

Experimental Study on Rockfall Mechanism of Platy Rock on a Complex Slope

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Received: 9 February 2020; Accepted: 16 April 2020; Published: 20 April 2020

Abstract: The rock fall trajectory and its mechanisms are the most difficult to predict, owing to the complexity of the slope and the Irregular shape of falling rocks. To acquire a better knowledge of the rock fall mechanism of platy rock and to investigate the influence of various impact parameters, a comprehensive physical model experimental study was undertaken based on 3D printing technology using a high-speed camera and specially developed block release system. Based on the experimental results, the effects of the slope angle on the stopping position, the instantaneous kinetic energy and collision position of platy rock block were analyzed. Meanwhile, the effects of movement forms of platy rock before and after collision on the normal coefficient of restitution and the tangent coefficient of restitution were discussed. It is observed that rock fall trajectory depends not only on slope material characteristics, slope angle but also on factors related to the platy block (weight, size and shape). The experimental results showed the value of restitution coefficient exceeding 1 has an important relation with the combination of various movement forms (including the flip motion) and the change of movement forms of platy rock before and after the collision. A new feasible experimental method for research and prevention of rock fall disaster was put forward. It would be important and helpful to the geo-hazard control work.

Keywords: rock fall; complex slope; platy rock; 3D printing technology; model test; rock fall trajectory

1. Introduction

Rockfall hazards is a kind of geological hazards that occurs frequently. Statistics from China's geological environment information site shows that rock fall has become one of the major geological hazards in China. For example, in 2016, there was 9710 geological hazards in China, of which 1484 were rock fall hazard, accounting for 15.3% of the total, resulting in 405 dead or missing, and a direct economic loss of 3.17 billion yuan [1]. In 2017, a total of 7521 geological hazards occurred across the country, resulting in 354 dead or missing persons and a direct economic loss of 3.59 billion yuan [1]. In 2018, 2966 geological hazards occurred in China, including 858 rock fall hazards, accounting for 28.9%, resulting in 112 dead or missing persons, and a direct economic loss of 1.47 billion yuan [1]. Rockfall hazards has caused a great threat to life and property. Rockfall hazards are characterized by strong uncertainty, randomness, and concealment, in which the shape of the falling rock is one of the important factors affecting the uncertainty of the rock fall on a rocky slope. However, it is still very

difficult to predict and prevent the rock fall hazards using the current experimental method. To reduce the loss caused by the rock fall hazards, it is necessary and important to study the rock fall mechanism of irregularly shaped falling rock using new experimental methods.

In recent years, many scholars have carried out a series of studies on the characteristics and protection measures of rock falls of falling rocks using theoretical analysis, field investigation, statistical analysis, experimental methods, numerical simulation analysis, etc., focusing on the uncertainty of the rock fall of a rocky or soil slope around falling rocks shape, size, falling orientation, and slope angle, providing a theoretical basis for the prevention and control of collapse disasters [2–31]. Among these, the physical model experiment is an important means of analyzing the motion mechanism of falling rock collapses. To facilitate the study, the scholars have simplified the laboratory model experiments, including simplifying the irregular slope shape to a straight slope with adjustable slope angle, and the falling rock to ball block, square block, strip block, etc. For example, by way of the simplified laboratory model experiment, researchers have confirmed that the rebound and recovery coefficient of the rock fall block does not only depend on the material characteristics of the slope; but it is also closely related to the slope angles, collision velocity, weight, size and shape of the block [2,12,32]. The simplified laboratory model experiments and numerical simulations have been done to find that steep slopes and hard ground surfaces cause a high bounce height of falling rocks. Moreover, light rocks bounce higher than heavy rocks, and rocks with round shapes bounce high initially and then roll further away from the falling slope [33]. Much work has been carried out on the relationships between the maximum impact force and the kinetic energy, and modulus of elasticity determined by model experiments [34]. A number of laboratory model experiments have been conducted on simulating the motion characteristics of rock fall impact slope [14], and an empirical model has been proposed to estimate the lateral dispersion W/L of cubical blocks with different mass and release height [35] and the mechanism of the instability of potentially falling rock at the entrance of a tunnel and the characteristics of collapse movement of falling rock have been analyzed [11]. A volume of work has been done on analyzing the influence rule of impact velocity, block mass and block hardness on the rock fall recovery coefficient [3]. Several studies have been performed on the variation rule concerning the coefficient of restitution of a spherical pebble impact slope [6]. The results of some laboratory model experiments discovered that the restitution coefficients in excess of unity. The cause was considered to be a combination of parameters such as low impacting angle, rotational energy and block angularity [5,36–40].

The above laboratory physical model experiment methods have provided a good explanation of the rock fall movement characteristics of regular falling rock on an inclined slope and have good guiding significance. However, because the slopes and the falling rocks in nature are more complex and irregular [31], the movement type of the irregular falling rocks is also diverse before and after the collision. The above researches had not analyzed and summarized the movement types of the irregular block before and after the collision and the effects of movement types on the normal coefficient of restitution and the tangent coefficient of restitution had not been discussed. Based on this, this paper takes the Xiangbipu rock slope in the Shexianju scenic spot in Zhejiang Province as an example, using a three-dimensional modeling with unmanned aerial vehicle (UAV) tilt photography, to accurately identify the potentially platy falling rock (in one direction, the length, width and height ruler are clearly smaller than the other two directions), construct the three-dimensional model of the slope, and use 3D printing technology to reconstruct the slope and falling rock model. Through the self-developed release device of falling rocks, the rock fall trajectory of platy rock is reproduced repeatedly using a high-speed video camera. On this basis, the rock fall mechanism of platy rock is studied to provide a reference for the design of passive protective measures for protection against geological hazards.

