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The effects of cushion's particle size and thickness on coefficient of restitution under the rockfall impacts

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Abstracts: Gravel cushion is widely used for rockfall prevention in open-pit mine to absorb energy, the energy-consumption and buffer mechanism of different thickness and particle size of gravel cushion under the impact effects are studied. A series of laboratory tests for different cushion are conducted, combining the blocks' volume and drop height. The First tests nder the condition of same release height of rockfall are carried out, the results indicate that under the different impact energy, the change of cushion's thickness have an obviously different effects on the coefficient of restitution (*COR*) of cushion. The second tests under the condition of same cushion thickness are conducted, when the blocks of different radius colliding with the cushion of same thickness, the *COR* change range of blocks of a big radius is larger than those blocks with a relatively small radius. For further research the influence degree of cushion's particle size and thickness on the *COR* when rockfall moving through the cushion, based on orthogonal test principle, 32 orthogonal tests are conducted, the influence law of all factors on *COR* and damage depth ***L*** of cushion are explored. The test results show that the cushion's thickness ***h*** should be considered firstly during the process of the cushion design, and reasonable cushion not only effectively reduce *COR*, but also maintain its stability, which provides theoretical and practical basis for the wide application of cushion design to control rockfall.

Keywords: Rockfall; cushion's thickness; laboratory test; particle size, coefficient of restitution (COR).

1. Introduction

Rockfall brings serious hazards to working areas and facilities in the world's open-pit mine area. The surface of slopes is seriously weathered, the mining disturbance force is strong, landslides and rock-body collapse are prone to occur during the rainfall. Rockfall means that stones roll down slope after instability caused by gravity or exogenic action, and finally shock the obstacle or rest in the gentle zone (Huang et al., 2007). The distribution of rockfall is wide, it happens suddenly, causing serious threats to people's life and property safety within its limits (Pantelidis, 2009; Pantelidis, 2010). In recent years, with the frequent disasters of rockfall, numerous scholars at home and abroad have taken in-depth study to the movement characteristics of rockfall through field tests or numerical simulation. For example, the collision rebound phenomenon of test blocks in sandy slope is studied through indoor small-scale test, semi-size and large-scale tests (Heidenreich, 2004; and Labiouse, 2009). On the basis of Hertz contact theory, the view that material accords with ideal elastic-plastic characteristics is assumed, and the calculation modes for normal collision coefficient of restitution and tangential collision coefficient of restitution of spheres are studied, respectively (Thornton et al., 1998). Numerical simulation software is adopted to analyze the movement characteristics of rockfall, the protection of dam construction, road construction and historical places adopt the software 'RocFall 3.0' to calculate the movement velocity and locus of rockfall, avoiding the damage of project. (Topal et al., 2006; Koleini and Van Rooy, 2011; Saroglou et al., 2012; Sadagah, 2015).

Based on the above research, the protection measures are put forward to control rockfall. The trees have a significant blocking effect on the rolling stones, the interception influence tests of trees on rockfall are designed based on the analysis of collision probability of trees and rockfall, and the velocity change, movement distance of rockfall and the collision probability between trees and rockfall are researched (Huang, 2010; Notaro, 2012). A large-scale field test of the impact caused by rockfall on reinforced concrete beams is conducted, the dynamic response process is studied and compared with the numerical simulation results (Kishi et al., 2002 and 2010; Bhatti et al., 2009 and 2010). Rockfall concrete barriers are classified as rigid barriers, they absorb most of the impact and all of the residual kinetic energy of the falling rock instead of dissipating it as flexible nets do. Experiences have shown that rigid walls have a tendency to break under high-impact loads, and shatter, sometimes violently (Badger et al., 2009). Because of their relatively small size, these barriers cannot contain large-sized rocks or high-energy rockfall. Concrete barriers are generally believed to be suitable for rockfall protection where the resulting impact energy is in the range of 60 kJ to 100 kJ or where catchment ditch effectiveness needs improvement (Descoeudres et al., 1999). The method that setting short CFT members between pillar and cover plate in rock shed is proposed, and the deformation and energy absorption characteristics of the supporting member are studied through test and theoretical analysis (Delhomme et al, 2005; Mommessin et al, 2004). Combing the blocks' quality and drop height, a large number of experiment for different soil are carried out, the influence of soil characteristics on the impact response of rockfall are studied (Kawahara et al., 2006).

