



Characteristics of landslide-debris flow accumulation in mountainous areas

Zhang Qing-zhao^{a,b}, Pan Qing^a, Chen Ying^{c,*}, Luo Ze-jun^a, Shi Zhen-ming^{a,b}, Zhou Yuan-yuan^a

^a Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China

^b Key Laboratory of Geotechnical and Underground Engineering, Ministry of Education, Shanghai, 200092, China

^c Shanghai Lixin University of Accounting and Finance, School of Business Administration, Shanghai, 201209, China



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ABSTRACT

Landslide-debris flow is a sudden geological hazard in mountain areas, which is characterized with large scale, fast speed and wide impact range, and often causes disastrous accidents. In this study, an indoor sliding chute test was used to study the movement process of the landslide-debris flow and its accumulation pattern in the valley, taking into account the initiated gradient and particle size distribution. Besides, the model test was reproduced by PFC and the numerical models were constructed to fit the actual situation of landslide-debris flow. The results show that the collision of particles occurs during the movement of landslide-debris flow, and obvious sorting phenomena occur in the final deposit. Coarse particles distribute in the front and surface of the deposit while fine particles distribute in the back and bottom. The initiated angle has a certain effect on the morphology of the deposit: larger initiated angle makes the deposit closer to the opposite bank of the valley. Particle gradation has a significant impact on the form and distribution of deposit as well, with the increase of the proportion of coarse particles, the deposit of fine particles shrinks to the center of the rear edge, the profile of the deposit is more flat and uneven, the deposit is closer to the opposite bank of the valley, and the angle of the deposit profile increases significantly.

1. Introduction

Landslide-debris flow is a sudden geological hazard in mountain areas, which is characterized with large scale, fast speed and wide impact range, and often causes disastrous accidents (Zhou et al., 2013). At the same time, the landslide-debris deposit is very easy to cause secondary disasters, such as another landslide-debris flow, and landslide damaged waves generated in reservoirs, which would expand the scope of disaster impact (Dai et al., 2005; Huang, 2009; Hungr et al., 2014). Here it is noted that debris deposit refers to the materials of debris flow deposited in the mountain valley. Especially, the southwest mountain area of China is a high-incidence area of landslide-debris flow. For example, the Wenchuan earthquake triggered a series of landslide-debris flow. Furthermore, the landslide-debris deposit existed as a source of new landslide-debris flow. Besides earthquakes, rainfall is an important factor in triggering landslide (Iverson, 2000). So there were more landslide-debris flow occurred under the action of rainstorm. It was estimated that the number of related landslide-debris flow was about $3 \times 10^4 \sim 5 \times 10^4$, causing casualties of more than 450. Additionally, due to the earthquakes, a landslide-debris flow in this area has caused intense

activities, which possibly continues 10–30 years or even longer (Cui et al., 2010). The morphology of landslide-debris deposit determines its scale and is an important factor affecting the stability of deposit, and the distributions of the particles with different sizes in the deposit affect its overall strength. Therefore, the morphology and particle distributions of landslide-debris deposit have a great impact on its stability and failure process and mode. In order to grasp the stability and destruction of landslide-debris deposit and prevent the occurrence of secondary geological disasters, it is necessary to have a clear understanding of the movement and accumulation process of landslide-debris deposit and to analyze the accumulation characteristics. Here it is noted that accumulation refers to the deposit of debris flow in the mountain valley.

At present, many achievements have been made in the studies of landslide-debris flow. In particular, a lot of scholars have systematically investigated the whole process of landslide-debris flow, including initiation mechanism, movement process and accumulation characteristics based on indoor physical model tests and numerical simulations. The numerical simulation technology has made a great leap in the recent decade. Many scholars (Evans et al., 2001; Cao et al., 2011; Huang et al., 2014; Bi et al., 2015; Zhao et al., 2017; Li et al., 2019) adopted numerical simulation to reproduce the whole process of real landslide-debris

* Corresponding author.

E-mail address: 20170099@lixin.edu.cn (C. Ying).

bodies, such as Tangjiashan and Niumian Ditch, from start-up to accumulation, and analyzed the movement characteristics and accumulation law of debris flow. Some scholars (Crosta et al., 2006; Li et al., 2011, 2018; Utili et al., 2015) used numerical simulation to study the general law of the movement and accumulation characteristics of accumulation body under different geological factors, mainly taking into consideration the fluctuation of sliding surface, erosion of the surface below the sliding surface and friction coefficient of the sliding surface.

Zhou and Ng (2010) conducted a field study in the Dongchuan Debris Flow Observation and Research Station, and proposed a method to predict the rheological properties of debris flows through the dimensional analysis, and revealed the flow behavior of large-scale natural debris based on the field data. However, it is difficult to obtain the field monitoring data, so model test has become an important means to study the movement and accumulation process of landslide-debris flow. Hungr and Morgenstern (1984a,b) observed the flow characteristics of dry sand in the whole process through high-speed sliding model test, and obtained the movement law of the sliding body after breaking up in high-speed movement. Iverson and Richard (1997) summarized predecessors' research results and raised a more reasonable model of debris flow based on the large-scale flume experiments. Pudasaini et al. (2005) and Chen et al. (2011) used dry sand to simulate the movement of debris flow, and recorded the sliding state of debris flow on the slope by PIV technology, so as to obtain the velocity evolution characteristics of debris flow. Iverson (2005) further proposed a forecasting model to predict runout of rock and debris avalanches. Johnson et al. (2012) employed large-scale debris-flow experiments with the water-saturated sands and gravels to investigate the formation of lateral levees enriched with the coarse particles. Tang et al. (2013) carried out a series studies on the debris flow impact by a large flume and proposed a pressure equation for the debris flow impact. Kokelaara et al. (2014) used fine sand and glass balls as model materials, and discovered the main factors affecting the long-distance movement of debris flow. Pudasaini et al. (2008) and Scheidl et al. (2014) carried out experiments on curved inclined grooves under real three-dimensional terrain conditions, and discussed the influence of curved terrain on accumulation characteristics. Hao et al. (2014, 2015) used indoor physical model tests to study the particle separation of landslide debris flow in the movement process, and discussed the formation mechanism of reverse sequence characteristics of high-speed long-distance landslide-debris flow accumulation body on the basis of field investigation and experimental results. Sulpizio et al. (2016) carried out laboratory experiments with natural materials to study the movement of grain flow on slopes, and recorded particle velocities by sensors buried in the depositional area to study the variation of the morphology of the depositional area with the gradient of the slope. Iverson et al. (2016) studied the run-up behavior of debris flows through the large-scale laboratory experiments, and developed a simple analytical model and a depth-integrated numerical model. Ng et al. (2017a,b) conducted physical model tests with glass beads and fine sand of different sizes to study the initiation mechanism and accumulation law of landslide debris flow. Wang et al. (2017) simulated the sliding and accumulation process of landslide debris flow under specific conditions through indoor model test and obtained the distribution of landslide debris flow deposits. He analyzed the distribution law and studied the movement mechanism of landslide debris flow based on the test results. However, up to now, most studies only studied the accumulation characteristics of debris flow on flat land and few studies were carried out on model tests of debris deposit in mountain valleys.