2. Model Experiment

The purpose of this experiment is to study the movement law of the platy rock in the complex steep rock slope through the physical model experiment of the potential platy falling rock in the Xiangbipu rock slope in Shenxianju scenic spot in Zhejiang Province and provide a reference for the design and construction of engineered protection. It shows the shape of the slope and potentially platy rock of the Xiangbipu in Shenxianju scenic spot in Figure 1. Through field investigations, UAV aerial photography and 3D laser scanning, the potential falling rock was identified. The size of the potential falling rock was 12.14 m (length), 1.96 m (width) and 19.02 m (height) and the main lithology of the slope body is tuff.

In this experiment, 3D printing was used to make the physical models using the polylactic acid material (PLA). The physical and mechanical parameters of PLA materials and tuff obtained through laboratory experiments including density test, uniaxial compressive strength test, Brazil splitting strength test, tri-axial compression test are shown in Table 1. According to dimensionless analysis, the similarity constants of the model were determined as shown in Table 1. According to the similarity constant in Table 1, the size of the falling rock was scaled at 1:150, as shown in Figure 1.

Table 1. The physical and mechanical parameters of slope model material.

Indicators	Physical Quantities	Slope Prototype (Tuff)	Physical Model (PLA)	Similarity Constants
Material Parameters	Modulus of Elasticity (Pa)	7.73×10^9	3.48×10^9	$S_E = 0.45$
	Density (kg / m^3)	2892	1000	$S_\rho = 0.35$
Geometric Features	Width (m)	84	0.56	$S_l = 0.004$
	Height (m)	240	1.6	$S_l = 0.004$

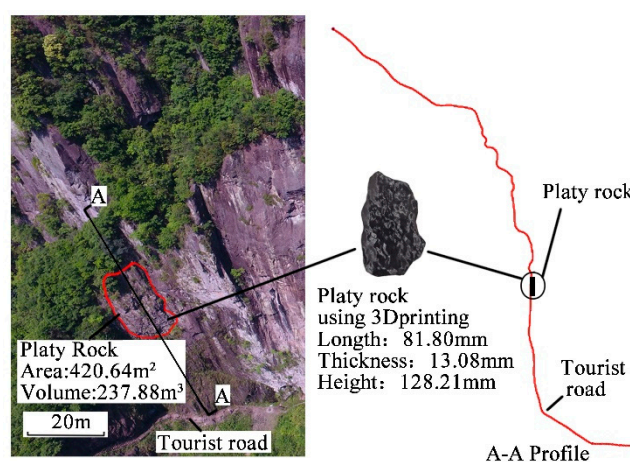


Figure 1. Shenxianju Xiangbipu slope.

2.1. Model Experiment System

As shown in Figure 2, the model experiment system consists of a slope model, block release device and data acquisition system.

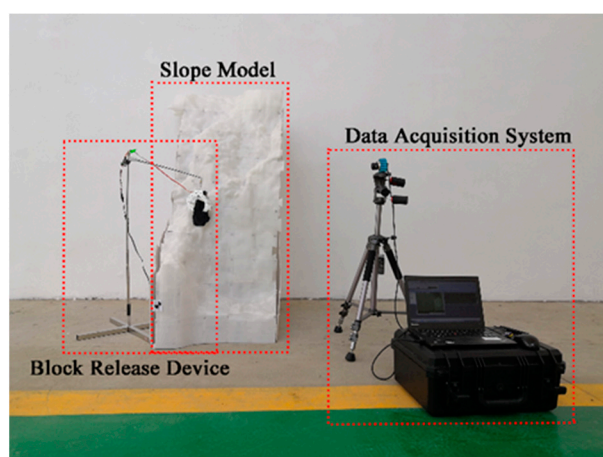


Figure 2. Schematic diagram of the experiment equipment (unit: mm).

2.1.1. Slope Model

According to the geometric similarity constant $S_l = \frac{1}{150}$, the slope model is scaled to a 3D model of 1 m × 1.5 m (width and height). The 3D printer (Einstart-p, SHINNING 3d technology co., LTD Hangzhou, China) was used to cut the model into mortise and tenon blocks suitable for printing size (as shown in Figure 3) with printing, splicing, and hot melt adhesive for forming, to prevent the free movement of each module in the direction of x, y, or z. After printing and splicing, the final slope model is shown in Figure 2.

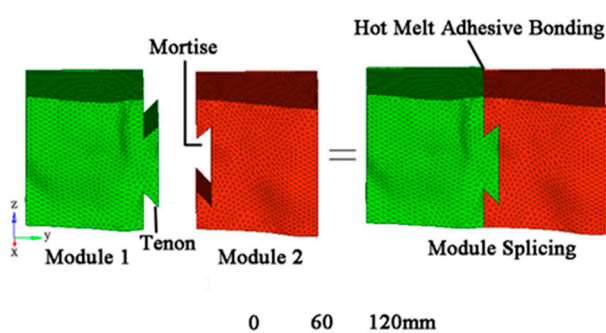


Figure 3. Schematic diagram of the experiment equipment (unit: mm).

