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Abstract

The basal friction coefficient is crucial to the flow characteristics of granular flow hazards, while fluctuating force is an effective feedback of the interaction between granular flows and the base and may affect variations in the basal friction coefficient. Flume-type physical model tests were used to clarify the flow characteristics of steady granular flows under different thicknesses. The basal tangential and normal forces were directly measured using a three-component force sensor, and the basal fluctuating force and basal friction coefficient were obtained. The results show that: (1) Granular flows exhibit obvious stratification characteristics under different thicknesses. When the granular flow thickness reaches 3 cm, the flow structure changes, with an interlocking structure forming among the bottom particles and promoting the occurrence of shear dilatancy; however, no interlocking structure or shear dilatancy is observed at thicknesses of 1 cm and 2 cm. (2) By normalizing the fluctuating force of the granular flow, it is found that both the normalized tangential and normal fluctuating forces decrease exponentially with increasing granular flow thickness, indicating that the intensity of the basal fluctuating force is directly related to the granular flow thickness. (3) As the granular flow thickness increases, the relationship between the basal fluctuating force and the basal friction coefficient changes from negative to positive correlation. In addition, increasing granular flow thickness can significantly enhance the collision frequency and intensity between particles, markedly increasing the dynamic friction force between particles while clearly weakening the dynamic friction force between particles and the base. The weakening of the dynamic friction force between particles and the base promotes the formation of interlocking structures among particles and induces shear dilatancy, ultimately leading to a significant reduction in the basal fluctuating force and basal friction coefficient of the granular flow.

Full Text

Study on the Basal Friction Coefficient of Steady Granular Flows under Different Thicknesses

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Abstract: The basal friction coefficient is crucial to the flow characteristics of granular-flow hazards, while fluctuating force is an effective feedback of the interaction between granular flow and the base and may influence changes in the basal friction coefficient. Inclined-chute physical model experiments were used to clarify the flow characteristics of steady granular flows under different thicknesses. The basal tangential and normal forces were directly measured using a three-component force sensor, and the basal fluctuating force and basal friction coefficient were obtained. The results show that: (1) Granular flows exhibit obvious stratification characteristics under different thicknesses. When the granular-flow thickness reaches 3 cm, the flow structure of the granular flow changes; an interlocking structure forms among the basal particles and promotes the occurrence of dilatancy. However, no interlocking structure or dilatancy is observed in granular flows with thicknesses of 1 cm and 2 cm. (2) By normalizing the fluctuating force of the granular flow, it is found that the normalized tangential and normal fluctuating forces both decrease exponentially with increasing granular-flow thickness, indicating that the strength of the basal fluctuating force is directly related to granular-flow thickness. (3) As granular-flow thickness increases, the relationship between the basal fluctuating force and the basal friction coefficient changes from negative correlation to positive correlation. Moreover, increasing granular-flow thickness can significantly enhance the frequency and intensity of collisions between particles, causing the dynamic friction between particles to increase markedly, while the dynamic friction between particles and the base weakens obviously. The weakening of dynamic friction between particles and the base promotes the formation of interlocking structures among particles and induces dilatancy, ultimately causing a significant reduction in the basal fluctuating force and basal friction coefficient of the granular flow.

Keywords: granular flow; flow characteristics; basal fluctuating force; basal friction coefficient; granular-flow thickness

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Landslides are widespread in the arid and semi-arid regions of China, especially in alpine canyon areas[1-2]. After a landslide occurs, the sliding mass usually becomes unstable under the control of internal and external dynamic geological processes. Through intense friction and collision, the rock mass undergoes fragmentation and moves in the form of a granular flow[3-4]. During the movement of a granular flow, interactions among its internal particles and between the particles and the base often lead to high-speed, long-runout motion, thereby causing greater casualties. Interactions among particles and between particles and the base are the key to explaining the flow characteristics and dynamic behavior of granular flows. However, their modes of action are difficult to observe in field investigations, which has also led to an insufficiently complete interpretation of the mechanisms of particle dynamics[5-8]. Therefore, further study of the interaction between granular flow and the basal layer is of great significance for revealing its dynamic characteristics and for risk assessment.

Scholars generally believe that collisions among particles during the movement of granular flows change their modes of motion, thereby altering the basal friction coefficient of the granular flow and affecting its flow characteristics[9-13]. Louge et al.[14], through low-angle inclined-chute experiments, found that particle collisions and enduring friction control the motion characteristics of granular flows; the random kinetic energy generated by interparticle collisions enhances particle motion and diffusion and bears part of the normal stress, thereby reducing the effective friction coefficient of the granular flow. Holyoake et al.[15] found experimentally that the nonuniformity of particle-flow velocity and the instability of the shear layer can induce phenomena such as longitudinal vortices inside the granular flow, and they suggested that this phenomenon increases the basal friction force of the granular flow. Brodu et al.[16], through numerical simulation, found that granular flows with larger masses form more complex internal structures during the stable-motion stage, producing "supporting flows" composed of secondary flows, particle clusters, and pore gases, thereby reducing the basal friction coefficient of the granular flow. Zhu et al.[17] found through experiments that under a condition with an angle of 25°, when the parti

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When the thickness of the granular flow increases to $3D \sim 4D$ (D is the particle diameter), collisions among particles intensify, and the mode of motion changes from a combination of rolling and sliding toward supported flow. A dilute granular-gas layer forms at the base, thereby reducing the effective friction coefficient of the granular flow.

The interaction between particles and the base also has a profound influence on the basal friction coefficient of the granular flow during motion[1]. The interaction forces between particles and the base include the sustained friction generated by particle sliding and the collisions between particles and the base. The former may be regarded as mean forces, reflecting the overall motion characteristics of the granular flow, including tangential and normal mean forces. Wang et al.[2], using the basal layer of the Yigong high-speed long-runout landslide in Bomi County, Tibet Autonomous Region, China, as the experimental material, carried out high-speed rotary shear tests of the basal layer under different shear rates and normal stresses, revealing that the equivalent basal friction coefficient of the basal layer weakens as shear rate and normal stress increase. The latter are fluctuating forces generated by instantaneous collisions between

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individual particles or particle clusters and the base[3], reflecting the local interaction between particles and the base, including tangential and normal fluctuating forces[4]. Miller et al.[5], through continuous shear tests on glass-bead particles, found that force chains play an important role in determining the overall basal-force distribution and fluctuations. Li et al.[6] found through chute tests that an increase in the content of coarse particles in the sliding mass produces larger normal fluctuating forces, thereby reducing the basal friction coefficient of the granular flow. Yu et al.[7], by directly measuring basal friction forces during granular-flow motion, found that the normal and tangential fluctuating forces at the base of the granular flow are negatively correlated with the basal friction coefficient, indicating that larger tangential fluctuating forces are conducive to particle propagation.