The above protection researches are mainly applicable to the conventional human settlements, and it is expensive and inconvenient to take these measures to control rockfall in open-pit mine. The energy consumption layer laid on the safety platform is a relatively common way to prevent and control rockfall in open-pit mine (Heierli et al., 1981; Labiouse et al., 1996). However the previous researches on cushion are seldom concerned with the effects of cushion's particle size on the movement characteristic of rockfall, especially for the joint effects of gravel cushion's particle size and thickness on coefficient of restitution (*COR*) have not been explored so far. During the process of mining, a large amount of mullock are produced, mullock can be broken into particle of different size through the crusher, which can be paved on the platform as energy consumption layer. A certain thickness of gravel cushion on the platform can effectively absorb the impact energy of rockfall to achieve a buffer effect, reducing the impact load caused by rockfall on the protective structure and the kinetic energy of rockfall, which makes the rockfall eventually resisted on the platform. Because the impact of rockfall and gravel cushion is short, it involves complicated elastic-plastic deformation and energy conversion, and the energy absorption performance of gravel cushion with different thickness and particle size are quite different under the rockfall impacts, how to determine the energy-consumption buffer mechanism of gravel cushion has become the key to the cushion design and calculate the following rockfall movement, so the effects of cushion's particle size and thickness on *COR* under the rockfall impacts should be furtherly studied to control the rocfall effectively.

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2 Coefficient of restitution

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It is difficult to predict a rebound locus, several parameters, such as the strength, roughness, stiffness and inclination of slope and blocks, have obvious influences on the rebound locus of rockfall (Labiouse and Heidenreich 2009), but the calculation method of rebound locus according to the COR is widely used(Giani, 1992), and the definitions of COR are various (Chau et al. 2002).

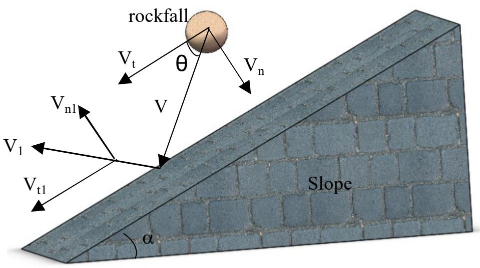

Fig. 1 Motion model of rockfall

For a block impacting a rocky slope (Figure 1), based on the theory of inelastic collision, the coefficient of restitution (COR) is defined as Eq.1:

$$V_{COR} = \frac{V_1}{V} \qquad (1)$$

Where V and V_1 are the velocity magnitude of the incident and rebound stage of the locus, respectively (m/s).

The V_{COR} consists of normal and tangential parts, and the normal (R_n) and tangential (R_t) coefficients are defined as Eq.2:

$$R_n = \frac{V_{n1}}{V_n} \qquad R_t = \frac{V_{t1}}{V_t} \qquad (2)$$

Where R_n and R_t are the normal and tangential restitution coefficients, respectively, V_n, V_{n1} are the normal parts and V_t, V_{t1} are the tangential parts of the block's velocity, before and after the impact, respectively (m/s).

The blocks' total energy E of the block consist of the translational (E_0) and the rotational (E_W) energy (Eq.3), and the total energy coefficient (ET_{COR}) is proposed (Eq. 4)::

$$\mathrm{E} = E_0 + E_w = \frac{1}{2}mv^2 + \frac{1}{2}I\,\omega^2 \qquad (3)$$

$$\mathrm{ET_{COR}} = \frac{\frac{1}{2}mV_1{}^2 + \frac{1}{2}I\omega_1{}^2}{\frac{1}{2}mV^2 + \frac{1}{2}I\omega^2} = \frac{0.6mV_1{}^2}{0.6mV^2} = \frac{V_1{}^2}{V^2} = \mathrm{V_{COR}}^2 \qquad (4)$$

Where m is the block' quality, $\boldsymbol{I}$ is the block's inertia moment, ω and ω_1 are the angular velocity, before and after the impact, respectively.