2.1.2. Block Release Device

The block release device is composed of five parts (as shown in Figure 4), including the base, vertical extension rod, horizontal extension rod, mechanical gripper, and control circuit board. According to the size of the slope model and the position of the rock fall block, the release device can control the position of the mechanical gripper by adjusting the positions of the vertical and horizontal expansion rods. By controlling the circuit board, the grasping and releasing action of the mechanical gripper can be operated. Therefore, the initial position of the rock fall block stone can be accurately controlled and the interference of human factors can be effectively avoided.

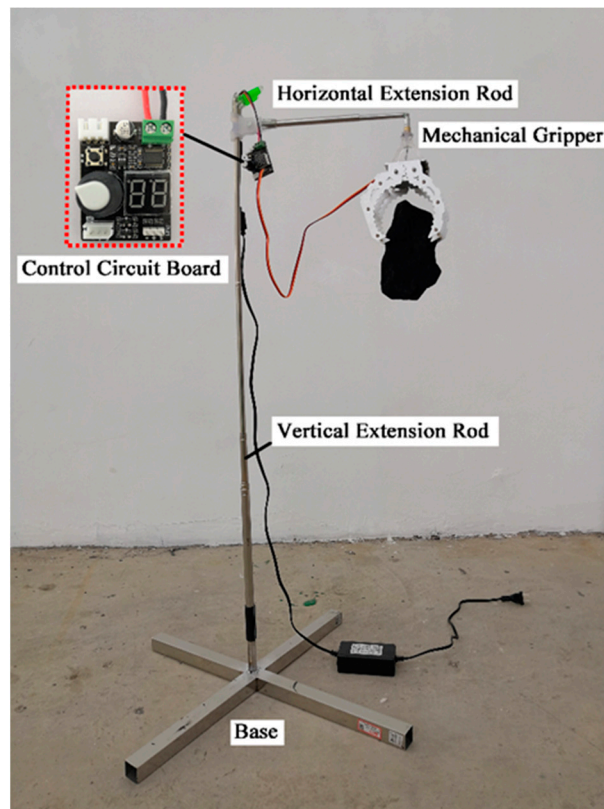


Figure 4. Block release device.

2.1.3. Data Acquisition System

As shown in Figure 5, the data acquisition system is composed of a high-speed camera FR800 (NorPix, Inc. , Montreal, Canada), Thinkpad computer and the software TroublePix v3.2.1.124, for high-speed digital video (NorPix, Inc. , Montreal, Canada). The frequency of image acquisition is 800 frames per second.



Figure 5. Data acquisition system.

2.2. Experimental Procedure

The experiment is carried out according to the following procedures:

(1) According to the principle of aerial photogrammetry [41], the slope image data was acquired using the tilt photography of five routes, including East, South, West, North and orthoimage, with the help of a PHANTOM 4 UAV(SZ DJI Technology Co., Ltd. , Shenzhen, China). Among them, the UAV camera of the East, South, West and North routes form a 45° angle with the horizontal plane,

and the UAV camera of the orthoimage route forms a 90° angle with the horizontal plane. Using software such as ContextCapture Center Master v4.4.14.60 (Bentley Systems, Incorporated, Exton, United States), Autodesk ReCap 6.0 (Autodesk Inc., San Rafael, USA) and Cyclone 9.1 (Leica Geosystems AG, Gallen, Switzerland), combined with the principle of reverse modeling [42,43], the collected image data is generated into a three-dimensional model, and then, the position, shape, size, area and volume of the platy rock of the slope are identified.

(2) According to the principle of geometric similarity to scale the model, print and splice the slope and the platy rock model using Einsert-p (SHINNING 3d technology co., LTD Hangzhou, China).

(3) Use the block release device to grasp the platy rock and adjust the vertical and horizontal extension rods of the block release device to place the platy rock at the initial position.

(4) Open TroublePix v3.2.1.124 software, set the influence collection frequency to 800 frames/second, and release the platy rock through the block release device after data collection begins.

(5) Capturing the complete rock fall motion video of the platy rock using TroublePix v3.2.1.124 software.

(6) In this experiment, repeat Steps (3) to (5) were performed 70 times to obtain sufficient data corresponding to repeated experiments for the rock fall of the platy rock.

3. Experimental Results and Analysis

According to the experimental procedure described in Section 2.2, 70 repeated experiments were conducted on the rock fall of the platy rock of the xiangbipu slope in the Shexianju scenic spot. The experiment results are shown in Figure 6.

