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Original Research Article

Research on Normal Restitution Coefficient of Rockfall Collision

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Abstract: In the process of designing the engineering protection, the accuracy of calculating the trajectory of rockfall movement mainly depends on the value of normal restitution coefficient. The rockfall collision process is captured by DIMS9100 analysis system in the indoor physical model test where velocity parameters under different rockfall size, slope gradient, incident velocity and slope material conditions are collected. Then the normal collision restitution coefficient can be obtain by analyzing velocity parameters before and after collision. The results show that the normal restitution coefficient is not significantlyassociated with the size of rockfall and the incident velocity, but only related to the slope and the mechanical properties of slope materials; The material change from soil layer, simulated lawn to concrete, the corresponding stiffness increases as slope gradient of the soil layer, simulated lawn and concrete increases respectively, and therefore the normal recovery coefficient also shows an increasing trend. When the slopegradient and slope materials are considered in practical engineering applications, the normal restitution coefficient range of rockfall collision is 0.32 ~0.62 and the value of normal restitution coefficient is smaller than that of the existing data. It indicates that thevelocity decreases greatly in the normal direction during the test.

Keywords: Motion trajectory; Normal restitution coefficient; Physical model test; Degree of reduction.

1. Introduction

When designing engineering protection, the motion path of falling rocks bouncing and colliding is an important design basis, and the accuracy of calculating the motion path of falling rocks needs to consider the influence of various factors on the normal recovery coefficient. Therefore, for the rational design of protective structures, the normal recovery coefficient is a necessary parameter.

At present, domestic and foreign scholars have conducted certain research on the importance of collision recovery coefficient in protective engineering, and have achieved some preliminary results. MANGWANDI et al[1]. conducted research based on numerical simulation techniques, using the principles of Young's modulus, yield stress, and contact mechanics to analyze the influence of material particles on the collision recovery coefficient, and obtained a reasonable collision recovery coefficient. Based on finite element software research, Li Yiliang et al[2]. analyzed the recovery coefficients under different definitions during the collision process. By comparing the differences in energy before and after the collision, they obtained more accurate collision recovery coefficients and derived the applicability of the recovery coefficient calculation formula. In engineering applications, different definitions need to be combined with actual situations. He Siming et al[3]. used a combination of contact theory and tangential contact theory to derive specific calculation methods for the normal and tangential recovery coefficients of rolling stone collision motion, and applied them in practical engineering. Yang Haiqing et al[4]. used kinematic theory and contact mechanics as the research basis, considered the elastic-plastic mechanical properties of ground materials, analyzed the changes in normal recovery coefficient caused by the shape, velocity, and ground materials of falling rocks, and derived the formula for calculating the normal recovery coefficient of slope motion trajectory related to the shape of falling rocks and ground materials. Chau et al[5]. conducted experiments using physical models to analyze the influence of rockfall shape, slope gradient, and impact velocity on the recovery coefficient. They derived that the impact on the normal recovery coefficient

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was significant, while the impact on the tangential recovery coefficient was not significant. Ye Siqiao et al[6]. conducted model experiments to study the influence of rockfall slope material, slope gradient, rockfall shape, falling height, and implementation quality on the value of normal recovery coefficient. They derived that the value of normal recovery coefficient for rockfall collision is influenced by slope material and slope. Ye Siqiao et al[7]. conducted model experiments to study the tangential recovery coefficient of rockfall collision, which gradually increases with the slope surface from soft to hard, the slope from large to small, the mass from small to large, and the height from large to small. Zhang Guangcheng et al. combined on-site experiments with numerical calculations and found that the normal collision recovery coefficient is only related to the mechanical properties of the soil material, while the tangential recovery coefficient is considered from two aspects: incident velocity and soil material.

