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Analysis of Rockfall Hazards Stopping position and Energy dissipation Based on Orthogonal experiment

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Abstract. Many factors affect the movement of rockfall. Thus, this study explored the influence of rockfall shape, slope angle, angular velocity, slope hardness, rockfall mass, and slope surface roughness on the stopping position and potential energy loss rate based on an orthogonal experiment. To study the key factors affecting the movement of rockfall, 2500 sets of orthogonal tests were carried out by using ROCFALL 8.0 (ROCSCIENCE) numerical simulation program. SPSS19.0 software was used to perform importance analysis and correlation analysis on the test results. The analysis results show that rockfall shape has the greatest influence on the stopping distance. There is a significant positive linear correlation between the number of rockfall edges and the stopping distance of rockfall on the asphalt road. The slope angle has the greatest influence on the potential energy loss rate, and there is a significant negative linear correlation between the slope angle and the potential energy loss rate. In the case of a low angle slope, the stopping position of rockfall is more concentrated. Therefore, in the process of mountain engineering construction, more attention should be paid to the influence of rockfall shape and slope angle on rockfall hazard protection.

1 Introduction

Unstable rock mass will collapse under the influence of gravitational force, mechanical weathering, and the presence of interstitial water forming the rockfall hazard [1]. With the development of road construction in mountainous areas, rockfall often poses a threat to road safety, which causes serious damage to mountain roads and results in great losses both in lives and properties [2].

The movement of the rolling rock is affected by many factors, thus, it is hard to predict the trajectory of rockfall, namely, the zones under the threat of rockfall are still a problem [3][4]. The research results of the energy consumption of rockfall can provide data support for the design of the rockfall protection net. Among them, there are many factors that affect the energy loss rate of rockfall. For example, a study showed that as the impact angle increases, the normal coefficient of restitution during impact will decrease, and the kinetic energy loss rate will increase significantly [5]. The coefficient of restitution is affected by rockfall shape slope roughness, rockfall mass, slope materials, impact angle, and angular velocity, which controls the rebound process of rockfall in the collision, and then affect the trajectory of rockfall [6][7], from the physical model experiment, it is concluded that the more irregular the shape of the rock, the lower the coefficient of restitution [8]. Many scholars use numerical simulation programs to study the movement characteristics of rockfall, the influence of the rockfall shape on the movement is studied by the rigid body analysis method [9][10]. The influence of the rockfall shape and size on the bounce height can be studied by ROCFALL numerical simulation program, which shows the spherical rocks with irregular shape has high kinetic energy and bouncing ability [11]. The statistical analysis of rockfall stopping position and energy dissipation is difficult to be carried out by field test because of the high number of tests and the great cost of manpower [12], for this reason, ROCFALL 8.0 numerical simulation program is adopted to carry out a large number of groups of rockfall simulation experiments.

To study the area where the rolling rock stop and the causes of energy loss during the movement of rockfall, and provide engineering technical support for the prevention and control of rockfall hazard in mountainous highway areas. This study uses an orthogonal experiment to explore the influence of rock shape, slope angle, angular velocity, slope surface hardness, rockfall mass, and slope surface roughness on the stopping distance and potential energy loss rate, then obtains the critical factors that affect the rockfall motion. The law of the stopping position of rockfall is drawn, and the law that affects the energy loss of the rolling rock is summarized.

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2 Numerical simulation principle and model establishment

2.1 Basic assumptions

This experiment used ROCFALL 8.0 (ROCSCIENCE) to numerically simulate the movement of rockfall, which uses the rigid body analysis method to set the shape of the rock, the hardness of the slope (reflecting the impact crater caused by the impact of the rock on the slope), rolling friction, sliding friction, and the roughness of the irregular fluctuation of the slope as the input parameters. Besides, there is some hypothesis [13]: The mass of rockfall is large enough and it moves at low speed so that the influence of air resistance on the movement of rockfall can be ignored. In the process of collision, the broken condition of the rolling rock is never considered. The rock shape is a two-dimensional shape stretched in the third dimension to form a cylinder. The mass of the rolling rock in each test is constant.

2.2 Model establishment

2.2.1 Collision model

The coefficient of restitution is taken as the index to evaluate the energy consumption in the rockfall impact process, defining R_n and R_t, which are the most commonly used parameters in rockfall studies [14][15]. The equations are as follows:

Normal coefficient of restitution:

$$R_n = \frac{V_{n2}}{V_{n1}} \tag{1}$$

Tangential coefficient of restitution:

$$R_t = \frac{V_{t2}}{V_{t1}} \tag{2}$$

Where V_{n2}, V_{n1} and V_{t2}, V_{t1} are the normal and tangential components of the rock velocity before and after the collision.

2.2.2 Parameter setting of the numerical simulation model

In this numerical simulation test, discrete element slope body models of five slopes(30°, 40°, 50°, 60°,70°) were established (Fig. 1 shows discrete element analysis model of 60 ° slope). The slope surface material is selected as exposed bedrock, and the platform material at the bottom of the slope is selected as asphalt. Set the total height of the slope as 55m, and the rockfall release position is 5m above the top of the slope. Slope modeling process include the unevenness and looseness of the covering layer, the slope is set to five degrees of hardness: Soft (s), Medium soft (ms), Medium (m), Medium hard (mh), Hard (h). The smaller the slope hardness is, the greater the deformation of the slope overburden during the impact between rockfall and the slope surface, and more sliding friction will be generated during the impact process. Considering the uneven undulation of the overburden, the slope is set to five different roughness (R:1, 2, 3, 4, 5), Roughness decreases as the number increases [13]. Specific numerical simulation setting parameters [16] are shown in Table 1.