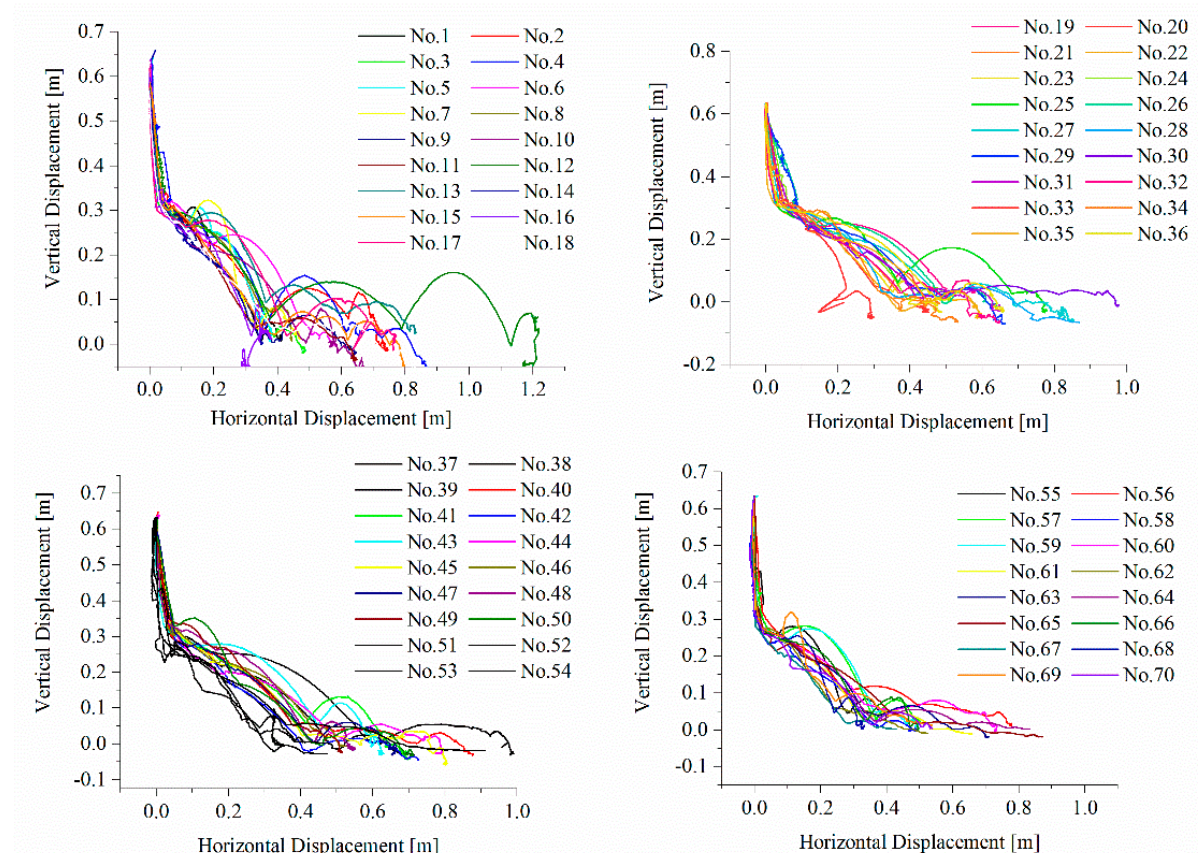


Figure 6. Results of repeated experiments on rock falls at Xiangbipu Slope.

The movement trajectory, shown in Figure 6, indicates that when the rock fall occurs, platy rock moves in free fall along the steep slope at the top of the slope, colliding at the gentle slope and making

a bouncing or sliding movement. After multiple bouncing collisions, the platy rock slides along the gentle slope at the foot of the slope and stops at the gentle slope outside the foot of the slope. The repeated experiment shows that there is a great safety hazard in the viewing lounge area. Because it is the area that the platy rock must pass through when it collapses.

3.1. Rockfall Movement Trajectory

By using a high-speed camera, the process of the rock fall movement of the platy rock is restored, and the rock fall movement of the platy rock on the steep rock slope can be divided into four processes: rock fall initiation, block falling, block sliding (or bouncing), and rock fall stopping, as shown in Figure 7.

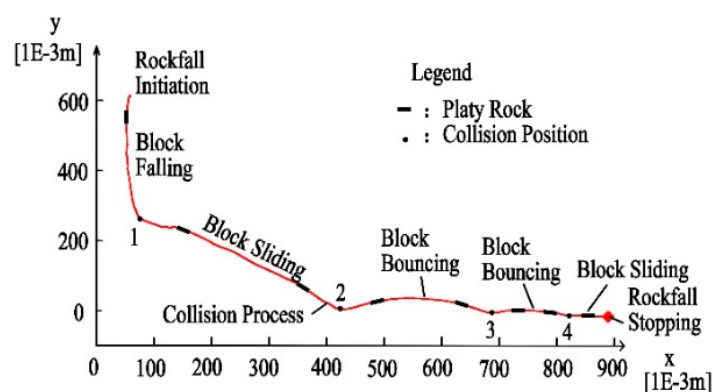


Figure 7. The rock fall trajectory of the platy rock.

3.2. Stopping Position Analysis of Platy Rock Rockfall

After rock fall initiation, the platy rocks moved on the slope and constantly collided with the slope. Finally, all the platy rocks stopped in the platform area (EF) outside the slope foot. Figure 8 shows the section of the experimental slope. Figure 9a shows the results of 70 times repeated experiment.

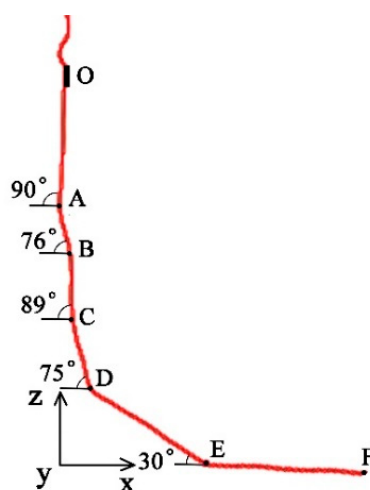


Figure 8. The profile of the experimental slope.

