Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 9929119, 11 pages
https://doi.org/10.1155/2021/9929119

Research Article

Investigating the Effect of Preimpact Energy Dissipation on Coefficient of Restitution regarding the Slope-Boulder Interaction

Ran Bi, Shaoying Li, Gou Liu, Jianxi Ren, and Yongjun Song

Department of Civil and Architectural Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China

Correspondence should be addressed to Ran Bi; ranbiwork@xust.edu.cn

Received 13 March 2021; Revised 29 March 2021; Accepted 5 April 2021; Published 16 April 2021

Academic Editor: Sang-Bing Tsai

Coefficient of restitution is regarded as a dominating parameter in rockfall research. Generally, small-scale experiments were developed without considering interactions between boulder and slope. However, preimpact moving statuses are essential to evaluate rockfall behaviors. To reveal the effect of preimpact interactions on coefficient of restitution, energy dissipation considering initial velocity, surface type, and slope angle is executed based on medium-scale tests. The results show that (1) as the inclination of initial velocity, higher rebound height, and the declining normal coefficient of restitution occur, a determinable linear function could demonstrate relationships among energy dissipation and all coefficient of restitution; when initial velocity exceeds 5 m/s, the recovery ability shows and produces an increasing trend with respect to the variation of kinematic coefficient of restitution and kinetic energy coefficient of restitution. (2) As the surface material varies, slope hardness and rebound ability influence normal coefficient of restitution, and the surface roughness and rotation feature dominate tangential coefficient of restitution; considering preimpact slope and boulder interactions, four types of coefficient of restitution follow declining trend with different material sequence. (3) Slope angle affects normal coefficient of restitution, and tangential coefficient of restitution relatively descends 18% and inclines 10% when the angle ranges from 30° to 75°; regarding preimpact moving status, it differs from bounce times. The correlation between preimpact energy dissipation and four coefficients of restitution can be represented by the same decreasing linear function, when increasing the slope angle.

1. Literature Review

In mountainous area, rockfall has always been considered as a random and frequent occurring natural disaster aroused by human activity or weathering influence (erosion, saturation, earthquake, rainfall, and freezing) with no objection [1–3]. It threatens both the surrounded residents and the nearby infrastructural facilities. Enormous economic losses of the facilities and huge injuries and deaths attract people's attention [4–6]. Various techniques and measures were conducted to predict and evaluate the runout zone and impulsive force of the moving rock [7–13]. With regard to applying the most appropriate and effective precaution, trajectory, impact force, and impulsive energy are particularly essential, which all correlate to the application of key configuration of coefficient of restitution [14–16]. The rock moving status reveals the runout zone, movement form (fall, roll, slide, and rebound), and bounce height. As for the impact force and energy, it indicates the kinetic status of the falling rock and dominates the barrier protection. In order to facilitate the practical application, empirical, theoretical, laboratory, and numerical techniques are employed by researchers, which are all relevant or based on these factors. Thus, the study is aiming at moving statuses and kinetic features of the rock. To be specific, physical and mechanical factors of bounce frequency and dissipation parameters in accord with energy variation and coefficient of restitution (COR) are considered.

To date, various types of efforts are explored to deal with the rockfall analysis [17–19]. Analytical model, laboratory investigation, numerical simulations, and barrier evaluation are chiefly measured as adopted previously [20–24]. Block moving status dominates the threatened area, bounce height,

and piling zone, which researchers have studied as the designing basis of defense structure, such as vegetation planting, restraining nets, and catch walls. Morphological and geological conditions are considered, which correspond to slope material (soil, rock, and scree) as varied in tests. Efforts have been focused on the slope, which include slope angle, height, roughness, compaction degree, and vegetation cover [25–27]. The natural and artificial tests corresponding to in situ and laboratory test are employed, which demonstrate that the after-impact motion traits are not affected by the slope characteristic when considering COR influence [28–30]. The research of rockfall states that the characteristics of moving status after impact are influenced not only by slope properties, but also by other key parameters correlating to the boulder.