Table 1. Setting parameters of numerical simulation

Number of released rocks	100
Slope R_n	0.35
Slope R_t	0.85
Asphalt R_n	0.40
Asphalt R_t	0.90
Rockfall density(kg/m³)	2700
Horizontal velocity(m/s)	0.5
Vertical velocity(m/s)	-0.5

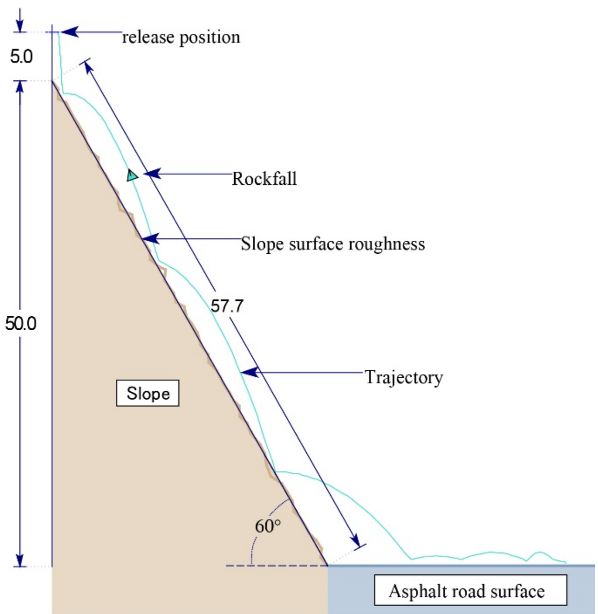

Fig. 1 Discrete element analysis model of 60 ° slope

2.3 Potential energy loss rate

According to the law of conservation of energy, define the total kinetic energy of rockfall before its first collision with the asphalt road as E, namely:

$$E = G - Q = Mgh\text{-}Q \tag{3}$$

Where, M is the mass of rockfall, kg; g is the acceleration of gravity, taking the value of 9.8m/s²; h is the initial releasing height of rockfall, with a value of 55m; G is the initial gravitational potential energy, kJ; Q is the energy lost by rockfall in the process of slope movement, kJ.

To explore the energy loss of rockfall in the process of moving on the slope, the concept of potential energy loss rate (P) is proposed. P is the ratio of the energy lost in the process of rockfall movement to the initial gravitational potential energy of rockfall. The P calculation formula is as follows:

$$P = \frac{Q}{G}100\% = \frac{G-E}{G}100\% \tag{4}$$

2.4 Orthogonal experimental design

The purpose of this study is to explore the influence of rockfall shape (S), slope angle (A), initial angular velocity (W), slope hardness (H), rockfall mass (M), and slope roughness (R) on stopping distance (D) (the horizontal stopping distance on asphalt road of rockfalls.) and potential energy loss rate of rockfall. To reduce the number of tests, the orthogonal test theory was used to design the test scheme [17][18]. Five kinds of angular rockfall were selected: triangle, tetragon, pentagon, hexagon, and octagon. (Fig.2)

The six parameters of S, A, W, H, M, and R were selected as the basic factors of the experiment, according to the characteristics of these factors, five levels were taken for each factor, the test method of factor influence analysis can be arranged in Table $L_{25}(5^6)$ [19] (Table 2).

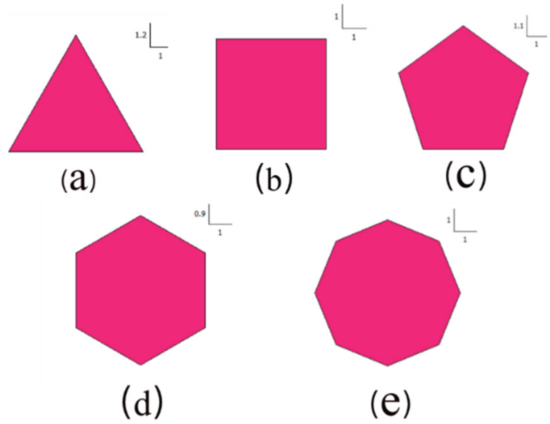

Fig. 2 Shapes of rock used in the simulation

(a) triangle, (b) tetragon, (c) pentagon, (d) hexagon, (e) octagon

Table 2 Factors and levels of orthogonal experiment

Factors Levels	S	A/(°)	W/(°/s)	H	M/kg	R
1	Triangle	30	0	Soft(s)	500	1
2	Tetragon	40	500	Medium soft(ms)	1000	2
3	Pentagon	50	1000	Medium(m)	1500	3
4	Hexagon	60	1500	Medium hard(mh)	2000	4
5	Octagon	70	2000	Hard(h)	2500	5

Considering the randomness of the rolling movement, the Monte Carlo sampling method was used to carry out a statistical analysis of rolling motion [13]. To make the results more representative, each test select 100 rocks, taking the average value of 100 rockfalls stopping distance as D. According to the 3σ criterion (68-95-99.7 principle), the data distributed in the (μ-σ, μ+σ) were taken as the total kinetic energy of rockfall. The orthogonal test results are listed in Table 3.