At present, studies of changes in the internal structure, mean forces, and fluctuating forces of granular flows mainly focus on granular-flow mass and particle size, while understanding of the influence of granular-flow thickness remains lacking. Roche et al.[8] measured the basal friction coefficient of granular material flowing on an inclined plane through physical model tests, and found that increasing the thickness of the granular flow reduces the basal friction coefficient. However, it remains unclear how changes in thickness cause changes in the internal structure of the granular flow and thereby influence the basal friction coefficient. Li et al.[9], Yu et al.[10], and Yu Xiao et al.[11], through chute tests, revealed the influence of basal fluctuating forces on the mobility of granular flows during flow, showing that there is a relationship between particle–base collision effects and the basal friction coefficient. However, their studies mainly focused on particle size and lacked consideration of thickness. Therefore, this study takes dry granular flows as the research object and uses granular-flow thickness as the experimental variable. Through chute-type physical model tests, it clarifies the flow characteristics and internal structural changes of granular flows of different thicknesses, as well as their relationships with basal fluctuating forces and the basal friction coefficient, with the aim of providing theoretical reference for research on granular-flow mechanisms in arid regions and new ideas for the prevention and control of geological hazards in arid regions.

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1 Experimental Design and Data Analysis

1.1 Test Apparatus and Similarity Ratio

An inclined chute device composed of an organic-glass base plate and side walls was fabricated, and the base was roughened for use in this experiment. The total length of the chute is 200 cm, the bottom width is 20 cm, and the inclination angle is adjustable within the range of $30^{\circ} \sim 40^{\circ}$. It was made with an aluminum-alloy frame. To facilitate monitoring of the motion state of the granular flow inside the chute, both the side walls and the bottom plate were made of transparent organic glass. The experimental particles were stored in advance in a rectangular material box at the top of the chute, with a length of 40 cm, width of 22 cm, and height of 40 cm; its maximum capacity was 35.2 L. The material box was equipped with a double-layer gate system. The inner gate layer, closer to the material box, could be used to preset the gate-opening height so as to control the thickness of the granular flow; the outer layer was an automatic release gate. At the start of the experiment, the button was activated, the outer gate automatically sprang open, and the particles were released into the flow-through region of the chute (Fig. 1).

The monitoring system consisted of two parts: a force-monitoring system and an image-monitoring system. The force-monitoring system consisted of a force plate (5.9 cm $\times$ 5.9 cm), a three-component force sensor, and a support. It was installed in the middle-lower part of the base plate, 1.7 m from the baffle of the material box, and could simultaneously measure tangential and normal forces. The sensor was a piezoresistive force sensor, model 9327C from Kistler, with a sensitivity of 0.01 N, a maximum measurable force of 50 N, and a data-acquisition frequency of 1 kHz. During the experiment, the release of the granular flow caused vibrations in the chute base, and such vibrations could introduce a certain error into the data collected by the force sensor. To minimize this error, while keeping the force plate flush with the base, a 0.5 mm gap was reserved to ensure that the three-component force sensor was relatively independent of the base. The gap was sealed with a thin polypropylene film to prevent fine particles from falling in. In this study, the sensor was calibrated with weights, so that the linear measurement error was no greater than 2%. The image-monitoring system consisted of two high-speed cameras, respectively

Visible labels in Fig. 1 include: material box; 40 cm; 40 cm; gate opening; 200 cm; Camera 1; Camera 2; force plate; basal normal force; basal tangential force; 20 cm; flow.

Figure 1. Schematic diagram of the chute test device

Fig. 1 Schematic diagram of chute test device

The motion process of the particle flow in the chute was monitored from directly above and from the side by the force-monitoring system. This measurement system can accurately and synchronously capture the key parameters required in this study.

The chute-type particle-flow model test must satisfy geometric similarity, kinematic similarity, and dynamic similarity. Among these, geometric similarity is determined by normalizing the model dimensions; dynamic similarity is studied between the physical model and the actual working condition using the Froude number, since gravity is the principal driving force; and kinematic similarity describes the motion characteristics of the particle flow, which is the focus of verification in this study. The Froude number is the ratio of inertial force to gravitational force and controls the force-related similarity in chute particle flows. In this study, a partial-similarity method

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was used for the model tests.

Kinematic and dynamic similarity:

$$(\mathrm{Fr})_{\mathrm{m}} = (\mathrm{Fr})_{\mathrm{p}} = \frac{v_{\mathrm{m}}}{\sqrt{g \times h_{\mathrm{m}}}} = \frac{v_{\mathrm{p}}}{\sqrt{g \times h_{\mathrm{p}}}} \tag{1}$$

where $(\mathrm{Fr})_{\mathrm{p}}$ and $(\mathrm{Fr})_{\mathrm{m}}$ are the Froude numbers of the prototype and the model, respectively; v_{p} is the prototype flow velocity ($\mathrm{m} \cdot \mathrm{s}^{-1}$); v_{m} is the model flow velocity ($\mathrm{m} \cdot \mathrm{s}^{-1}$); g is the gravitational acceleration ($\mathrm{m} \cdot \mathrm{s}^{-2}$); h_{p} is the prototype flow depth (m); and h_{m} is the model flow depth (m).

In the dimensionless equation, $(\mathrm{Fr})_{\mathrm{p}} = (\mathrm{Fr})_{\mathrm{m}}$. Assuming that the experimental model and the prototype are in the same gravitational field, the velocity scale and flow-depth scale can be calculated using the Froude number. The Froude number of the laboratory physical model test is approximately 3.1, corresponding to a prototype gully-type particle-flow event with a velocity close to $16.8\ \mathrm{m} \cdot \mathrm{s}^{-1}$ and a flow depth of about 3 m.

$$(\mathrm{Fr})_{\mathrm{m}} = (\mathrm{Fr})_{\mathrm{p}} = 3.1 \tag{2}$$

$$\gamma_{\mathrm{v}} = \frac{v_{\mathrm{p}}}{v_{\mathrm{m}}} = 7.74 \tag{3}$$

where γ_{v} is the flow-velocity similarity ratio.

Geometric similarity:

$$\gamma_{\mathrm{h}} = \frac{h_{\mathrm{p}}}{h_{\mathrm{m}}} = \gamma_{\mathrm{v}}^2 = 59.9 \tag{4}$$

where γ_{h} is the flow-depth similarity ratio.

1.2 Test Materials

In this study, medium-fine quartz sand with an average particle size of 0.32 mm was selected as the test material (Fig. 2a). The coefficient of nonuniformity of the quartz sand was 1.72, the coefficient of curvature was 1.05, and the cumulative amount of particles with sizes in the range of 0.1-0.4 mm was 83.55% (Fig. 2b). The dry density of the quartz sand was 2.69 $g \cdot cm^{-3}$, the internal friction angle was 30.5°, and the specific surface area was 110 $m^2 \cdot kg^{-1}$. Direct shear tests were used to obtain a friction coefficient of 0.547 between the quartz sand and the rough base. Before each test, the granular material was pre-dried to prevent particle agglomeration, so that it was close to its original particle-size state, and was then placed into the hopper.