When the dangerous rock-body breaks away from the parent body, it will inevitably generate collision with slope during rolling process along the slope and lose the energy. The approximate calculation formula for the total kinetic energy of rockfall is derived from engineering surveys (Yang et al., 2005).

$$\mathrm{E} = E_0 + E_w = 1.2E_0 = 0.6mV^2 = 0.6m(V_n{}^2 + V_t{}^2) \qquad (5)$$

3. Experimental Studies

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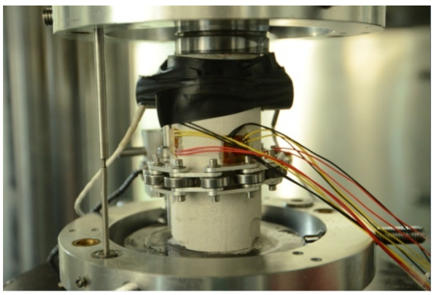
3.1 Experimental material and apparatus

In order to study the effects of cushion's particle size and thickness on COR conveniently under the rockfall impacts, the high-strength gypsum material are adopted to simulate rockfall in the test, the recommend value of sample's moisture content is in the range 30% to 50% in previous study (Chau et al., 2002). Spherical blocks with diameters of 2cm, 3cm, 4 cm and 5cm are made with a moisture content of 40% (Figure 3), for further research on the properties of gypsum materials, six standard cylindrical samples with a moisture content of 40%, which possess 5cm diameter and 10cm height, are tested to obtain the uniaxial compressive strength. The uniaxial compression test is shown in Figure 2. Due to the test error, the ultimate compressive strength of six samples is different, so the average value is considered as the compressive strength of the material. The average value when the specimens are destroyed is 6.48Mpa, indicating that the gypsum sample of present moisture content is enough to prevent shattering during the collision process (Ulusay et al., 2007; Aydin, 2009).



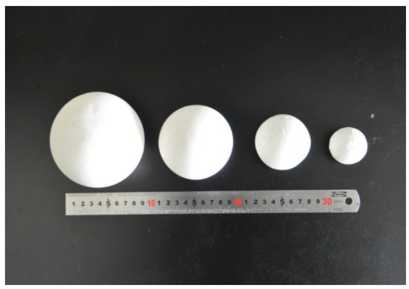


Fig. 2 standard specimen under uniaxial compression test Fig. 3 Sample of different sizes of spherical gypsum

In order to explore the effect of different thickness and particle size of cushion on the rolling motion of rockfall, massive gypsum boards made of same proportion as blocks are broken, gypsum particles groups with sizes of 0.2, 0.6, 1.0, 1.4, 1.8 and 2.4 cm are selected by sieve to simulate the gravel cushion, as shown in Figure 4.

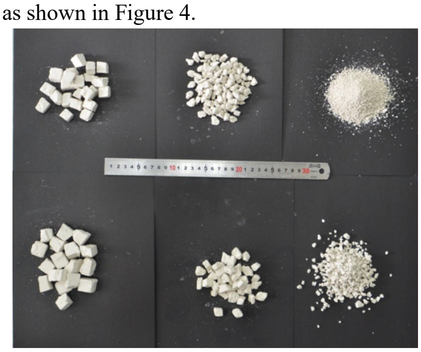


Fig. 4 Screening granules of different particle sizes

A simple rolling stone releasing device is shown in Figure 5, a slant tube with adjustable inclination and height is used to adjust the impact translational velocity of blocks (Asteriou et al., 2012). The colliding blocks slide and roll through the tube to collide with the plate. Two synchronized digital cameras (1024* 1024 pixels) are adopted in the tests to acquire the blocks' velocity in Stereoscopic space (Bouguet 2008; Asteriou et al., 2013). The cameras, which can obtain the motion, velocity, and kinetic energy automatically, are placed near the impact surface

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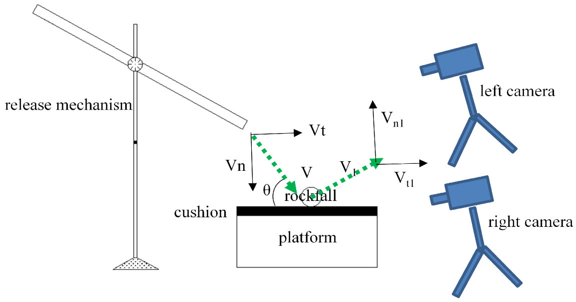
(see Figure 5), and the capture rate of camera is 200 fps.



5(a) model of laboratory test system

5(b) laboratory test system

Fig. 5 The experimental apparatus

The collision surface is a plate made of the same material as the blocks. The plate is 40cm*40cm* 8cm in volume. For simulating different thickness of cushion, a great amount of hollow gypsum board whose volume is 40cm*40cm* 2cm are made, and a part whose volume is 30cm*30cm* 2cm is cut in the middle of each board to be filled with the gypsum particle. In order to accurately measure the speed of blocks by cameras, and avoid the interference of the motion of cushion's particles affected by the collision, the cushion is blackened (see Figure 6).