Therefore, in this paper, physical model tests are used to simulate the movement process of landslide-debris flow and its accumulation form in valleys under different initiated gradients. The effects of initiated gradient and particle gradation on the accumulation form and particle distribution of landslide-debris deposit in mountain valleys are taken into consideration, which could provide not only a basis for further study on the stability of landslide-debris deposit but also a useful reference for disaster prevention and mitigation engineering design.

2. Materials & methods

2.1. Test materials

In this paper, the process and characteristics of the natural falling accumulation of the landslide are investigated. The material of this landslide-debris is generally dry without the action of water flow, which is manifested as landslide-debris flow rather than debris flow. The accumulation area of the landslide-debris body is a dry valley without flow and the landslide-debris deposit naturally accumulates, among which the initiated angle of landslide-debris and the gradation of landslide-debris are important factors affecting the accumulation characteristics. The size of materials in debris deposit varies widely, ranging from boulders, several meters in diameter, to clay particles, several microns in diameter. So there are great differences in the gradations of different landslide-debris flow. After comparing the gradation of many different landslide-debris deposits, three typical gradation types are proposed: (1) Materials with mainly fine particles; (2) Materials with even gradation; (3) Materials with mainly coarse particles. On the one hand, for the small size of the model tests, the maximum particle size of the model is set as 60 mm (Hao et al., 2014). On the other hand, many scholars selected the materials with a diameter less than 10 mm as the minimum particle size (Jop et al., 2006; Ng and Choi et al., 2016a,b, 2019). However, the test in the present work is conducted in the natural drying state in an open space so that a large amount of dust can be produced from the fine particles, which may affect the photogrammetry and observation effect. Therefore, the fine particles below 4 mm are removed to meet the test requirements. Finally, the gradation shown in Fig. 1 is selected for the indoor physical simulation test.

2.2. Test equipment

Based on previous studies of the physical model test of landslide-debris flow accumulation process (Faug et al., 2003, 2004, 2008; Choi et al., 2016a,b), an indoor landslide-debris flow system is built. The system is mainly composed of a hopper, a start-up zone, a sliding zone, a valley area and an observing system, as shown in Fig. 2. Designers of granular physics experiments can commonly disregard scaling problems because there is no need to consider the effects of water (Iverson and Richard, 2015). So the size of the debris bin is 50 cm × 40 cm × 30 cm (length × width × height), the starting zone is 0.6 m in length, 1.0 m in width, and the inclination angle is adjustable from 40° to 60° while the sliding zone is 2.0 m in length, 1.0 m in width, and 40° in inclination angle. The sidewall of sliding bed is made of plexiglass, through which the movement process of landslide-debris particles can be observed and recorded directly. In the valley area, the simplified 90° V-shaped concrete trench is used to simulate the actual mountain valley. The slope foot of the trench is 45°, the net depth of the design is 32 cm and the width of the trench is 2.5 m. It should be noted here that such V-shaped concrete trench is quite different from rigid barrier or wall. The barriers are commonly artificially installed in sliding regions to resist flows (Choi et al., 2016a,b; Song et al., 2017; Ng et al. 2017a,b, 2019a) while the mountain valley is a natural area for debris deposit. Due to these differences, the effects of debris flow on barrier are studied. It is also noted that the barrier angle is less than 90° to the slide bed (Faug, 2015; Iverson et al., 2016; Choi et al., 2019) while the aim of the present work is to study the accumulation form of landslide-debris deposit in valley because the angle of virtual valley is 90°. In addition, a high-speed camera is a common tool for recording test procedures (Ng et al., 2015, 2019b). So our observing system includes a high-speed camera and two ordinary cameras (Fig. 2). The high-speed camera is facing the sliding zone to record the movement of landslide-debris flow, filming at 179 Hz. And the two ordinary cameras are used to record the side view and top view of the landslide-debris deposit.

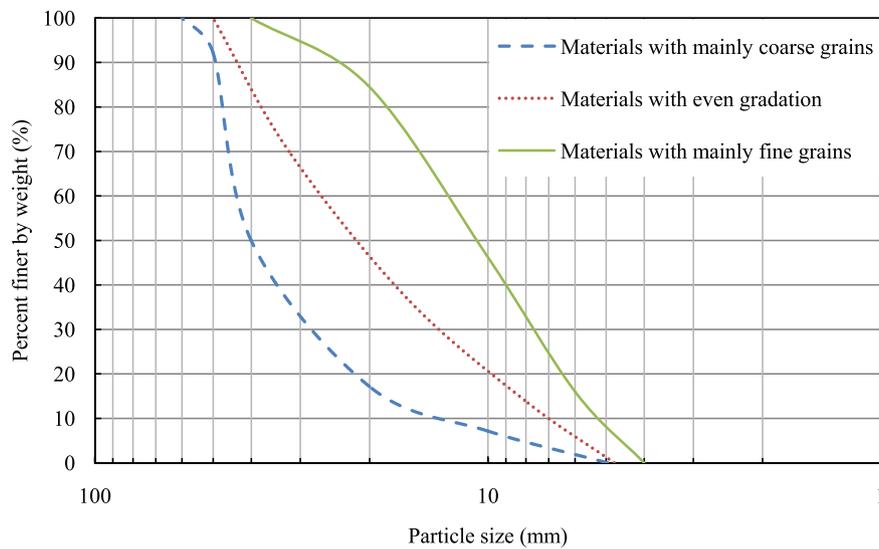


Fig. 1. Gradation curves of test materials.

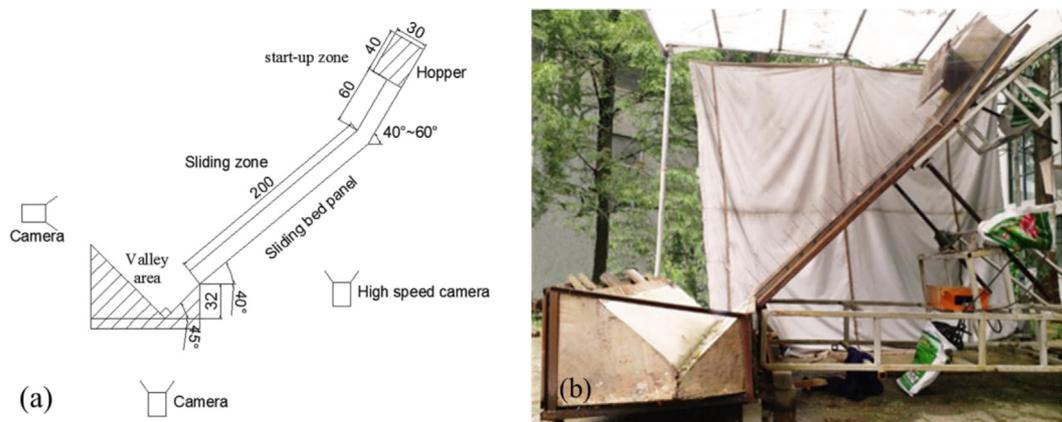


Fig. 2. Test equipment: (a) sketch map; (b) photo of the scene.