The research results indicate that the influencing factors of the normal recovery coefficient need to be considered from multiple aspects, and the existing values of the normal recovery coefficient only consider the slope material factor. However, the connection between the results of collision recovery coefficient experiments and collision theory has not yet been established, making it difficult to scientifically measure the rationality of collision recovery coefficients. This article uses indoor physical model experiments to study the changes and values of the normal recovery coefficient caused by factors such as the size of falling rocks, slope gradient, incident velocity, and slope material.

2. Physical Experimental Research

2.1 Experimental Model

Considering the slope gradient as a factor affecting the normal recovery coefficient, the slope is manually stacked; The falling stones are made of granite with sizes of 10cm, 15cm, and 20cm; The slope materials used include soil layer, simulated lawn, and concrete. The soil layer slope can utilize the existing stacked soil slope as shown in Figure 1 (a); The grass slope is a 3cm thick simulated lawn purchased and placed on a concrete slab slope as shown in Figure 1 (b); Choose a specially customized concrete slab with a length of 1.2m, width of 0.5m, and thickness of 0.2m for the concrete slope, as shown in Figure 1 (c).

Figure 1 Slope of different materials.

2.2 Test Process

2.2.1 Test Equipment

The key to the experiment is to capture and analyze the motion during the impact of falling rocks on the slope, in order to obtain the corresponding motion parameters. The experiment uses the Oriental Xinrui DIMS9100 3D motion capture and analysis system, which uses 8 near-infrared high sensitivity cameras and other auxiliary equipment to capture the trajectory of the falling rock movement. It can accurately capture the position and velocity values at any time during the falling rock movement process, and is widely used in 3D motion capture and analysis.

2.2.2 Test Layout

(1) Mark ball pasting.

To accurately capture the trajectory of the falling rock movement of the sphere, Mark balls were selected to be attached around the test specimen as tracking points for near-infrared high-sensitivity camera image acquisition.

(2) The arrangement of cameras.

To ensure the capture range, the dedicated near-infrared high-sensitivity camera is evenly distributed in a 360 degree space and fixed on a steel frame specially built for the experiment. There are a total of 8 cameras in the experiment, with an average of 2 cameras in each direction. They are firmly fixed at the 3m high steel pipes around them in order of numbering, and then connected one by one through dedicated cables and the interface of the DIMS controller.

(3) Software system.

After obtaining the calibration parameters of the camera in 3D space, real-time high-precision 3D motion data capture software can be used for 3D capture. Multiple near-infrared high sensitivity dedicated cameras are used to synchronously capture identification points, recognize identification point images, calculate three-dimensional coordinates of spatial identification points, automatically track and match, and save the identification point trajectory database as shown in Figure 2.

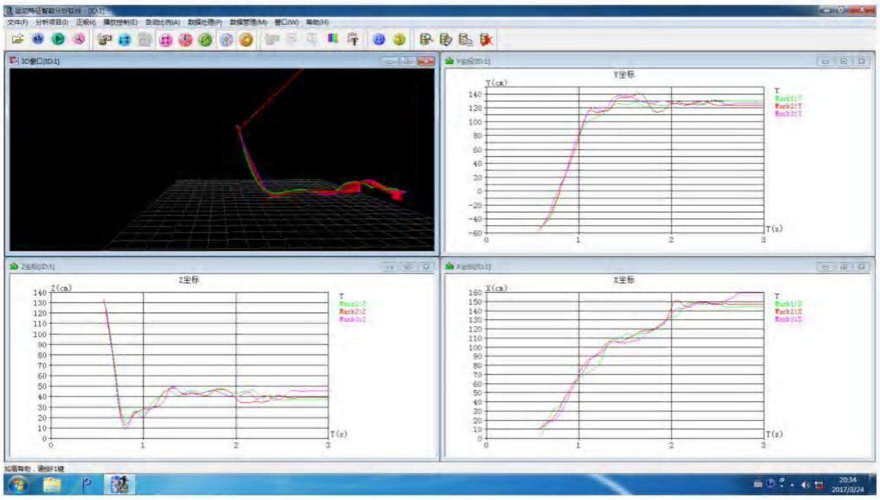

Figure 2 High precision 3D motion data capture software.

