Geoenvironmental Disasters

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Study on dynamic mechanism of granular flow erosion and entrainment based on DEM theory

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Abstract

Background Granular flows are common on the Qinghai–Tibet Plateau and the Hengduan Mountains in China, and their dynamic process processes have obvious erosional and entrainment effects. On the one hand, the volume of the granular flow increases by a factor of several or ten, which significantly increases its ability to cause a catastrophe; on the other hand, the eroded loose material affects the granular flow dynamics process and changes its state of motion.

Methods In this paper, the dynamic mechanism of granular flow erosion and entrainment is investigated by DEM simulation.

Purpose The effects of different substrate materials and substrate boundary conditions on granular flow erosion and entrainment are analyzed, and the effects of material mixing caused by erosion and entrainment on the state of motion of granular flow are discussed. It was verified that the kinetic mechanisms of granular flow erosion and entrainment includes impact erosion, ploughing, and shear abrasion.

Results And discovered that small matrix particle size, small matrix boundary friction, and small matrix thickness lead to stronger ploughing and shear abrasion; Large matrix fractal dimensions result in stronger ploughing and weaker shear abrasion, and the granular flow does not entrain large amounts of material to the accumulation zone. Meanwhile, the dynamics of erosion and entrainment of granular flow were investigated, and the results showed that: 1. The greater the erosion rate, the greater the velocity and kinetic energy of the granular flow, the greater the distance traveled, and the smaller the apparent friction angle (i.e., the greater the mobility). 2. The amount of small granules in a granular flow changes its fluidity, the more small granules there are, the more fluid it is. 3. The fit reveals that the substrate fractal dimension has the strongest effect on the velocity and kinetic energy of granular flow, followed by substrate thickness and substrate boundary friction.

Keywords Granular flow, Erosion and entrainment, DEM, Dynamic mechanism

Introduction

During the potential energy and kinetic energy transformation process of granular flow has obvious dynamic erosion effect, so that its volume increased by several times or even a dozen times, showing a rare high-speed remote chain disaster phenomenon, even if the dry granular flow does not contain water will cause great harm to the downstream residents' production and life. (Yin et al. 2017; Yin and Wang 2020; Hungr et al. 2014). Granular flows ("granular flow" and "avalanche" are

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used interchangeably (Dufresne 2012) throughout this manuscript) mostly occur in high mountain valley areas, especially in the Qinghai–Tibet Plateau region and the Hengduan Mountains region of China. For example, the Xinmao Village landslide (Xu et al. 2017; Wen et al. 2017) in Mao County, Sichuan, China (2017) killed a dozen people and left more than seventy missing, and a number of catastrophic granular flows, such as the Baige granular flow (Yang et al. 2023; Wang et al. 2022) in Tibet, China (2018), the Wenjiagou granular flow (Hu et al. 2018) triggered in the Wenchuan area after the 2008 Wenchuan earthquake, Wailai and Tsada landslide on the Tibetan Plateau (Chen et al. 2020; Dai et al. 2022), posed a great threat to human lives and infrastructure safety. These granular flows usually have characteristics such as large size, extremely high speed, extra-long movement distance, strong mobility and huge impact damage energy, and have obvious erosion and entrainment effect during movement. They are one of the major types of mega-geological hazards that cause mass casualties worldwide and have attracted widespread attention.

The dynamic mechanism of granular flow erosion and entrainment has been of great interest to researchers in the field for many years. Hungr and Evans (2004) suggested that granular flow erosion benefits from liquefaction of the base material. Through physical modeling, Barbolini et al. (2005) concluded that the granular flow erodes the substrate material mainly through abrasive action and plowing of the leading edge. Dufresne (2012) found that erosion consists mainly of plowing, abrasion, deformation waves, and changes in pore water pressure and even liquefaction of substrate materials in the presence of water. Lu et al. (2016; 2018), Zhou et al. (2016), Iverson et al. (2011), Haas et al. (2016), Li et al. (2012), studied the relationship between granular flow erosion and entrainment effects and the composition of the base material, the composition of the granular flow material, and the physical and mechanical properties of the base boundary, and discussed the granular flow erosion and entrainment mechanism. At this stage, the kinetic mechanisms of erosion and entrainment of granular flows have been summarized into three main points, such as impact erosion, ploughing erosion, and shear abrasion. It is noteworthy that most of the studies rely on the continuous medium theory for discussion. However, the current constitutive equations describing the co-motion of materials after mixing in the continuous medium theory are not mature enough to objectively simulate and analyze the erosion and entrainment processes in the motion of particulate flow. The DEM theory is a good way to circumvent this problem by calculating the contact relationship of each particle unit to clarify its motion state.

The occurrence of granular flow erosion and entrainment, on the one hand, increases the volume of the granular flow and significantly enhances its catastrophic capacity; on the other hand, the mixing of base material and granular flow material has a profound effect on the granular flow's own dynamic process, making it more mobile and far-reaching. Hungr and Evans (2004) proposed the wrapping and promotion effect, i.e. the erosion of granular flow and the entrainment of weak base material during its movement, which on the one hand increases the volume of the landslide and changes the composition of the slide material; on the other hand, it also reduces the frictional resistance of the bottom surface, thus increasing the mobility of the granular flow. However, what factors control and influence this feedback effect is still to be further studied, and at the same time there is still a lack of understanding of the role of the nature of the basement material and the substrate boundary in this process. At the same time, at this stage, there are still problems such as the lack of precision in the calculation of existing mathematical models and the reasons for the extreme mobility unclear, which need to be studied urgently.

In this study, a numerical model was established by using DEM discrete medium theory, which reproduced the motion process of granular flow under different base materials and substrate conditions, monitored the changes of granular flow dynamics parameters from the particle scale, investigated the role of erosion and entrainment of granular flow under different substrate materials and substrate boundary conditions (In this manuscript, erosion and entrainment are defined in this way: Erosion: a mechanical process by which the bed material is mobilized by the flow; Entrainment: a mechanical process by which the eroded material is incorporated (entrained) and taken along with by the flow (Pudasaini and Krautblatter 2021), and explored the feedback of the substrate materials entrapped by the granular flow on its dynamics, which is of great scientific significance and practical value for engineering construction and disaster prevention and mitigation work in southwest China's Transverse Mountain area and Qinghai–Tibet Plateau region.

DEM numerical simulations

Discrete medium model

In this study, the discrete medium theory is used for numerical modelling by LS-DYNA, the number of physical model tests (Yin et al. 2023) is used as a modelling reference, and the DEM model parameters are calibrated by physical model tests.