2.3. Test procedures

According to the different topographic conditions, the main research factors are determined as the slope of the start-up zone (50°, 60°) and the gradation of debris (materials with mainly fine particles, materials with even gradation and materials with mainly coarse particles). The width of sliding bed is 50cm. The effects of different starting angles and gradation of debris on the movement process and accumulation form of debris particles are mainly analyzed (Table 1). The deposit length, width, gradient and distribution of debris particles were obtained through multiple tests under different conditions.

3. Results

3.1. Analysis on movement and accumulation of debris particles

There are generally three types of movement of landslide-debris particles on the sliding bed, which are sliding, rolling and bouncing. With distinct edges and corners and light weight, small particles usually move in the form of rolling and bouncing on the inclined plane. With regular shape, smooth surface and heavy weight, most large particles move in the form of sliding on the inclined plane. Fig. 3 shows the movement process of debris with materials with even gradation. Taking the test conditions of 60° start zone, 40° main sliding zone and debris with materials with even gradation as examples, the movement and

accumulation process of debris particles are described and analyzed. As shown in Fig. 3, when $t = 0.3$ s, the debris slips from the bin and gradually thins down from the bin mouth, the lateral shape of the debris is approximately triangular; when $t = 0.5$ s, the length of the debris increases on the slope surface and the thickness at the turning point of the slope surface is the largest; when $t = 0.8$ s, the debris basically covers the whole slope surface, and the front edge of the debris is at the moment of entering the valley; during the period from $t = 0.8$ s to $t = 2.0$ s, the debris accumulates. Comparing with the first three photos, it can be observed that a large number of large particles emerge during the movement, appear on the surface of debris particles, and finally accumulate in the

Table 1 Test conditions of debris sliding accumulation.

Group No.	Sliding slope/°	Promoter slope/°	Particle composition
1	40	60	Materials with mainly fine particles
2		60	Materials with even gradation
3		60	Materials with mainly coarse particles
4	50	50	Materials with mainly fine particles
5		50	Materials with even gradation
6		50	Materials with mainly coarse particles

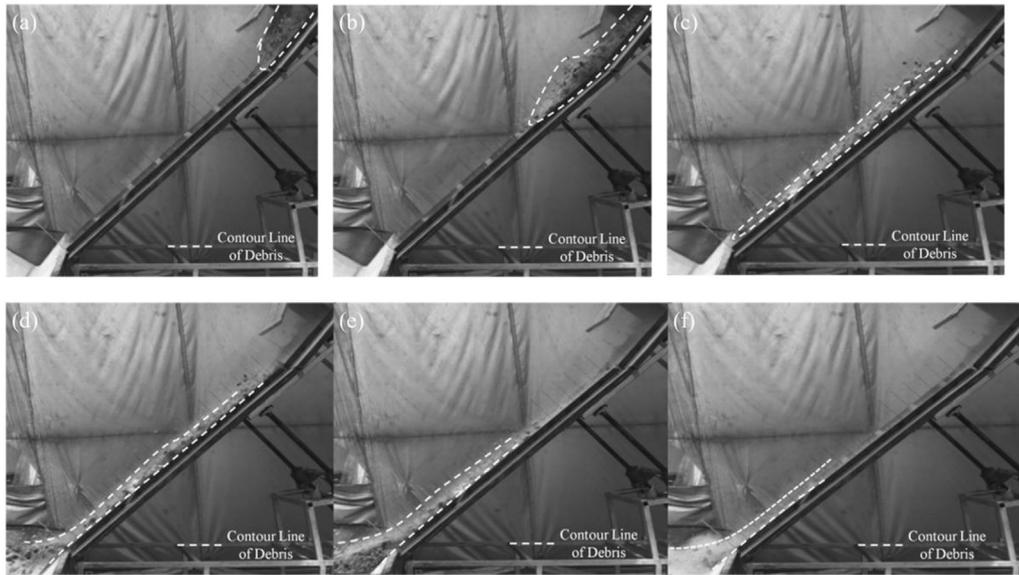


Fig. 3. Movement process of debris with materials with even gradation: (a) $t = 0.3s$; (b) $t = 0.5s$; (c) $t = 0.8s$; (d) $t = 1.0s$; (e) $t = 1.5s$; (f) $t = 2.0s$.

groove at the front of the sliding groove.

The debris begins to accumulate when it enters the groove at $t = 0.8s$. Fig. 4 shows the final geometric form of the debris deposit. The debris begins to accumulate in the groove from the center of the sliding groove and begins to accumulate on both sides of the groove with the development of the accumulation. Fig. 4 shows obvious sorting characteristics. Small particles mainly accumulate at the rear edge of the deposit, while large particles mainly accumulate at the front edge of the deposit. In the process of sorting, the main motion direction of particles includes not only the flow direction of particles flow, but also the normal direction of particles flow. In such a stage, fine particles pass through the gaps between coarse or medium particles and reach the bottom of the particles flow. At the same time, the fine particles have smaller mass and larger energy loss due to collision and friction in the process of movement. Because the mass of coarse particle is big, carrying bigger energy in motion process, it can easily move forward over small particles and eventually accumulate in the leading edge.

In order to better analyze the influence of the particle distributions on the movement and accumulation of the landslide-debris flow, the time of entering valley and the time of completing accumulation of three groups of particles were compared based on the observing system (as shown in Fig. 5). The time of debris entering valley and completing accumulation will change with the change of particle gradation. The larger the proportion of coarse particles, the shorter the time of entering valley and completing accumulation.

3.2. Effects of starting angle of slope

During the movement of landslide-debris particles, the movement direction and total energy will change with the change of the starting

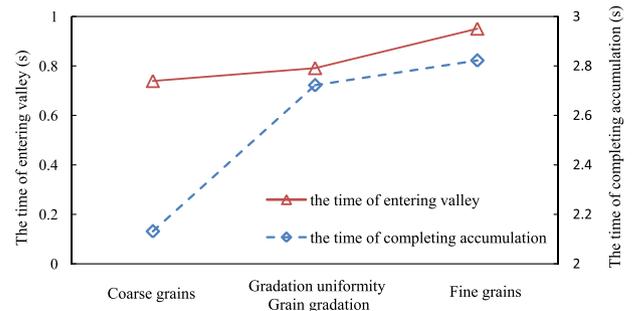


Fig. 5. Time of entering valley and completing accumulation of three groups of debris.

angle of the slope. By changing the angle of the starting zone, the initial failure angle of the sliding body will change, and the debris particles will get different starting speed. By changing the angle of the starting zone and keeping the angle of the sliding zone at 40° , the experiment was conducted to study the influence of the initial starting angle of the sliding body on its movement and accumulation. The experimental results show that there are small differences in movement state between landslide and debris flow for different starting angles, and finally the particles under the two conditions move and accumulate to form debris deposit.