Table 3 Result of orthogonal experiment

No	S/ edge	A/ (°)	W/ (°/s)	H	M/ kg	R	E/kJ	D/m	P/%
1	3	30	0	s	500	5	0.00	0.00	100
2	3	40	500	ms	1000	4	71.30	0.00	86.7
3	3	50	1000	m	1500	3	161.9	1.89	79.9
4	3	60	1500	mh	2000	2	579.2	11.6	46.2
5	3	70	2000	h	2500	1	1148	17.0	14.8
6	4	30	500	m	2000	1	0.00	0.00	100
7	4	40	1000	mh	2500	5	287.5	9.45	78.6
8	4	50	1500	h	500	4	106.1	17.2	60.6
9	4	60	2000	s	1000	3	343.1	14.7	36.3
10	4	70	0	ms	1500	2	485.2	12.2	39.9

11	5	30	1000	h	1000	2	67.4	0.00	87.5
12	5	40	1500	s	1500	1	84.3	13.9	89.5
13	5	50	2000	ms	2000	5	523.6	23.5	51.4
14	5	60	0	m	2500	4	675.1	17.1	49.9
15	5	70	500	mh	500	3	158.9	15.9	41.0
16	6	30	1500	ms	2500	3	0.0	0.00	100
17	6	40	2000	m	500	2	94.8	24.0	64.8
18	6	50	0	mh	1000	1	251.4	23.5	53.3
19	6	60	500	h	1500	5	463.0	28.1	42.7
20	6	70	1000	s	2000	3	819.3	21.2	24.0
21	8	30	2000	mh	1500	4	201.3	0.00	75.1
22	8	40	0	h	2000	3	424.7	37.0	60.6
23	8	50	500	s	2500	2	643.4	23.5	52.2
24	8	60	1000	ms	500	1	162.6	27.3	39.6
25	8	70	1500	m	1000	5	398.3	29.9	26.1

3 Stopping distance analysis of rockfall

3.1 Importance analysis of influencing factors for stopping distance

3.1.1 Range analysis

Import the orthogonal test data results in (Table 3) into the SPASS data processing program for range analysis processing and obtain the stopping distance range analysis calculation table (Table 4). The K value is the sum of the test data of various factors in a certain level state, and the $\bar{K}$ value is the average of the corresponding K value. The calculation formula is as follows:

$$\bar{K} = \frac{K}{5} \tag{5}$$

R is the range value of each factor, the calculation formula of range value is as follows:

$$R = \bar{K}_{\max} - \bar{K}_{\min} \tag{6}$$

The range value can measure the fluctuation degree of data. The bigger the range value is, the greater the influence of this factor on the index is. Conversely, the smaller the range is, the less influence this factor on the index is. According to the calculation results of range R in Table 4, it can be seen: $R_S = 17.45 > R_R = 9.64 > R_H = 7.8 > R_M = 7.45 > R_W = 6.02 > R_A = 2.88$ R_S is the maximum, then S has the greatest influence on D, while R_A is the minimum, indicating that A has the least influence on D among the six factors, and the degree of influence of each factor on D is as follows: S>R>H>M>W>A.

Table 4 Range analysis and calculation table of stopping distance

	Level	S	A/(°)	W/(°/s)	H	M/kg	R
K	1	30.6	0	89.98	73.4	84.5	81.8
	2	53.6	84.5	67.68	63.1	68.1	71.5
	3	70.5	89.6	59.9	73.0	56.2	90.9
	4	97.0	98.9	72.75	60.5	93.5	34.3
	5	117	96.5	79.41	99.5	67.2	91.0
$\bar{K}$	1	6.13	0	18	14.7	16.9	16.3
	2	10.7	16.9	13.54	12.6	13.6	14.3
	3	14.1	17.9	11.98	14.6	11.2	15.1
	4	19.4	19.7	14.55	12.1	18.7	8.58
	5	23.5	19.3	15.88	19.9	13.4	18.2
R		7.4	2.8	6.02	7.8	7.45	9.64

3.1.2 combinatory analysis for stopping distance

To analyze the most optimal level of each factor more intuitively, the level is taken as the abscissa and the stopping distance is taken as the ordinate. The relationship diagram between factors and indicators (Fig.3) shows the average test data of each factor and each level. By visually viewing the average test data of each level and comparing it with the graph, it is easy to find that the level combination which makes the farthest stopping distance of rockfall, it can be concluded that when S=8, A=60°, W=0°/s, H=hard, M=2000kg, R=5, the stopping distance of rockfall is the largest.

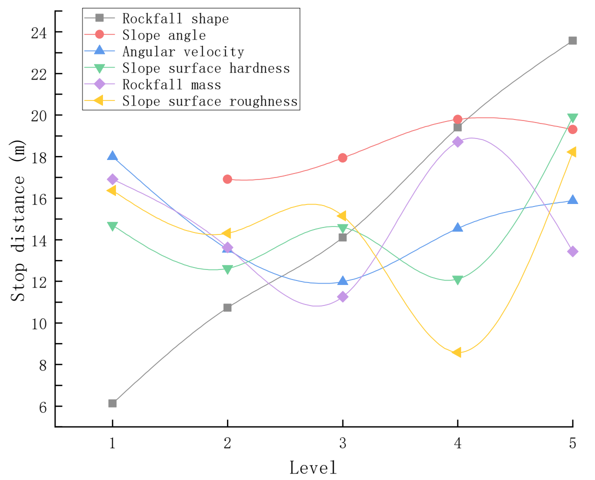

Fig. 3 Relationship between stopping position and all influence factors

3.2 Correlation analysis of influencing factors

3.2.1 Linear regression analysis

In order to explore the correlation between the six parameters and the stopping distance of rockfall, the SPASS program was used for linear regression analysis to establish the relationship between these six factors and the stopping distance of rockfall. According to the results of linear regression analysis, the R^2 value of the model is 0.622, which means that six factors as independent variables can explain 62.2% of the change reasons of D. The f test of the model shows that the model passes the f test (F=4.944, $p=0.004<0.05$), indicating that at least one of the six factors as independent variables will have an impact on D, the fitting model formula are constructed as follows:

$$D=26.448+3.539S+0.415A-0.001W+0.987H+0.102R \quad (R^2=0.622) \tag{7}$$

Besides, according to the multicollinearity test of the model, the VIF value in the model is all less than 5, which means there is no collinearity problem. Moreover, the D-W value is near the number 2, which indicates that the model does not have autocorrelation and there is no correlation between the sample data. Therefore, the model is good. It is concluded that the shape of rockfall and the slope angle has a significant positive influence on the stopping distance, and the shape of rockfall has a greater influence on the stopping distance than the slope angle. However, angular velocity, slope surface hardness, rockfall mass, and slope surface roughness do not influence stopping distance.