The discrete media model consists primarily of a hopper, two sections of inclined chutes, and a platform. As shown in Fig. 1, the hopper is 14 m high from the ground,

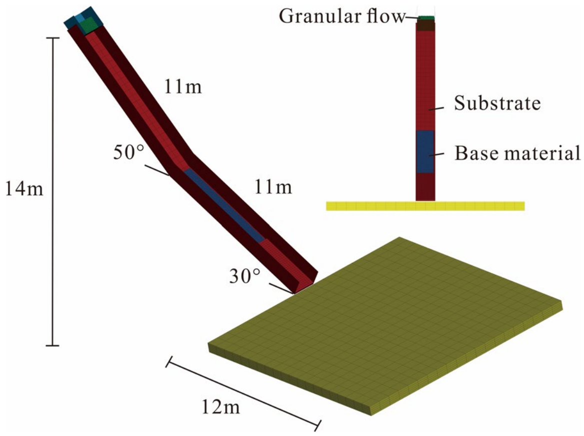


Fig. 1 Discrete media model

Table 1 Discrete media model eigen parameter settings

Materials	Density (kg/m^3)	Poisson's ratio	Young's modulus (Pa)
Substrate	7000	0.25	3.0×10^{11}
Base material	3100	0.2	2.1×10^{9}
Granular flow	3600	0.2	3.5×10^{9}
Stacking platform	7000	0.25	3.0×10^{11}

the first section of the inclined trough is at an angle of 50° to the horizontal plane and is 11 m long, the second section of the inclined trough is at an angle of 30° to the horizontal plane and is 11 m long, the length of the base material is 8 m, and the platform is 12 m long, 12 m wide and 0.7 m high.

In conventional numerical simulation calculations, only macroscopic parameters of geotechnical bodies (which can be obtained from experiments) are generally required, while numerical calculations of granular flow focus on fine-scale parameters of granular units, such as friction, damping, and so on. Due to the objective complexity of the fine structure of the geotechnical body and the imperfection of the current mechanical theory, the quantitative relationship between the fine and macroscopic parameters of the geotechnical body has not been established at this stage (Sammis 1987).

The contact model in this study uses a spring damping model. And in this study, a large number of calculations were carried out using different parameters, which were calibrated by the effects of granular flow erosion and entrainment effects (e.g., contact patterns between granular flows and substrate materials, evolution of erosional entrainment effects and granular flow displacements) in the physical modeling experiments, and finally a reasonable selection of parameters was chosen for the analysis.

As shown in Table 1, the intrinsic parameters such as substrate density (i.e., inclined trough), Poisson's ratio, and Young's modulus in the discrete medium model are set to 7000 kg/m^3, 0.25, and 3.0×10^{11} Pa, respectively; The intrinsic parameters such as density of base material, Poisson's ratio and Young's modulus are selected as 3100 kg/m^3, 0.2 and 2.1×10^{9} Pa, respectively; The intrinsic parameters such as granular flow density, Poisson's ratio and Young's modulus were selected as 3600 kg/m^3, 0.2, and 3.5×10^{9} Pa, respectively. After extensive calculations, the contact parameters such as dynamic friction coefficient, static friction coefficient, normal damping and tangential damping of granular flow particles, base material, base material and substrate (i.e., base boundary friction), base material and platform, granular flow and substrate, and granular flow and platform in the discrete media model were selected as shown in Table 2.

Program design

The discrete medium model analysis mainly explores the granular flow erosion and entrainment power conversion characteristics, erosion and entrainment effect characteristics and its action mechanism from the perspectives of base material particles (particle size and

Table 2 Discrete media model contact parameter setting

Contact	Friction factor		Damping factor	
	Static friction coefficient	Coefficient of dynamic friction	Normal damping	Tangential damping
Base material	0.6	0.1	0.7	0.4
Granular flow	0.6	0.1	0.7	0.4
Base—substrate	0.6/0.8/1.1	0.1/0.3/0.5	0.6/0.8/1.1	
Base—platform	0.8	0.4	0.8	
Granular flow—substrate	0.6	0.1	0.6	
Granular flow—platform	0.8	0.4	0.8	

Table 3 DEM discrete media model analysis scheme design

Number	Source area particles (mm)	Substrate particles (mm)	Thickness of base material (m)	Substrate boundary friction (μ)
S1	16–32	4–8	0.1	M
S2	16–32	8–16	0.1	M
S3	16–32	D = 2.5	0.1	M
S4	16–32	D = 3.0	0.1	M
S5	16–32	D = 3.5	0.1	M
S6	16–32	4–8	0.1	L
S7	16–32	4–8	0.1	H
S8	16–32	8–16	0.15	M
S9	16–32	8–16	0.20	M

Low base friction (L) static friction coefficient 0.6, kinetic friction coefficient 0.1; Medium base friction (M) static friction coefficient 0.8, kinetic friction coefficient 0.3; High base friction (H) static friction coefficient 1.1, kinetic friction coefficient 0.5

fractal dimension), base boundary friction and base material thickness. The specific scheme design is shown in Table 3.

The fractal dimension of the base material is calculated based on the relationship between particle size and particle number in geophysical fluids (Eq. 1) elaborated by Sammis et al (1987), and the granular particles are approximated as spheres, and the particle mass m in each particle size range is obtained under the total mass of granular particles M (Eq. 2), and the larger the fractal dimension D, the more small-sized particles are present in the base material grading combination.

$$N(d) = N_0\left(\frac{d}{d_0}\right)^{-D} \quad (1)$$

where D is the fractal dimension, N_0 is the number of particles of reference particle size d_0, and N is the number of particles of particle size d.

$$m = \frac{M\overline{d_i d_{i+1}}^3}{\left(\overline{d_i d_{i+1}}^{3-D} + \overline{d_{(i+1)} d_{(i+2)}}^{3-D} + \cdots + \overline{d_{(i+n)} d_{(i+n+1)}}^{3-D}\right)} \overline{d_i d_{i+1}}^{-D} \quad (2)$$

where M is the total mass of the substance (kg), m is the mass of the particle in the particle size range, and $\overline{d_i d_{i+1}}$ is the average particle size in the particle size range i to $i+1$ (mm).

Model validation

The DEM modeling in this study was based on the inclined channel used in the physical model test (Yin et al. 2023), so the reliability of the DEM model was verified by comparing the contact mode between the granular flow and the base material, the evolution process of erosion entrainment action, and the effect of the erosion action between the physical model test and the numerical simulation of the DEM. As shown in Fig. 2, in the physical model test, when the front of the granular stream contacts the base material, the granular stream pushes the base material below and in front of it forward and the base material is eroded by the granular stream in the form of significant ploughing. Note that after granular flow erosion and entrainment has occurred, the underlying base material is subjected to shear abrasion by the forward flowing granular flow. These are consistent with the phenomena observed in the DEM numerical simulations (See Chapter 3 for a description of the DEM results).