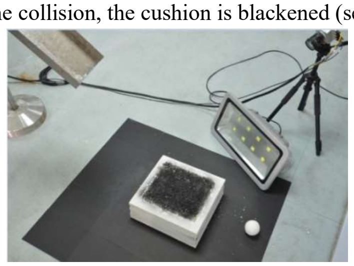


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Fig. 6 Laboratory rolling stones model test

3.2 Experimental procedure

The spherical blocks of 2cm, 3cm, 4cm, 5cm radius (see Figure 3) are applied in laboratory test, and the falling blocks are released from 1.2m height, the effects of cushion's thickness and particle size and block volume on *COR* are studied in this experiment. The block is inserted into one side of tube, and after sliding and rolling through the tube to collide with the collision surface. The impact surface is a plate to simulate the platform before paving the cushion. After paving the cushion on the plate, for each series, the thickness is adopted as 2cm, 4cm, 6cm, 8cm, 10cm, 12cm, 14cm respectively. The cushion's particle sizes are taken as 0.2cm, 0.6cm, 1.0cm, 1.4cm, 1.8cm and 2.4cm, respectively. In order to avoid the chance of test, "three tests for the mean" method is adopted, and the average value is set as the final results. In total, four series for 516 testing cases are carried out.

Meanwhile, in order to investigate the effect of rockfall released from different movement height on the COR of cushion, the experiments that blocks of 2cm, 3cm, 4cm and 5cm radius fall down from 0.4m, 0.8m, 1.2m and 1.6m respectively to collide with 8cm thickness cushion of different particle sizes are carried out, four series for 288 testing cases are carried out.

3.3 Experimental results and discussion

3.3.1 The experiment results

The blocks are released from 1.2m height to collide with the plate before paving the cushion, the results of *COR* are shown in Figure 7.

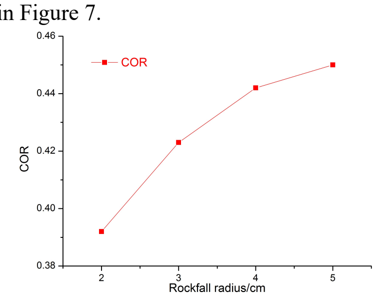
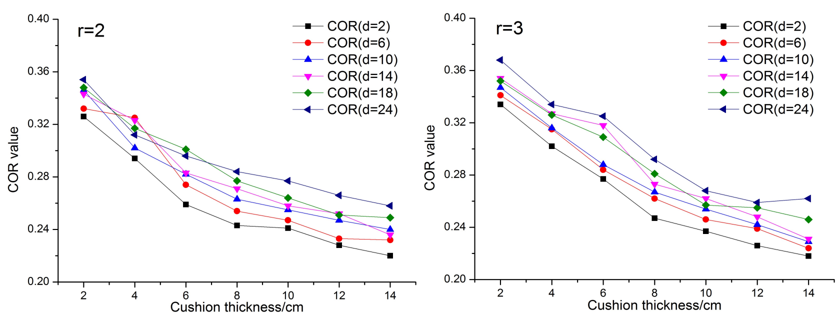


Fig. 7 The COR of different blocks' collision with the plate

After paving the cushion on the plate, the experiments that rockfall of different volume released from 1.2m movement height collide with various cushion and particle size of cushion are conducted, the results of which are given in Figure 8.



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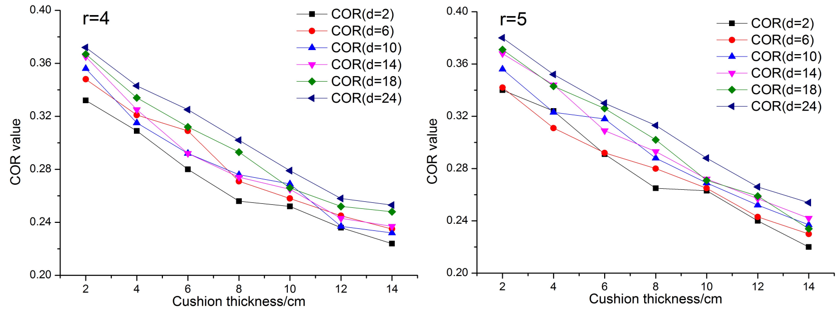

Fig. 8 The COR comparison of different blocks released from 1.2m height

The tests that rockfall of different volume released from different movement height collide with 8cm thickness cushion of various particle size respectively, the results of *COR* are shown in figure 9.

