Numerical analysis of rockfall fragmentation mechanism

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ABSTRACT: Fragmental rockfall is one kind of common geological disaster in mountainous areas. In this paper， the discrete element method, particle flow code (PFC) is used to simulate the impact and fracture process of rock mass， analysis the impact process of rock mass at different falling heights and impact angles， and the variation trend of impact force， velocity and the number of cracks in the rock mass. The results show that the velocity of rock mass decreases sharply and the crack develops rapidly after impact on the slope. With the increase in falling height， the rock mass velocity changes in a "second step shape"， and the number of broken blocks increases while decreasing the rock mass size. With the increase of slope angle， the "double peak phenomenon" of impact force becomes less obvious. The results provide a theoretical basis for the numerical simulation of fragmental rockfall and hazard assessment.

Keywords: fragmental rockfall; PFC; impact angle; impact force.

1 INTRODUCTION

Rockfall hazards, including small-scale blocks, falls and large-scale rock avalanches, are the result of tension-based damage to slope geotechnical bodies. This is one of the most common geological hazards in mountainous regions of southwest China, characterized by extensive distribution, high abruptness, and disaster-causing potential. On June 24, 2017, a high-level rock avalanche in Xinmo village, Mao County, Sichuan, with a volume of 45×10^5 m^3, demolished 64 farm buildings and killed 73 people. After a high-level rockfall destabilizes and damages, high potential energy is converted to high kinetic energy, and then a huge number of fragmented blocks travel in the form of granular flow with enormous destructive force. Rock blocks are typically regarded as rigid bodies, such as Tang (2003) used recovery coefficients to characterize the velocity change during inelastic collisions when establishing the equations of motion in the collision phase; He (2009) obtained the impact force from the viewpoint of energy conservation using the principle of elastic-plastic mechanics. However, a large number of cases have demonstrated that impact fragmentation of crumbling bodies and slopes is a common occurrence, particularly for rock bodies with high weathering and low strength, which greatly increases the hazard risk due to the fragments' varying sizes and independent motion trajectories (Figure 1). Thus, it is essential to examine the impact fragmentation process to enhance our understanding of the dynamics of rockfall dangers and to design efficient preventative and control strategies.

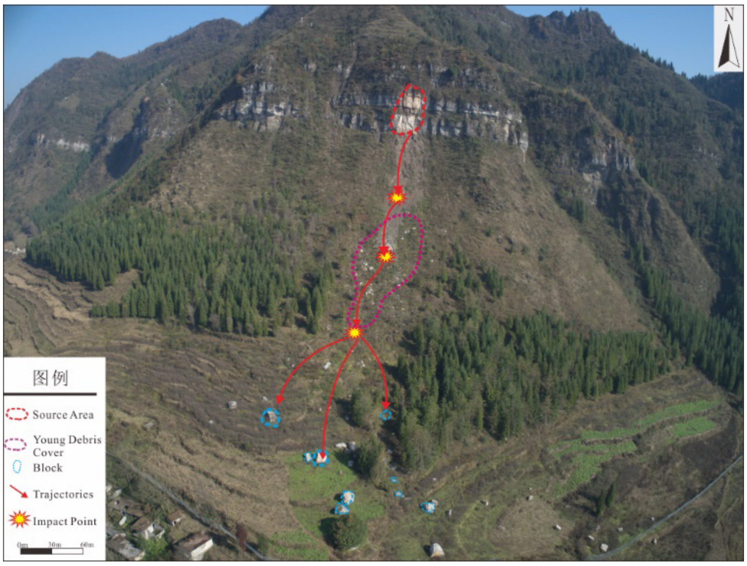


Figure 1. Diagram of the dynamic fragmentation.