(4) Experimental control.

The falling rock is lifted to a designated height by a wireless mechanical gripper using a crane, and the mechanical gripper is controlled to open through a wireless remote control. The entire process of falling rocks hitting the slope and bouncing up is processed through the DIMS9100 3D motion capture system, which captures the motion process through 8 dedicated near-infrared high sensitivity cameras. The motion trajectory is then captured using the software provided by the system, as shown in Figure 3.

3. Experimental Results and Analysis

In the study of physical model experiments, in order to clearly elucidate the various factors that affect the normal recovery coefficient, the variation patterns of the minimum, average, and maximum values are selected, and combined with bar charts, single factors related to the value of the normal recovery coefficient are analyzed.

3.1 The Influence of the Size of Falling Rocks on The Normal Recovery Coefficient

Figure 4 shows the variation curve of the normal recovery coefficient with respect to the size of falling rocks. The minimum value of the normal recovery coefficient is distributed between 0.08 and 0.1, the average value is distributed between 0.52 and 0.54, and the maximum value is distributed between 0.81 and 0.83. The size of falling rocks has little fluctuation in the value of the normal recovery coefficient, and there is almost no significant difference. It can be inferred that no matter how the size of the falling rock changes, the values of the normal recovery coefficient (minimum, average, and maximum) will not change significantly, indicating that the size of the normal recovery coefficient is not affected by the change in the size of the falling rock.

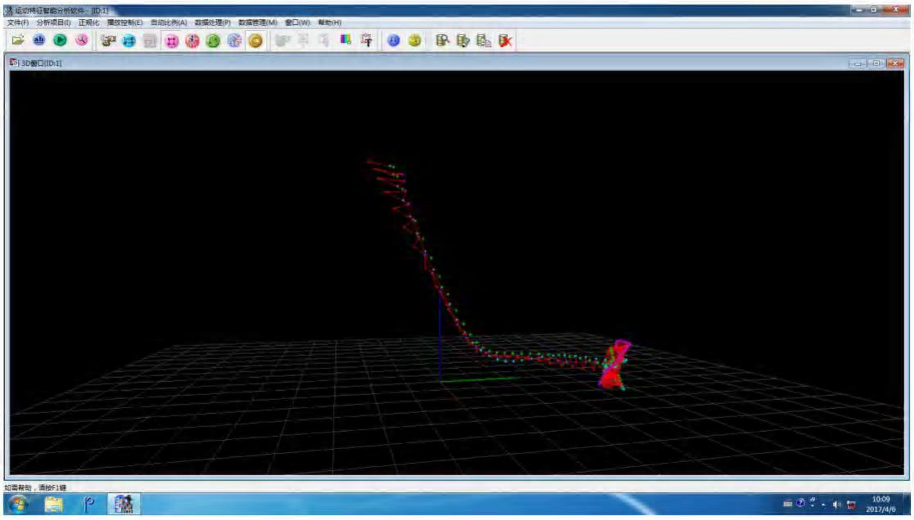

Figure 3 DIMS9100 3d motion trajectory.

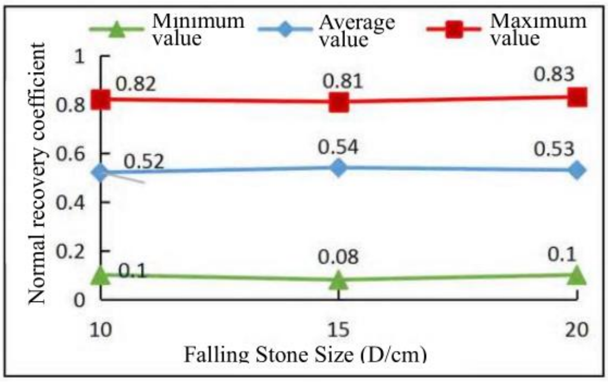

Figure 4 The influence of the size of falling rocks on the normal collision recovery coefficient.