Regarding the boulder features (type, mass, scale, shape, and stiffness), systematic experimental investigations are operated to figure the influence on bouncing phenomenology of rock. Indeed, mass is discovered to control the normal coefficient of restitution [31]. Moreover, shape somehow correlates to all coefficient of restitution and kinetic features, which not only relies on slope material, but also depends on impact angle and other configuration of rock during the impact. The dynamic factors associate with the interactions between the macro topography features of slope and the physical and mechanical properties of boulder. For instance, it has reached consensus that the outcropping material dominates the rebound of boulder [23, 32, 33]. As the concern characteristics of impact velocity, tests confirm that the coefficient of restitution tested depends on it severely [31, 34]. Additionally, the kinematic parameters of impact show that more normal impact with respect to less rock rebounds [35].

However, prior tests are carried on small or medium scale, where the efforts are not focused on the preimpact status of the boulder and would not reflect the truly influence on COR and impact energy. It only deals with the temporary moment just before and after the impact, which may ignore the comprehensive function of the preinteractions between the slope and boulder. Indeed, more attention needs to be paid to the preimpact status, which corresponds exactly to the whole process of the actual situation. Thus, the key configuration study should be based on both the impact moment and the process prior to it.

Therefore, a suitable and practical rockfall experiment should be designed to simulate and reflect the physic and mechanic features of rockfall. Afterwards, the estimation of affecting factors on the rockfall would be conducted on a more credible and pertinent method. In addition, the analysis highly relies on the experimental technique, which means that the measuring devices must be in accord with the accuracy requirement. Thus, a reliable modeling system should explore how to meet this acquirement. Moreover, physical features of slope angle and surface type are applied, while the kinetic features of boulder initial velocity are discussed. These features are not well-documented regarding the preimpact interaction effect according to the previous study. Therefore, a special designed rockfall modeling system is adopted in this paper. The major critical factors are evaluated and analyzed according to the moving variation and energy dissipation.

2. Laboratory Investigation

2.1. Rock Specimens. The sand rock was gathered from Weinan rocky mountain of Shaanxi Province, where the rockfall was frequent and treated as a serious threat to the surrounding area. Samples were shaped and polished as in Figure 1, in which the geometric features are shown in Table 1. The specimens that did not meet the requirement were all eliminated to guarantee the accuracy. The physical and mechanical properties of the natural rock applied here were examined according to the uniaxial compression tests.

2.2. Experimental Setup. The experimental campaign was implemented in terms of initial velocity, cushion type, and slope angle. Initial velocities are investigated in terms of seven levels, which range from 1 m/s to 7 m/s. The slope was verified and shaped with angles of 30°, 45°, 60°, and 75°, respectively. The planeness and compactness were monitored during the whole procedure to guarantee the uniform standard when angle varied. For the colliding cushion, four different types in terms of real in situ situation were considered. Each slope surface was thick enough to distinguish the cushion colliding difference among the four types, which eliminate the effect of the bellowed foundation material.

The variation of slope surface would result in rock motion difference, and four types of slope material were considered. According to the practical circumstance, four commonly applied materials of sand, rock-like material, vegetation, and wooden board were studied. The corresponding properties of the slope material conducted in the experiment are shown in Table 2. Different types corresponded to different situations. Sand surface was related to sand slope, and concrete was for rock slope. Plastic simulated turf was targeted on vegetation slope, while wood material was studied for soft or strong weathering rock type of slope.

The apparatus required for conducting colliding tests in the laboratory was prepared as demanded, which was a releasing mechanism, a fast-cam recording system, and the corresponding analyzing system as in Figure 2. The fast-cam recording system was operated by high-speed camera and recording system (Photron FASTCAM view). A computer was employed to connect the high speed camera and the high speed transmission data cable. In the Photron FASTCAM view software, the film of the rock motion could be checked and clipped on demand. Also, the motion can be played back frame by frame to guarantee the shooting quality.