However, under natural conditions, it is difficult to fully observe the rockfall of the crumbling surface and the fragmentation process, mainly by field surveys, physical experiments and numerical simulation methods to analyze the rocky structure of its crumble area and the volume distribution of the accumulated blocks and replay the fragmentation process. Giacomini et al. (2009) examined the effects of impact angle and impact energy on fragmentation and determined that impact angle was the most influential component. Haug et al. (2016) conducted 109 rock avalanche simulation experiments to examine the effects of fragmentation on movement distance and energy by varying the release height and impact angle using a sloping channel model, and the results demonstrated that as the degree of fragmentation increased, the movement distance and energy increased proportionally. With increasing fragmentation, the frontal movement distance and distance to the centre of gravity of the pile increased, respectively. Lv et al. (2017) carried out the rolling stone test, which analyzed the fracture degree of the rolling stone through multi-factor coupling collision, and found that the mechanical properties and collision velocity were the main factors controlling the fracture, and the "splash effect" caused the speed of the broken block to increase. Lin et al. (2020) examined the effect of structure on dynamic fracture by modifying the structural characteristics of the rock mass, also discovered that the distance of movement of the mass core was proportional to the degree of fracture, and they proposed a diffusion model of rock avalanche movement.

Numerical simulations are utilized extensively as a straightforward research tool, primarily in the continuous media and discrete element method. Wang and Tonon (2011) investigated the effects of impact velocity, ground stiffness, impact angle, and primary cracking on dynamic fragmentation using the discrete element approach and showed that the production of cracks was mostly dependent on the normal impact force. de Blasio et al. (2016) employed the DEM approach to analyze the dynamic fragmentation process of granite masses. They discovered that when the slope dip angle was larger than 70 degrees, the resultant block size was more uniform, but the furthest block was the largest. Zhao et al. (2018) utilized the discrete element open-source software ESyS-Particle to analyze the motion of 16 groups of jointed rock masses, revealing the internal force chain propagation law of rock masses during dynamic fragmentation, and discovering that joints were the primary cause of contact stress concentration and obstruction of stress wave propagation. PFC is a discrete element particle approach based on the BPM (Bonded Particle Model) model, which may more accurately reflect the mechanical characteristics of rock masses by integrating rock masses with bonding bonds between discrete units (Potyondy and Cundall, 2004). When the external stress surpasses a certain threshold, the bond fails and the fracturing effect occurs.

Thus, this paper builds a generalized slope model of rockfall impact and fragmentation through statistics of typical cases in Guizhou and uses discrete element software PFC2D to simulate the impact and fragmentation process, focusing on the analysis of the effects of fall height and slope on rockfall impact force, velocity, crack development and fragmentation block size distribution characteristics. The research findings can give substantial technological support for the scientific prevention and management of rock avalanche catastrophes in mountainous regions.

2 METHODOLOGY

2.1 Methods for model development

The PFC2D discrete element technique analyzes the material as a collection of discrete units and employs a contact instantaneous model to compute the contact forces between the contacting particle units, based on Newton's second law, to derive the force state of the discrete units. During the computation, the displacement and force conditions of neighbouring contact sites are recorded in real time by establishing record monitoring points. The software includes three types of contact models: contact stiffness model, sliding model, and parallel bonding model. The parallel bonding model can transfer forces and moments between particles, and its bonding strength has a good correlation with the strength of the rock material, allowing it to simulate the rock fragmentation process effectively. As particles move in concert, they create not only tension and shear stresses but also moments that restrict the particles' ability to rotate in concert. As external pressures exceed tension and shear stresses, the parallel bond model fails and fractures form in the rock mass; when the cracks penetrate, the rock mass seems to be fractured.

2.2 Numerical computation model creation

The statistics of 27 typical prototype instances in Guizhou were utilized to develop a computer model of the slope impact fragmentation process caused by a rock avalanche. The slope's geometric properties primarily consist of slope form, slope height, and slope gradient. The generalized slope calculation model is shown in Figure 2. The model slope height is 180m, the middle slope is 30°, 45°, and 60°, the toe slope is 10°, and the rock mass fall height is 10m, 20m and 30m. The rock body measures 20 meters by 20 meters with a level dip of 20 degrees, a joint dip of 70 degrees, and a joint penetration of 0.5 meters. As indicated in Table 1, a total of nine sets of experiments were designed. This work adopts a 1:1 model to replicate the rock-free fall impact slope fragmentation process, without addressing the initiation phase, to limit the size effect. The model comprises 23960 randomly generated bound particles. A parallel bonding model is used between the particles, a linear contact model is established between the particles and the wall, and a smooth jointing model is employed for the jointing contact approach.