In order to better verify the reliability of the DEM numerical simulations, we calibrated various parameters in the numerical simulations, such as damping coefficients and friction factors, by the displacement of the granular flow after erosion and entrainment have occurred. We use S1 for parameter calibration, use a large number of parameter values for numerical simulation, and compare the granular flow displacements in the simulation results with the granular flow displacements in the physical model tests. Finally, we chose a set of parameters to make the numerical simulations in high agreement with the granular flow displacements in the physical model tests. We therefore believe that this discrete medium model simulates the physical model test well.

Kinetic mechanisms

Impact erosion

After the granular flow starts, the high-speed falling process carries huge energy, and due to the complex and changing terrain in the high mountain canyon area, the granular flow inevitably collides violently with the mountains on both sides and the soil materials on the slope. As shown in Fig. 3, the leading edge of the granular flow under the action of huge impact force and the base material violent contact, so that the base material plastic deformation, controlled by the energy decay, so that erosion to a certain depth, the formation of impact groove. In this process, the impact force of the granular stream gives the base material forward momentum, and

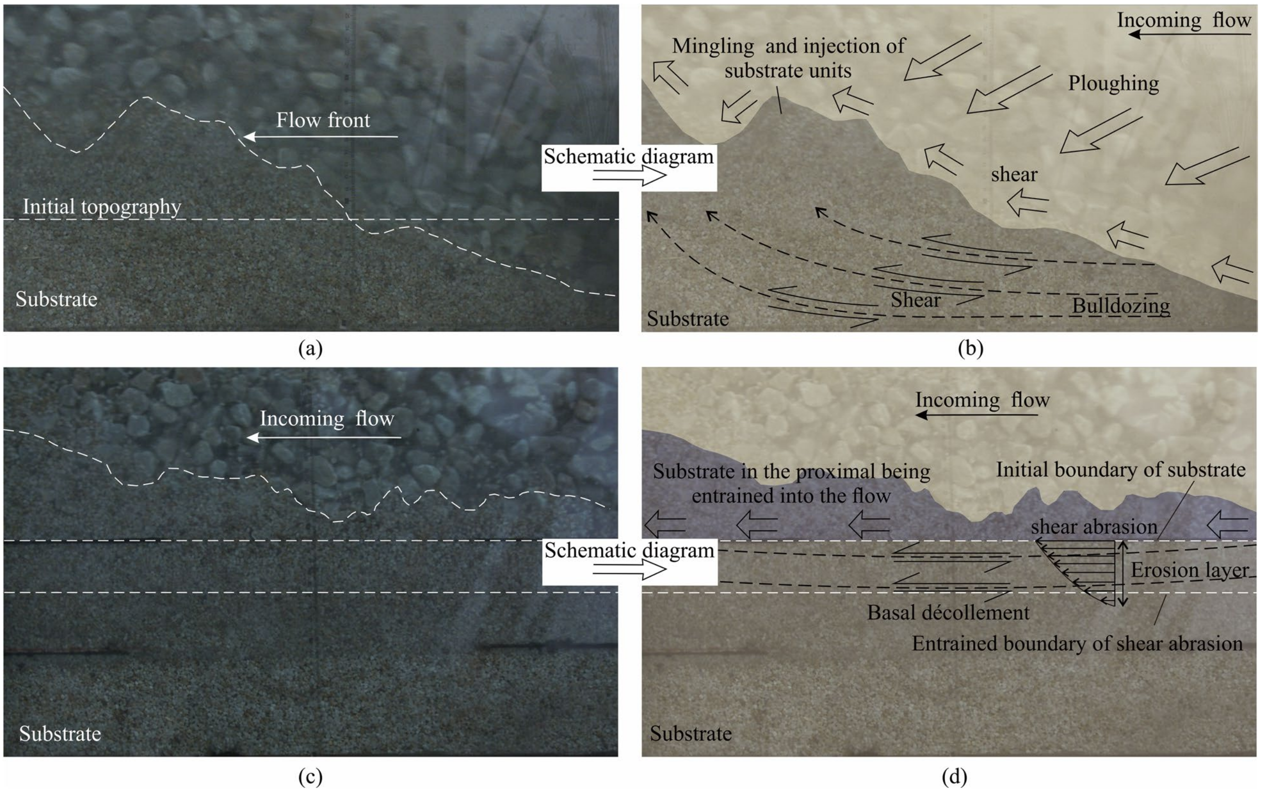


Fig. 2 Erosion and entrainment in physical model test (Yin et al. 2023). **a** Granular flow extrusion and propulsion of substrate materials **b** Schematic diagram of granular flow extruding and pushing the substrate material **c** Granular flow mobilizes substrate material movement **d** Schematic diagram of granular flow mobilizes substrate material movement

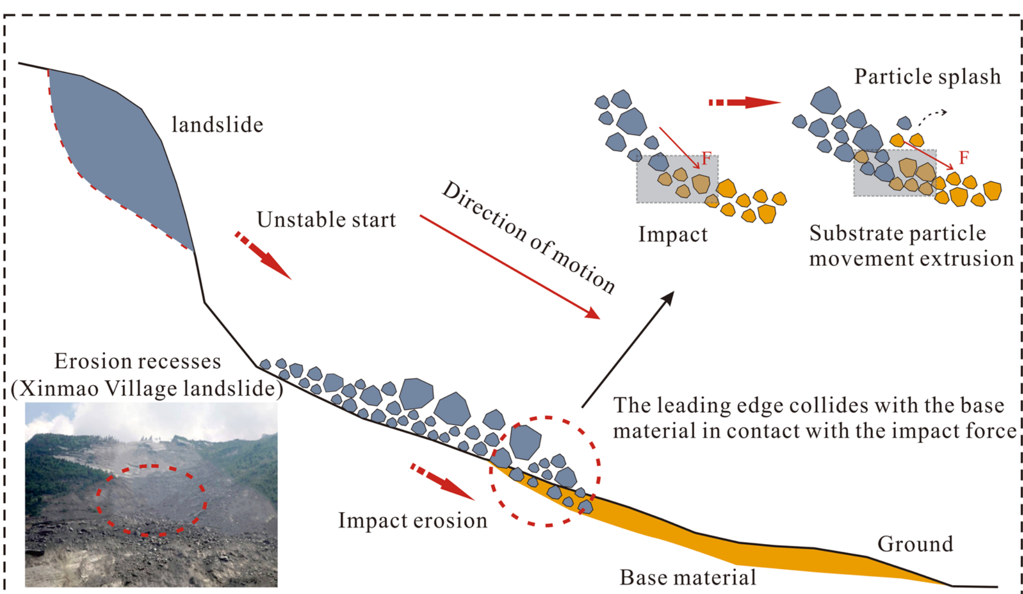


Fig. 3 Impact erosion pattern diagram

the density of the base particles gradually increases in the accelerated motion. The movement of the granular flow particles is blocked because of the collision contact with the base material, and their speed decreases. It is worth noting that the collision contact between the granular stream and the base material is at a certain angle, which makes it have the particle splash phenomenon.