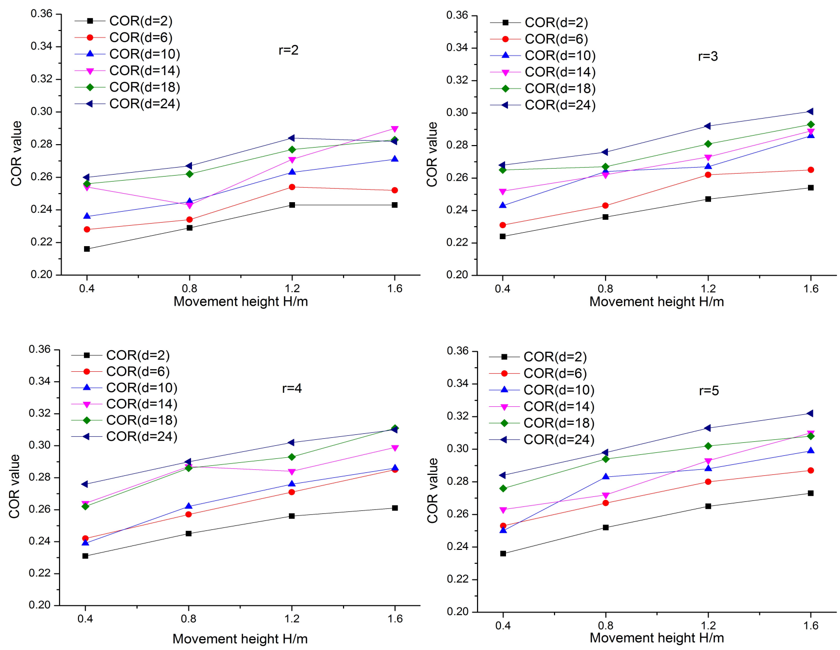

Fig. 9 The COR comparison of different blocks' collision with 8cm thickness cushion

3.3.2 The discussion

From the above figures we can see that the cushion's thickness and particle size have a great influence on the *COR* of cushion, while the influence of rockfall radius is relatively low. When the cushion's particle size is small and thickness is great, the *COR* of cushion will be small, and its energy-consumption effects can be obvious. With the increase of rockfall's radius and movement height, the impact energy increases dramatically when rockfall colliding with cushion (Kawahara et al., 1998). Under the low impact energy, the change of cushion's thickness has a relatively low effect on the *COR* of cushion, and the cushion of small thickness also has certain energy-absorbing effect, which can be verified by Pei (2016) and Kawahara (2006). However, under the high impact energy, the energy-absorption effect of different thickness gravel cushion is obviously different.

Because the small thickness cushion can be compressed in a very short time, which make the rockfall is more likely to be affected by the adamant platform, reducing the cushion's thickness is equivalent to increasing the effective stiffness of the cushion, which limit the buffer and energy-absorbing effect of cushion to a great extent. When the cushion's thickness is relatively small, the *COR* increase significantly as the decrease of cushion's thickness. However, when the cushion's thickness is relatively large, this trend is no longer obvious.

When the blocks are released from 1.2m, the *COR* is large before laying the cushion, the *COR* decrease obviously with the increase of cushion's thickness after laying the gravel cushion, which agrees with the observation given by Kawahara (2005), but when the cushion reaches a certain thickness, namely, the ratio of the rockfall radius ***r*** to the cushion's thickness ***h*** is form 1/4 to 1/3, with the increase of cushion's thickness, the reduction rate of *COR* become low gradually. As the decrease of cushion's particle size, *COR* is more sensitive to the cushion's thickness of small particle size than the cushion thickness of relatively big particle size, the change range of *COR* of small particle size caused by the variety of thickness is more wider, and as the increase of cushion's thickness of big particle size, the *COR* of cushion change relatively slightly.