Table 1. Parameters of the test.

Test number	Impact face angle	Lithology	Fall heights	Rock stratum dip angle	Joint dip angle	Through Degree
1	30°	limestone	10m	20°	70°	0.5
2	30°	limestone	20m	20°	70°	0.5
3	30°	limestone	30m	20°	70°	0.5
4	45°	limestone	10m	20°	70°	0.5
5	45°	limestone	20m	20°	70°	0.5
6	45°	limestone	30m	20°	70°	0.5
7	60°	limestone	10m	20°	70°	0.5
8	60°	limestone	20m	20°	70°	0.5
9	60°	limestone	30m	20°	70°	0.5

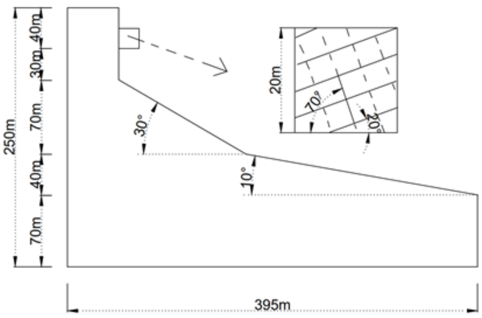


Figure 2. Numerical model of dynamic fragmentation.

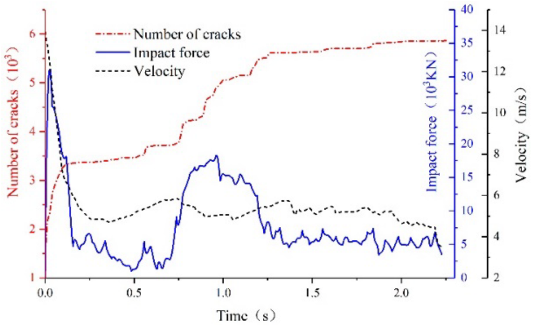


Figure 3. Curves of rock mass velocity, number of cracks, and ground impact force over time.

2.3 Numerical simulation parameter calibration

The parameters of the numerical simulation were calibrated using the results of static uniaxial compression measurements conducted on rock samples in the field. The fine-view parameters under uniaxial compression loading were derived from the final calibrated uniaxial compression loading without taking the compression-density section into account. The uniaxial compression stress-strain curves derived from simulations of fine-view parameter values are in general agreement with the two sets of indoor testing, and the fine-view parameter values were chosen according to Table 2.

Table 2. Micro-properties of limestone.

Microparameters	Value	Microparameters	Value
Density /(kg*m^3)	2600	Poisson's ratio	0.1
Minimum particle size/mm	0.5	Parallel bond modulus/(GPa)	25
Particle size ratio (R_{max}/R_{min})	1.66	Parallel bond stiffness ratio	2.5
Modulus /(GPa)	25	Parallel bond normal stiffness /(MPa)	20
Stiffness ratio	2.5	Parallel bond tangential stiffness /(MPa)	15

