body.

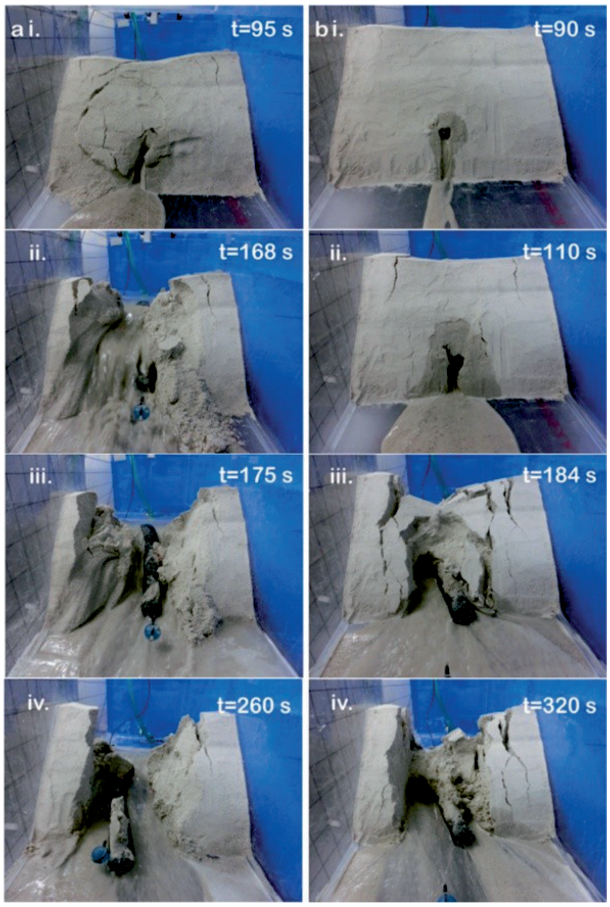

Fig. 10. Diagram of failure process of landslide dam model test [50].

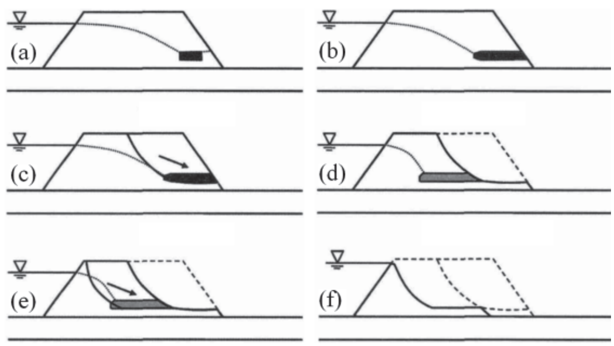

Fig. 11. Diagram of failure process of landslide dam model test [3]: a) seepage, b) piping, c) instability, d) piping again, e) instability again, and f) dam break.

Table 2. Physical properties of the materials used in the laboratory tests.

Dry density (kg/m^3)	Specific gravity	Relative density	Permeability coefficient of dam material (cm/s)
1950	2.69	0.22	0.037

channel expansion, dam crest settlement, hydraulic cracking, and progressive failure. Shi et al. calculated the seepage stability of landslide dam with strong permeable zone by finite element method [3]. The results showed that the seepage failure of the landslide dam was a progressive cycle of piping and downstream dam slope collapse due to the existence of a strong permeable zone (Fig. 11). The piping of downstream dam slope soil was first induced in the strong permeable zone. Then, under the effect of seepage, the piping channel gradually expanded and developed upstream of the dam. With the development of the piping channel, the loss of fine particles at the channel reduced the strength of soil, which led to the collapse of the upper dam. Then the next round of piping and downstream dam slope collapse continued until the width of the dam crest was small. Finally, the landslide dam would slide or overflow would occur.