Besides the aforementioned device, analysis software (Photron FASTCAM analysis) was applied to resolve the data. The displacement, velocity, and acceleration curves in terms of the motion time could work out directly by the software. It could also zoom in the rock motion at any time point to observe the rock-slope collision. The variation at the impact moment could be detected by 1 frame/s. In the analysis software, two types of coordinate could be selected,

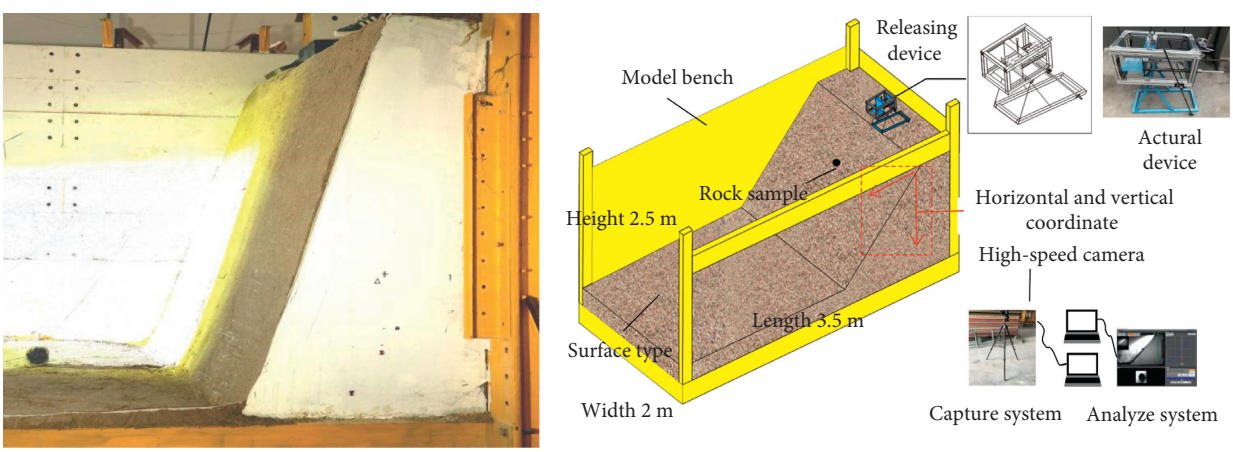
Figure 1: Rock sample of sandstone adopted in the tests.

Table 1: Basic geometric characteristics of spherical samples.

The number	Diameter (cm)	Sphericity	Density (kg/m^3)	Compressive strength (MPa)	Poisson's ratio	Elastic modulus (GPa)
5	6.021 ± 0.023	0.9999	2.5×10^3	34.7	0.24	19.6
8	9.876 ± 0.018	1.0000	2.5×10^3	34.6	0.25	19.5
4	13.862 ± 0.0483	1.0000	2.5×10^3	34.8	0.26	19.4

Table 2: Calculation parameters of the slope material.

Material	Unit weight (kN/m^3)	Internal friction angle (°)	Elastic modulus (MPa)	Poisson's ratio	Thickness (cm)
Plastic simulated turf	6.86	20	7.8	0.24	2
Sand	15.40	30	15.0	0.25	4
Wood	17.15	37	35.0	0.20	2
Concrete	21.56	40	50.0	0.17	4



(a) (b)

Figure 2: The rockfall modeling system: (a) the general view of the real test slope and (b) a schematic representation components adopted in the rockfall physical modeling system.

which are static and dynamic coordinates. Here, the static coordinate was applied according to the analyzing demand. The horizontal coordinate was chosen based on the horizontal plane of the slope. Angles between vertical and horizontal coordinates were 90°. The actual coordinates employed in the test were marked on the slope as shown in Figure 2(b). The camera was set in front of the slope model to film the slope, in which the sights of the camera lens were perpendicular to the slope. Thus, the slope in the camera was changed into two dimensions, and the rock motion could be captured more clearly. The displacement and other related parameters of the rock motion were all exported and analyzed on the basis of these coordinates. After selecting the coordinates, the rock was selected by the capture box

demand. The analyzer was operated to obtain the motion data. Thus, the parameters of coefficient of restitution and other related controlling factors could be acquired upon the output data.

To be specific, the releasing mechanism was designed to hold the sample in the desired position and provide the initial velocity by spring combination system for this laboratory test. The releasing position and angle could be controlled by altering the laying platform, as shown in Figure 3. To guarantee the comparability among different groups, the rocks were all placed at the same position on the platform even without studying the effect of the initial velocity. The apparatus was laid up on the top edge of the slope with the fixed angle as shown in Figure 2(b). The angle adjusting process was illustrated with steps in Figure 3. The rock dived down by the effect of gravity with no initial velocity, when considering the factor of slope angle and surface material. For the initial velocity study, the rock was applied with spring force at the start position. A threaded rod was used to control the hand wheel to impose the anticipated force. After releasing the pin bolt, the rock would eject with the desired initial velocity.