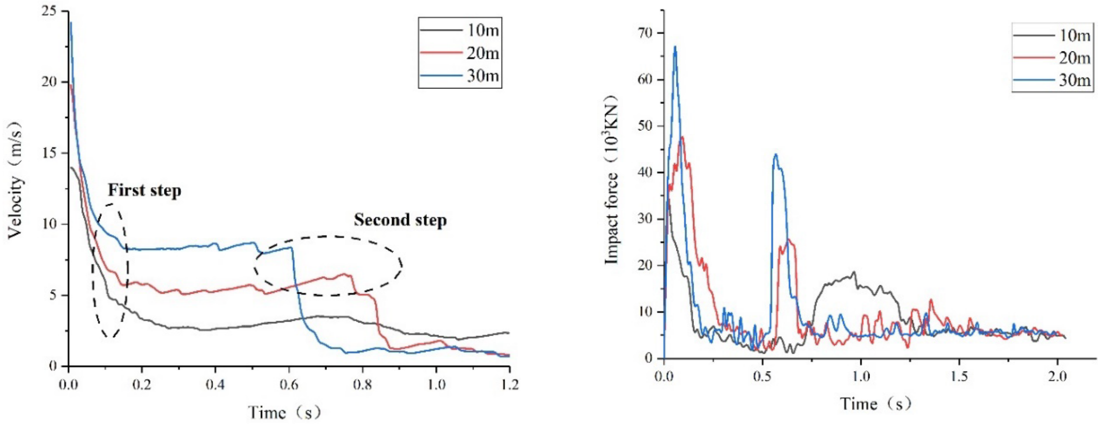
3 RESULTS

3.1 Phases of the impact fragmentation method

Figure 3 illustrates the link between velocity, number of fractures, and impact force development over time at the point of monitoring the centre of gravity of the boulder mass. Contact-disintegration stage (0-0.13s), the velocity drops rapidly and the rock mass disintegrates along the level and semi-through joints, with a rapid increase in the number of cracks and a small amount of debris produced. In the extrusion-fragmentation phase (0.13s-1.20s), the fragmented blocks begin to separate from one another. As a result of the interaction between the inertial force and the slope response force, the fragmented blocks begin to compress one another. At this point, the impact force is violently oscillating, a dense number of cracks are formed, and stress waves propagate and reflect back and forth in the rock mass until the number of cracks essentially remains constant, the fragmentation process is essentially complete, and the impact force is drastically reduced. In the independent movement phase of the fractured block (after 1.2s), the block velocity falls gradually, the impact force varies at a low horizontal position, and the number of fractures remains essentially constant.

3.2 *Impact of drop height on the process of impact fragmentation*

As shown in Figure 4, the influence of varied fall heights (10m, 20m, and 30m) on the impact fragmentation process was analyzed using a 30° impact surface slope. The velocity reduces in a straight line when the bulk of the rock disintegrates upon impact with the slope. 10m fall height, the rock mass core velocity declines abruptly and then continues to fluctuate and decrease, but for 20m and 30m fall heights, the rock mass core velocity decreases sharply after a brief oscillation. While impact fragmentation is an energy-intensive operation, if the total potential energy of the rock body is low, and the block's kinetic energy after fragmentation is low. In contrast, if the total potential energy is high, resulting in a subsequent reduction in velocity below the velocity of the 10 m fall height. It can be observed that as the fall height increases, the "secondary step phenomenon" on the velocity-time relationship curve becomes more pronounced, and as the fragmentation energy consumption rises, the degree of fragmentation increases.



a Velocity-time curves   b Impact force-time curves

Figure 4. Curves of rock mass velocity, crack number and ground impact force with time at different heights.

The curve of the rock impact force vs time is depicted in Figure 4b, which demonstrates a "double peak phenomenon." The "first peak" occurs almost instantly, when the lower left corner of the rock body has just touched the slope, and energy is released instantaneously; the "second peak" occurs earlier and is shorter in duration as the fall height increases, indicating that the greater the total potential energy of the rock body, the shorter the duration of the mutual crush collision. The shorter the collision's duration.

3.3 *Effect of slope gradient on the process of impact fragmentation*

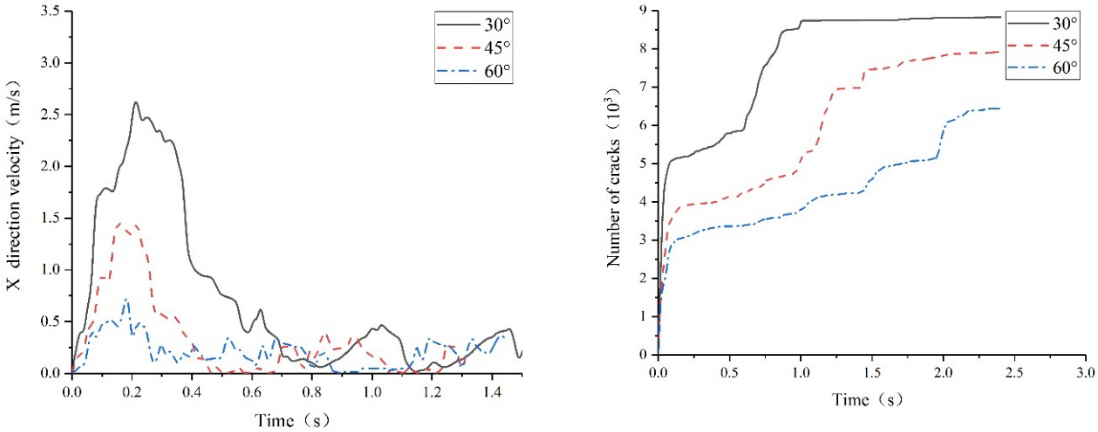
As illustrated in Figure 5, a fall height of 20m was used to examine the influence of internal cracking, stiff slope force, and velocity variation on the impact fragmentation process of the core rock at varied impact surface slopes (30°, 45°, and 60°). It can be observed in Figure 5a that the smaller the slope of the impact surface, the more the loss of kinetic energy and the greater the velocity change during the impact fragmentation process. In addition, when the impact surface's slope increases, the rock impact process becomes less severe, there is no apparent time separation between the first and second stages of rock fragmentation, and the "step phenomenon" of velocity change in the y-direction vanishes. As shown in Figure 5b, as the slope of the impact surface lowers, more and quicker fractures are generated in the rock mass.