Figure 5 shows the distribution range of the normal recovery coefficient with respect to the size of the falling rock. It can be seen that the dispersion of the normal recovery coefficient with respect to the size of the falling rock is relatively small, which meets the requirements for calculating the normal motion path of the falling rock collision. Therefore, there is no significant difference in the distribution of the normal recovery coefficient with respect to the size of the falling rock. At the same time, it indicates that the distribution of the normal recovery coefficient is relatively concentrated in the range of 0.2 to 0.6.

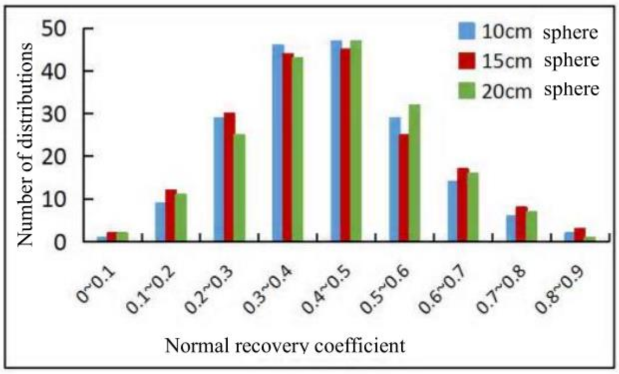

Figure 5 Distribution of normal recovery coefficient with respect to the size of falling rocks.

3.2 The Influence of Slope Gradient on the Normal Recovery Coefficient

Figure 6 shows the variation curves of the minimum, average, and maximum values of the normal recovery coefficient for different slope angles. It can be seen that the distribution of values for the minimum normal recovery coefficient is between 0.08 and 0.12, the distribution of values for the average normal recovery coefficient is between 0.49 and 0.62, and the distribution of values for the maximum normal recovery coefficient is between 0.83 and 0.97; As the slope gradient gradually increases, the relative normal recovery coefficient (minimum, average, and maximum) also gradually increases, indicating that the change in slope gradient has a significant impact on the value of normal recovery coefficient.

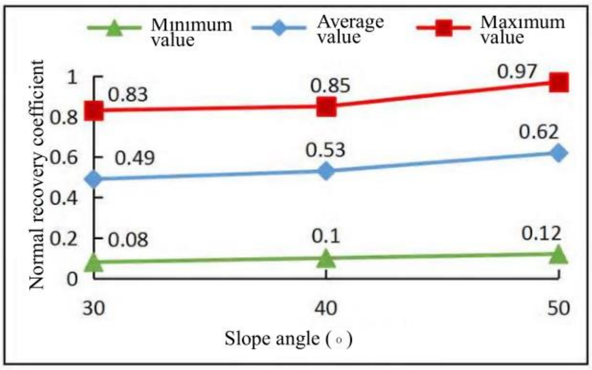

Figure 6 Impact of slope gradient on normal collision recovery coefficient.

Figure 7 shows the distribution range of the slope slope on the normal recovery coefficient. When the slope is 30° or 40° , the dispersion of the collision recovery coefficient is small, and the value of the normal recovery coefficient is mainly concentrated between 0.3 and 0.6; When the slope is 50° , the dispersion of the collision recovery coefficient is large, and the values of the normal recovery coefficient are mainly concentrated between 0.3 and 0.9; In summary, in engineering protection design, not considering the slope gradient as an impact on the normal recovery coefficient value lacks safety considerations. As the slope changes from 30° to 50° , there are differences in the corresponding distribution numbers, and there is a trend of greater dispersion.