Base on the top view of debris deposit recorded by the camera, a simplified plan projection map of the accumulation area is drawn with the edge of the chute outlet as the horizontal axis and the centerline of the slide bed panel as the longitudinal axis (as shown in Fig. 6). As shown in the figure, the geometric form of the debris deposit with materials with

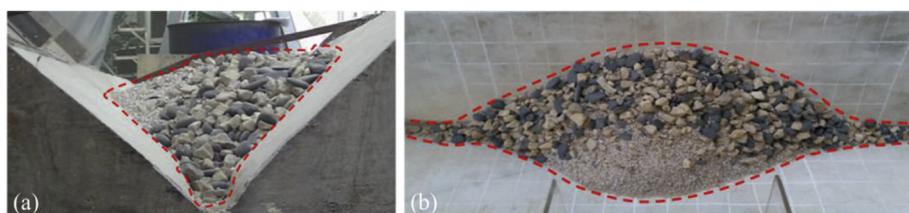


Fig. 4. Geometric form of accumulation body of debris with materials with even gradation: (a) side view; (b) top view.

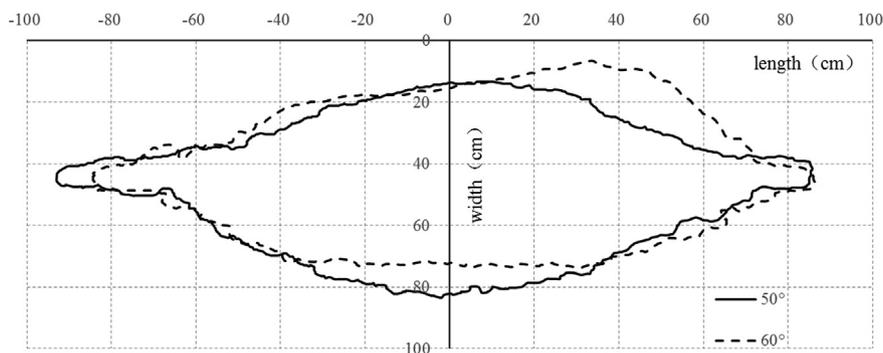


Fig. 6. Effects of start zone angle on the form of debris accumulation body.

even gradation is basically similar under different starting angles. However, there are slight differences in the accumulation area. The accumulation area formed when the start angle is 50° is closer to the outlet of the chute than that formed when the starting angle is 60° , which indicates that the angle of the start-up area will accelerate the movement of debris. The larger the angle, the faster the initial velocity, the farther the accumulation area in the groove is away from the outlet of the chute, and the farther the movement distance of the debris flow is. At the same time, the particle distribution on the surface of the deposit is observed. Coarse particles are distributed in the front of the deposit, and fine particles are distributed in the back of the deposit. Coarse particles carry much more energy than fine particles in the process of accumulation. Collision and rebound occur between the groove and the sidewall, resulting in

"overturn", which eventually leads to the result that coarse particles not only concentrate in the front, but also distribute in the middle of the debris deposit.

3.3. Effects of debris particle gradation

In the process of landslide-debris sliding movement, collisions occur among internal particles and between particles and sliding surfaces. The collisions among particles will be different for debris with different particle gradations, and their motion state and accumulation characteristics will also be affected by gradation. In this experiment, three groups of debris with equal volume yet different gradations were selected to carry out landslide-debris accumulation test, so as to study the effect of

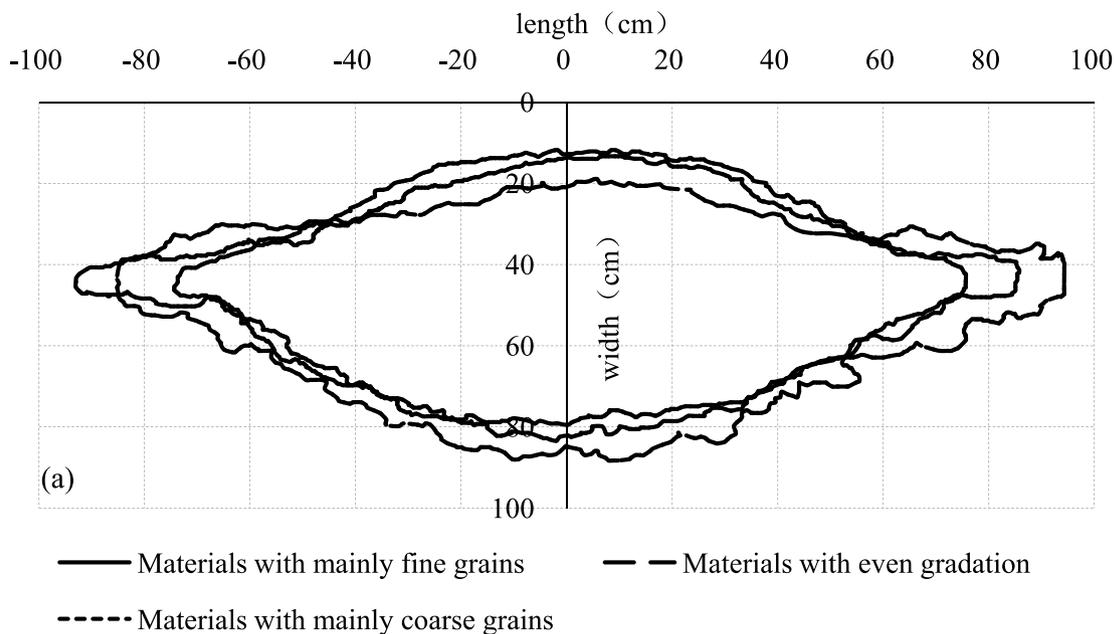


Fig. 7. Top view of debris deposit of three different gradations: (a) contour lines of debris deposit of three different gradations; (b) materials with mainly fine particles; (c) materials with even gradation; (d) materials with mainly coarse particles.

particle gradation on the form of debris deposit. Fig. 7 shows the geometric contour of debris deposit and the overhead view of debris accumulation area formed by deposit with different particle gradations sliding down when the starting angle is 60° . It can be found from the test results that with the change of particle gradation, the overall contour of the accumulation area does not change much, but with the increase of the proportion of coarse particles, the contour shape gradually becomes flat and narrow, and the contour of the accumulation area is no longer smooth and becomes more uneven.

At the same time, it can also be found that the contour line moves downward gradually with the increase of coarse particles, and the distance of debris movement increases. With the increase of coarse particles in the particle composition, the accumulation area of particles gradually moves towards the opposite bank of the groove. Under the same condition, the mass of coarse particles is much larger than that of fine particles, so it has a greater inertia. The coarse particles, after sorted behavior, are mostly located in the surface, and the resistance of which is small. Therefore, coarse particles are more likely to rush to the front of the accumulation area, and the landslide-debris deposit dominated by coarse particles is bound to move towards the other side of the valley.

For debris mainly composed of fine particles, although the same gravitational potential energy is obtained at the start-up stage, due to the small mass of single particles, loose contact between particles, frequent collision and more energy loss, the kinetic energy loss of debris transformed from gravitational potential energy is obvious when the debris moves to the outlet of the groove, so the deposit is located closer to the outlet of the sliding groove. According to the theory of dissipation pressure, the larger the particle size is, the easier it tends to move to the surface (Bagnold, 1954). The fine particles move at the bottom, and fully contact with the sliding surface, so the friction effect is obvious, resulting in a large amount of energy loss, further promoting fine particles to stop at the back edge of the accumulation area. In contrast, the coarse particles move on the surface of debris flow with less friction, and move on the top of fine particles, which can easily fly over fine particles and accumulate further away.