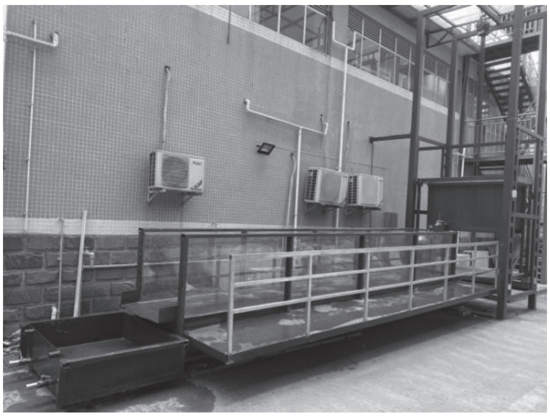

Fig. 12. Large scale geotechnical flume model.

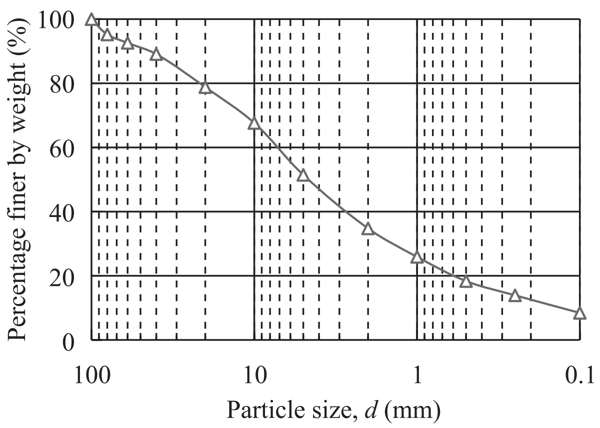

Fig. 13. Particle size distributions curves.

The authors designed a large-scale geotechnical model trough (Fig. 12) to carry out the seepage test of a landslide dam with a strong permeable zone in the center of the landslide dam bottom. Referring to field investigation and relevant literature [35, 40, 41], the particle size distribution curve of soils used in the test is determined (see Fig. 13). The soil in the highly permeable area in the model is composed of the particles of 2-60 mm part of the particle size distribution curve. The basic mechanical parameters of soil are shown in Table 2. The maximum and minimum dry densities of test soil are 2240 kg/m^3 and 1880 kg/m^3, respectively. According to Liu's classification criteria, the soil is susceptible to piping [52].

In addition to the basic assumptions of field tests, the laboratory test also has the following assumptions: (1) The upstream inflow flow is constant, and the rate of water level rise in front of the dam does not affect the seepage failure of landslide dam. (2) Water content of soil does not influence seepage failure of landslide dam. (3) The water only moves inside the landslide dam and does not leak to the deep dam foundation. Three parallel tests were carried out, and their results were similar.

The location of the tensiometer in the dam is shown in Fig. 14. The model test results are shown in Fig. 15 to 18. The whole failure process of landslide dam can be divided into four stages. In the first stage, the flow first seeped out from the strong permeable zone at the dam bottom with the increase in upstream water level (see Fig. 15a). And downstream discharge and turbidity were rising rapidly. And the tension meters P-1 and P-2 first responded. When the tensiometer P-3 began to respond, its internal piping channel gradually formed (see Fig. 17). Downstream discharge and turbidity were rising rapidly. The hydraulic gradient near the strong permeability zone first increased to the peak value gradually, then decreased sharply and then increased again, and finally tended to be stable (see Fig. 18). The infiltration front gradually moved from the strong permeability area to the dam crest. And the tensiometers at different locations inside the dam began to respond in the order of P-1, P-2, P-4, P-5, P-3 and P-6 (see Fig. 17). In the second stage, the amount of fine particles lost in the dam gradually increased, and the piping channel continuously expanded. As the piping channel could not support the above self-weight and the internal collapse would occur, part of the piping channel was blocked, thus the downstream discharge and turbidity were gradually reduced and tended to stable. In this stage, the average values of downstream discharge and turbidity were 3.41 L/min and 124.5