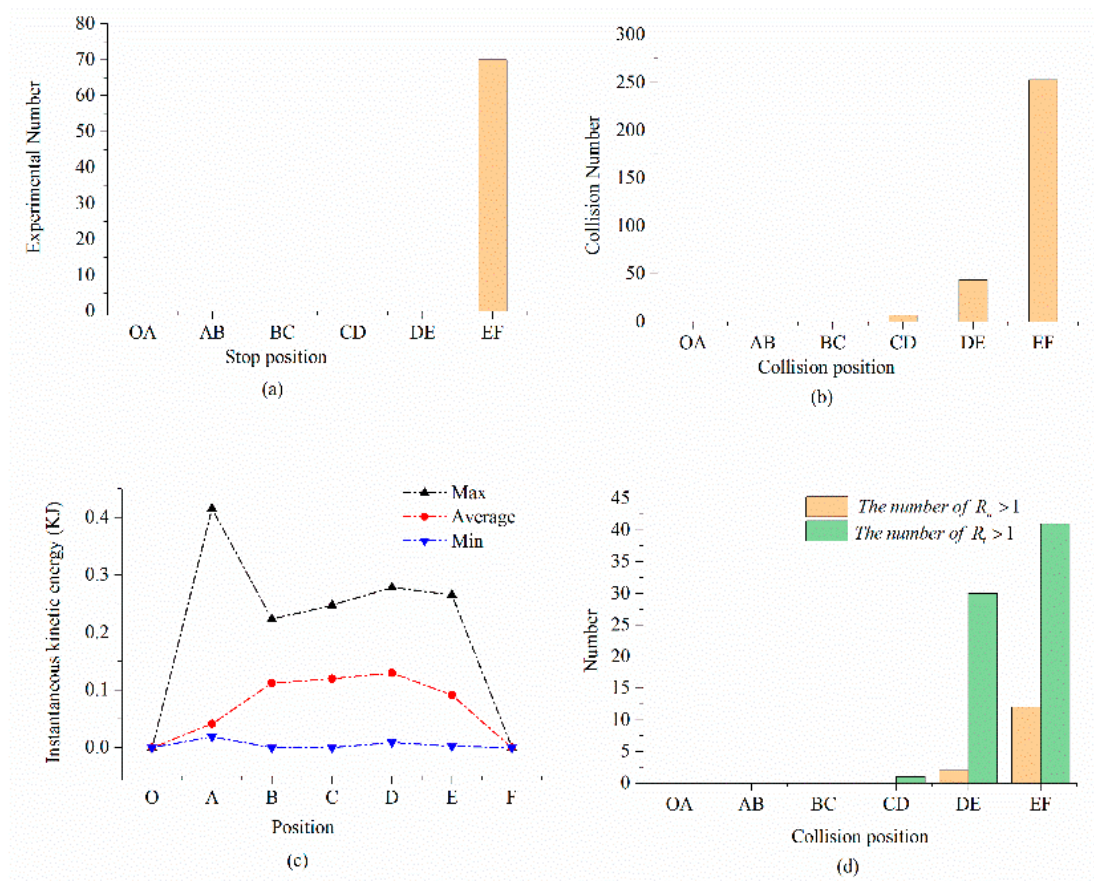


Figure 9. (a) The stop position of the platy rock movement; (b) collision position of platy rock movement; (c) the instantaneous kinetic energy curve platy rock movement; (d) the slope position of the collision point where $R > 1$.

The experiment shows that the platform can limit the rock fall movement and reduce the rock fall threat to the construction.

3.3. Collision Position Analysis of Platy Rock Movement

In the 70 repeated experiments, 303 collisions have occurred between the platy rock and the slope. Figure 9b shows that the collision position of the platy rock rockfall was related to the slope. The collision and bouncing have occurred in the areas of CD, DE and EF with gentle slopes. The sliding has occurred in the areas of OA, AB and BC with steep slopes.

Figure 9c shows that the instantaneous kinetic energy of platy rock has increased during the period of free fall and sliding movement (O~C area in Figure 9c). During the collision (C~F area in Figure 9c), the instantaneous kinetic energy of platy rock has decreased. Therefore, collision is an important way to consume the energy of platy rock fall.

The above analysis shows that the collision probability of platy rock in the gentle slope area is higher than that in the steep slope area. At the same time, the collision process consumes part of the energy of platy rock fall. The probability of the rock fall movement stopping in the platform area is higher than other area. Therefore, cutting slope and platform design is an important engineering measurements to consume the energy of platy rock rockfall and reduce the risk.

3.4. The Analysis of Restitution Coefficient

The coefficient of restitution can express in terms of velocities or energies, indicating the amount of velocity or energy dissipated during the ground collision [2,17,19,22,32]:

$$R_n = \frac{|v_{rn}|}{|v_{bn}|}, \quad R_t = \frac{|v_{rt}|}{|v_{bt}|}, \quad R = \frac{E_r}{E_b} = \frac{m(v_{rn}^2 + v_{rt}^2) + I(\omega_r)^2}{m(v_{bn}^2 + v_{bt}^2) + I(\omega_b)^2} \quad (1)$$

where v and ω are the translational and rotational velocity respectively, m is the mass and I is the moment of inertia about the center of the platy rock. The subscripts “ r ” and “ b ” characterize the velocity or energy before and after the collision, respectively.