3.2.2 Analysis of the relationship between rockfall shape and the stopping distance

According to the range analysis results, it is known that rockfall shape has the greatest influence on the stopping distance, and rockfall shape has a significant positive correlation with the stopping distance. To further explore the influence of rockfall shape on the stopping distance, a linear regression curve between rockfall shape and the stopping distance is made (Fig. 4), as shown in the graph the stopping distance and rockfall edge number have stronger linear positive correlation relation, explain namely as the increasing of rockfall edge number, the movement ability of rockfall enhances, the stopping distance is further.

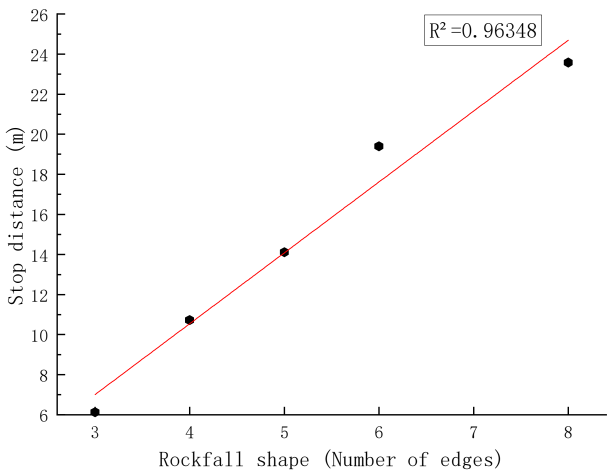

Fig. 4 Linear regression curve between rockfall shape and the stopping distance

The stopping position information diagrams of different rockfall shapes at slopes of 40°, 50°, 60°, and 70° were made (as shown in Fig. 5). In the case of low-angle slope (40°, 50°), the distribution of stopping positions of the same rockfall shape is more concentrated, while in the case of high-angle slope (60°, 70°), the distribution range of stopping positions of the same rockfall shape is larger. Under the condition of different slope angles is showed with the increase of the number of edges, rockfall stopping distance is also increasing, this is due to the different rockfall with the increase of the number of edges, its contour is close to the roundness. After contact with the asphalt road surface, different rockfall shape with different characteristics of the movement (Fig.6, Fig.7), the movement ability of octagon rockfall is stronger than triangle rockfall, in the process of rockfall rolling, variations in the height of the center of mass (COM) of triangular rock is bigger than octagon rock, this leads to triangle rolling rock accumulated losses of energy in the center of the mass height change process is greater than that in octagon rock, when turns rolling moment of inertia is less than the force of gravity on the ground contact, rolling rock namely stop rolling state. As the sliding friction coefficient is larger than the rolling friction coefficient, it can be seen that more kinetic energy is consumed in the sliding process, so the stopping distance of the triangular rolling rock is shorter than that of the octagon rock.

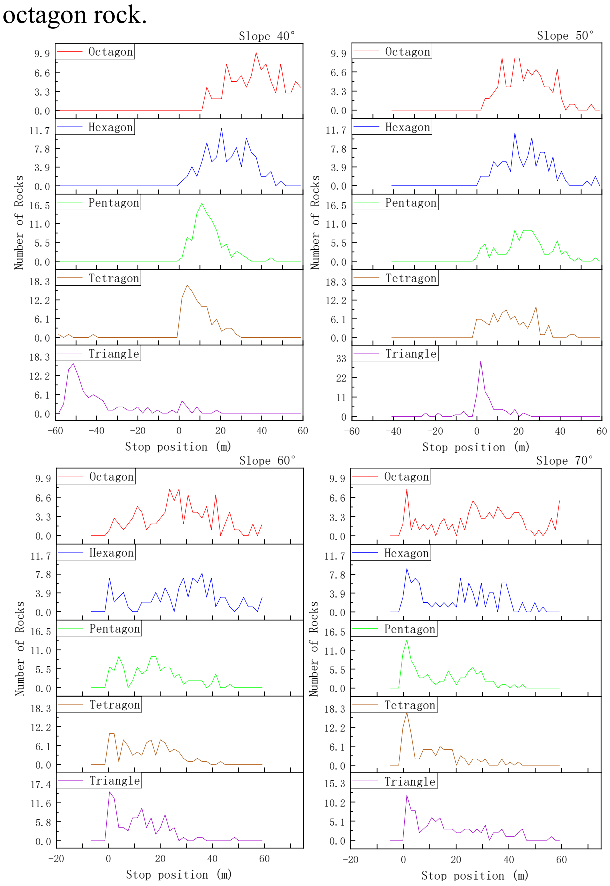

Fig. 5 70° stopping position information of different rock shapes

A coefficient RS is proposed to evaluate the geometric profile of a rolling rock, which is defined as the ratio of the distance from the COM to the ground and the distance from the contact point of the ground to the COM:

$$RS = \frac{h}{r} \tag{8}$$

Where, h is the distance between the COM and the ground; R is the distance from the contact point of the ground to the COM.

In the process of movement $RS_{octagon} > RS_{triangle}$, namely, the rotational moment generated by the gravity of the triangular rolling rock is greater than that of an octagon rock. It can be shown that the rotational torque required by triangular rolling rock is larger, as a result, the triangle is more likely to change from a rolling state to a sliding state. During the rotation of the rolling rock, the height of the COM variation is: $\Delta h = r - h$, the COM variation value of triangle rock is higher than the octagon one, it takes more energy for triangle rock to produce the rotation effect. Thus, there is a conclusion that the movement ability of triangle rock is better than octagon rock.