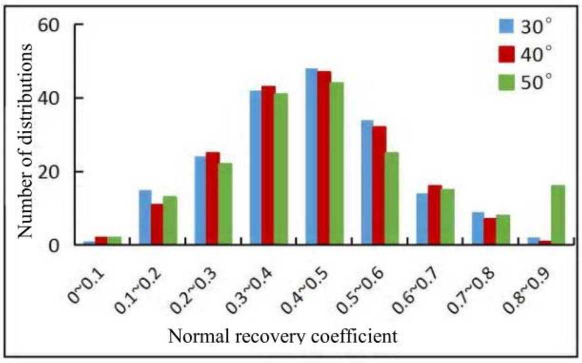

Figure 7 Distribution of slope gradient on normal recovery coefficient.

3.3 Impact of Incident Velocity on Normal Recovery Coefficient

As shown in Figure 8, the variation curve of the normal collision recovery coefficient with respect to the falling height is shown, and the incident velocity is reflected by the falling height of the falling rock. It can be seen that under the three falling heights, there is no significant difference in the normal recovery coefficient (minimum, average, and maximum) with the increase of falling height, and the fluctuation is also within the range of the trajectory of the falling rock collision motion. The increase in incident velocity is safe for the trajectory of a falling rock collision, indicating that no matter how the incident velocity changes, it does not have any impact on the value of the normal recovery coefficient.

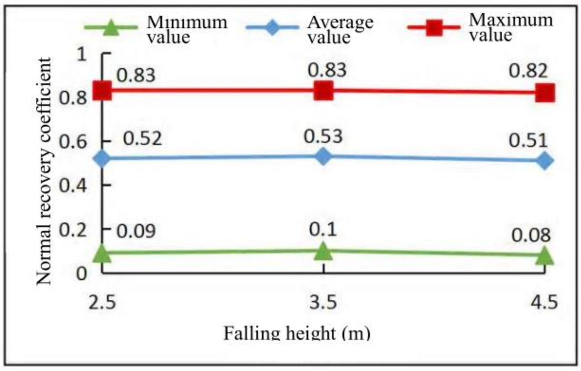

Figure 8 Effect of falling height on normal collision recovery coefficient.

As shown in Figure 9, the distribution of the number of intervals for the normal recovery coefficient is relatively balanced and the dispersion is relatively small. When the value of the normal recovery coefficient is in the range of 0.3~0.6, the number of distributions accounts for more than 65%, indicating that within the distribution range of 0.3~0.6, the number of distributions becomes more concentrated. However, the incidence velocity and normal recovery coefficient show a relatively gentle trend.

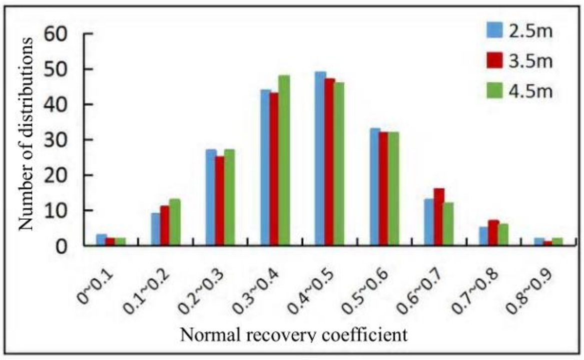

Figure 9 Distribution of normal recovery coefficient with respect to falling height.

3.4 The Influence of Slope Materials on the Normal Recovery Coefficient

Figure 10 shows the variation curves of the minimum, average, and maximum values of the normal recovery coefficient from soil layer, simulated lawn to concrete slope materials in the experiment. As the slope material gradually changes from soft to hard, its normal recovery coefficient (minimum, average, and maximum values) gradually increases, especially with a more significant increase in the average value, ranging from 0.32 to 0.53. This indicates that the greater the stiffness of the slope material, the greater the corresponding velocity reduction in the normal direction; The smaller the stiffness of the slope material, the smaller the corresponding velocity reduction in the normal direction. The mechanical properties of the slope material have a significant impact on the value of the normal recovery coefficient in the trajectory of a falling rock collision.