When the cushion's thickness is 8cm, as the movement height of block increases, the *COR* also increases, but when the blocks of different radius colliding with the cushion of same thickness, the *COR* change range of blocks of a big radius is larger than those blocks of a relatively small radius. When the blocks move from a relatively low height, the *COR* of cushion is more likely to be affected by the particle size compared with the blocks released from high height. As the cushion's particle size is large, the difference of collision parts between the rockfall and cushion are great, resulting in a wide range of *COR* of cushion.

4 Orthogonal test design

4.1 Orthogonal test procedure

To explore the influence degree of cushion's particle size and thickness on the *COR* when rockfall moving through the cushion, orthogonal test theory is adopted to take test program design (Tao et al., 2009). When these factors cannot be considered in full, the leading factor is considered preferentially to achieve the expected effects to a great extent. The rockfall radius ***r***, movement height ***H***, cushion's thickness ***h*** and particle size ***d*** four parameters are selected to be taken as the basic factors of test. According to the characteristics of 4 factors, the number of level of every factor is 4, as shown in Table 1:

Table 1 All factors and levels of orthogonal test

Factor level	Rockfall radius ***r/cm***	Movement height ***H/m***	Cushion's thickness ***h/cm***	Particle size ***d/cm***
Level 1	2	0.4	2	0.2
Level 2	3	0.8	4	0.6
Level 3	4	1.2	6	1.0
Level 4	5	1.6	8	1.4

In order to improve the test accuracy, and all the factors are 4 levels, the testing program of $L_{32}(4^9)$ arrangement factor can be selected. The ***COR*** and damage depth ***L*** of cushion are taken as

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test indexes to explore the influence degree of 4 factors (Pichler et al., 2005).

Considering that the rockfall motion has large randomness, each case is tested three times to obtain the mean as the final result, so as to improve the accuracy of experiments, the test results are shown in Table 2.

Table 2 Orthogonal test results

Test number	Rockfall radius *r/cm*	Movement height *H/m*	Cushion's thickness *h/cm*	Particle size *d/cm*	Damage depth of cushion *L/cm*	***COR*** of cushion
1	2	0.4	2	0.2	0.65	0.278
2	2	0.8	4	0.6	0.74	0.273
3	2	1.2	6	1.0	0.93	0.282
4	2	1.6	8	1.4	1.05	0.295
5	3	0.4	2	0.6	0.58	0.294
6	3	0.8	4	0.2	1.45	0.265
7	3	1.2	6	1.4	1.03	0.317
8	3	1.6	8	1.0	1.60	0.280
9	4	0.4	4	1.0	0.62	0.296
10	4	0.8	2	1.4	0.56	0.338
11	4	1.2	8	0.2	2.60	0.256
12	4	1.6	6	0.6	2.20	0.284
13	5	0.4	4	1.4	0.61	0.309
14	5	0.8	2	1.0	0.58	0.328
15	5	1.2	8	0.6	2.12	0.280
16	5	1.6	6	0.2	2.85	0.273
17	2	0.4	8	0.2	1.36	0.216
18	2	0.8	6	0.6	1.24	0.265
19	2	1.2	4	1.0	1.13	0.302
20	2	1.6	2	1.4	0.68	0.358
21	3	0.4	8	0.6	0.92	0.231
22	3	0.8	6	0.2	1.49	0.256
23	3	1.2	4	1.4	1.08	0.327
24	3	1.6	2	1.0	0.84	0.351
25	4	0.4	6	1.0	0.77	0.287
26	4	0.8	8	1.4	0.81	0.281
27	4	1.2	2	0.2	1.03	0.336
28	4	1.6	4	0.6	1.96	0.318
29	5	0.4	6	1.4	0.67	0.292
30	5	0.8	8	1.0	1.05	0.275
31	5	1.2	2	0.6	1.14	0.347
32	5	1.6	4	0.2	2.54	0.294

4.2 Optimization analysis and discussion of test results

4.2.1 Optimization analysis method (flow)

In this test, analysis method is preferred to optimize the calculation result and the

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optimization process is shown in Figure 10.