1.3 Experimental Design

To clarify the influence of particle-flow thickness on the flow characteristics of particle flows, five particle-flow thickness groups were designed in this experiment, namely 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm. To ensure data reliability and repeatability, each group of tests was conducted three times, and the final values used were the averages.

1.4 Data Collection and Analysis

Through analysis of the test results, the kinematic and dynamic characteristics of the particle flows in each test group were studied, including the flow characteristics and flow velocity of the particle flow, the tangential and normal forces at the particle-flow–base-plate interface, and fluctuations in the basal force during particle-flow motion.

1.4.1 Particle-Flow Velocity Analysis To quantify the velocity field of the particle flow, particle image velocimetry (PIV) was used to process the continuous image frames captured by the high-speed camera; this technique is often used in particle-flow experiments

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. The PIV analysis method solves two consecutive images

(a) Test material

(b) Particle-size distribution curve

Vertical axis in (b): Cumulative percentage content / %

Horizontal axis in (b): Particle diameter / 10^{-6} m

Size-class labels in (b): silt; sand; medium; coarse; fine; medium; coarse

Fig. 2 Test materials and particle size distribution curve the cross-correlation function to calculate pixel displacement. The region of interest (ROI) is divided into sub-grids or interrogation windows. In this study, PIV processing was performed using the fast Fourier transform (FFT) algorithm included in the MATLAB PIVlab toolbox[^30]. The final results were obtained through processes including loading the image sequence, preprocessing (such as smoothing and denoising), windowed processing, frequency-domain analysis, and data post-processing (such as filtering and interpolation). Compared with traditional methods, this approach has higher accuracy and faster efficiency.

1.4.2 Acquisition of Bed Forces In this study, a three-component force sensor was used to directly obtain the bed shear force (flow direction) and normal force, in order to characterize the interaction between the particle flow and the bed[^12,^31]. Under different test conditions, the bed friction coefficient of the particle flow was also used to evaluate the influence of particle-flow thickness on the interaction between the particle flow and the bed[^12–^13]. The calculation formulas are as follows:

$$\mu = \frac{F_x}{F_z} \tag{5}$$

$$F_i' = F_i - \overline{F_i} \tag{6}$$

where μ is the bed friction coefficient of the particle flow; F_x is the bed shear force of the particle flow (N); F_z is the bed normal force of the particle flow (N); F_i' is the bed fluctuating force (N); F_i is the instantaneous bed force (N); $\overline{F_i}$ is the mean bed force (N); and i denotes the force component. The time series of mean force was obtained by automatically calculating the mean force over 0.02 s intervals under all test conditions. Then, the bed-force fluctuation value was determined by subtracting the mean bed-force time series from the original signal.

To further reveal the relationship between bed-force fluctuations and particle-flow dynamics, a dimensionless parameter $\Delta F_i/\overline{F_i}$ is introduced:

$$\frac{\Delta F_i}{\overline{F_i}} = \frac{\sqrt{\frac{1}{n}\sum_1^n \left(F_i' - \overline{F_i}\right)^2}}{\overline{F_i}} \tag{7}$$

where $\Delta F_i/\overline{F_i}$ is the normalized fluctuating force of the particle flow; ΔF_i is the overall standard deviation of the repeated force data; and n is the number of signal measurements in the experiment.

2 Results and Analysis

2.1 Flow Characteristics of the Particle Flow

The internal structural sections of particle flows with thicknesses of 1 cm, 3 cm, and 5 cm are shown in Fig. 3. Under the same particle-flow thickness, the interval between adjacent times is 20 ms. The study found that, in particle flows of different thicknesses, the modes of particle motion differ significantly.

When the particle-flow thickness is 1 cm (Fig. 3a–c), particles near the top (P1 particles) mainly undergo interparticle collision and overturning; particles near the middle (P2 particles) mainly move in the form of overturning; and particles near the bottom (P3 particles) mainly undergo rolling of themselves. Within the same time interval, the motion distance of P1 particles is much greater than that of P2, and the motion distance of P2 particles is much greater than that of P3 particles.

When the particle-flow thickness is 3 cm (Fig. 3d–f), collisions and overturning among particles near the top (P1 particles) become more intense, and the range of particle motion expands significantly. As the particle-flow motion time increases from 0 ms to 40 ms, particles (P2 particles) move downward. Collisions among particles near the middle (P3 particles) are significantly enhanced, as manifested by the fact that, within the same time interval (relative 0–40 ms), the displacement of P3 particles is much greater than that of the middle particles (P2 particles) under the 1 cm thickness condition (Fig. 3a–c). Particles near the bottom (P4 particles) are still dominated by rolling, but the rolling speed is extremely slow; as time increases (relative 0–40 ms), the particles are nearly stationary.

It is noteworthy that when the particle-flow thickness is 5 cm (Fig. 3g–i), an obvious wave phenomenon appears at the top of the particle flow.

2.2 Analysis of Particle-Flow Velocity

The side-view high-speed photographs of the particle flow were processed using PIV technology, and velocity-distribution cloud maps of particle flows with different thicknesses were obtained (Fig. 4). The field of view is 4 cm × 6 cm, and the results are averaged from images processed over 30 frames, with an interval of 0.67 ms between frames. Previous studies have shown that the flow velocity of a particle flow increases significantly with increasing particle-flow thickness and decreases with depth[^22]. From the sectional velocity cloud maps obtained by image processing in this study, it can be seen that when the particle-flow thicknesses are 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm, the maximum velocities all occur at the surface, with values of 0.40 $m \cdot s^{-1}$, 0.70 $m \cdot s^{-1}$, 0.90 $m \cdot s^{-1}$, 0.95 $m \cdot s^{-1}$, and 0.98 $m \cdot s^{-1}$, respectively; the minimum motion velocities all occur at the bottom, with values of 0.05 $m \cdot s^{-1}$, 0.10 $m \cdot s^{-1}$, 0.13 $m \cdot s^{-1}$, 0.15 $m \cdot s^{-1}$, and 0.16 $m \cdot s^{-1}$, respectively. The variation of velocity along the direction of motion is not obvious. When the particle-flow thickness is 4 cm or 5 cm, banded low-velocity zones appear in the particle flow near the surface[^12], and negative arrows appear around the banded low-velocity zones (Fig. 4d–e), indicating that particles at the front hinder the motion of particles behind them, thereby reducing the local particle motion velocity.

2.3 Bed-Force Characteristics of the Particle Flow

The bed force of a particle flow refers to the shear force and normal force generated when particles interact with the bottom boundary during flow, and it can reflect the interaction between particles at the bottom of the particle flow and the bed. The temporal variations of bed shear force and normal force throughout the flow process of particle flows with different thicknesses are shown in Fig. 5.