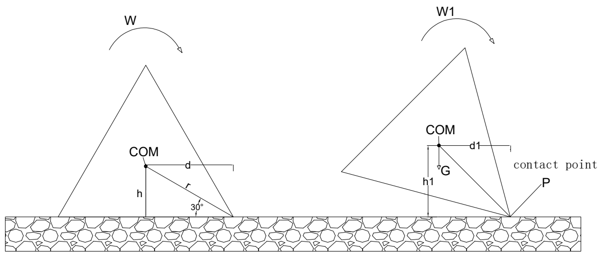

Fig. 6 The movement process of triangle rock

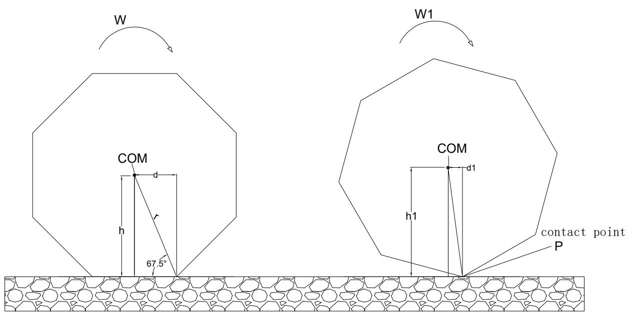

Fig. 7 The movement process of octagon rock

4 Potential energy loss RATE

4.1 Importance analysis of influencing factors for potential energy loss rate

4.1.1 Range analysis

Import the orthogonal test data results in (Table 3) into the SPASS data processing program for range analysis processing and obtain the potential energy loss rate range analysis calculation table (Table 5). The range value can measure the fluctuation degree of data. The bigger the range value is, the greater the influence of this factor on the index is. Conversely, the smaller the range is, the less influence this factor on the index is. According to the calculation results of range R in Table 5, it could be seen as follows:

$$R_A = 63.33 > R_W = 16.06 > R_S = 14.82 > R_R = 11.1 > R_H = 10.91 > R_M = 9.01$$

R_A is the maximum, then A has the greatest influence on P, while R_M is the minimum, indicating that M has the least influence on P among the six factors, and the degree of influence of each factor on P is as follows: A> W> S> R> H>M.

Table 5 Potential energy loss rate range analysis and calculation table

Level	S	A/(°)	W/ (°/s)	H	M/kg	R

	1	327.8	462.6	303.8	302.1	306.1	297.4
	2	315.5	380.4	322.8	317.8	290.0	290.8
K	3	319.4	297.6	309.8	320.8	327.3	341.9
	4	284.9	214.9	322.5	294.4	282.3	272.3
	5	253.7	145.9	242.5	266.2	295.6	298.9
	1	65.56	92.52	60.77	60.43	61.23	59.48
	2	63.12	76.09	64.56	63.57	58.01	58.17
$\bar{K}$	3	63.89	59.52	61.96	64.16	65.47	56.99
	4	56.98	42.98	64.51	58.89	56.46	68.09
	5	50.75	29.19	48.5	53.25	59.12	59.79
R		14.82	63.33	16.06	10.91	9.01	11.1

4.1.2 Combinatory analysis for potential energy loss rate

To find the most optimal level of each factor more intuitively, the level is taken as the abscissa and the potential energy loss rate is taken as the ordinate. The relationship diagram between factors and indicators (Fig.8) shows the average test data of each factor and each level. By visually viewing the average test data of each level and comparing it with the graph, it is easy to find that the level combination which makes the maximum potential energy loss rate of rockfall, it can be concluded that when S=3, A=30°, W=500°/s, H=medium, M=1500kg, and R=4, the potential energy loss rate of rockfall is the largest.

4.2 Correlation analysis of influencing factors

4.2.1 Linear regression analysis

To explore the correlation between the six parameters and the potential energy loss rate of rockfall, the SPASS program was used for linear regression analysis to establish the relationship between these six factors and the potential energy loss rate of rockfall. According to the results of linear regression analysis, the R^2 value of the model is 0.922 which means that six factors as independent variables can explain 92.2% of the change reasons of P. The f test of the model shows that the model passes the f test ($F=35.49$, $p=0.001<0.05$), indicating that at least one of the six factors as independent variables will have an impact on P, the fitting model formula is constructed as follows:

$$P=167.27-3.04S-1.59A-0.005W-1.91H-0.001M+0.27R \quad (R^2=0.922) \qquad (9)$$

Also, according to the multicollinearity test of the model, it is found that all VIF values in the model are less than 5, which means there is no collinearity problem. Moreover, the D-W value is near the number 2, which indicates that the model does not have autocorrelation and there is no correlation between the sample data. Therefore, the model is good. It can be seen that the shape of the rolling rock, slope angle, and angular velocity have a significant negative influence on the potential energy loss rate. The slope angle has the greatest influence on the potential energy loss rate of the rolling rock, but the slope surface hardness, rockfall mass, and the slope surface roughness do not influence on the potential energy loss rate.