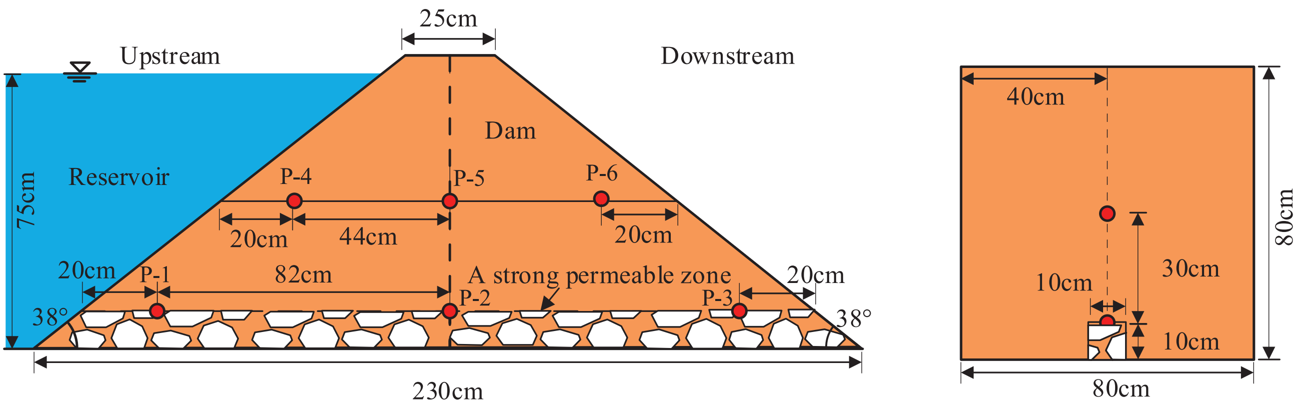

Fig. 14. Distribution and serial number of the monitoring points in the landslide dam: a) longitudinal section, b) cross section. (where the red circle indicates the tension meter).

NTU, respectively (see Fig. 16). Some cracks appeared on the downstream slope. The tensiometers at different positions inside the dam and the hydraulic gradient near the strong permeability area were basically stable. In the third stage, a new pipe channel formed, and the downstream discharge and turbidity gradually increased again (see Fig. 16). Downstream discharge and turbidity were rising rapidly. When t = 212 min, the downstream discharge and turbidity reached their peak at 4.8 L/min and 639.11 NTU, respectively. In the fourth stage, several cracks appeared on the downstream dam surface, the downstream dam slope collapsed, and the piping channel would be blocked again (see Fig. 15). The downstream discharge and turbidity began to decrease again. Finally the downstream discharge remained constant.