The effects of the influencing factors were conducted by single factor analysis method. For example, when dealing with slope angle effect, the other parameters in the test remained the same. It means that only the slope angle varies. Before setting the sample, the high speed camera was adjusted in the required position. The recording system was tested before the experiment. Then, the rock sample was placed on the platform of the releasing device, in which the device was positioned on the top edge of the shaped slope. The spring force did not need to apply on the rock until the initial velocity factor was explored. The sample was released under the gravity effect. Simultaneously, the camera controlled by the recording system was activated to film the whole moving process until the moving was done. The recording film of rock motion was input into the Photron FASTCAM analysis software. Through the analyzing software, the corresponding displacement, velocity, and acceleration direct information of the rock motion could word out. Data were exported in the end to provide the targeting motion parameters for further analytical study.

3. Effects of Three Controlling Factors on Coefficient of Restitution

Three critical effect factors are considered as the initial velocity, surface material, and slope angle, respectively. Coefficient of restitution, as one of the key factors that dominates the feature of rockfall, is investigated. Four types of definitions are commonly applied, which are normal coefficient of restitution (R_n), tangential coefficient of restitution (R_t), kinematic coefficient of restitution (R_v), and kinetic energy coefficient of restitution (R_E). The normal tangential and kinematic coefficients of restitution are defined by the velocity before and after the impact. The algorithm formulas are

$$R_n = \frac{v_{pn}}{v_{in}}, \quad R_t = \frac{v_{pt}}{v_{it}}, \quad R_v = \frac{v_p}{v_i}, \tag{1}$$

where v_{pn}, v_{pt} and v_{in}, v_{it} present the normal, tangential, and total velocity at the rebound and impact moment just after and before the collision. The remaining kinetic energy coefficient of restitution is in accordance with the kinetic energy and displays the ratio of the energy before and after the collision. The algorithm formula is

$$R_E = \frac{E_p}{E_i}, \tag{2}$$

where E_p and E_i represent the kinetic energy of the boulder at the reaching and leaving impact moments.

Thus, the behaviors of coefficient of restitution subjected to three factors could be acquired, which could provide a broad perspective of its mechanism.

3.1. Effect of the Initial Velocity on Coefficients of Restitution. Repetitive free fall tests were conducted, in which the boulder was designed with seven types of initial velocity from 1 m/s to 7 m/s. Wooden surface with a slope angle of 45° is selected to represent and study the velocity variation. Five representative results of normal coefficient of restitution were elaborated as shown in Figure 4.

It can be told that R_n possesses a general decreasing trend while increasing the initial velocity. Two sectioned linear functions could represent the variation and match the ranging of R_n. Lower R_n is offered according to higher velocities. The initial velocity influences R_n in a decreasing way, which reveals that the initial velocity possesses more normal velocity dissipation when velocity inclines.

3.2. Effect of Slope Material on Coefficients of Restitution. Repetitive free fall tests were conducted, in which the slope was designed with four types of surface material, that is, sand, wood, artificial plastic, and cement, respectively. No initial velocity of boulder together with a slope angle of 45° is selected to represent and study the surface variation. Five representative results of normal coefficient of restitution were elaborated as shown in Figure 5.

It could be told that R_n follows a decreasing trend when the surface type varies, which is combined with the sequence of cement, wood, plastic, and sand. The trend of R_n is influenced by the surface stiffness and type of rebound ability. At the temporary impact, the slope and rock interact with each other, which would lead to compression divergence according to the hardness difference. Here, the hardness of slope surface applied in the experiment is cement > wood > sand > plastic, which could result in the variation of material compression,