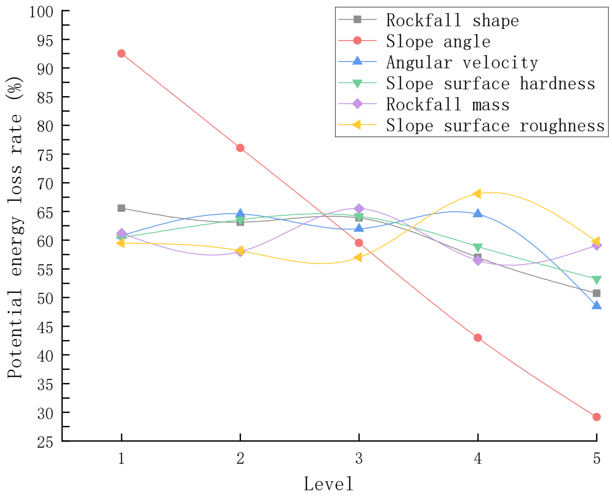

Fig. 8 Relationship between potential energy loss rate and all influence factors

4.2.2 Analysis of the relationship between slope angle and the potential energy loss rate

According to the range analysis results, it is known that the slope angle has the greatest influence on the potential energy loss rate, and there is a significant negative correlation between the slope angle and the potential energy loss rate. To further explore the influence of the slope angle on the potential energy loss rate, a linear regression curve between the slope and the potential energy loss rate is made (Fig.9). It can be seen that there is a strong linear negative correlation between slope angle and potential energy loss rate, with the increase of slope angle, the potential energy loss rate of the rolling rock decreases. The less energy the rolling rock consumes in the process of moving on the slope, the more total kinetic energy left while rockfall reaches the bottom of the slope.

As the above results show that with the increase of the edge number, the potential energy loss rate decreases, namely, the energy loss of the rolling rock in the process decreases. With the increase of slope angle, the potential energy loss rate of the rolling rock decreases. As the angular velocity increases, the potential energy loss rate of the rolling rock decreases.

The energy consumption of the rolling rock has a great relationship with the two major processes of the collision and friction, and to find the relationship between the slope angle and the times of the rolling rock striking the slope, the relationship between the total kinetic energy and its position under different slope angles is drawn (Fig. 10, Fig.

11, Fig. 12 and Fig. 13). These figures show that with the increase of slope angle, the number of energy mutations of the rolling rock has been reduced, namely, fewer collisions with slope surface, the contact time between rock and slope surface is reduced, hence the energy dissipations of rockfall are reduced. It concludes: In the project, try to increase the friction contact between the rolling rock and the ground to increase the energy consumption.

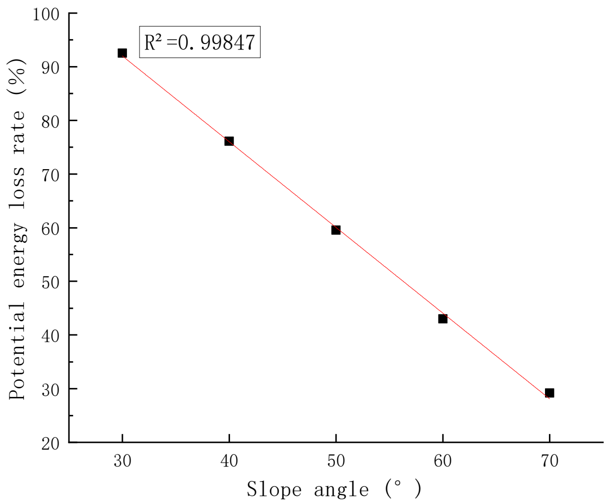

Fig. 9 Linear regression curve between rockfall shape and the potential energy loss rate

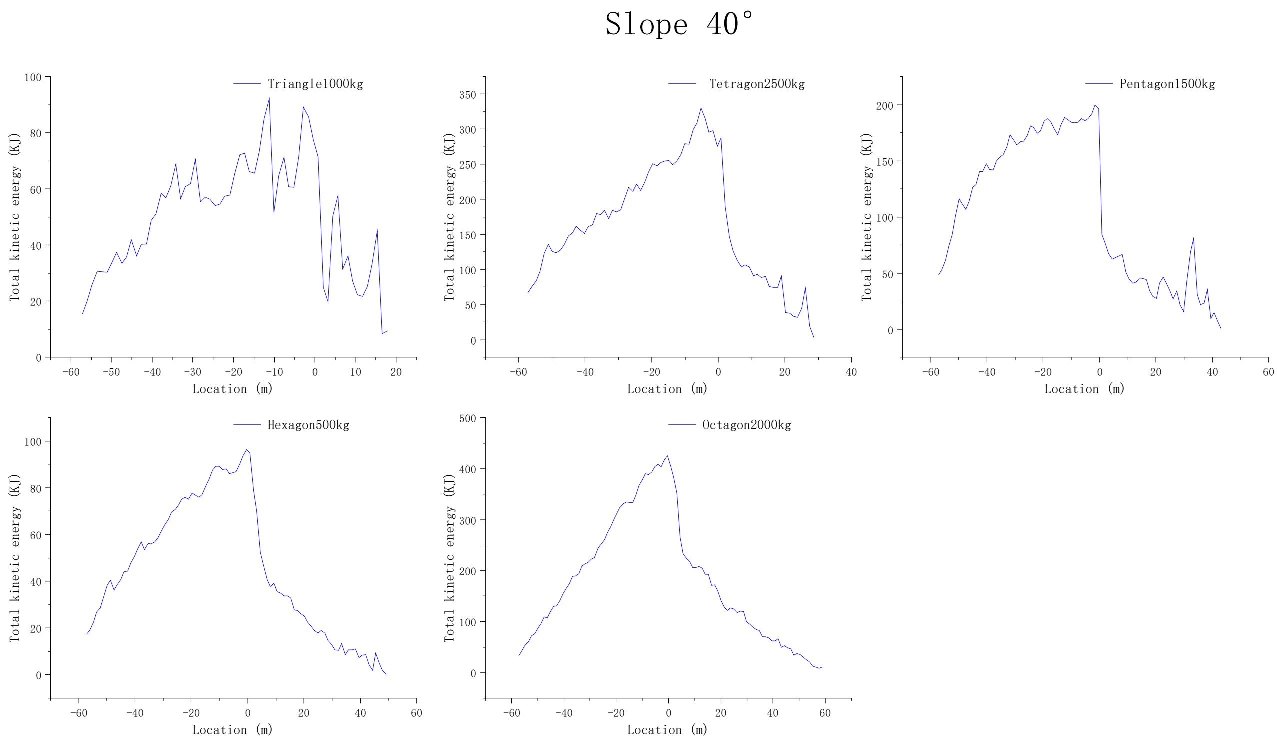

Fig. 10 Relationship between the total kinetic energy and the moving position of different rockfall shapes and masses on the 40° slope