When the head of the flow reaches the force-measuring plate, the bed shear force and normal force begin to increase. Subsequently, as the middle part of the flow arrives, the shear force and normal force increase rapidly and synchronously to peak values within 2–3 s, and remain in this state for a period of time. This state can be regarded as the stage in which the flow velocity and thickness of the particle flow at the force-measuring plate have reached stability and are in a relatively stable phase[^12,^15]. As the tail⋯

(a) Particle-flow thickness 1 cm (relative time 0 ms)
(b) Particle-flow thickness 1 cm (relative time 20 ms)
(c) Particle-flow thickness 1 cm (relative time 40 ms)

(d) Particle-flow thickness 3 cm (relative time 0 ms)
(e) Particle-flow thickness 3 cm (relative time 20 ms)
(f) Particle-flow thickness 3 cm (relative time 40 ms)

(g) Particle-flow thickness 5 cm (relative time 0 ms)
(h) Particle-flow thickness 5 cm (relative time 20 ms)
(i) Particle-flow thickness 5 cm (relative time 40 ms)

Note: The red dashed lines and yellow dashed lines are the boundaries between different particle layers.

Fig. 3 Sectional diagram of the internal structure of particle flows of different thicknesses

Upon the arrival of the flow, the tangential force and normal force decrease rapidly and finally tend toward 0. This indicates that, after flowing out of the gate, the particle flow undergoes a thickness-increasing stage, a thickness-stable stage, and a thickness-decreasing stage. It is worth noting that, starting from 3 cm, the tangential-force and normal-force curves in the stable stage both show a slight rise, reflecting that the thickness of the middle flow gradually becomes unstable. During the experiment, the instant at which the particle flow is released produces a certain vibration effect on the inclined chute, causing deviations in the records of the highly sensitive sensors. As a result, at 3 cm and 4 cm, the basal tangential force exhibits an anomalous negative value for a period before rising, but this has no substantial effect on the experimental results.

2.4 Fluctuation characteristics of basal forces

Basal-force fluctuation refers to the fluctuation amplitude of the tangential force and normal force exerted by the bottom of the particle flow on the force-measuring plate relative to their mean values

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. It can be used to reflect the intensity of the mutual collisions between particles and the base. The fluctuation characteristics of the tangential force and normal force on the force-measuring plate for particle flows of different thicknesses are shown in Fig. 6. As the thickness of the particle flow increases, the fluctuation amplitudes of both the basal tangential force and the basal normal force decrease, indicating that increasing the particle-flow thickness limits the collision interaction between particles and the base and reduces the collision energy between particles and the base. This may be because, when the particle-flow thickness increases, the packing density of the particles increases, the rolling of bottom particles tends to stop (Fig. 3b), and the collisions between particles and the base weaken. To further discuss the influence of particle-flow thickness on basal fluctuating forces, the basal tangential and normal fluctuating forces will subsequently be normalized in the discussion section.

2.5 Characteristics of the basal friction coefficient in the stable-thickness stage

The basal friction coefficient is an important parameter for evaluating the strength of friction between the particle flow and the base, and is defined as the ratio of tangential force to normal force. From the basal tangential force and normal force, the variation with time of the basal friction coefficient for particle flows of different thicknesses is obtained (Fig. 7). Its development pattern is basically the same as the time-dependent development patterns of the tangential force and normal force. The difference is that, because the decreasing rates of the tangential force and normal force differ, the basal friction coefficient of the tail flow shows a sudden increase; at 3 cm and 5 cm, the maximum value can reach four times that in the stable stage. The negative values of shear force mentioned above cause the basal friction coefficient under the 3 cm and 4 cm conditions to exhibit an anomalous negative value for a period during the rising stage, but this has no effect on the experimental results.

Fig. 4 Side views of particle flows of different thicknesses and the corresponding velocity distribution

- (a) 1 cm
  Velocity / m · s^{-1}: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40
- (b) 2 cm
  Velocity / m · s^{-1}: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70
- (c) 3 cm
  Velocity / m · s^{-1}: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90
- (d) 4 cm
  Low-speed zone
  Velocity / m · s^{-1}: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90
- (e) 5 cm
  Low-speed zone
  Velocity / m · s^{-1}: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90

Note: Black arrows indicate velocity vectors; red arrows indicate the supplemented missing velocity vectors.

Fig. 5 Relationship between the base force of particle flows of different thicknesses and time

Legend: red line—tangential force; blue line—normal force; black line—mean force.

- (a) 1 cm
  Rising stage; stable stage; declining stage
  y-axis: base force / N
  x-axis: time / s
- (b) 2 cm
  Rising stage; stable stage; declining stage
  y-axis: base force / N
  x-axis: time / s
- (c) 3 cm
  Rising stage; stable stage; declining stage
  y-axis: base force / N
  x-axis: time / s
- (d) 4 cm
  Rising stage; stable stage; declining stage
  y-axis: base force / N
  x-axis: time / s
- (e) 5 cm
  Rising stage; stable stage; declining stage
  y-axis: base force / N
  x-axis: time / s

Fig. 6 Relationship between base fluctuation force of particle flows of different thicknesses and time

Legend: red—tangential fluctuating force; blue—normal fluctuating force.

- **(a) 1 cm**
  Vertical axis: base fluctuation force/N; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(b) 2 cm**
  Vertical axis: base fluctuation force/N; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(c) 3 cm**
  Vertical axis: base fluctuation force/N; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(d) 4 cm**
  Vertical axis: base fluctuation force/N; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(e) 5 cm**
  Vertical axis: base fluctuation force/N; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.

Fig. 7 Relationship between base friction coefficient of particle flows of different thicknesses and time

Legend: blue—base friction coefficient; black—average value.

- **(a) 1 cm**
  Vertical axis: base friction coefficient; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(b) 2 cm**
  Vertical axis: base friction coefficient; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(c) 3 cm**
  Vertical axis: base friction coefficient; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(d) 4 cm**
  Vertical axis: base friction coefficient; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.
- **(e) 5 cm**
  Vertical axis: base friction coefficient; horizontal axis: time/s.
  Stages: rising stage; stable stage; descending stage.

To avoid, as far as possible, uncertainty caused by errors in the experimental apparatus and by drastic changes in the structure of the tail flow, this study selected the time series of the base friction coefficient during the stable stage.

In earlier research on the base friction coefficient, Roche et al.[12] found that the base friction coefficient was negatively correlated with flow thicknesses of 2 cm, 4 cm, and 6 cm. On the basis of Roche' s work, this study further investigates the relationship between the two.