Judging from particle distribution on the surface of the deposit, there is obvious particle sorting phenomenon in the group tests of debris with different gradations. After the process of starting, sliding and accumulation, the coarse particles are mostly concentrated in the front of the accumulation area near the opposite side of the groove, while the fine

particles are mostly concentrated in the back edge of the accumulation area. During the whole process of observation, when debris particles rush out of the chute and enter the groove, the particles have already separated. Because of slow speed, fine particles quickly stop moving when they enter the valley, and gather at the end of the valley, blocking the subsequent arrival of fine particles. For coarse particles, because of its fast speed, they can directly cross the area where fine particles accumulate and fly to the farther valley to accumulate on the other side. The accumulation area shows a typical reverse sequence structure. For the debris deposit with three different gradations, with the increase of coarse particles, the fine particles belt of the deposit gradually decreases, and finally gradually shrinks to the outlet of the sliding chute.

With the change of particle gradation, the proportion of coarse particles in the debris increases gradually, and the debris rushes farther to accumulate, as shown in Fig. 8. Different lines represent the profiles of debris deposit with different gradations. With the increase of coarse particles, the deposit gradually migrates to the opposite bank, the inner stacking height decreases, and the outer stacking height increases significantly, which shows an obvious "climbing" phenomenon. Comparing the profile, it is not difficult to find that with the increase of coarse particles, the contour line presents obvious unevenness and the angle between the contour line and the level increases gradually. The phenomenon can also be explained by the theory of dissipative pressure. With the increase of the proportion of coarse particles and the decrease of the number of fine particles, more and more coarse particles move on the surface of the debris flow, maintain a high kinetic energy and rush to the other side of the trench to accumulate. At the same time, the decrease in the number of fine particles moving at the bottom of the debris flow will inevitably lead to the decrease of fine particles deposited in the inner side of the trench, which will lead to the decrease in the source and height of the deposit at the back edge.

4. Analysis

The landslide-debris movement and accumulation process involves complex mechanical behaviors such as sliding, collision and accumulation, and is characterized with large deformation and large displacement. The deposit is mainly caused by the rapid accumulation of rock and soil. With loose structure, loose composition and poor cementation, it can be regarded as a discontinuous discrete medium material. The discrete

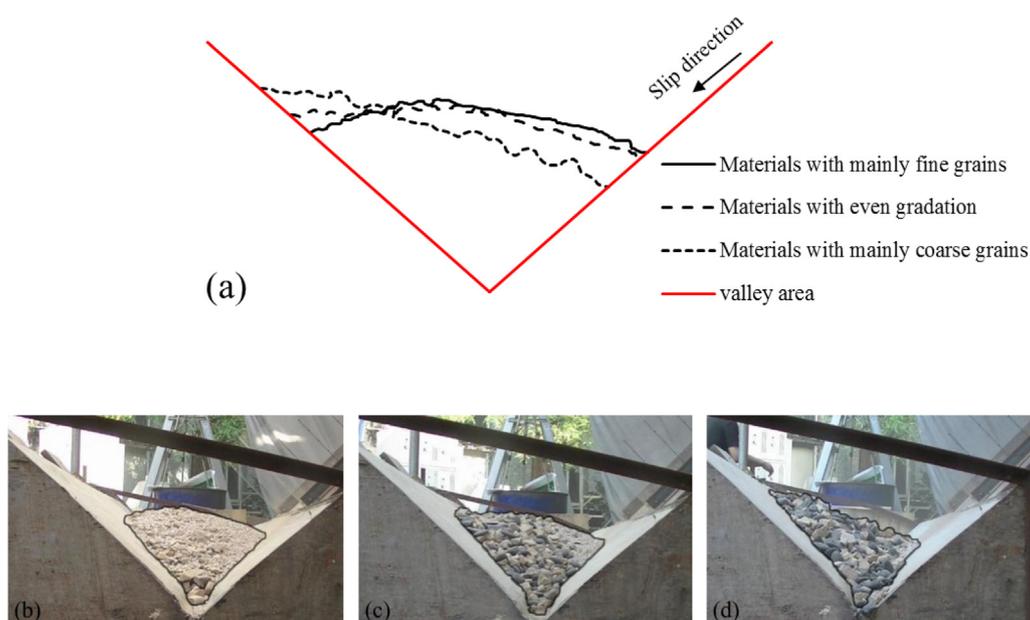


Fig. 8. Side view of debris deposit of three different gradations: (a) contour lines of debris deposit of three different gradations; (b) materials with mainly fine particles; (c) materials with even gradation; (d) materials with mainly coarse particles.

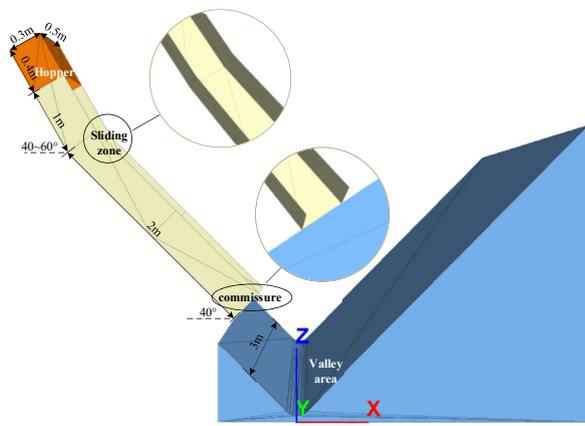


Fig. 9. Geometric construction of discrete element model.

element method is based on the differential equation mechanics of plane motion. Such a method is mainly used to study the discontinuous medium such as rocks, and is suitable for analyzing the large deformation and discontinuous problems. PFC^{3D} is an application software developed by ITASCA on the basis of the discrete element method, which can be used to simulate the motion and interaction of disc or spherical particle medium based on the discrete element method. In the present work, PFC^{3D}5.0.27 is used to conduct the numerical simulations, and the CPU of the computer used is the Inter Xeon E5-2643 v4.

4.1. Discrete element modelling

In the numerical simulation, the geometric construction of the discrete element model is matched with the model test. The left-most point of the vertical view of the valley bottom axis is taken as the coordinate origin, where the Y-axis points to the right of the valley, the X-axis points to the opposite bank of the landslide along the valley bottom boundary, and the Z-axis is parallel to the gravity line in the opposite direction. The geometric model consists of three parts: material box, landslide surface and valley. Landslide surface is the slope where particles begin to slide. It is called source slope. The other side of the valley is called opposite bank slope, as shown in Fig. 9.

After the geometric model is constructed, particles need to be generated according to the above gradation curve to fill the bin. The total volume of particles is calculated according to 65% of the hopper volume, and the number of particles generated in material bins under different gradations will be different. As shown in Fig. 10, the total number of uniformly graded particles is about 44,000, the total number of coarse particles is about 15,000, and the total number of fine particles is about 127,000.

In the selection of contact model, this paper decides to adopt anti-rotation linear model to realize double control of sliding friction coefficient and rolling friction coefficient of wall element, so as to achieve more reasonable simulation. Through the inversion test, the parameters

Table 2
General value of particle parameters.

Parameter	Contact modulus e_c (Pa)	Stiffness ratio k_n/k_s	Grain density ρ (kg/m ³)	Normal critical damping coefficient	Tangential critical damping coefficient
Value	10 ⁷	1	2650	0.4	0.2

Table 3
Values of friction coefficient under different grain gradation.