In the DEM discrete medium model analysis, it is found that when the granular flow (green particles) comes into contact with the base material (blue particles), the surface particles of the base material are lifted by the granular flow and move forward in the form of waves or wakes (Fig. 4).

Ploughing

Granular flow and grass-roots material contact, through a strong impact shovel into the grass-roots material, under the control of power consumption erosion of a certain depth, after which the granular flow further movement, rapid extrusion push grass-roots material forward displacement. In this process, the granular flow on the one hand drives the contact surface near the grassroots material shear flow, so that the front and lower grassroots material covers the rear grassroots material, resulting in the thickening of the grassroots material bulge; On the other hand, similar to the bulldozer bulldozing action to give the grass-roots material forward momentum to achieve granular flow on the grass-roots material propulsion, this process of shear flow and propulsion is always decreasing layer by layer (Fig. 5).

The smooth sides and flat bottom of the V-shaped erosional trough at the site of the Baige landslide may be the result of ploughing. Influenced by the hard lithology of the lower part, the down-cutting action of the leading edge of the Baig landslide granular flow is difficult to continue, and the subsequent force transfer of the granular flow drives the ploughing action of the base material, and the shear flow of the base material and the pushing action of the granular flow on the base material cause the surface to form erosional grooves with relatively flat and smooth sides and bottom.

In the DEM discrete medium model analysis, it is observed that the granular flow (green particles) initiates ploughing action on the base material (blue particles), driving the base material particles into shear flow and converging into the leading edge of the granular flow, during which the base material apparently rises and thickens to form a mound, and the moving granular flow covers the mound to carry it away. In the ploughing action and the shear flow of the base material driven by the granular flow occurs at the same time is the pushing effect of the granular flow on the base material, this pushing effect is carried out layer by layer, it can be observed that the surface layer of the base material is eroded the most amount, to the deeper part of the base material is gradually reduced, forming a boundary surface with a certain slope.

As shown in Fig. 6, the slope of the boundary surface formed by the ploughing action of the granular flow and the base material does not change significantly under the influence of the particle size of the base material, except