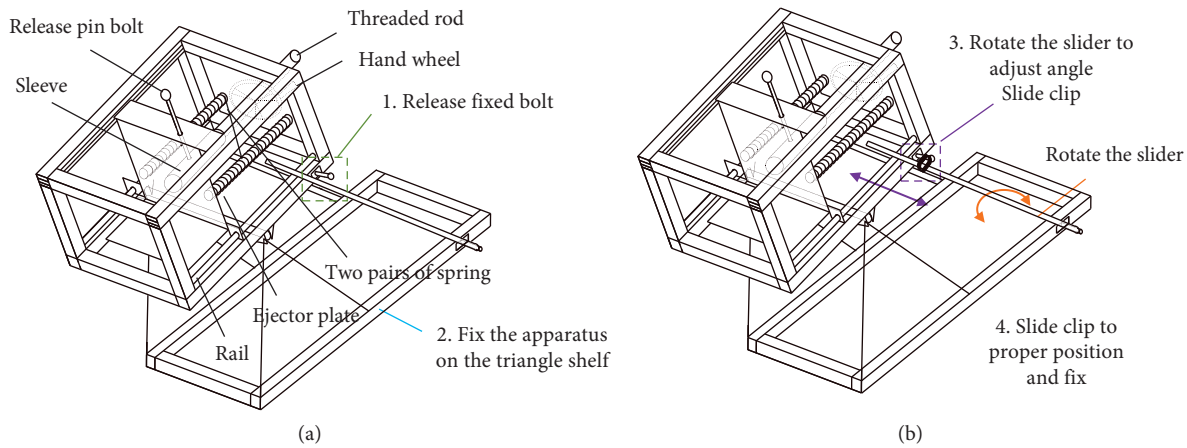


Figure 3: The self-designed rock releasing apparatus: (a) the schematic representation components of the releasing apparatus and (b) the angle adjusting procedure.

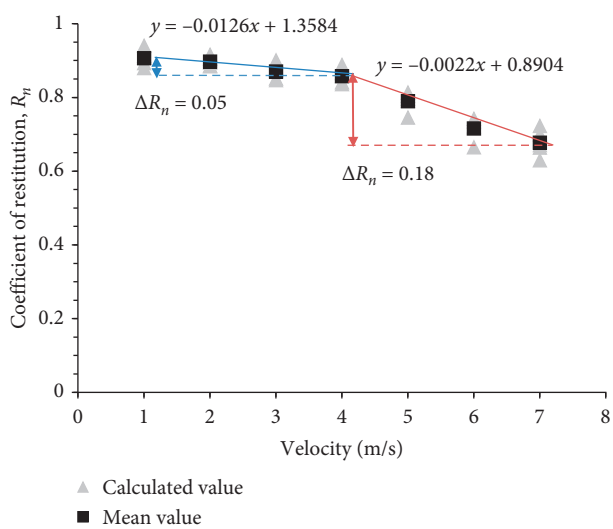


Figure 4: The effect of initial velocity on normal coefficient of restitution.

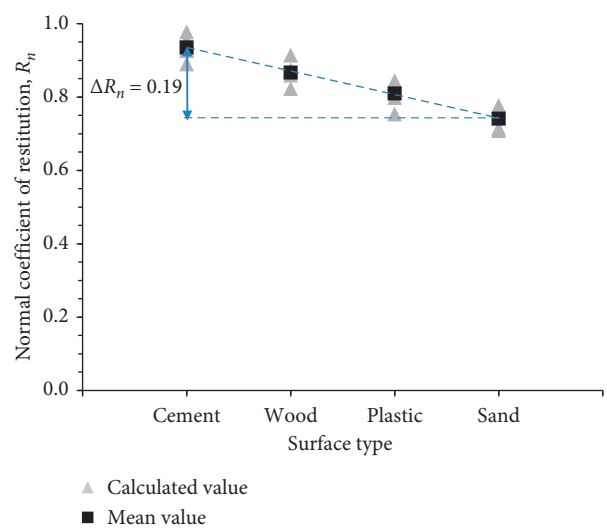


Figure 5: The effect of surface type on normal coefficient of restitution.

and, at the end, it causes the changing of energy dissipation. Except for the material compression effect, the surface rebound ability counting on the material would also affect the velocity before and after the impact. The laboratory test data confirms that plastic slope presents better velocity recovery ability than sand slope, which even transcends the hardness effect.