Considering that the movement process of the platy rock during the collision is more complex and the duration is very short, it is difficult to accurately capture the immediate velocity before and after the collision, and the error is very large. Therefore, to facilitate the analysis, the author defines the coefficient of restitution as the ratio of the average velocity of the rebound stage after the collision to the average velocity of the compression stage before the collision, that is:

$$\bar{R} = \frac{\bar{E}_r}{\bar{E}_b}, \quad \bar{R}_n = \frac{\bar{v}_{rn}}{\bar{v}_{bn}}, \quad \bar{R}_t = \frac{\bar{v}_{rt}}{\bar{v}_{bt}} \quad (2)$$

In the above formula, R, R_n, R_t are the restitution coefficients, the normal coefficient of restitution and the tangent coefficient of restitution, respectively. $\bar{E}_r, \bar{v}_{rn}, \bar{v}_{rt}$ are the average energy dissipated, the normal average velocity and the tangent average velocity of the platy rock after the collision, respectively. $\bar{E}_b, \bar{v}_{bn}, \bar{v}_{bt}$ are the average energy dissipated, the normal average velocity and the tangent average velocity before the collision, respectively.

Among the 303 collisions, there were 86 times for $R > 1$. Of these, there were 14 times for $R_n > 1$ and 72 times for $R_t > 1$. This article has carried on thorough research on the 86 times for $R > 1$ and related causes were investigated.

The experiment found that the motion type of platy rock before and after the collision was a combination of one or more motion types in Figure 10. These collisions have mainly occurred in the area of DE (slope angle $i = 30^\circ$) and EF (slope angle $i = 0^\circ$) with slow slope (as shown in Figure 9d).

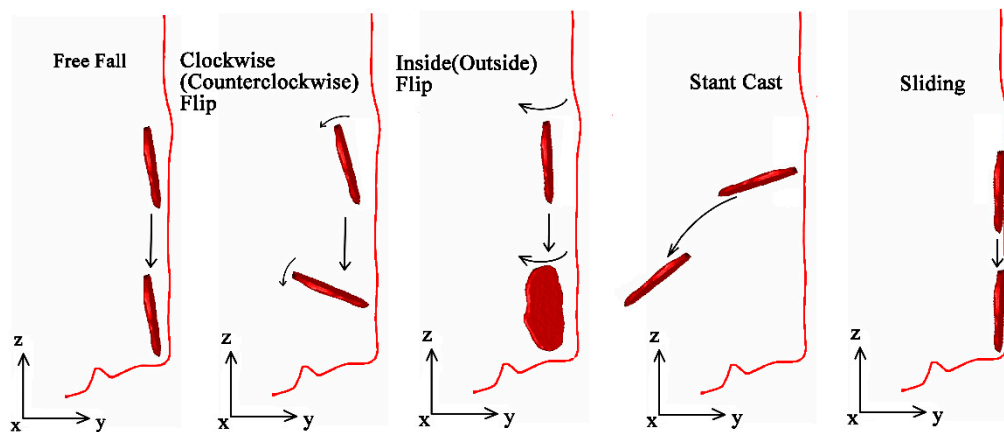


Figure 10. The basic type of motion of the platy rock.

Figure 11 shows that under the condition of the same slope, the movement type of platy rock before and after the collision was an important reason for the occurrence of $R_n > 1$. In the fourteen times of collisions with $R_n > 1$, there were six types of motion before and after collision respectively and all of them include flip motion. There were two times of collisions in the EF area ($i = 0^\circ$) and twelve times of collisions in the DE area ($i = 30^\circ$). In the EF area, the movement types have changed before and after the collision. The average value R_n was different for different movement types. The same characteristics have also held in the DE area.