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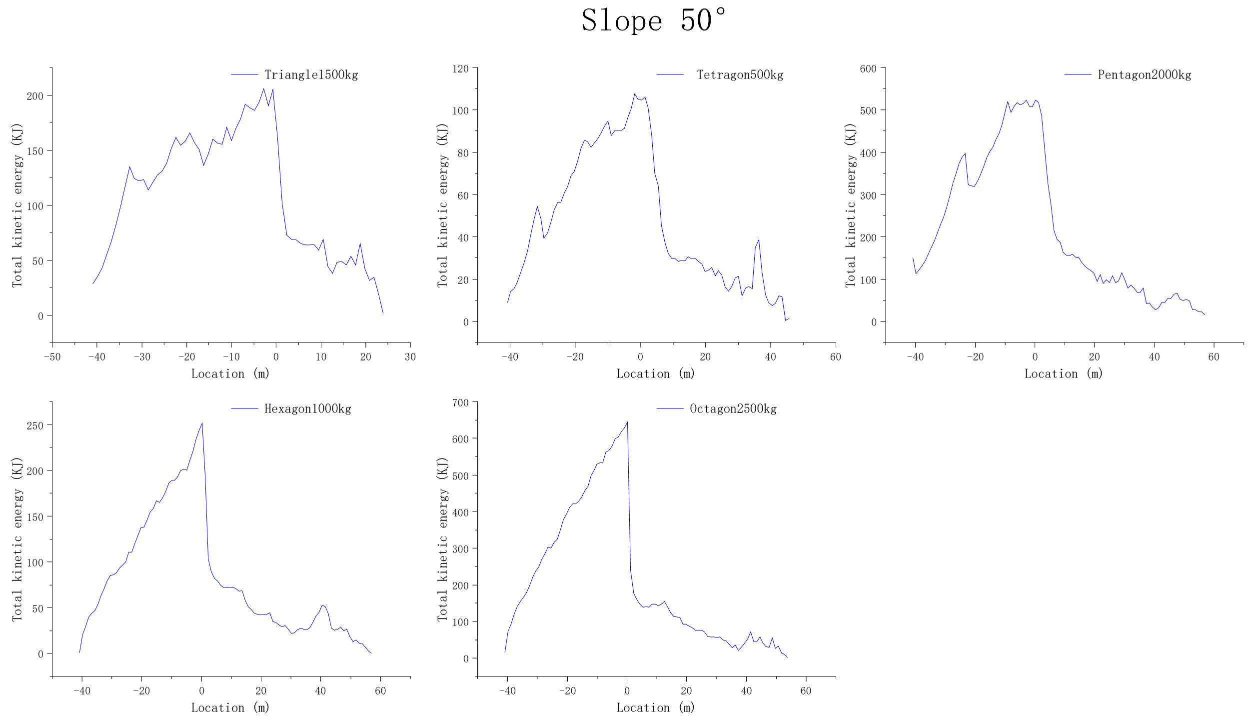

Fig. 11 Relationship between the total kinetic energy and the moving position of different rockfall shapes and masses on the 50° slope