4 CONCLUSIONS

In this research, the PFC2D discrete element approach is used to investigate the dynamic fragmentation features of the collapsed body under varied fall heights and impact surface slope circumstances, and the following findings are derived.

(1) The impact fragmentation process of rock avalanche slopes has distinct temporal features, i.e. fragmentation happens initially near the impact site, then disintegration occurs along the face and joint surface, and a new fracture surface is generated within the block.

(2) Under the conditions of different fall heights, there is a "step effect" in the velocity variation of rock avalanche slope impact, and a "double peak phenomenon" in the impact force; under the conditions of different impact slopes, as the angle increases, the impact fragmentation process becomes less violent, and the variation of impact velocity becomes more pronounced. The "step phenomena" progressively fades away, while the "double-peak phenomenon" of impact force becomes less apparent.



a Velocity-time curve in the X direction　　　b Number of cracks-time curves

Figure 5. Curves of rock mass velocity, crack number and ground impact force with time at a different impact angle.

REFERENCES

Tang H M, Yi P Y. Research on dangerous rock movement route[J]. Journal of Chongqing Jianzhu University, 2003, (1):17–23. (in Chinese with English abstract).

He SM, Wu Y, Shen J. Simplified calculation of impact force of massive stone in debris flow[J]. Journal of Natural Disasters,2009,18(5): 51–56(in Chinese with English abstract).

A. Giacomini, O. Buzzi, B. Renard. Experimental studies on fragmentation of rock falls on impact with rock surfaces[J]. International Journal of rock mechanics and mining sciences,2009,46(4).

Øystein Thordén Haug,Matthias Rosenau,Karen Leever, et al. On the energy budgets of fragmenting rockfalls and rockslides: Insights from experiments[J]. Journal of Geophysical Research: Earth Surface,2016,121(7).

Lv Q, Zhou C F, Yu Y, et al. Experimental study on fragmentation effects of rockfall impact upon slope[J]. Chinese Journal of Rock Mechanics and Engineering,2017,36(Suppl. 1): 3359-3366(in Chinese with English abstract).

Lin Q W, Cheng Q G, Li K, et al. Contributions of Rock Mass Structure to the Emplacement of Fragmenting Rockfalls and Rockslides: Insights From Laboratory Experiments[J]. Journal of Geophysical Research: Solid Earth,2020,125(4).

Wang Y, Tonon F. Discrete element modeling of rock fragmentation upon impact in rock fall analysis[J]. Rock mechanics and rock engineering,2011,44(1): 23-35.

De Blasio F V, Crosta G B. Fragmentation and boosting of rock falls and rock avalanches[J]. Geophysical Research Letters,2016,42(20):8463-8470.

Zhao T,Crosta G B,Dattola G,et al. Dynamic fragmentation of jointed rock blocks during rockslide-avalanches: Insights from discrete element analyses[J]. Journal of Geophysical Research: Solid Earth, 2018, 123(4):3250-3269.

Potyondy D O, Cundall P A. A bonded-particle model for rock[J]. International journal of rock mechanics and mining sciences, 2004, 41(8): 1329-1364.