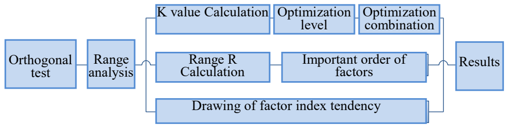

Fig. 10 Optimization analysis flow chart of test

The rockfall radius ***r***, movement height ***H***, cushion's thickness ***h*** and particle size ***d*** four parameters belong to factor set $\boldsymbol{x}\in$(A, B, C, D), level number of all factors is set as 4, then it can calculate the test statistical parameter under ***y*** level of factor set X that K_{xy} (x=A, B, C, D; y=1, 2, 3, 4), that is, sum the all test result index P_{xy} containing the Y level of factor X, then divide the total number of level to obtain the average value k_{xy}, in which, P_{XY} is the random variable of normal distribution:

$$k_{\mathrm{xy}} = \frac{K_{\mathrm{xy}}}{4} = \sum P_{xy} / 4 \qquad (6)$$

Where K_{xy} is the satistical parameter of the ***x*** factor at the ***y*** level, k_{xy} is the average value of K_{xy}, and R_y is the range of the ***y*** factor.

It can be judged from k_{xy} that ***x*** factor optimization level and optimization combination, if the larger the index value is, the optimum it is, then select the level increasing the index value, that is, the corresponding level of maximum value of all factors k_{xy}; on the contrary, if the smaller the index value is, the optimum it is, select the corresponding level of minimum value of all factors k_{xy}. The corresponding parameter combination of optimal level of all factors is the optimal parameter combination. R_y has reflected the amount of variation of test index when the ***y*** factor level is fluctuating. The larger the R_y is, the more sensitive the factor to the influence of test index. According to R_y, the importance order of factors can be judged and the optimization level and optimization combination of ***x*** factor can be judged from k_{xy}.

4.2.2 The analysis results and discussion

Range analysis is taken to analyze the orthogonal test results shown in Table 2, the influencing factors range analysis of ***COR*** and damage depth ***L*** of cushion are shown in Table 3, then the optimum parameter combination including rockfall radius ***r***, movement height ***H***, cushion's thickness ***h*** and particle size ***d*** are obtained to reduce *COR* effectively according to it.

Table 3 influencing factors range analysis of all evaluation indexes

Evaluation index	Levels	Rockfall radius ***r/cm***	Movement height ***H/m***	Cushion's thickness ***h/cm***	Particle size ***d/cm***
COR of cushion	k_1	0.285	0.271	0.325	0.270
	k_2	0.288	0.287	0.296	0.285
	k_3	0.298	0.305	0.281	0.301
	k_4	0.299	0.306	0.267	0.313
	R_y	0.014	0.035	0.058	0.043
Damage depth of cushion ***L***	k_1	0.97	0.78	0.76	1.75
	k_2	1.12	0.99	1.26	1.35
	k_3	1.33	1.38	1.40	0.94
	k_4	1.44	1.72	1.44	0.81
	R_y	0.47	0.94	0.68	0.94

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The following conclusions can be obtained through Table 3:

(1) The influence degree of all factors on *COR* of cushion is respectively: cushion's thickness ***h***>particle size ***d***> movement height ***H***> rockfall radius ***r***;

(2) The influence degree of all factors on damage depth ***L*** of cushion is respectively: particle size ***d*** =movement height ***H*** > cushion's thickness ***h*** > rockfall radius ***r***.

To further explore the effects of each factor on test indexes, the *E-I* tendency figures are drawn (Tao et al., 2017), the level of all factors is X-coordinate (*E*), the average value of test index is Y-coordinate (*I*). The *E-I* tendency drawings have intuitively reflected the tendency of test index with the change of factor level, which can point direction for further test, as shown in Figure 11 and Figure 12.