Friction coefficient	Ball-ball	Ball-landslide facet	Ball-valley facet
Materials with mainly coarse particles	0.35	0.12	0.08
Materials with even gradation	0.4	0.15	0.1
Materials with mainly fine particles	0.45	0.18	0.12

are constantly adjusted to make the strength of rock particles conform to the macroscopic results. Finally, the parameters of numerical simulations are determined as shown in Table 2 and Table 3.

4.2. Experimental results of numerical simulation of landslide-debris flow accumulation

Three kinds of debris particles with different gradations were simulated under the condition of slope foot of the start zone is 60° and that of the sliding zone is 40°. The numerical simulation of the movement process of landslide-debris flow with materials with even gradation is shown in Fig. 11. By comparing the movement process of numerical simulation (Fig. 11) with model test result (Fig. 3), it can be seen that the debris shape is basically the same as that of that of the model test when the particles are released into the start-up zone. When the particles enter the sliding zone through the turning point, the shape of the debris is elongated and the geometric shape is basically the same. Finally, after the particles enter the valley, the length and thickness of the residual debris on the slope gradually become smaller. In conclusion, the results for the model tests and numerical simulations are in good agreement with each other in the movement process.

Fig. 12 shows the numerical simulation results of three kinds of graded debris accumulation. In the side view, the left side is the landslide bank, the right side is the opposite bank, in the top view, the lower side is the landslide side, and the upper side is the opposite side of the landslide. At the same time, it can be seen when compared with Figure 7 (b)~(d) and Figure 8 (b)~(d) that: (1) The inclination angle of the deposit surface, length and particle size distribution have a high coincidence. (2) From the side view, it can be seen that with the increase of the coarse particles, the angle of the accumulation area tending to the bank of the landslide gradually increases, which is reflected in the overhead view: The contour lines of the accumulation area on the side of the landslide bank gradually decrease, while the contour lines on the opposite side of valley gradually increase. That is to say, the debris gradually moves towards the opposite bank of the valley. (3) The distribution of particles is also regular. Large

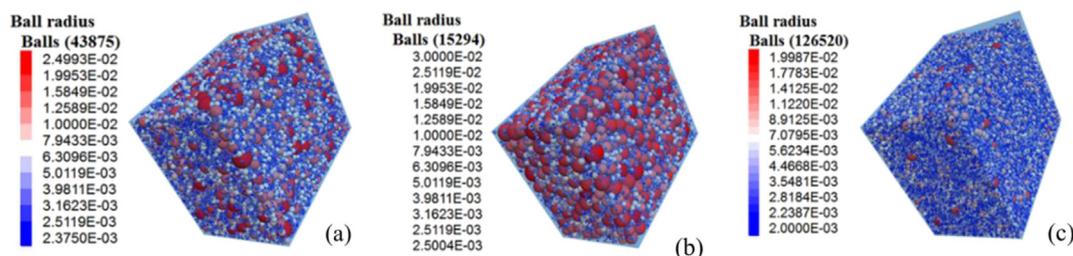


Fig. 10. Materials of three different gradations in discrete element model: (a) materials with mainly fine particles; (b) materials with even gradation; (c) materials with mainly coarse particles.

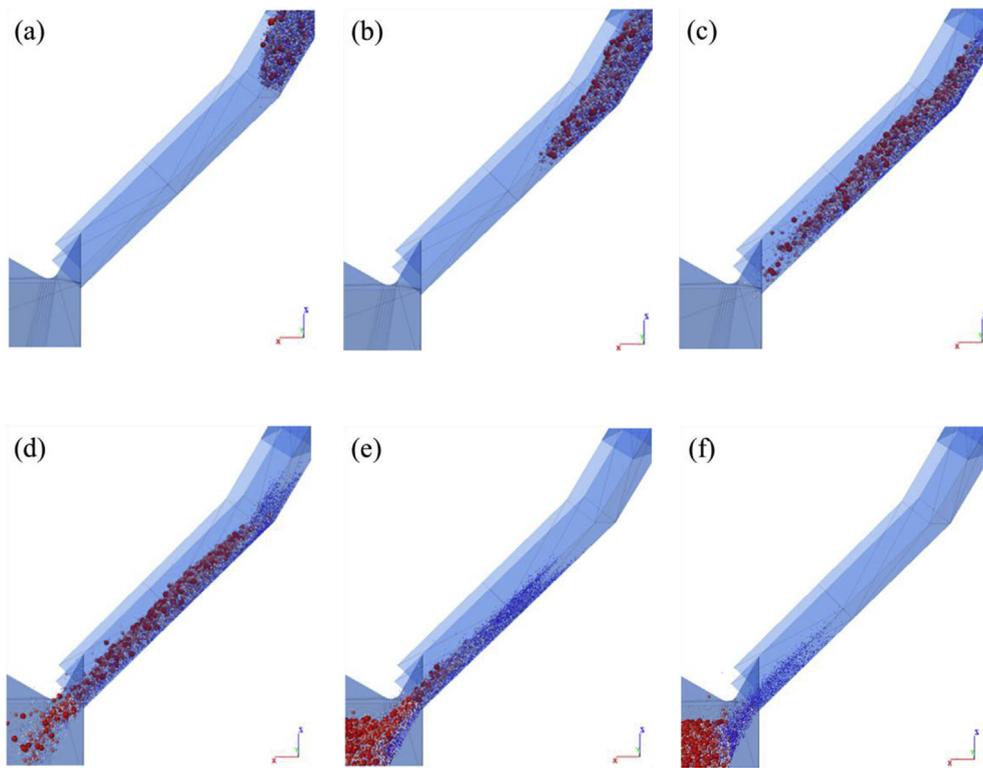


Fig. 11. Numerical simulation results of the movement process of evenly graded debris body: (a) $t = 0.3$ s; (b) $t = 0.5$ s; (c) $t = 0.8$ s; (d) $t = 1.0$ s; (e) $t = 1.5$ s; (f) $t = 2.0$ s.