The base friction coefficient first increased and then decreased as the particle-flow thickness increased (Fig. 8). When the particle-flow thickness increased from 1 cm to 2 cm, the base friction coefficient rose from 0.68 to 0.84, indicating that, at this stage, the dynamic friction between the particles and the base was enhanced, leading to greater energy dissipation during motion. When the thickness increased to 3 cm, the base friction coefficient rapidly decreased to 0.72, indicating that a greater particle-flow thickness instead weakened the base friction coefficient of the particle flow. This phenomenon suggests that when the particle-flow thickness reaches 3 cm, the mode of motion among particles may change, thereby causing changes in the internal structure and affecting the contact mode between the basal particles and the base, ultimately weakening the base friction coefficient. The influence of the internal structure of the particle flow on its dynamic characteristics and on the base friction coefficient will be further analyzed in the discussion section.

Fig. 8 Relationship between the base friction coefficient and particle-flow thickness during the thickness-stabilized stage
Fig. 8 Relationship between the base friction coefficient and particle flow thickness during the thickness stabilization stage

3 Discussion

3.1 Influence of particle-flow thickness on flow characteristics

To obtain a comprehensive understanding of the dynamic characteristics of particle flow, the first point of concern is the change in flow structure during its motion. According to the particle-flow motion images and the PIV analysis results, and following the classification of Li Kun et al.[32] and Duan Jian et al.[33], the particle flow in this study is divided from bottom to top into a quasi-stationary layer, a dense layer, and an inertial layer; an overview of each layer is shown in Table 1. Among them, the quasi-stationary layer has high particle density and low velocity; the inertial layer has low particle density and high velocity; and the particle density and velocity of the dense layer lie between those of the quasi-stationary layer and the inertial layer (Fig. 9).

The above experimental results indicate that particle-flow thickness is an important factor affecting the flow characteristics of particle flow. During particle-flow motion, owing to the action of the normal force, the interparticle voids in the quasi-stationary layer and dense layer are small; the particles are in close contact and form force chains. During the motion of a particle flow with a thickness of 1 cm, the force chains persist for a relatively short time, and fracture and reorganization occur frequently; collisions between particles and the base are frequent, and the contact between particles and the base is dominated by point contact.

When the particle-flow thickness reaches 3 cm, the normal force increases and strengthens the interlocking force between the basal particles and the rough base. The duration of the force chains among basal particles becomes longer, and fracture and reorganization are suppressed. Particle rolling slows down, the particles in the quasi-stationary layer tend to become stationary[34], and the contact mode transitions from point contact to surface contact. The velocity of particles in the dense layer increases from 0.15 $m \cdot s^{-1}$ to 0.35 $m \cdot s^{-1}$; collisions among particles begin to become intense, the dynamic friction among particles increases, and evident dilatancy begins to appear on the shear plane. Davies[35], in his study, considered that a high velocity at the base of a debris flow would intensify particle collisions and produce dilatancy. This study further identifies the cause of the occurrence of dilatancy. As the particles in the quasi-stationary layer tend to remain stationary, some particles at the bottom of the dense layer can, to the greatest extent, be joined together with concave–convex pores,

Table 1 Overview of the quasi-stationary layer, dense layer, and inertial layer
Tab. 1 Overview of the quasi-stationary layer, dense layer, and inertial layer

Particle-flow thickness / cm	Quasi-stationary layer: maximum flow velocity / $m \cdot s^{-1}$	Quasi-stationary layer: flow characteristics	Dense layer: maximum flow velocity / $m \cdot s^{-1}$	Dense layer: flow characteristics	Inertial layer: maximum flow velocity / $m \cdot s^{-1}$	Inertial layer: flow characteristics
1	0.05	Collisions between particles and the base are relatively frequent	0.15	Interparticle motion is dominated by rolling	0.40	Interparticle motion is dominated by rolling and collisions

Particle-flow thickness / cm	Quasi-stationary layer: maximum flow velocity / $m \cdot s^{-1}$	Quasi-stationary layer: flow characteristics	Dense layer: maximum flow velocity / $m \cdot s^{-1}$	Dense layer: flow characteristics	Inertial layer: maximum flow velocity / $m \cdot s^{-1}$	Inertial layer: flow characteristics
2	0.10	Contact between particles and the base changes from point to surface	0.25	Interparticle motion is dominated by rolling	0.70	Interparticle motion is dominated by rolling and collisions
3	0.13	Particle motion tends to become stationary	0.35	Interparticle collisions intensify, and dilatancy appears	0.90	Interparticle collisions become more intense, and surface fluctuations begin to appear
4	0.15	Particle motion tends to become stationary	0.38	The amplitude of interparticle collisions increases slightly	0.95	Surface fluctuations intensify

Particle-flow thickness / cm	Quasi-stationary layer: maximum flow velocity / $m \cdot s^{-1}$	Quasi-stationary layer: flow characteristics	Dense layer: maximum flow velocity / $m \cdot s^{-1}$	Dense layer: flow characteristics	Inertial layer: maximum flow velocity / $m \cdot s^{-1}$	Inertial layer: flow characteristics
5	0.16	Particle motion tends to become stationary	0.40	The amplitude of inter-particle collisions increases slightly	0.98	Surface fluctuations intensify

(a) 1 cm

- Base
- Force-chain formation
- Force-chain release

(b) 3 cm

- Surface fluctuation
- Dilatancy
- Longitudinal diffusion of particles
- Onset of saltation
- Saltating-layer particles
- Particle collision
- Dilatancy

(c) 5 cm

- Surface fluctuation
- Intensified collisions
- Particles rise
- Particle saltation
- Particles fall
- Saltating-layer particles
- Dilatancy

Particle velocity: slow → fast

Legend: inertial state (layer); dense state (layer); quasi-static state (layer); base (particles); force chains; interlocking structure; collisions between particles; displaced particles and direction.

Fig. 9 Schematic diagrams of the flow characteristics of particle flows of different thicknesses

During motion, these particles have difficulty undergoing rotational rolling and form an interlocking structure (Fig. 9b). On this basis, the increase in particle velocity enables the particles behind them to use this structure as a point of force application and saltate forward; the particles change from a low-potential-energy state to a high-potential-energy state, thereby producing dilatancy. During saltation, high-speed particles dissipate less energy and collide with the particles above, thereby affecting collisions among particles in the inertial layer. Under the combined influence of the intense collisions among the inertial-layer particles themselves and the particles in the dense layer, fluctuations begin to appear on the surface of the inertial layer (Fig. 9b).

As the thickness of the particle flow increases to 5 cm, no major change occurs in the internal structure of the particle flow; rather, collisions among particles in the inertial layer become more intense, and the surface fluctuations of the particle flow caused by particles rising and falling after collision become more pronounced (Fig. 9c). The normal and tangential forces of the particle flow begin to increase during the stage of stable thickness, which also demonstrates that the particle-flow thickness begins to become unstable (Fig. 5d–e). This indicates that when the velocity during particle-flow motion reaches a certain threshold, the instability of the flow dynamics leads to destruction and reconstruction of the internal particle structure, shifting toward a state dominated by inertial forces

⋯random motion[36]; the collision frequency of the particles increases, and turbulence ultimately forms in the inertial layer.