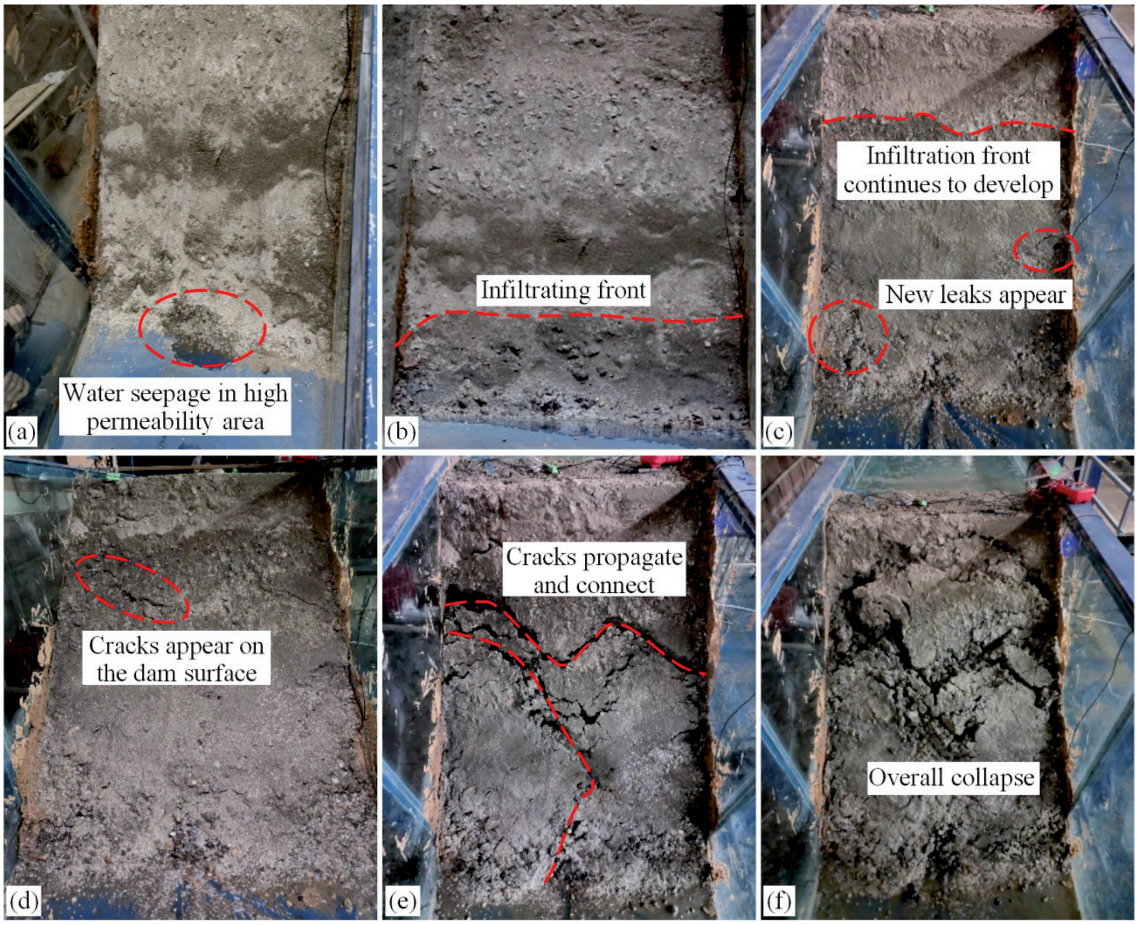

Fig. 15. Diagram of failure process of landslide dam model test: a) t = 17 min, b) t = 32 min, c) t = 65 min, d) t = 146 min, e) t = 182 min, and f) t = 396 min.

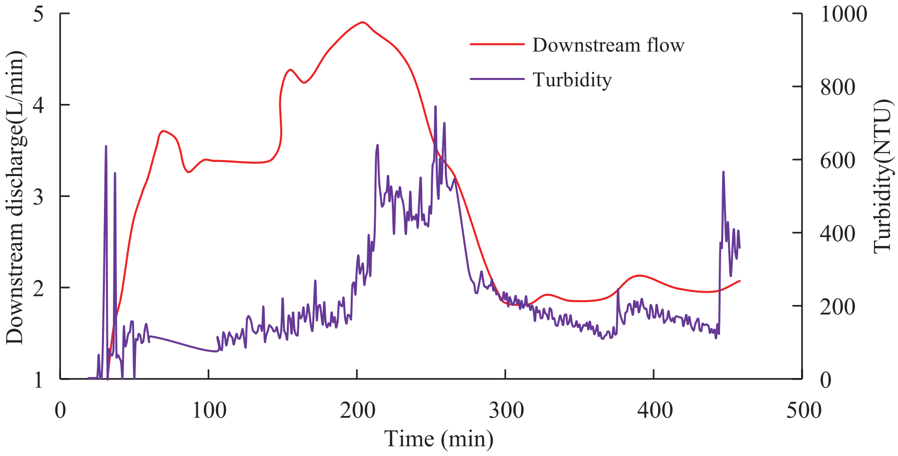

Fig. 16. Variation in Flow and turbidity with time of downstream of landslide dam.