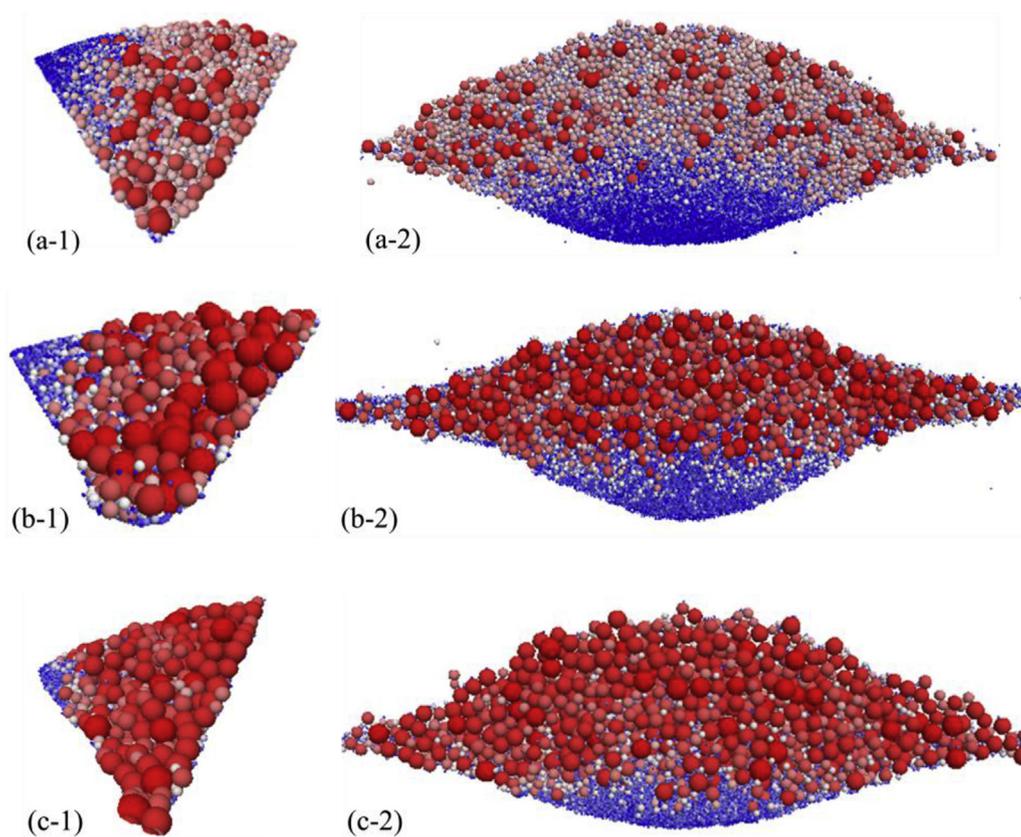


Fig. 12. Numerical simulation results of geometric form of debris accumulation body with three different gradations: (a) materials with mainly fine particles (a-1) side view (a-2) top view; (b) materials with even gradation (b-1) side view (b-2) top view; (c) materials with mainly coarse particles (c-1) side view (c-2) top view.

particles gather in advance on the opposite side of the valley, while small particles lag behind on the side of the landslide bank. At the same time, the shape and location of the boundary between large and small particles are also consistent.

Finally, it should be pointed out that based on the above laboratory model tests, the present work has provided an insight view on the movement process and accumulation characteristics of the landslide-debris flow in mountainous areas. However, the mechanism for the landslide-debris movement and accumulation is very complex, especially, if considering the size of the model tests, it is therefore impossible to perfectly restore the actual situation. In addition, there are still some problems to be explored in the future, such as the influence of valley morphology on the final deposit, size effect, and so on. At the same time, combining with the established numerical model, it will be worthwhile to conduct a further study on the mechanism of movement and accumulation of landslide-debris flow under the influence of different factors, e.g., a stream.

5. Conclusions

This paper simulates the start-up, migration and accumulation process of landslide-debris flow in mountainous area through indoor physical model test. Two factors, namely slope foot and debris particle gradation in the start-up area, are considered and the debris migration and accumulation process is simulated by PFC^{3D} to study the effects of both on the movement and accumulation of landslide-debris particles. The main conclusions are drawn as follows:

- (1) After collision and separation of landslide-debris particles during movement, obvious sorting phenomena occur during the accumulation process. Coarse particles are widely distributed in the front and surface of the deposit, and fine particles are widely distributed in the back and bottom of the deposit.
- (2) The starting angle of landslide-debris flow has a certain influence on the shape of the deposit. The larger the starting angle, the closer the deposit is to the opposite bank of the valley, and after collision between the coarse particles of the deposit and the opposite bank of the valley, the more obvious 'overturn' phenomenon occurs.
- (3) particle gradation has a significant impact on the morphology and distribution of debris deposit. With the increase of the proportion of coarse particles, the accumulation area of fine particles shrinks to the center of the rear edge, the shape of the deposit is more flat and uneven, the accumulation area is closer to the other side of the valley, and the angle of the accumulation area profile increases significantly.
- (4) Combining with the existing physical simulation experiments, PFC^{3D} is used to reproduce the model tests, and the numerical model which is in good agreement with the physical model tests is obtained, which lays a foundation for further study of the movement and accumulation characteristics of landslide-debris flow.

Declarations

Author contribution statement

Q.-Z., Zhang & Y. Chen: Conceived and designed the experiments.
 Q. Ping: Performed the experiments.
 Z.-J. Luo: Analyzed and interpreted the data.
 Z.-M. Shi: Contributed reagents, materials, analysis tools or data.
 Y.-Y. Zhou: Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Bagnold, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newton fluid under shear. *Proc. R. Soc. Lond.: Math. Phys. Sci.* 225, 49–63.
- Bi, Y.Z., Fu, Y.S., He, S.M., Wu, Y., 2015. Simulation of the whole process of Niumiangou creek rock avalanche triggered by the earthquake using a distinct element method. *Chin. J. Geol. Hazard Control* 26 (03), 17–25.
- Cao, Y.B., Dai, F.C., Xu, C., et al., 2011. Discrete element simulation of deformation and movement mechanism for tangjiashan landslide. *Chin. J. Rock Mech. Eng.* 30 (S1), 2878–2887.
- Chen, R.H., Kuo, K.J., Chen, Y.N., et al., 2011. Model tests for studying the failure mechanism of dry granular soil slopes. *Eng. Geol.* 119 (1), 51–63.
- Choi, C.E., Goodwin, G.R., Ng, C.W.W., et al., 2016a. Coarse granular flow interaction with slit structures. *Geotech. Lett.* 6 (4), 1–8.
- Choi, C.E., Ng, C.W.W., Goodwin, G.R., et al., 2016b. Flume investigation of the influence of rigid barrier deflector angle on dry granular overflow mechanisms. *Can. Geotech. J.* 53 (10), 1751–1759.
- Choi, C.E., Ng, C.W.W., Liu, H.M., et al., 2019. Interaction between dry granular flow and rigid barrier with basal clearance: analytical and physical modelling. *Can. Geotech. J.* published online.
- Crosta, G.B., Imposimato, S., Roddeman, D.G., 2006. *Continuum Numerical Modelling of Flow-like Landslides. Landslides from Massive Rock Slope Failure.* Springer Netherlands, pp. 211–232.
- Cui, P., Zhuang, J.Q., Chen, X.C., et al., 2010. Characteristics and countermeasures of debris flow in wenchuan area after the earthquake. *J. Sichuan Univ. (Eng. Sci. Ed.)* 42 (05), 10–19.
- Dai, F., Lee, C., Deng, J., et al., 2005. The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, southwestern China. *Geomorphology* 73 (3), 277–278.
- Evans, S.G., Hungr, O., Clague, J.J., 2001. Dynamics of the 1984 rock avalanche and associated distal debris flow on Mount Cayley, British Columbia, Canada; implications for landslide hazard assessment on dissected volcanoes. *Eng. Geol.* 61 (1), 29–51.
- Faug, T., 2015. Depth-averaged analytic solutions for free-surface granular flows impacting rigid walls down inclines. *Phys. Rev.* 92 (6), 062310.
- Faug, T., Gauer, P., Lied, K., et al., 2008. Overrun length of avalanches overtopping catching dams: cross-comparison of small-scale laboratory experiments and observations from full-scale avalanches. *J. Geophys. Res. Earth Surf.* 113 (F3).
- Faug, T., Naaim, M., Bertrand, D., et al., 2003. Varying dam height to shorten the run-out of dense avalanche flows: developing a scaling law from laboratory experiments. *Surv. Geophys.* 24 (5-6), 555–568.
- Faug, T., Naaim, M., Naaim-Bouvet, F., 2004. An equation for spreading length, center of mass and maximum run-out shortenings of dense avalanche flows by vertical obstacles. *Cold Reg. Sci. Technol.* 39 (2-3), 0–151.
- Hao, M.H., Xu, Q., Yang, L., Yang, X.G., Zhou, J.W., 2014. Physical modeling and movement mechanism of landslide-debris avalanches. *Chin. J. Rock Soil Mech.* 35 (S1), 127–132.
- Hao, M.H., Xu, Q., Yang, X.G., et al., 2015. Physical modeling tests on inverse grading of particles in high speed landslide debris. *Chin. J. Rock Mech. Eng.* 34 (03), 472–479.
- Huang, R.Q., 2009. Some catastrophic landslides since the twentieth century in the southwest of China. *Landslides* 6 (1), 69–81.
- Huang, Y., Cheng, H., Dai, Z., et al., 2014. SPH-based numerical simulation of catastrophic debris flows after the 2008 Wenchuan earthquake. *Bull. Eng. Geol. Environ.* 74 (4), 1137–1151.
- Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. *Landslides* 11 (2), 167–194.
- Hungr, O., Morgenstern, N.R., 1984a. Experiments on the flow behavior of granular materials at high velocity in an open channel. *Geotechnique* 34 (3), 405–413.
- Hungr, O., Morgenstern, N.R., 1984b. High velocity ring shear tests on sand. *Geotechnique* 34 (3), 415–421.
- Iverson, R.M., 2000. Landslide triggering by rain infiltration. *Water Resour. Res.* 36 (7).
- Iverson, R.M., 2005. Forecasting runout of rock and debris avalanches. *Landslides Massive Rock Slope Fail.* 49, 197–209.
- Iverson, R.M., George, D.L., Logan, M., 2016. Debris-flow run-up on vertical barriers and adverse slopes. *J. Geophys. Res. Earth Surf.* 121, 2333–2357.
- Iverson, R.M., Richard, M., 1997. The physics of debris flows. *Rev. Geophys.* 35 (3), 245.
- Iverson, R.M., Richard, M., 2015. Scaling and design of landslide and debris-flow experiments. *Geomorphology* 244, 9–20.
- Johnson, C.G., Kokelaar, B.P., Iverson, R.M., et al., 2012. Grain-size segregation and levee formation in geophysical mass flows. *J. Geophys. Res.* 117 (F1), F01032.