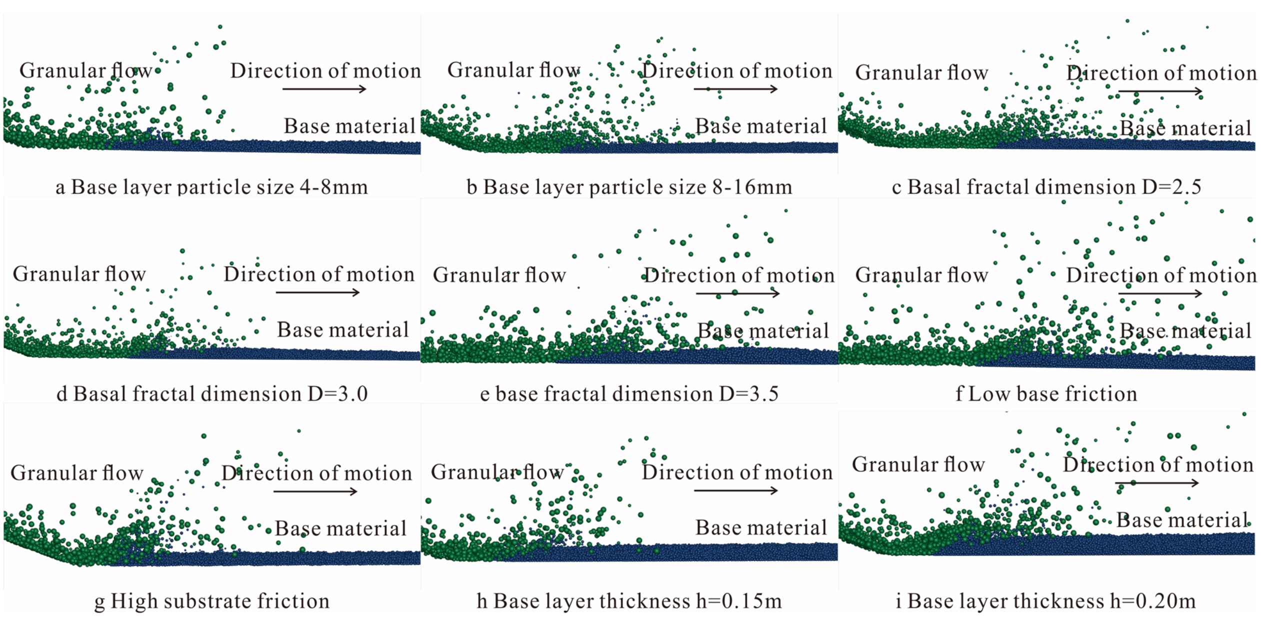


Fig. 4 Impact erosion simulation diagram

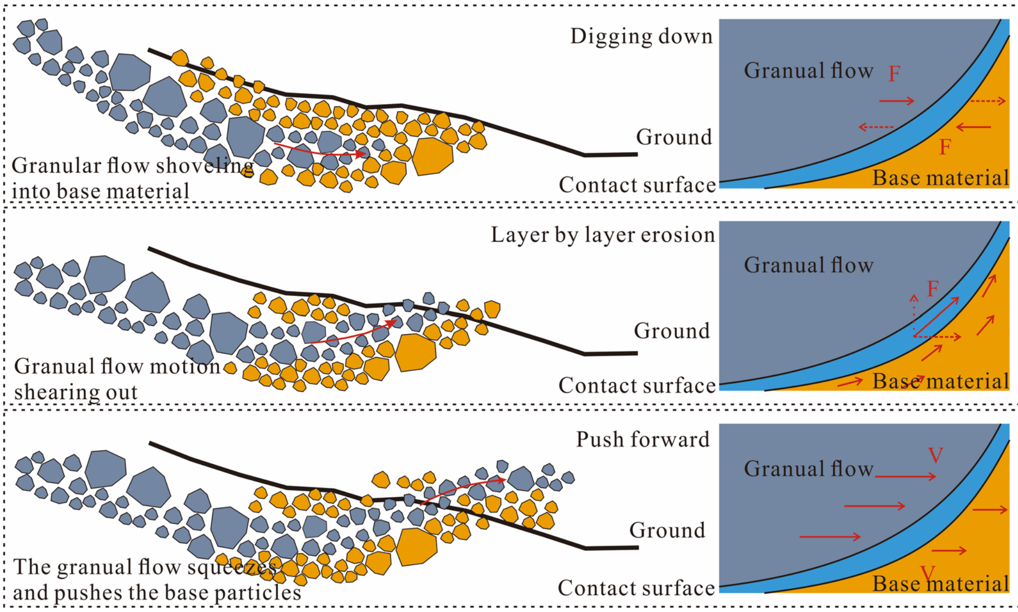


Fig. 5 ploughing pattern diagram

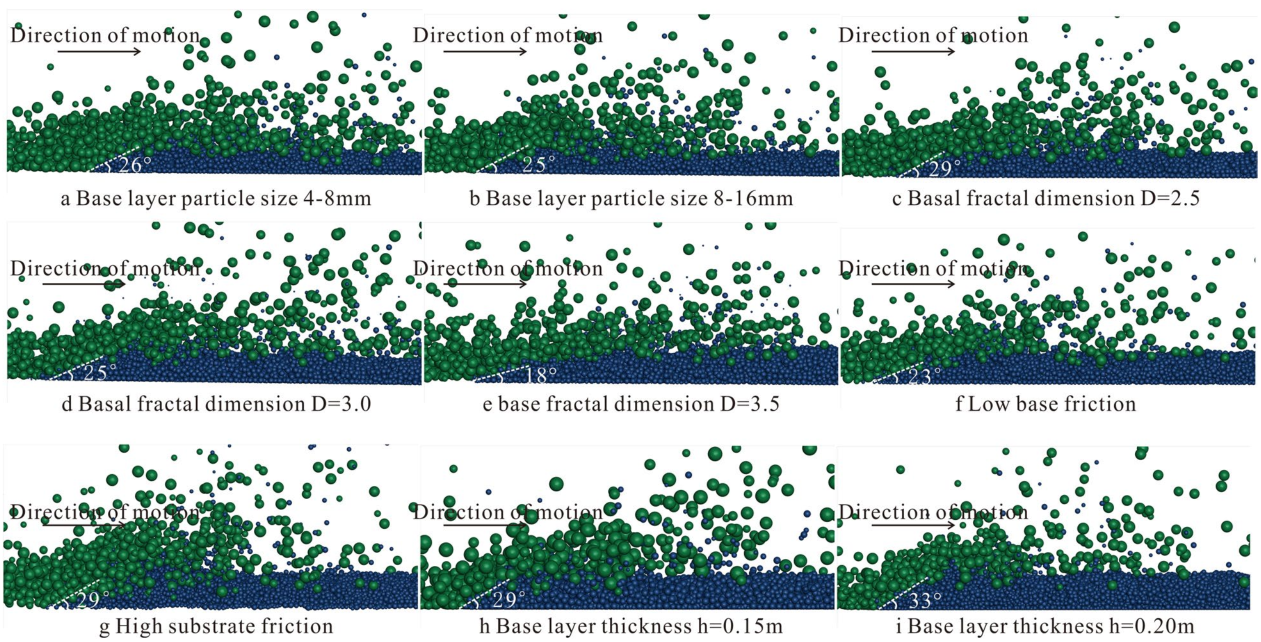


Fig. 6 ploughing simulation diagram

that more particles of the granular flow are mixed into the base material under the large particle size, which leads to a relative increase in the velocity and kinetic energy of the movement of the base material under the large particle size. Influenced by the increase of the fractal dimension of the base material, the slope of the boundary surface gradually becomes slower, which means that the increase of the small particle content of the base material will increase the ploughing and cutting effect of the granular flow, especially the pushing effect on the base material. This pushing may be more to make the subgrade material particles compressed and crowded, and will not transfer much force to the subgrade material, causing rapid movement of the subgrade material, resulting in a lot of erosion.

Under the effect of high substrate boundary friction, the deep particles of the substrate material are difficult to be eroded by the granular flow under the control of high friction, and this control effect shows a gradual weakening toward the shallow part of the substrate material, which eventually forms a steeper slope boundary surface. Influenced by the increase of the thickness of the subgrade material, the slope of the boundary surface gradually increases due to the higher inertial mass of the subgrade material under the high thickness, and the upper part of the subgrade material exerts higher pressure on the lower part of the subgrade material. Under the effect of this strong pressure, the substrate friction increases, the control effect on the substrate material is increased, the pushing effect of the granular flow on the substrate material is obviously weakened, the velocity and kinetic energy of the substrate material movement are obviously reduced, and the degree of ploughing becomes lower.

In order to better describe the degree of erosion by plowing, the erosion quantity M^* (the ratio of the mass of eroded substrate material M_{LQ} to the total mass of substrate material M_{LJ} under ploughing) is characterized by the dimensionless parameter M^* (Eq. 3).

$$M^* = \frac{M_{LQ}}{M_{LJ}} \tag{3}$$

As shown in Fig. 7, the displacement of the substrate material and the thickening of the bulge in the ploughing effect decrease for large substrate material grain size, indicating that the shear flow of the substrate material driven by the granular flow and the pushing effect of the granular flow on the substrate material decrease with the increase of the substrate material grain size, the erosion amount M^* decreases, and the ploughing effect is low. Under the large substrate fractal dimension, the displacement of the substrate material and the thickening of the bulge in the ploughing effect both increase, indicating that the shear flow of the substrate material driven by the granular flow and the pushing effect of the granular flow on the substrate material both increase with the increase of the substrate material fractal dimension. It is noted that the erosion amount M^* is slightly increased at this time, while the erosion rate E_M (Fig. 8) of the granular flow decreases with increasing fractal dimension, which means that although a large number of particles are eroded by the ploughing action at large fractal dimension, these particles are not entrained by the granular flow to the accumulation area, but rest on the substrate material after movement.