Influencing Factors of Seepage Failure of Landslide Dam

The physical and mechanical properties of landslide dam particles, the geometric size of the dam body, and the reservoir inflow rate are the main factors that affect seepage failure.

The experimental study showed that the break time of landslide dam decreased with the increase in downstream slope angle and dam height, and the thinner the piping channel was to the downstream slope toe, the faster the break happens [49-51]. The critical hydraulic gradients to cause dam crest collapse increased with the increase in initial water content, dam height, and dam crest width. Jiang et al. found that the larger the downstream slope angle and the shorter the seepage path, the easier the seepage channel was to form [14]. The less the inflow rate and the longer the storage time, the more likely the penetrating seepage channel was to form. Considered the influence of dam geometry, dam soil characteristics, and riverbed conditions, the seepage failure model test of landslide dam indicated that the dam lifespan and its corresponding failure mode are affected by the hydraulic conductivity of dam particles [53]. The model test results from Awal et al. showed that the seepage flow increased with the increase in water level and storage capacity of the barrier lake and the size of the initial piping channel [54]. When the initial piping channel was located in the middle and the bottom of the dam, the seepage discharge would be greater. Zhu et al. found that whether a complete seepage path could be formed in the dam depended on the content and distribution of coarse particles, and whether the seepage path would be blocked depending on the content of fine particles [55]. Xiong et al. conducted landslide dam flume model tests using quartz sands with three different gradations [56]. It was found that the gradation of soils had a great influence on the failure mode of landslide dams. There were many horizontal cracks in the landslide dam made of gap-graded sand and it was prone to piping failure. The values of the slope angle of downstream-face also had a significant effect on the failure mode of the landslide dam. For the relatively smaller slope angle of downstream-face, the dam failure might be triggered by the overtopping of the dam crest. When the downstream slope angle was 7° to 25°, the seepage first exited at the downstream slope toe. Then the seepage channel gradually expanded to the upstream

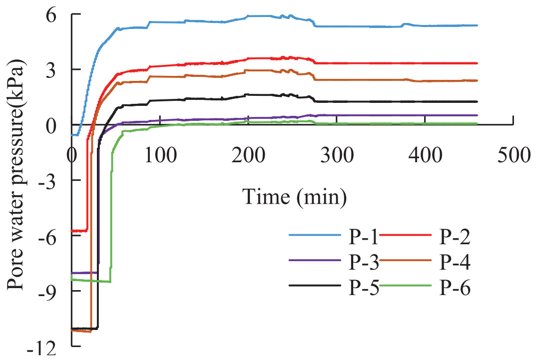

Fig. 17. Variation in pore water pressure with time at different points in the landslide dam.

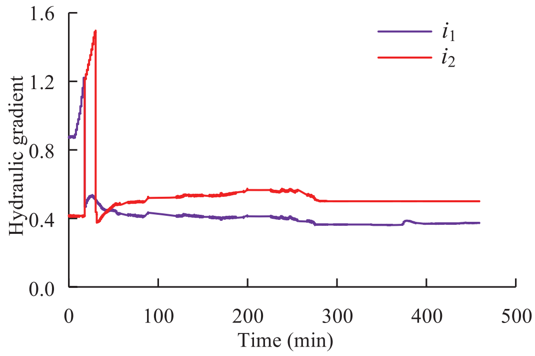

Fig. 18. Variation in hydraulic gradient with time near the high permeability zone.

and finally resulted in the dam failure [57]. According to the difference in the content of coarse and fine particles of the dam particle, the dam particles could be divided into four types: fine matrix controlled, medium particle controlled, coarse matrix controlled, and balanced composition [58]. Based on the results of 11 groups of landslide dam model tests, it was concluded that the failure mode of landslide dams was directly related to different types of dam particles [58].