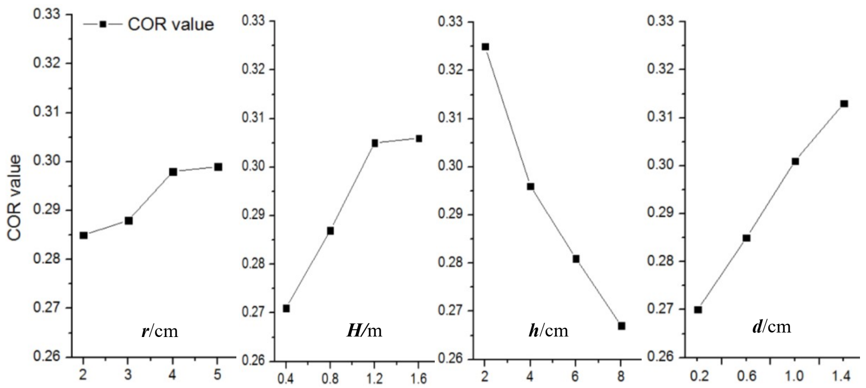

Fig. 11 Tendency of each factor on COR of cushion

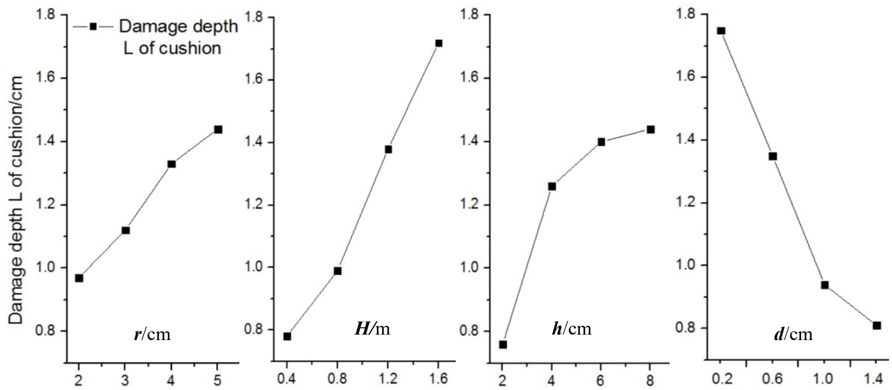

Fig. 12 Tendency of each factor on damage depth ***L*** of cushion

The following conclusions can be obtained through Figure 11 to Figure 12:

(1) The smallest optimal parameter combination of *COR* of cushion is: A1B1C4D1; that is, when *r*=2cm, *H*=0.4m, *h*=8, *d*=1.4, the *COR* of cushion is the smallest (Figure 11).

(2)The most shallow optimal parameter combination of damage depth ***L*** of cushion is: A1B1C1D4. That is, when *r*=2cm, *H*=0.4m, *h*=2, *d*=1.4, the damage depth ***L*** of cushion is the most shallow (Figure 12);

To sum up, the cushion's thickness ***h*** has the most significant influence on the *COR* of cushion, while it has the relatively minor effects on the damage depth ***L*** of cushion; secondly is particle size ***d***, but the cushion is easy to be destroyed, when the rockfall of high kinetic energy colliding with the cushion of small particle size; the influence degree of rockfall radius ***r*** on the two indexes is far less than other factors. When the gravel cushion are used to control the rockfall of slope, the control effect and durability are taken into account (Pichler et al., 2005), therefore the cushion's thickness ***h*** should be considered firstly, the optimal thickness is 3 or 4 times of the universal size of rockfall radius. The samller particle size is, the samller *COR* is, but the cushion is more likely to be destroyed, so the reasonable particle size can be determined combined with the size and position of rockfall, so that the cushion not only achieve the effect of reducing *COR*, but also maintain its stability.

5 Conclusions

Through the laboratory collision tests, the buffer and energy-dissipation mechanism of various cushion under different impact energy is studied, the following conclusions are obtained:

1. Compared with conventional protection measures, the gravel cushion design makes full use of waste mullock produced in the process of mine extension, which can be broken into different particle size conveniently, it can not only reduce the cost of preventing rockfall and mullock transportation obviously, relieving the problem that the dump of mine is overloaded, but also achieve the better control effect, which realizes the goal of 'stone conquers stone'.

2. Under the low impact energy, the change of cushion's thickness has a relatively low effect on the *COR* of cushion, while under the high impact energy, the energy-absorption effect of different thickness gravel cushion is obviously different. Therefore, in the process of the cushion design, the estimated quality and falling height of the potential dangerous rock are investigated, and the impact energy of the rockfall can be roughly estimated.

3. The cushion's thickness ***h*** has the most significant influence on the *COR* of cushion, the optimum cushion's thickness and particle size can be obtained by taking the control effect, economic rationality and structural reliability into account. The samller particle size is, the samller *COR* is, but the cushion is more likely to be destroyed, the reasonable particle size can be determined combined with the size and position of rockfall, so that the cushion can not only achieve the effect of reducing COR, but also maintain its stability.

4. At present, the gravel cushion design on the platform cannot have a relatively reasonable rule to follow for majority of engineering personnel, which is a large blindness. The change of cushion's particle size could improve the effects of controlling rockfall, instead of only increasing the cushion thickness, which provides certain theoretical and practical basis for the wide application of cushion design to control rockfall in open-pit mine.

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