Under the high substrate boundary friction, the displacement of the substrate material and the thickening of the bulge in the ploughing effect decreased, indicating

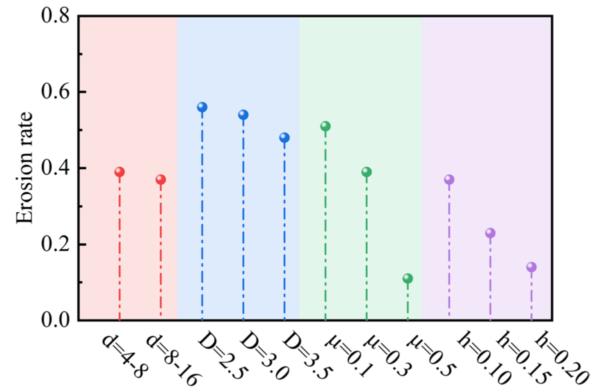
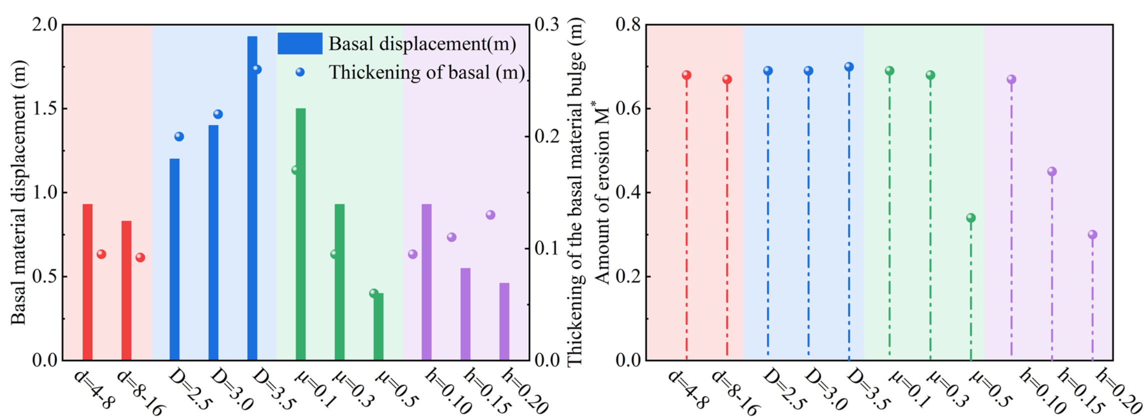


Fig. 8 Granular flow erosion rate



(a) Substrate material changes under ploughing

(b) Degree of erosion under ploughing

Fig. 7 Erosion and entrainment characteristics under ploughing action that the shear flow of the substrate material driven by the granular flow and the pushing effect of the granular flow on the substrate material were weakened with the increase of the substrate boundary friction, while the erosion amount M^* was significantly reduced at $\mu = 0.5$, and the degree of the ploughing effect was greatly reduced. This indicates that the shear flow of the base material driven by granular flow is enhanced and the pushing effect of the granular flow on the base material is weakened with increasing thickness of the base material, which may be due to the greater inertial mass and higher pressure of thicker base material, which makes it difficult to be pushed, whereas the shear flow driven by granular flow is rarely constrained by the mass and pressure of the base material. The shear flow driven by the granular flow is rarely constrained by the mass and pressure of the base material, but instead is augmented by the greater volume of the base material to produce a stronger shear flow. At the same `time, high thickness of substrate material tends to have lower erosion M^*, and it is possible that the pushing of substrate material by granular flow is the main form of ploughing action.

Shear abrasion

The granular flow covers on top of the base material and moves parallel to the base material, forming a shear impact zone in the contact, and the base material in the zone is affected by shear stress to shear movement, this process is accompanied by kinetic energy transfer downward layer by layer, and the loose base material is driven by the granular flow to flow along a certain shear surface, while the relatively stable base material overcomes the shear strength under the action of the granular flow to shear off (Fig. 9). As the shear abrasion continues, the shear surface moves further into the base material, and the granular flow erodes the base material layer by layer. In the lower accumulation area of Yigong landslide, granular flow shear abrasion occurs at the bottom and both sides of the accumulation body of Zamulong gully, leaving traces of shear abrasion of the particles. Similarly, the granular flow in the landslide of Xinmo Village in Maoxian County can transfer the excitation to the loose accumulation body, and the old landslide under the granular flow member can shear slip.

In the DEM discrete medium simulation analysis, it is found that the granular flow (green particles) carries the eroded substrate material (blue particles) over the substrate material, eroding the substrate material raised by the ploughing action on the one hand, and shearing wear with the substrate material on the other hand, giving the substrate particles momentum to move forward. As shown in Fig. 10, shear wear occurs on the substrate along a certain shear surface, and the shear surface gradually develops to the shallow part due to the increasing particle size of the substrate, which is consistent with the phenomenon observed in the physical model test, probably because the small size particles have less strength and are more easily eroded by the granular flow, and the analysis of the erosion rate also shows this point (Fig. 8). This can be influenced by the fact that a large number of small particles fill the gaps and improve the density of the substrate material on the one hand, and by the fact that the strong ploughing action under large fractal dimension causes more power consumption and the erosion ability of the granular flow in shear wear is greatly reduced on the other hand.

The effect of base boundary friction on shear wear is significantly influenced by the thickening of the base