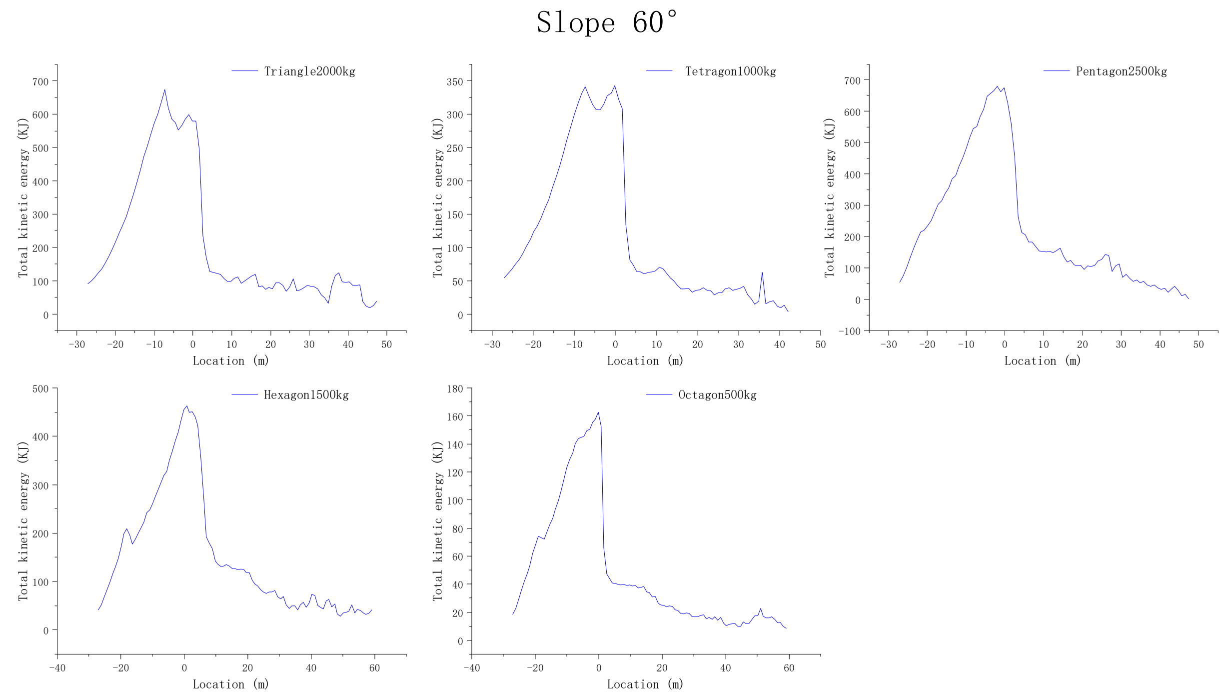

Fig. 12 Relationship between the total kinetic energy and the moving position of different rockfall shapes and masses on the 60° slope

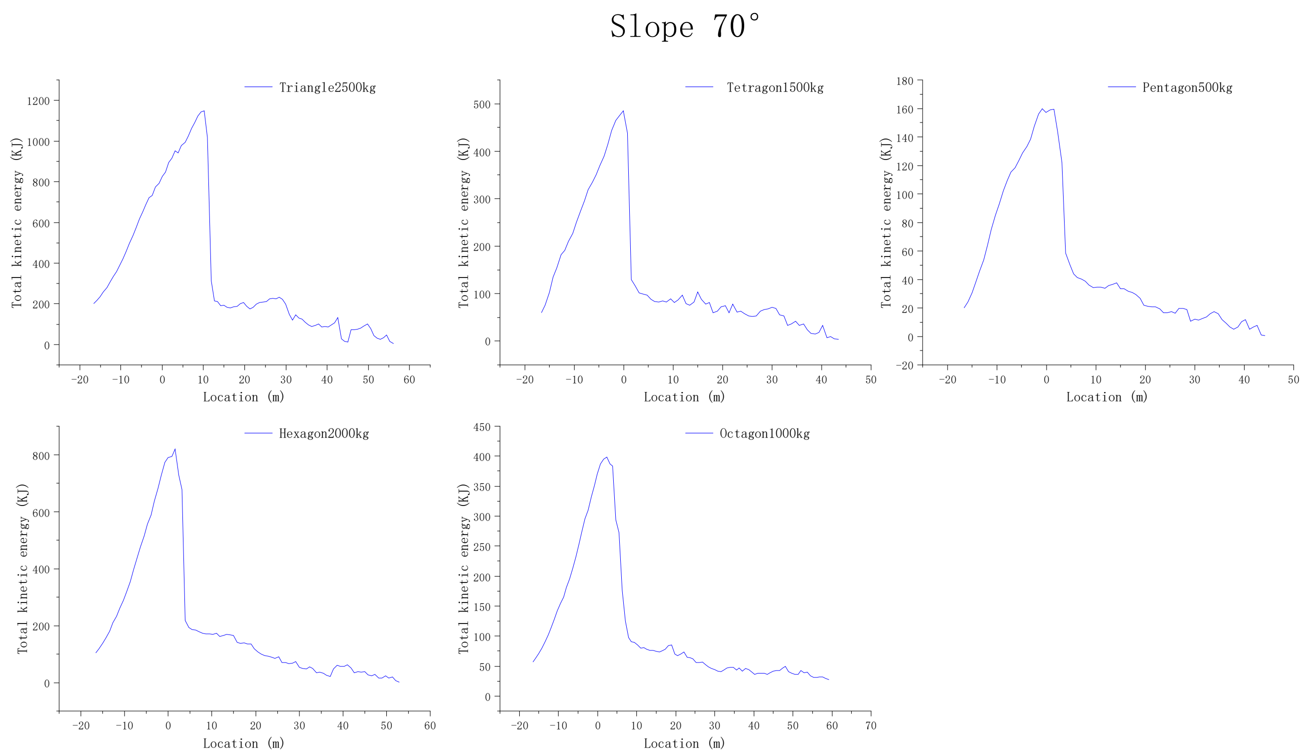

Fig. 13 Relationship between the total kinetic energy and the moving position of different rockfall shapes and masses on the 70° slope

5 Conclusion

In this paper, ROCFALL 8.0 program was used to study the effects of six parameters, namely, rockfall shape, slope angle, initial angular velocity of the rolling rock, slope surface hardness, rockfall mass, and slope surface roughness, on the stopping distance and potential energy loss rate of the rolling rock, and orthogonal tests were designed to investigate the effects of multiple factors on the movement of the rolling rock and energy consumption, and the following conclusions were drawn:

1. The shape of a rolling rock has a great influence on the stopping distance of a rolling rock. Subsequently, with the increase of the number of edges of a rolling rock, the stopping position of a rolling rock on the asphalt road also increases linearly with good correlation.

2. The geometric contour coefficient RS is proposed. With the increase of RS, the change range of the centroid position of a rolling rock is smaller in the process of moving, so the rolling rock has stronger movement ability and the stopping position of the rolling rock will also increase.

3. In the case of low-angle slope (40°, 50°), the distribution of stopping positions of the same rockfall shape is more concentrated, while in the case of high-angle slope (60°, 70°), the distribution range of stopping positions of the same rockfall shape is larger.

4. The slope angle has the greatest influence on the potential energy loss rate of the rolling rock. As the slope becomes steeper, the number of collisions between the rolling rock and the slope surface decreases. As a result, the remaining energy of the rolling rock is greater when it reaches the asphalt road, and the potential energy loss rate is negatively linearly correlated with the slope.

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