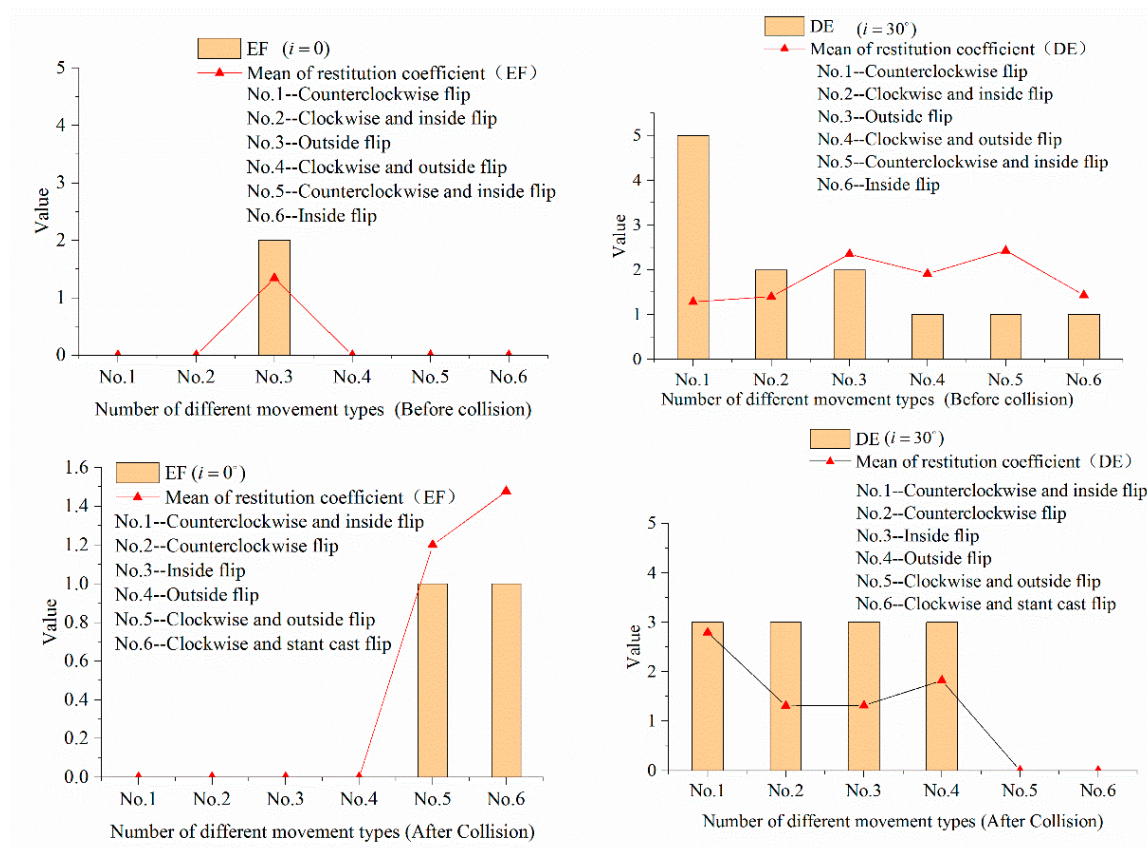


Figure 11. Movement type of platy rock and normal restitution coefficient.

Figure 12 shows that under the condition of same slope, the movement type of platy rock before and after the collision is also an important reason for the occurrence of $R_t > 1$. In the 72 times of collisions with $R_t > 1$, there were 41 times of collisions in the EF area ($i = 0^\circ$) and 31 times of collisions in the DE area ($i = 30^\circ$). In the EF area, there were thirteen types of motion before the collision and nine types of them include flip motion. The proportion was 69.2%. The average value R_t was different in various movement types. However, there were 12 types of motion after the collision and all of them include flip motion. The average value R_t was also different in various movement types. In the DE area, there were 13 types of motion before the collision and 10 types of them include flip motion. The proportion was 76.9%. There were 12 types of motion after the collision and 11 types of them include flip motion. The proportion was 91.7%. The average value R_t was also different in various movement types before or after the collision.

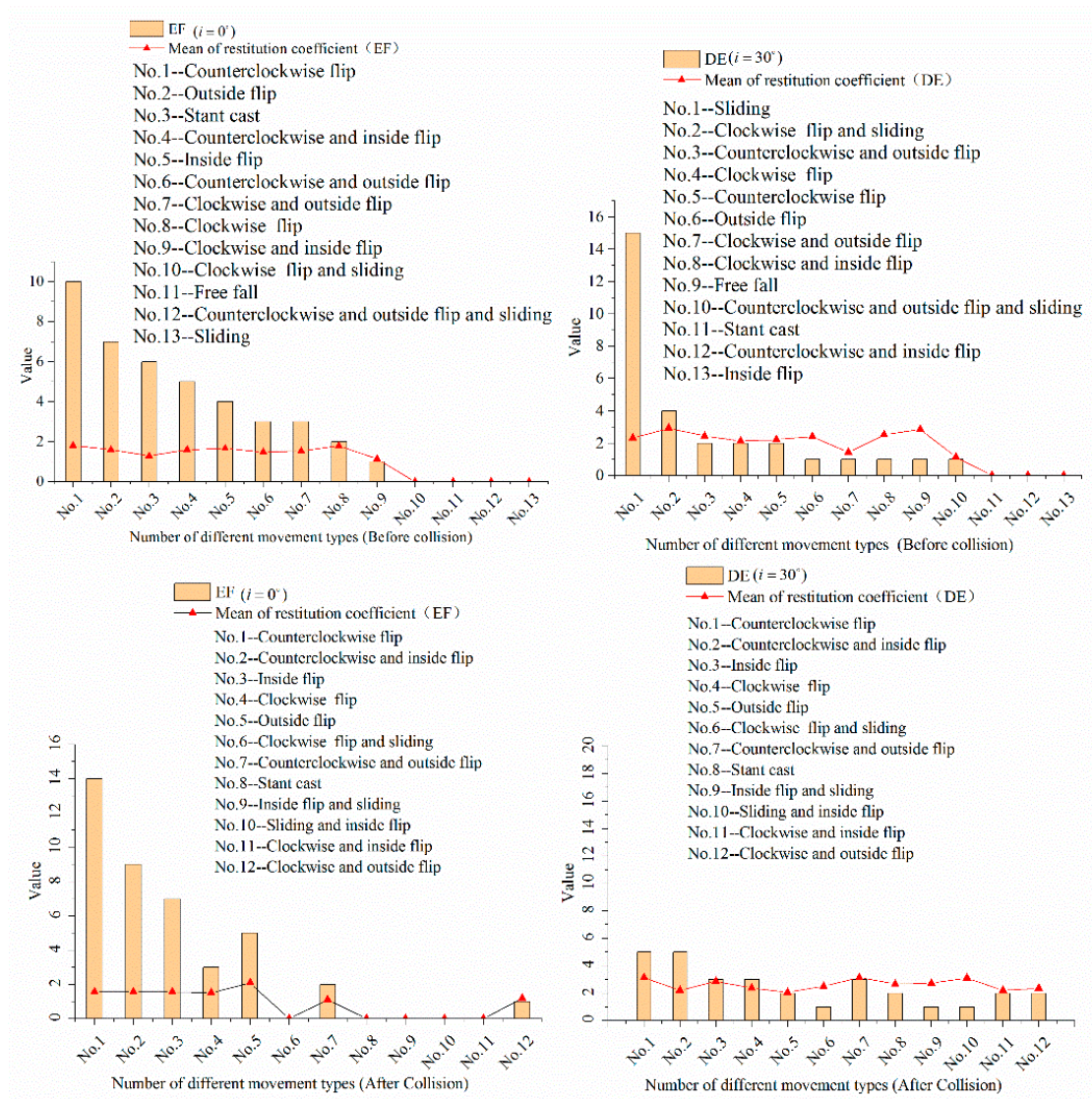


Figure 12. Movement type of platy rock and tangential restitution coefficient.