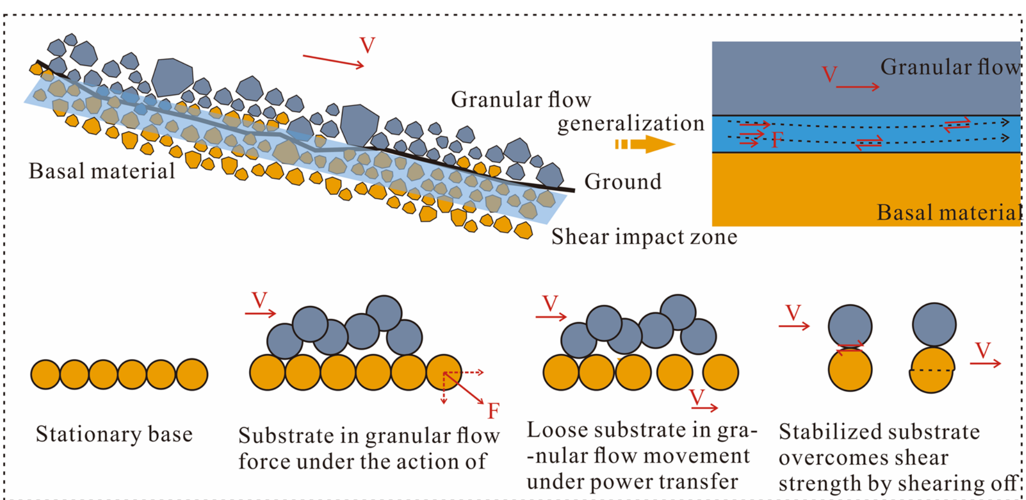


Fig. 9 Shear abrasion pattern diagram

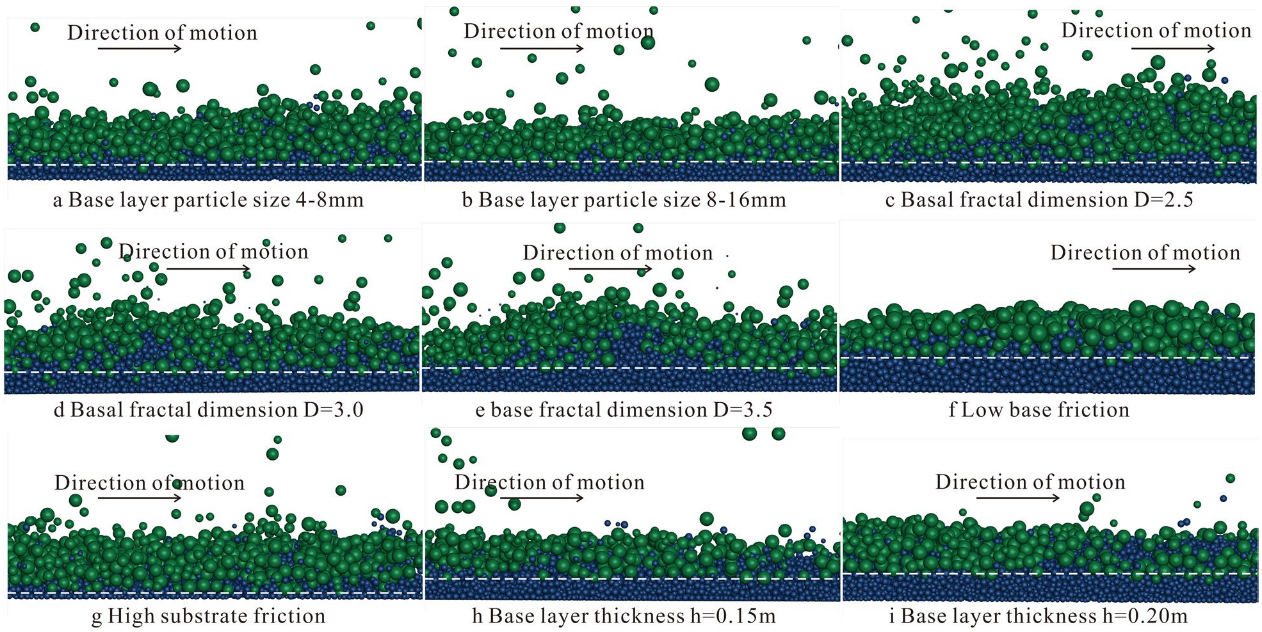


Fig. 10 Shear abrasion simulation diagram

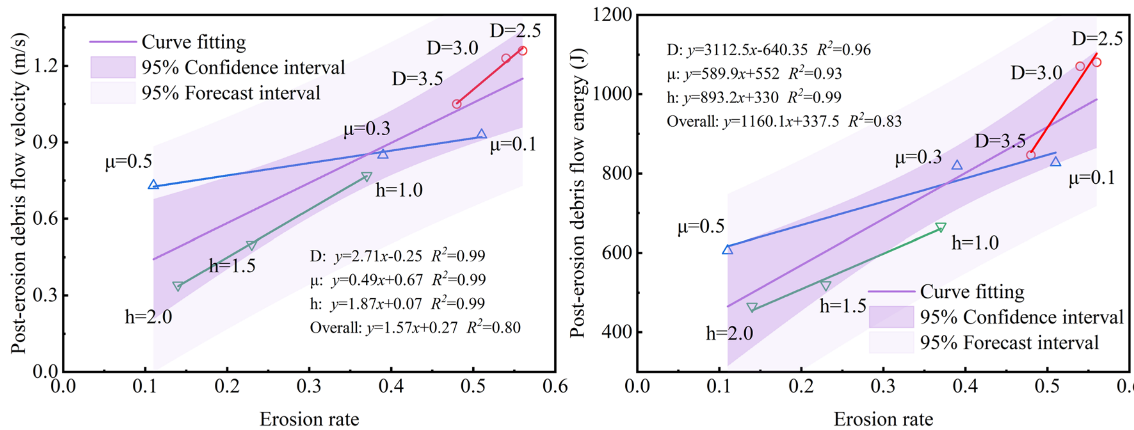
material bulge in the ploughing action, and the DEM analysis shows that the ploughing action under low base boundary friction is very strong, even to the end of the base material in a very strong posture, causing a significant thickening of the base material and making the final shear surface appear to be in a higher position under low base boundary friction. In fact, the final shear surface tends to be located more shallower as the base boundary friction increases, i.e., its ability to develop deeper becomes weaker as a result of the layer-by-layer control of the base material by the base boundary friction. Note that under high substrate boundary friction, the shear wear of the granular flow on the deep substrate material is significantly weakened, and most of the granular flow particles that enter the interior of the substrate material during energy transfer also quickly lose their kinetic energy and stop accumulating in the substrate material.

Effect of erosion and entrainment on granular flow kinetic characteristics

The material mixing that occurs when granular flow erosion entrains the substrate material greatly changes the physicochemical properties, kinematic state, and kinetic transition form of the granular flow. In this paper, the effects of granular flow erosion and entrainment on its kinetic characteristics are discussed in terms of erosion rate, substrate material, and substrate boundary characteristics based on discrete medium model analysis.

At the moment of erosion and entrainment of the granular flow, the velocity and kinetic energy of the motion do not change immediately, but experience a short delay before the force decays due to the strong energy recharge of the rear granular flow. After the erosion and entrainment occurs, the granular flow and the base material undergo a power transfer, and the energy of the granular flow inevitably decays, during which the changes in its velocity and kinetic energy are controlled by the erosion and entrainment. As shown in Fig. 11, the large erosion rate tends to correspond to higher granular flow velocity and kinetic energy (Pudasaini and Krautblatter 2021). In other words, the velocity and kinetic energy of the granular flow after erosion and entrainment show a positive correlation with the erosion rate ($R^2=0.80$, $R^2=0.83$), which is probably due to the fact that the larger granular flow volume under the large erosion rate gives the granular flow more potential energy addition, which is converted into kinetic energy during the movement, and compensates for the relatively high velocity and kinetic energy of the granular flow after erosion and entrainment. This potential energy is converted into kinetic energy, which can compensate for the power consumption of the granular flow under erosional entrainment, and make it have relatively high velocity and kinetic energy after erosion and entrainment.