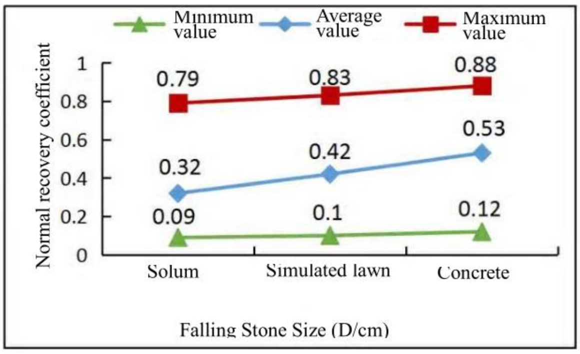

Figure 10 Effect of slope material on normal collision recovery coefficient.

Figure 11 shows that the normal recovery coefficient of slope materials is distributed in the range of 0~0.1, 0.7~0.8, and 0.8~0.9, with relatively scattered distribution numbers; When more than 70% of the normal recovery coefficients are in the range of 0.2~0.7, it can be seen that the difference in the number of distributions is relatively large; When analyzing slopes with different slope materials, the degree of discreteness generated is relatively high.

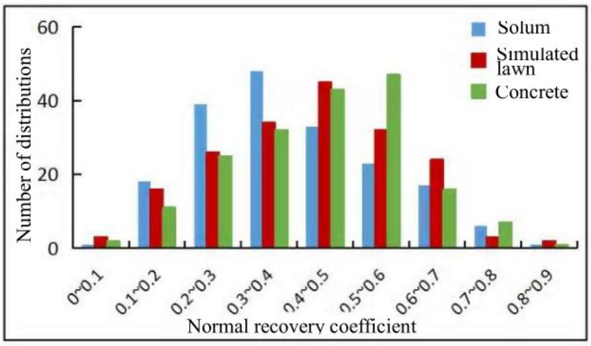

Figure 11 Distribution of normal recovery coefficient of slope materials.

4. Value of Normal Recovery Coefficient

According to existing research findings, the value of the normal collision recovery coefficient mainly depends on the mechanical properties of the slope material. The general description of slope materials is from soft to hard, and the normal recovery coefficient obtained is a single fixed value or interval value. Chau conducted research on physical model experiments and obtained a normal collision recovery coefficient of 0.393 for soil layer materials; The normal recovery coefficient of paving concrete material is 0.453; The normal recovery coefficient of rock materials is 0.487. Zhang Guangcheng used a combination of field experiments and numerical simulations to measure the normal recovery coefficient in the range of 0.25 to 0.8, while using numerical simulation technology to measure the normal recovery coefficient in the range of 0.26 to 0.78. There is a significant difference between the above values and the normal recovery coefficient obtained from indoor physical experiments in this article. The normal recovery coefficient measured through indoor physical model experiments in this article ranges from 0.32 to 0.53, and the corresponding normal velocity is relatively reduced during the process of rockfall collision motion. For the existing normal recovery coefficient, its value is relatively large.

Compared with relevant literature at home and abroad, the values of the normal recovery coefficient obtained by the US federal highway system using CRSP rockfall calculation software are shown in Table 1, and the values of the normal recovery coefficient obtained by the China Railway Ministry's Engineering Bureau using empirical theory are shown in Table 2. From the table, it can be seen that the value of the collision recovery coefficient mainly depends on the properties of the slope material.

Table 1 Values of normal recovery coefficient in CRSP calculation program.