In conclusion, the existence of a strong permeable zone makes the mode and process of seepage failure of landslide dams significantly different from that of the artificial dam. Many factors influence the seepage failure of landslide dams. Furthermore, the depositing characteristics of landslide dams are complex in practical engineering, and there are some differences between the real seepage failure characteristics and those from the indoor model test results. At the same time, it is not enough to consider the heterogeneity of landslide dams only from the perspective of high permeability areas. Besides, it is not enough to consider the non-uniformity of landslide dams only by including a high permeability zone. Therefore, more indexes are needed in the indoor model test to describe the non-uniformity of the landslide dam, and the test method should be improved continuously.

Discussion

Model Test and the Design of Dam Particle

The landslide dam is formed by the rapid deposition of landslide mass, the formation time is short, the actual sliding process cannot be monitored on-site, and the field large-scale landslide depositing test is very difficult, so the indoor model test has become the main research method [14, 49-51, 55, 58, 59]. In the test, geometric similarity, kinematic similarity, and dynamic similarity should be satisfied between the model and prototype, but not all relationships can be satisfied simultaneously in the model test. For the free surface flow dominated by gravity and inertial force, the Froudian number should be equal to design the model test. That is, the scale factor of Froudian number $\lambda_F = 1$ can maintain the dynamic flow similarity. The Froudian number can be calculated by [59].

$$F_r = U / (gL)^{0.5} \quad (1)$$

where U is the flow velocity (m/s); g is the acceleration of gravity (m/s^2) and L is the control length of the model (m).

In the seepage erosion model test of landslide dam, the maximum particle size of potential eroded fine particles is significantly different under different hydraulic conditions. It is unreasonable to use equivalent substitution and similar grading methods to scale dam particles directly [9]. Most particles of landslide dams are cohesionless deposits. Under the action of seepage, soil particles in the dam not only bear water pressure, buoyancy, and drag forces, but also have self-gravity and friction between particles. Under these forces and resistances, the fine particles fall off, lift-off, and are eroded. Therefore, considering the stress condition and movement state of fine particles, the gradation of the model test can be determined by referring to the calculation formula of the critical initiated velocity of cohesionless sediment [60]:

$$v = (\frac{h}{D})^{0.14} \times (17.6 \frac{\gamma_s - \gamma}{\gamma})^{0.5} \quad (2)$$

where v is the flow velocity (m/s); h is the flow depth (m); γ_s and γ are the bulk density of the sediment and flow (kN/m^3), respectively; and D is the particle diameter (m).

Description of Depositing Characteristics of Landslide Dam

According to the shape of the channel and the elevation difference between the upstream and downstream, depositing types of landslide dams can be divided into three types: slowly sliding type, over-river type, and repeated cover type. The artificial dams used in the existing model tests are usually homogeneous or simply layered, and their shape is relatively regular. This simplification will be conservative for studying the seepage stability of landslide dams with different causes, different gradations, and different water storage conditions. Therefore, it is necessary to have an appropriate description index for the shape and relative hydraulic condition of the dam. Referring to the research results of geomorphology, the landslide volume has a great influence on dam formation and stability [5, 61]. And the dam height is an important variable to assess the stability of a landslide dam for both overtopping and piping failure mechanisms [62, 63]. Peng and Zhang proposed a coefficient of horizontal shape [64]:

$$S_h = V_d^{1/3} / H_d \quad (3)$$

where V_d is the volume of the landslide dam (m^3); Hd is the height of the dam (m). Eq. (3) illustrates that the relative relationship between dam volume and dam height could be used to represent the depositing characteristics of landslide dams.

The valley width can be used to characterize the valley obstruction aptitude from a landslide, so Stefanelli et al. proposed a new index, that is, the Morphological Obstruction Index [63]:

$$MOI = \log(V_d / W_v) \quad (4)$$

where W_v is the average width of the dammed valley (m). The relative relationship between dam volume and the width of the dammed valley could be used to reflect the depositing characteristics of landslide dams. Based on the three basic depositing types of landslide dam, combined with the horizontal shape coefficient (S_h) and the Morphological Obstruction Index, the depositing characteristics of landslide dams in practical engineering can be described more comprehensively.