3.2 Relationship between Basal Fluctuation Force and Basal Friction Coefficient

Fluctuation force generally originates from interactions and collisions between particles and the base. Collisions disturb the particles on the base or cause them to oscillate; during this process, particle kinetic energy is converted into fluctuation kinetic energy. For example, in studies of dynamic particle fragmentation, Wang Yufeng et al.[37–38] found that frequent collisions occurred between the sliding body and the underlying sliding surface, causing the kinetic energy of the high-speed sliding body to be continuously converted into fluctuation energy, so that the sliding surface was subjected to fluctuation forces of varying intensity. Moreover, such relatively high-intensity fluctuation forces are often related to the basal friction coefficient. For instance, by directly measuring the basal friction force during the movement of granular flows, Yu et al.[13] found that the normal and tangential fluctuation forces at the base of a granular flow were negatively correlated with the basal friction coefficient, indicating that a larger tangential fluctuation force is conducive to particle propagation.

To further reveal the relationship between basal fluctuation force and the basal friction coefficient, this study calculated the normalized standard deviation of the fluctuation force (Eq. 7). It can be observed that both the normalized tangential and normal fluctuation forces decrease exponentially as particle-flow thickness increases, indicating that the magnitude of basal fluctuation force is directly related to particle-flow thickness (Fig. 10). When particle-flow thickness increases from 1 cm to 2 cm, both the normalized tangential and normal fluctuation forces show a cliff-like decline. When particle-flow thickness continues to increase to 3–5 cm, the decrease in both normalized tangential and normal fluctuation forces becomes smaller, suggesting that a thickness of 2 cm is an important threshold for particle–base collisions. This indicates that the smaller the particle-flow thickness, the more frequent the reorganization and rupture of interparticle force chains, the stronger the collisions between particles and the base, and the greater the influence of fluctuation force on the overall motion. It should be noted that the basal tangential fluctuation force is always greater than the normal fluctuation force, indicating that tangential collisions are more significant, and that the tangential fluctuation force along the flow direction has a greater influence on the flow characteristics of granular flows than the normal fluctuation force.

The relationship between normalized fluctuation force and the basal friction coefficient shows that, when the particle-flow thickness is 1–2 cm, the basal friction coefficient increases as the normalized fluctuation force decreases; the basal friction coefficient is negatively correlated with both the normalized tangential and normal fluctuation forces (Fig. 11), which is consistent with the conclusion of Yu et al.[13] This indicates that, at this stage, the reduction in collisions between particles and the base enhances the basal friction coefficient between particles and the base. This may be because, as particle-flow thickness increases, the rupture and reorganization of force chains are suppressed, causing the particle–base contact mode to change from point contact to surface contact. The collision effect is weakened, the dynamic friction between the quasi-static layer and the base is enhanced, and the basal friction coefficient increases. This shows that, at this stage, rupture and reorganization of force chains are the main factors by which basal fluctuation force in granular flows affects the basal friction coefficient.

When particle-flow thickness continues to increase to 3–5 cm, the basal friction coefficient of the granular flow decreases as the normalized fluctuation force decreases, and the two show a positive correlation; this is a point worthy of attention (Fig. 11). Combined with the above study of granular-flow characteristics, it can be inferred that the enhancement of interparticle collision motion caused by increasing velocity, together with interparticle dilatancy caused by the emergence of an interlocking structure, may play a greater role in reducing the basal friction coefficient. Gou et al.[39] and Zhang et al.[40] both confirmed experimentally the influence of velocity on the basal friction coefficient. Gou et al.[39] found through experiments that when the shear rate applied to granular materials is greater than 0.1 $m \cdot s^{-1}$, the friction coefficient between particles and the base decreases sharply as velocity increases; Zhang et al.[40] used a thermo-poro-mechanical model to predict the transition of large landslides from creep to rapid motion, and found that the basal···

Fig. 10 Relationship between normalized fluctuation force and particle-flow thickness

Figure labels: y-axis, normalized fluctuation force; x-axis, particle-flow thickness/cm; legend, normalized tangential fluctuation force; normalized normal fluctuation force.

Fig. 11 Relationship between basal friction coefficient and normalized fluctuation force

Figure labels: y-axis, basal friction coefficient; x-axis, normalized fluctuation force; legend, normalized tangential fluctuation force; normalized normal fluctuation force.

The basal friction coefficient increases with increasing velocity below the critical velocity ($0.04\ m \cdot s^{-1}$), and decreases with increasing velocity after exceeding the critical velocity. At this stage, contact between particles in the quasi-static layer and the base is dominated by surface contact, and the dynamic friction force tends to reach its maximum. Short-duration collisions occur frequently between particles in the dense layer and the inertial layer, causing the collision-dominated dynamic friction between particles to increase significantly. Particles at the bottom of the dense layer also frequently flip upward using interlocked particles as pivots and undergo shear dilation. Finally, due to the influence of shear dilation in the upper part, the transfer of upper kinetic energy received by bottom particles decreases, and more kinetic energy is consumed in collisions among upper particles, thereby dispersing stress concentration. The adhesion between the quasi-static layer and the base decreases, leading to weakened collision and friction interactions between the particles and the base; consequently, both the basal fluctuation force and the basal friction coefficient decrease.

3.3 Comparison of Differences in Friction Coefficients under Different Tests

In this study, at an inclination angle of 38°, the basal friction coefficient of the particle flow obtained through the physical model tests reached a maximum of 0.84 and a minimum of 0.68, while the particle basal friction coefficient obtained through the direct shear test was 0.547. Combining this with the free-flow process of the experimental particle flow, it can be found that when the particle flow moves over a rough sliding surface and the thickness increases to 2 cm, particles in the quasi-static layer tend to become stationary; thereafter, the particle flow as a whole moves forward by rolling over this layer. As described above, because the particles in the dense layer and those in the quasi-static layer have similar particle sizes, some particles on the shear plane can interlock to the greatest extent with concave-convex voids to form an interlocking structure, providing a relatively large biting force. These particles are difficult to rotate and roll during motion, thereby providing favorable force-bearing points for the particles covering them, enabling the particles to accumulate a certain amount of strain energy and bear greater shear force. Therefore, a relatively large tangential force is required before particles near the shear plane can be displaced. In the direct shear test, however, the sand in the bottommost layer is very prone to rotational sliding during shearing; the particle structure near the shear plane changes continuously, causing particles on the shear plane to undergo continuous displacement even under a relatively small tangential force.

In summary, particle displacement and structural changes near the shear plane greatly affect the basal friction coefficient of the particle flow.