Slope features	Normal recovery coefficient
Extremely soft: easily penetrated by a few inches in boxing	0.1
Soft: Thumbs easily press in a few inches	0.1
Solid: Generally, the thumb can be pressed in a few inches with force	0.15
Hard: Thumbs are prone to leaving marks, but require extreme force to press in	0.15
Extremely hard: easily scratched by thumbnails	0.2
Durable: difficult to scratch with fingernails	0.2
Extremely soft rock: can be scratched by thumb nails	0.15
Soft rock: Geological hammers are prone to fragmentation and can be easily cut by small knives	0.15
Soft rock: difficult to cut with a small knife, can be struck with a geological hammer to create shallow pits	0.2
Medium rock: cannot be cut with a small knife, it will break after being hit by a geological hammer	0.25
Hard rock: requires more than one shot to break	0.25~0.3
Soft and hard rock: requires multiple attempts to break	0.25~0.3
Extremely hard rock: can only be cut by geological chisels	0.25~0.3

Table 2 Values of normal recovery coefficient for the former railway ministry works bureau.

Slope features	Normal recovery coefficient
Smooth and hard paving surface	0.37~0.42
Bedrock and conglomerate slopes	0.33~0.37
Hard soil slope surface	0.30~0.33
Soft protrusion surface	0.28~0.30

In summary, the values of the normal recovery coefficient at home and abroad are considered based on the slope material, without discussing the slope angle, which results in imprecise values and significant differences. Compared with existing research results, this article found through physical model experiments that the correlation between the value of the normal recovery coefficient and the size of the falling rock and the incident velocity is weak; The slope gradient and slope surface material have a relatively significant impact on the normal recovery coefficient. The experimental results show that the range of the normal recovery coefficient for rockfall collisions obtained by considering two factors: slope gradient and slope surface material is 0.32~0.62.

5. Conclusion

(1) The normal recovery coefficient obtained from indoor physical model experiments is relatively small compared to existing research results. Due to the relatively small bounce height of the impact slope of falling rocks, the reduction in the normal movement velocity of falling rocks is relatively large; However, the existing values of the normal recovery coefficient for rockfall collisions are relatively large. Due to the relatively high bounce height of the slope during rockfall collisions, the reduction in the normal movement speed of the rockfall is relatively small.

(2) The reasonable value range for the normal recovery coefficient is obtained from the comprehensive consideration of slope gradient and slope surface material, which is 0.32~0.62. In practical engineering applications, the larger the slope gradient, the greater the stiffness of the slope surface material, and the corresponding normal recovery coefficient; The smaller the slope gradient, the smaller the stiffness of the slope material, and the smaller its normal recovery coefficient.

References

1. MANGWANDI C, et al.The coefficient of restitution of different representative types of granule [J]. Chemical Engineering Science,2007,62(1/2):437-450.
2. Li Yiliang, Qiu Xinming, Zhang Xiong. Different definitions of recovery coefficients and their applicability analysis [J]. Mechanics and Practice, 2015 (06): 773-777.
3. He Siming, Wu Yong, Li Xinpo. Research on the Recovery Coefficient of Rolling Stone Impact Collision [J]. Geotechnical Mechanics, 2009, 30 (3): 623-627.
4. Yang Haiqing, Zhou Xiaoping. A new method for calculating the trajectory of rock falling on slopes [J]. Geotechnical Mechanics, 2009 (11): 3411-3416.
5. Chau K T, Wong RHC, Wu J J. Coefficient of restitution and rotational motions of rockfall impacts [J]. International Journal of Rock Mechanics and Mining Science,2002, 39: 69-77.
6. Ye Siqiao, Gong Shangqing. Model experimental study on normal recovery coefficient of rockfall collision [J]. China Railway Science, 2015 (04): 13-19.
7. Ye Siqiao, Gong Shangqing, Wang Linfeng, Xie Tao, Wang Zongjian. Research on the Value of Tangential Recovery Coefficient for Rockfall Collisions [J]. China Railway Science, 2018 (01): 8-15.
8. Zhang Guangcheng, Xiang Xin, Tang Huiming. On site testing and numerical calculation of the recovery coefficient of rockfall collision [J]. Journal of Rock Mechanics and Engineering, 2011, 30 (6): 126-127.