Evaluation of Seepage Stability of Landslide Dam Soils Based on Grading Entropy

The seepage erosion of the landslide dam can be divided into piping, boiling and contact scouring, etc. [59, 65]. Since the particle size distribution of landslide dam soils directly affects the seepage stability of the dam, many scholars have carried out a series of studies on this problem [62, 65-68]. It is very difficult to predict the seepage characteristics of a landslide dam for this kind of special depositing body which may contain tens of meters of boulders [68]. Furthermore, under the effect of seepage erosion, the particle size distribution of the dam soils is usually changed dynamically [68].

Some prediction models had been established based on the characteristic particle size of the dam soils and some useful conclusions had been drawn [69, 70]. For example, Chang and Odong used the median diameter D_{50} of the cumulative particle size distribution to build predictive models [70, 71]. However, the field investigation results obtained by Casagli et al. showed that the obvious bimodal distribution presented in the particle size-frequency distribution curve of the landslide dam soils, and the median diameter D_{50} only represented the smaller particle size [33]. Other scholars comprehensively considered some characteristic diameters such as D_{10}, D_{30}, and D_{60}, and used the coefficient of uniformity Cu to preliminary predict the failure mode and process of landslide dams [69, 70]. But these characteristic diameters only represent several certain points on the particle size distribution curve, and cannot represent all the information of the whole gradation. Hence, it is difficult to accurately describe the gradation characteristics so that access to the seepage stability of landslide dam soils is also difficult.

Lőrincz et al. proposed a conception of grading entropy to provide a new method to quantify the particle size distribution curve [72]. The grading information of soil particle size distribution can be extracted by statistical analysis. The particle size distribution can be divided into several fractions and all information of the complex particle distribution curve can be represented by two entropy parameters. The normalized parameters of grading entropy can be drawn in an entropy map. Compared with the traditional method to use characteristic diameters to represent the particle size distribution, this method has natural advantages, such as fewer parameters, the degree of disorder of particle gradation, and the dynamic change of grading caused by the loss of fine particles.

The two parameters of grading entropy are the entropy increment ΔS and the base entropy S_0 [72-74]:

$$\Delta S = -\frac{1}{\ln 2}\sum_{i=1}^{n} p_i \ln p_i \quad (5)$$

$$S_0 = \frac{\sum_{i=1}^{n} p_i (i-1)}{n-1} \quad (6)$$

where $p_i = M_i/M$ is the relative frequency of ith fraction, n is the number of fractions of a particle size distribution curve, M is the total weight of the soil sample (kg), M_i is the weight corresponding to the ith fraction (kg) (Fig. 19) [74]. The normalized relative basic entropy A and entropy increment B are:

$$A = \frac{\sum_{i=1}^{N} x_i \left(S_{0i} - S_{0min}\right)}{n-1} = \frac{\sum_{i=1}^{N} x_i (i-1)}{n-1} \quad (7)$$

$$B = \frac{\Delta S}{\ln n} \quad (8)$$

$S_{0\min}$ is the basic entropy when all soil particle sizes are in the first range, and it is also the minimum intrinsic entropy. The particle size distribution of landslide dam soils usually spans different orders of magnitude, and internal erosion is easy to occur due to seepage. The change in particle content in a certain range is caused by the loss of fine particles, which can be described by basic entropy. Entropy increment reflects the mixing degree between different particle sizes, which can be regarded as a measure of uncertainty of particle size distribution and an important parameter to judge the structural stability of granular particles.