4 Conclusions

(1) When the particle-flow thickness reaches 3 cm, the dynamic friction force of particles in the quasi-static layer on the base tends to reach its maximum. The particles at the bottom of the dense layer are fully interlocked with the voids in the quasi-static layer, making rotational rolling difficult and forming an interlocking structure. This structure promotes shear dilation and indirectly affects the motion characteristics of the dense layer and the inertial layer.

(2) Both the normalized tangential and normal fluctuation forces decrease exponentially with increasing particle-flow thickness, indicating that the intensity of fluctuation force is directly related to thickness. Among them, tangential collisions are more intense, indicating that the influence of tangential fluctuation force on particle-flow mobility is greater than that of normal fluctuation force.

(3) When the particle-flow thickness is 1–2 cm, the basal friction coefficient increases as the normalized fluctuation force decreases, and it is negatively correlated with both tangential and normal fluctuation forces. When the particle-flow thickness is 3–5 cm, the basal friction coefficient decreases as the normalized fluctuation force decreases, and the two are positively correlated. When the particle-flow thickness reaches 3 cm, the enhanced collision among particles in the dense layer and the interparticle shear dilation caused by the interlocking structure play a major role in reducing the basal friction coefficient.

References (References)

[1] Zhang Xiaoming, Su Xing, Zhang Jun, et al. Spatiotemporal variation and prediction of habitat quality in the Tongwei landslide area of Gansu Province

based on the PLUS-InVEST model[J]. Arid Land Geography, 2025, 48(7): 1220-1232. [Zhang Xiaoming, Su Xing, Zhang Jun, et al. Spatiotemporal variation and prediction of habitat quality in Tongwei landslide area of Gansu Province based on PLUS-InVEST model[J]. Arid Land Geography, 2025, 48(7): 1220-1232.]

[2] Zhao Guorong, Li Wanzhi, Liu Bing, et al. Characteristics of rainfall-type landslide disasters in eastern Qinghai and analysis of their causing rainfalls[J]. Arid Land Geography, 2025, 48(4): 632-639. [Zhao Guorong, Li Wanzhi, Liu Bing, et al. Characteristics of rainfall-type landslide disasters in eastern Qinghai and analysis of their causing rainfalls[J]. Arid Land Geography, 2025, 48(4): 632-639.]

[3] Davies T, Mcsaveney M. Mobility of long-runout rock avalanches[M]. Cambridge: Cambridge University Press, 2012: 50-58.

[4] Hungr O, Leroueil S, Picarelli L. The varnes classification of landslide types, an update[J]. Landslides, 2014, 11(2): 167-194.

[5] Liang Shichuan, Qiao Hua, Lü Dong, et al. Distribution characteristics and main controlling factors of geohazards in Ili Valley[J]. Arid Land Geography, 2023, 46(6): 880-888. [Liang Shichuan, Qiao Hua, Lü Dong, et al. Distribution characteristics and main controlling factors of geohazards in Ili Valley[J]. Arid Land Geography, 2023, 46(6): 880-888.]

[6] Bartali R, Nahmad-Molinari Y, Rodriguez-Liñán G M, et al. Gravity-driven monodisperse avalanches: Inertial- to frictional-dominated flow[J]. Rock Mechanics and Rock Engineering, 2020, 53(8): 3507-3520.

[7] Delannay R, Valance A, Mangeney A, et al. Granular and particle-laden flows: From laboratory experiments to field observations[J]. Journal of Physics D: Applied Physics, 2017, 50(5): 053001, doi: 10.1088/1361-6463/50/5/053001.

[8] Wang Y F, Xu Q, Cheng Q G, et al. Spreading and deposit characteristics of a rapid dry granular avalanche across 3D topography: Experimental study[J]. Rock Mechanics and Rock Engineering, 2016, 49(11): 4349-4370.

[9] de Blasio F V, Elverhøi A. A model for frictional melt production beneath large rock avalanches[J]. Journal of Geophysical Research:

Earth Surface, 2008, 113(F2): F02014, doi: 10.1029/2007JF000867.

[10] Dent J D, Burrell K J, Schmidt D S, et al. Density, velocity and friction measurements in a dry-snow avalanche[J]. Annals of Glaciology, 1998, 26: 247-252.

[11] Forterre Y, Pouliquen O. Flows of dense granular media[J]. Annual Review of Fluid Mechanics, 2008, 40(1): 1-24.

[12] Roche O, van den Wildenberg S, Valance A, et al. Experimental assessment of the effective friction at the base of granular chute flows on a smooth incline[J]. Physical Review E, 2021, 103(4): 042905, doi: 10.1103/PhysRevE.103.042905.

[13] Yu X, Wang D P, He S M, et al. Experimental determination of basal gas pressure and effective coefficient of friction for dry granular flow[J]. Acta Geotechnica, 2023, 18(7): 3889-3904.

[14] Louge M Y, Keast S C. On dense granular flows down flat frictional inclines[J]. Physics of Fluids, 2001, 13(5): 1213-1233.

[15] Holyoake A J, McElwaine J N. High-speed granular chute flows[J]. Journal of Fluid Mechanics, 2012, 710: 35-71.

[16] Brodu N, Delannay R, Valance A, et al. New patterns in high-speed granular flows[J]. Journal of Fluid Mechanics, 2015, 769: 218-228.

[17] Zhu Y, Delannay R, Valance A. High-speed confined granular flows down smooth inclines: Scaling and wall friction laws[J]. Granular Matter, 2020, 22(4): 82, doi: 10.1007/s10035-020-01053-7.

[18] Liu C H, Nagel S R, Schecter D A, et al. Force fluctuations in bead packs[J]. Science, 1995, 269(5223): 513-515.

[19] Wang Y F, Dong J J, Cheng Q G. Velocity-dependent frictional weakening of large rock avalanche basal facies: Implications for rock avalanche hypermobility?[J]. Journal of Geophysical Research: Solid Earth, 2017, 122(3): 1648-1676.

[20] Wang Y F, Dong J J, Cheng Q G. Normal stress-dependent frictional weakening of large rock avalanche basal facies: Implications for the rock avalanche volume effect[J]. Journal of Geophysical Research: Solid Earth, 2018, 123(4): 3270-3282.

[21] Artoni R, Richard P. Effective wall friction in wall-bounded 3D dense granular flows[J]. Physical Review Letters, 2015, 115(15): 158001, doi: 10.1103/PhysRevLett.115.158001.

[22] Yu X, Wang D P, Chen Z, et al. Experimental investigation on rheological behavior of dry granular mixtures based on direct measurement of basal friction[J]. Powder Technology, 2024, 438: 119674, doi: 10.1016/j.powtec.2024.119674.

[23] Yu X, Chen Z, He S M, et al. Experimental investigation of seismic signal characteristics arising from basal stress fluctuations in granular flow[J]. Rock Mechanics and Rock Engineering, 2024, 58(1): 927-945.