Figure 13 further illustrates that the change of motion type before or after the collision is also an important reason for $R_t > 1$ in platy rock rockfall.

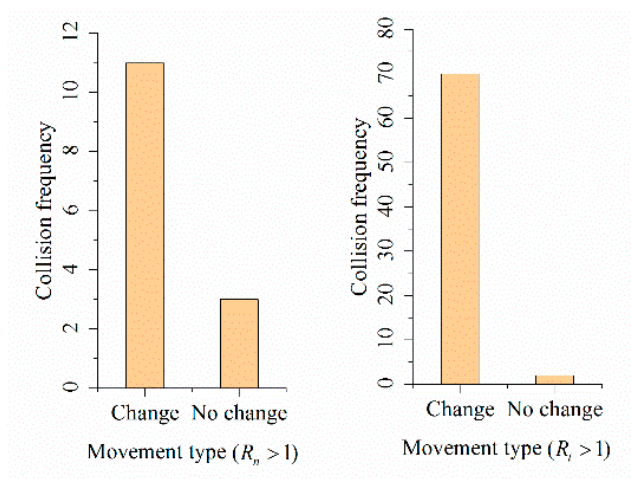


Figure 13. Change in the type of motion before and after the collision.

4. Discussion

The studies reported in this paper have sought to explore the mechanism of platy rock rockfall motion by the physical model experiment based on 3D printing technology as references for protection against rock fall disasters. This research method could better reproduce the platy rock rockfall process, suggesting that there is merit to the physical model experiment based on 3D printing technology.

The experimental results show that the trajectory of platy rock rockfall is different from that of other shapes [44]. Free fall, block sliding and block bouncing are the main movement types of platy rock, while block rolling is generally rare. These results can be explained by the complex and irregular shape of the platy rock.

The experimental results also confirm that the slope shape has an important influence on the stopping position and rock fall trajectory of platy rock. Our findings are substantial agreement with Huang Run-Qiu et al. [45]. The same rule is founded for instantaneous kinetic energy. Therefore, on the exposed rock slope, it is an effective engineering measurement by reducing the slope gradient and design platform in reducing the damage risk of the rock fall of platy rock.

Many scholars have found that the restitution coefficient is related to the block shape [2,46,47], the block mass [2,48], the Young's modulus [2,6,49,50], the dry density [51], the impact angle [2,6,46], the impact energy [2], the slope angle [2,6,46] and the drop height [2,48]. Restitution coefficients over unity have been reported by some researchers and the reason has been recognized by most scholars [5,36–40]. Our experimental results have confirmed that the restitution coefficient of platy rock was more likely to be greater than one in the low slope area than in the flat slope area because of the low impacting angle. It was consistent with the research results of other scholars. However, the experimental results also show that the restitution coefficient is also related to the movement type before and after the collision. The combination of various movement types (including the flip motion) and the change of movement types are important reasons bring the normal and tangential restitution coefficient is greater than one.

This paper only presents a model experiment method and the qualitative description for a single irregular platy rock rockfall mechanism under the conditions of the complex rock slope with a single lithology based on the method. Further work should be performed to quantitative statistical and regression analysis of the uncertain relationship between the movement types of platy rock regarding the fragmentation and the irregular shape with complex lithology based on the experiment method. It would provide a reference for engineering protection against rock fall and the modification of rock fall numerical simulation method.

5. Conclusions

In this study, a physical model experiment of the rock fall based on 3D printing technology was carried out for studying the rock fall movement mechanism of platy rock under the complex slope shape.

The new physical model experiment method has unique advantages in reproducing the rock fall process of irregular shape platy rock in complex slope. This method may apply to other types of rock fall experiments as well.

The rock fall trajectory, stopping position collision position and the instantaneous kinetic energy change rule of platy rock fall are related to the irregular shape of the platy rock and the slope angle.

It seems that the restitution coefficient of platy rock rockfall is not only related to the block shape, the blocks, the slope angle and other factors, but also to the movement type before and after the collision. The combination of various movement types (including the flip motion) and the change of movement types before and after a collision are also important reasons for the value of restitution coefficient exceeding one.

Author Contributions: Conceptualization, X.L.; and Z.Y.; methodology, Z.Y.; formal analysis, J.S.; investigation, H.L. and J.S.; resources, Z.C.; data curation, Q.O.; writing—original draft preparation, X.L.; writing—review and

editing, X.L.; J.S.; L.L. and X.W.; project administration, L.L. and X.W.; funding acquisition, X.L. and Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Zhejiang Province Public Welfare Technology Application Research Project (CN) (Grant No. 2017C33190), the National Natural Science Foundation of China (Grant No. 41672321) and the Key Program of the Chinese Academy of Sciences (Grant No. KZZD-EW-05-02).

Conflicts of Interest: The authors declare no conflicts of interest.

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