The analysis of the change in erosion rate caused by different conditions showed that the erosion rate decreased from 0.56 to 0.48 as the fractal dimension D of the base material increased from 2.5 to 3.5, and the high erosion rate also corresponded to higher granular flow velocity and kinetic energy, and the fitting showed that the



(a) Erosion rate and velocity (b) Erosion rate and kinetic energy

Fig. 11 Effect of erosion and entrainment on velocity and energy

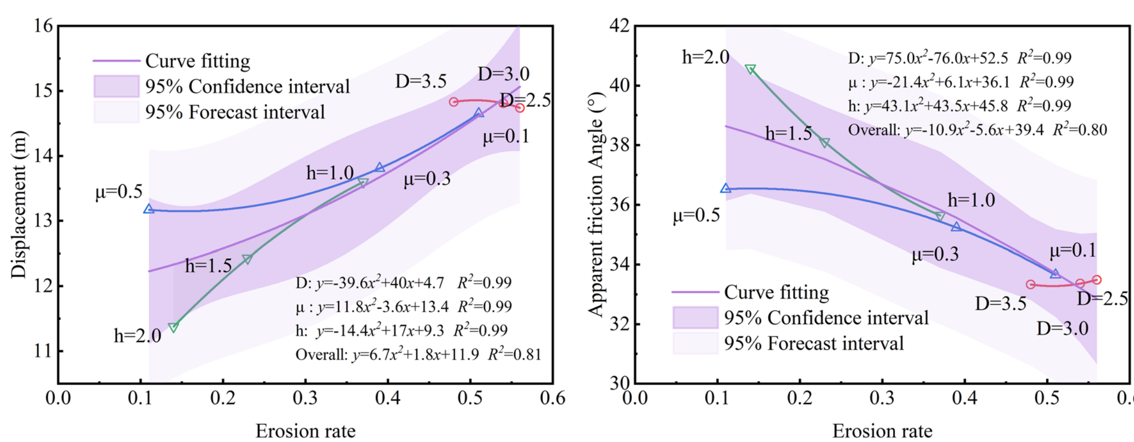
granular flow velocity and kinetic energy had a positive correlation with the erosion rate after erosion and entrainment ($R^2 = 0.99$ and $R^2 = 0.96$).

As the substrate interface friction μ increased from 0.1 to 0.5 kinetic friction coefficient, the erosion rate decreased from 0.51 to 0.11. The high erosion rate still corresponded to higher granular flow velocity and kinetic energy, and the fitting showed that granular flow velocity and kinetic energy had a positive correlation with erosion rate after erosion and entrainment ($R^2 = 0.99$, $R^2 = 0.93$).

As the thickness h of the substrate material increased from 0.1 to 0.2 m, the erosion rate decreased from 0.37 to 0.14. The high erosion rate still corresponded to higher granular flow velocity and kinetic energy, and the fitting found that the granular flow velocity and kinetic energy showed a positive correlation with the erosion rate after erosion and entrainment ($R^2 = 0.99$, $R^2 = 0.99$).

Among the fitted curves of erosion rate changes caused by different conditions, the slope of the fitted curve under the substrate fractal dimension condition is the largest, indicating that the substrate fractal dimension has the strongest influence on the feedback of granular flow erosion and entrainment dynamics. In contrast, the slope of the fitted curve under the basal boundary friction condition is the smallest, indicating that the basal boundary friction has the least effect on the kinetic feedback of granular flow erosion and entrainment. It can be seen that the influence of different substrate material and substrate boundary properties on granular flow erosion and entrainment velocity and energy feedback varies from strong to weak in the order of substrate material fractal dimension, substrate material thickness, and substrate boundary friction.

The feedback of the granular flow erosion and entrainment dynamics is most intuitively manifested by the



(a) Erosion rate and displacement (b) Erosion rate and apparent friction angle

Fig. 12 Effect of erosion and entrainment on movement distance variation of its displacement and apparent friction angle. As shown in Fig. 12, a high erosion rate always corresponds to a larger displacement, and the displacement has a positive correlation with the erosion rate; meanwhile, a high erosion rate always corresponds to a smaller apparent friction angle, and the apparent friction angle has a negative correlation with the erosion rate.

The relationship between erosion rate and displacement and apparent friction angle was observed for different substrate materials and substrate boundary conditions. It was found that unlike the substrate boundary friction and substrate thickness conditions, where a large erosion rate always leads to a larger displacement and a smaller apparent friction angle, a small erosion rate in the substrate fractal dimension conditions does not necessarily lead to a smaller displacement and a larger apparent friction angle. This is the greatly increased content of small and medium-sized particles in the base material under the large fractal dimension, and the erosion of the granular flow entrains the movement of a large number of small-sized particles, and although their erosion rate is small, these small-sized particles play a role similar to that of a "lubricant" under the granular flow (Li 2012), which improves the mobility of the granular flow and promotes the displacement of the granular flow over long distances.

Conclusions

Granular flows often occur in high mountain and canyon areas, causing large numbers of casualties, and are the focus and difficulty of research in the engineering geology community. At this stage there is no clarity about the effect of different base material and substrate boundary conditions on the erosion and entrainment of granular flow, and there is no conclusive evidence about the feedback and influence of entrained material on the motion of granular flow. Meanwhile, most of the current studies on the erosion and entrainment of granular flow are based on the continuous medium model, however, the theory of the motion of granular flow after mixing of materials in the continuous medium model is not yet mature. Therefore, this paper utilizes the discrete medium model (DEM) to obtain the motion law of each particle unit by calculating the contact relationship between them after mixing of materials, and analyzes and researches the kinetic mechanism of granular flow erosion entrainment, its characteristics, and the feedback effect of entrainment on the motion of granular flow, and arrives at the following conclusions.

1. There is an obvious erosion and entrainment effect in the dynamic process of granular flow, and its intensity is influenced by the nature of the base material and the substrate boundary: the increase of the particle size of the base material, the increase of the fractal dimension of the base material, the increase of the friction of the substrate boundary, and the increase of the thickness of the base material reduce the erosion volume and the erosion rate of the granular flow.
2. Ploughing action and shear wear are influenced by the nature of the base material and the substrate boundary: The small particle size of the substrate material, the large fractal dimension of the substrate material, and the low friction of the substrate boundary will promote the shear flow of the substrate material and the pushing effect of the granular flow on the substrate material in the plowing action, and the plowing action of the granular flow is weak. The thickness of the base material will promote the shear flow of the base material in the plowing action and inhibit the driving effect of the granular flow on the base material, the granular flow plowing action is weak. Small particle size of the substrate material, small fractal dimension of the substrate material, low substrate boundary friction and small thickness of the substrate material will promote shear wear.
3. Granular flow erosion and entrainment allows the base material to sink into the granular flow and greatly affects the granular flow dynamics processes: The larger the granular flow erosion rate is, the higher its motion speed and kinetic energy is, and the strong degree of base material and substrate boundary properties on the granular flow erosion and entrainment speed and energy feedback is in the order of base material fractal dimension, base material thickness and substrate boundary friction. The greater the granular flow erosion rate, the more distant displacement and smaller apparent friction angle it generally has, and the strong degree of base material and base boundary properties on granular flow erosion and entrainment displacement and mobility feedback in the order of base material thickness, base boundary friction a + nd base material fractal dimension. Although the erosion rate of the granular flow is smaller in a large fractal dimension, the large increase in small particles acts as a “lubricant” that makes the granular flow more mobile and displaceable over longer distances.

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Declarations

Competing interests
The authors declare no competing interests.

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