[24] Miller B, O' Hern C, Behringer R P. Stress fluctuations for continuously sheared granular materials[J]. Physical Review Letters, 1996, 77(15): 3110, doi: 10.1103/PhysRevLett.77.3110.

[25] Li K, Wang Y F, Cheng Q G, et al. Insight into granular flow dynamics relying on basal stress measurements: From experimental flume tests[J]. Journal of Geophysical Research: Solid Earth, 2022, 127(3): e2021JB022905, doi: 10.1029/2021JB022905.

[26] Yu Xiao, Luo Yutao, Liu Shiting, et al. Experimental study on effective friction coefficient of debris flow based on analysis of basal force fluctuation[J]. Journal of Arid Land Resources and Environment, 2023, 37(3): 68-76. [Yu Xiao, Luo Yutao, Liu Shiting, et al. Experimental study on effective friction coefficient of debris flow based on analysis of basal force fluctuation[J]. Journal of Arid Land Resources and Environment, 2023, 37(3): 68-76.]

[27] Wang Dongpo, Li Qinze, Bi Yuzhang, et al. Optimal layout of a new type of baffle based on high-risk areas of rock avalanches[J]. Rock and Soil Mechanics, 2020, 41(4): 1323-1332, 1365. [Wang Dongpo, Li Qinze, Bi Yuzhang, et al. Optimal layout of a new type of baffle based on high-risk areas of rock avalanches[J]. Rock and Soil Mechanics, 2020, 41(4): 1323-1332, 1365.]

[28] Li K, Wang Y F, Lin Q W, et al. Experiments on granular flow behavior and deposit characteristics: Implications for rock avalanche kinematics[J]. Landslides, 2021, 18(5): 1779-1799.

[29] Liu H, Zhao X, Frattini P, et al. Mobility and erosion of granular flows travelling on an erodible substrate: Insights from the small-scale flume experiments[J]. Engineering Geology, 2023, 326: 107316, doi: 10.1016/j.enggeo.2023.107316.

[30] Stamhuis E, Thielicke W. PIVlab-towards user-friendly, affordable and accurate digital particle image velocimetry in MATLAB[J]. Journal of Open Research Software, 2014, 2(1): 30, doi: 10.5334/jors.bl.

[31] Davies T, Mcsaveney M J, Hodgson K A. A fragmentation-spreading model for long-runout rock avalanches[J]. Canadian Geotechnical Journal, 1999, 36(6): 1096-1110.

[32] Li Kun, Cheng Qiangong, Lin Qiwen, et al. State of the art on rock avalanche dynamics from granular flow mechanics[J]. Earth Science, 2022, 47(3): 893-912. [Li Kun, Cheng Qiangong, Lin Qiwen, et al. State of the art on rock avalanche dynamics from granular flow mechanics[J]. Earth Science, 2022, 47(3): 893-912.]

[33] Duan Zhao, Liu Zhipeng, Zhang Ning, et al. Effects of volume and friction coefficient on the movement and deposition of rock avalanche[J]. Journal of Arid Land Resources and Environment, 2024, 38(5): 100-110. [Duan Zhao, Liu Zhipeng, Zhang Ning, et al. Effects of volume and friction coefficient on the movement and deposition of rock avalanche[J]. Journal of Arid Land Resources and Environment, 2024, 38(5): 100-110.]

[34] Dufresne A. Granular flow experiments on the interaction with stationary runout path materials and comparison to rock avalanche events[J]. Earth Surface Processes and Landforms, 2012, 37(14): 1527-1541.

[35] Davies T R H. Spreading of rock avalanche debris by mechanical fluidization[J]. Rock Mechanics, 1982, 15(1): 9-24.

[36] Guo X S, Sun J K, Liu Y H, et al. Rheological characterization and modeling of ultra-high-velocity fluidized submarine landslides[J]. Physics of Fluids, 2024, 36(12): 121705, doi: 10.1063/5.0243967.

[37] Wang Yufeng, Cheng Qiangong, Zhu Qi. Inverse analysis of the accumulation and grain-size characteristics and mechanism of the high-speed, long-runout landslide-debris flow triggered by the Wenchuan earthquake[J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(6): 1089-1106. [Wang Yufeng, Cheng Qiangong, Zhu Qi. Inverse

grading analysis of deposit from rock avalanches triggered by Wenchuan earthquake[J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(6): 1089-1106.]

[38] Wang Y F, Cheng Q G, Zhu Q. Surface microscopic examination of quartz grains from rock avalanche basal facies[J]. Canadian Geotechnical Journal, 2015, 52(2): 167-181.

[39] Gou H X, Hu W, Xu Q, et al. Variation in granular frictional resistance across nine orders of magnitude in shear velocity[J]. Journal of Geophysical Research: Solid Earth, 2024, 129(7): e2023JB028241, doi: 10.1029/2023JB028241.

[40] Zhang H, Liu W, He S, et al. A Thermo-Poro-mechanics model predicts the transition from creep to rapid movement of large landslides[J]. Rock Mechanics and Rock Engineering, 2024, 57(10): 8243-8261.

Base friction coefficient of steady-state particle flow under different thickness

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Abstract: The base friction coefficient is crucial to the flow characteristics of particle-flow disasters, and the fluctuation force is an effective feedback of the interaction between the particle flow and the base, which may affect the variation of the base friction coefficient. The flow characteristics of steady-state particle flow at different thicknesses were identified through inclined-trough physical model tests. The tangential and normal forces of the base were directly measured using a three-component force sensor, and the base fluctuation force and base friction coefficient were obtained. The results show that (1) the particle flow exhibits obvious stratification characteristics at different thicknesses. When the particle-flow thickness reached 3 cm, the flow structure of the particle flow changed, and a chimeric structure was formed between the bottom particles, promoting the occurrence of shear swelling; however, no chimeric structure or shear swelling phenomenon was observed at particle-flow thicknesses of 1 cm and 2 cm. (2) By normalizing the fluctuation force of the particle flow, it is concluded that both the normalized tangential and normal fluctuation forces decrease exponentially with increasing particle-flow thickness, indicating that the strength of the base fluctuation force is directly related to the particle-flow thickness. (3) As the particle-flow thickness increases, the relationship between the base fluctuation force and the base friction coefficient changes from a negative correlation to a positive correlation, and the increase in particle-flow thickness can significantly enhance the collision frequency and intensity between particles, thereby significantly increasing the dynamic friction force between particles and weakening the dynamic friction force between particles and the base. The weakening of the dynamic friction force between particles and the base promotes the formation of chimeric structures between particles and causes shear swelling, ultimately resulting in a significant reduction in the base fluctuation force of the particle flow and the base friction coefficient.

Keywords: granular flow; flow characteristics; base fluctuation force; base friction coefficient; particle-flow thickness

Note: Figure translations are in progress. See original paper for figures.

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