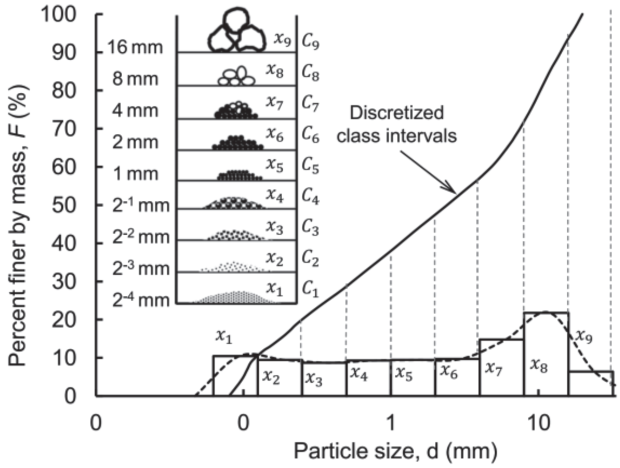

Fig. 19. Discretization of particle size distribution curves for 8 fractions [74].

S_0 for a known particle size distribution, based on the entropy mapping relation $f : \Delta \rightarrow [S_0, \Delta S]$ or normalized entropy mapping relation $f_n : \Delta \rightarrow [A, B]$, the two entropy parameters not only can reflect the characteristics of the whole particle size distribution curve, but also can reflect the variation of the particle size distribution curve caused by the loss of fine particles in different stages. According to the concept of grading entropy, the internal stability of landslide dam soil can be evaluated more accurately [75, 76]. The landslide dam model test also indicated that the seepage stability of the landslide dam soil can be quickly judged based on the particle composition of landslide dam soil, geometric parameters of the dam body and upstream hydraulic characteristics, which is of great significance for the assessment and prevention of landslide dam disasters [15, 58].

Conclusion

In this paper, the natural depositing characteristics of the landslide dam and advances in the model test for seepage failure were summarized. In line with the results of the field investigation, the existing problems are discussed, and the following conclusions can be drawn.

(1) According to the field investigation, the depositing characteristics of landslide dam are related to the lithology of landslide mass, slip path and slope structure of river bank, and so on. The structure of the landslide dam is loose and the particle size distribution varies widely. The dam material contains clay, silt and blocks of several tens of meters. At the same time, the particle distribution uniformity is poor, and the permeability of different parts of the dam may differ by several orders of magnitude. There may be a strong permeability zone in the landslide dam, which will be an important reason for the formation of piping channels.

(2) The seepage failure of landslide dams depends on many factors. The failure mode and process of landslide dam are different in different depositing modes, particle compositions and distributions, and hydraulic conditions. The whole failure process of landslide dams with a strong permeability zone at the bottom can be divided into four sequential periods. In the first period, water flow will first seep out from there. Fine particles will erode and piping channel is easy to form. In the second period, as the loss of fine particles increases, the piping channel gradually expands. Part of the piping channel is blocked when the piping channel fails to support the upper self-weight load and collapses. In the third period, a new piping channel forms, and the downstream discharge and turbidity gradually increase. In the fourth period, the dam model suddenly collapses, and several cracks appear on the downstream dam surface.

(3) For the test water flow is a free surface flow dominated by gravity and inertial forces, the experimental data should comply with the Froudian similarity ratio of hydrodynamic similarity. The maximum particle size of dam soil can be figured out by referring to the calculation method of the critical initiated velocity of cohesionless sediment. The horizontal shape coefficient, the Morphological Obstruction Index, and three depositing modes can be appropriately described as the depositing characteristics measure principals of landslide dams.

(4) Based on the grading entropy theory, the seepage stability of dam soils can be predicted accurately. The dynamic change of grading entropy can reflect the changing trend of the grading curve caused by fine particle loss, and judge the internal stability of dam soils. Added with other information, for instance, geometric parameters and hydraulic conditions, the failure mode and process of the landslide dam can be predicted in advance.

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Conflicts of Interest

The authors declare no conflict of interest.

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