- Jop, P., Forterre, Y., Pouliquen, O., 2006. A constitutive law for dense granular flows. *Nature* 441 (7094), 727–730.
- Kokelaar, B.P., Graham, R.L., Gray, J.M.N.T., et al., 2014. Fine-grained linings of leveed channels facilitate runoff of granular flows. *Earth Planet. Sci. Lett.* 385 (1), 172–180.
- Li, T.H., Fan, X.Y., Jiang, Y.J., 2018. Influence of gradation on the impact effect of landslide debris flow. *Mt. Res.* 36 (02), 289–297.
- Li, T.H., Fan, X.Y., Jiang, Y.J., 2019. Numerical simulation study of solids segregation in landslide debris flow. *J. Southwest Univ. Sci. Technol.* 34 (01), 26–33.
- Li, X.L., Tang, H.M., Xiong, C.R., Lou, H.M., 2011. Numerical simulation of flow and deposit in process of rock avalanche. *J. Eng. Geol.* 19 (2), 168–175.
- Ng, C.W.W., Choi, C.E., Au-Yeung, S.C.H., et al., 2015. Flume investigation of landslide granular debris and water runoff mechanisms. *Géotech. Lett.* 5 (January–March), 28–32.
- Ng, C.W.W., Choi, C.E., Koo, R.C.H., et al., 2017a. Dry granular flow interaction with dual-barrier systems. *Géotechnique*, pp. 1–14.
- Ng, C.W.W., Choi, C.E., Liu, L.H.D., et al., 2017b. Influence of particle size on the mechanism of dry granular run-up on a rigid barrier. *Géotech. Lett.* 7 (1), 79–89.
- Ng, C.W.W., Choi, C.E., Cheung, D.K.H., et al., 2019a. Effects of dynamic fragmentation on the impact force exerted on rigid barrier: centrifuge modelling. *Can. Geotech. J.* 56 (9), 1215–1224.
- Ng, C.W.W., Choi, C.E., Goodwin, G.R., 2019b. Froude characterisation for single-surge unsteady dry granular flows: impact pressure and runoff height. *Can. Geotech. J.* published online.
- Pudasaini, S.P., Hsiau, S.S., Wang, Y.Q., et al., 2005. Velocity measurements in dry granular avalanches using particle image velocimetry technique and comparison with theoretical predictions. *Phys. Fluids* 17 (9), 1–10.
- Pudasaini, S.P., Wang, Y., Sheng, L.T., et al., 2008. Avalanching granular flows down curved and twisted channels: theoretical and experimental results. *Phys. Fluids* 20 (7), 073302–073312.
- Scheidt, C., McArdell, B.W., Rickenmann, D., 2014. Debris-flow velocities and super elevation in a curved laboratory channel. *Can. Geotech. J.* 52 (3), 305–317.
- Song, D., Ng, C.W.W., Choi, C.E., et al., 2017. Influence of debris flow solid fraction on rigid barrier impact. *Can. Geotech. J.* 54 (10), 1421–1434.
- Sulpizio, R., Castioni, D., Rodriguez-Sedano, L.A., et al., 2016. The influence of slope-angle ratio on the dynamics of granular flows: insights from laboratory experiments. *Bull. Volcanol.* 78 (11), 77.
- Tang, J.B., Hu, K.H., Zhou, G.D., et al., 2013. Debris flow impact pressure signal processing by the wavelet analysis. *J. Sichuan Univ.* 45 (1), 8–13.
- Uthi, S., Zhao, T., Houlsby, G.T., 2015. 3D DEM investigation of granular column collapse: evaluation of debris motion and its destructive power. *Eng. Geol.* 186, 3–16.
- Wang, J.C., Lu, K.L., Zhu, D.Y., 2017. Indoor modeling test for regularity of deposit position of landslide-debris avalanches. *J. Eng. Geol.* 25 (06), 1509–1517.
- Zhao, T., Dai, F., Xu, N.W., 2017. Coupled DEM-CFD investigation on the formation of landslide dams in narrow rivers. *Landslides* 1–13.
- Zhou, G.D., Ng, C.W., 2010. Dimensional analysis of natural debris flows. *Can. Geotech. J.* 47 (7), 719–729.
- Zhou, J.W., Cui, P., Fang, H., 2013. Dynamic process analysis for the formation of Yangjiagou landslide-dammed lake triggered by the Wenchuan earthquake. *Landslides* 10 (3), 331–342.