3.3. Effect of Slope Angle on Coefficients of Restitution. Repetitive free fall tests were conducted, in which the slope was designed with four types of surface angle, that is, 30°, 45°, 60°, and 75°, respectively. No initial velocity of boulder together with the slope material of sand cushion is selected to represent and study the slope angle variation. Five representative results of normal coefficient of restitution are elaborated as shown in Figure 6.

The general trend of R_n appears to decrease as the slope angle increases. A linear function can match the pattern well. It indicates that the slope angle could influence the R_n with a deterministic declining trend as the angle inclines. When the angle varies from 30° to 75°, the values range from 0.77 to 0.62 with the deduction of 0.14. The effect of slope angle on R_n could be easily discovered.

4. Correlations between Coefficient of Restitution and Energy Dissipation

The test results in terms of coefficient of restitution are demonstrated as mentioned previously. The coefficient of restitution is based on the impact occurring at the slope foot. Velocities before and after the impact are essential. However, the impacting status before collision at the slope corner is controlled by the rock-slope interaction. Thus, the interaction divergence among multiple affecting parameters should be considered. The rockfall interaction variation may lead to large kinetic energy divergence for rock before the bottom impact. This again proves the essential necessity of

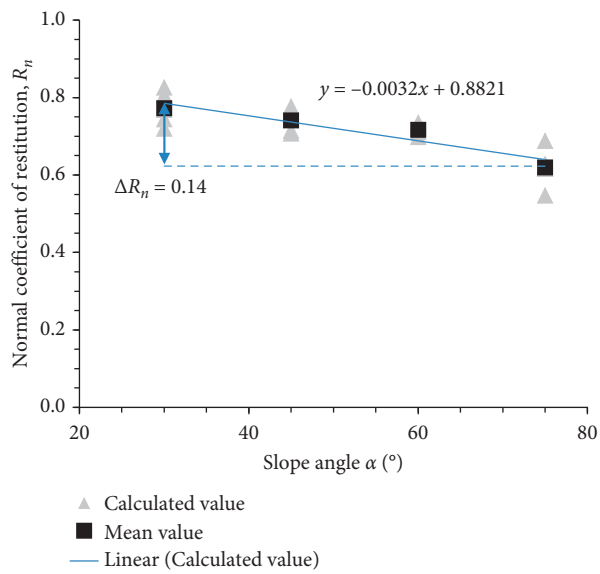


Figure 6: The effect of slope angle on normal coefficient of restitution.

interaction analysis rather than only paying attention to the individual collision without considering the previous rock moving status. Here, energy dissipation divergences in terms of initial velocity, surface type, and slope angle parameters at the slope interval are considered. The correlations between the slope arousing effect and energy dissipation are developed. The energy dissipation displayed as the ratio of the test acquired kinetic energy and the calculated kinetic energy. The formula is

$$\xi_{\text{transit}} = \frac{E_{\text{mesured}}}{E_{\text{calculated}}} = \frac{E_m}{E_c}, \tag{3}$$

where ξ_{transit} is the energy dissipation coefficient, E_m is developed based on the test measured velocity according to kinetic energy theorem, and E_c is obtained based on energy conservation law without considering the impact loss between rock and slope. The kinetic energy is calculated by using the sum of initial kinetic energy and gravitational energy.

4.1. The Correlations of COR and Energy Dissipation considering Initial Velocity. The rock energy dissipation along the slope considering four surface types is investigated. The relationship between energy loss and coefficient of restitution is demonstrated in Figure 7.

The R_n presents a downward trend when the velocity increases as shown in Figure 7(a). Higher initial velocity accompanies more normal velocity dissipation. The slower initial velocities exhibit more overlap than large initial velocities. The descending trend could be described by a linear function with high fitting precision as $R^2 = 0.998$. Considering the moving status and coefficient of restitution features, it also conforms to the rule. The only difference is that a deterministic linear function replaces the sectional function.

Generally, the normal and tangential direction mechanisms considering the influencing factors are indicated differently. But the initial velocity effect acts the same function on R_n and R_t. The values all decrease as the initial velocity increases. The counteraction imposes at the speed of 5 m/s, where a recovery of tangential velocity appears. The same behaviors could be observed in R_v and R_E as plotted in Figures 7(c) and 7(d). The linear functions for R_n, R_t, and $R_v$are nearly the same.

The initial velocity mechanism on different directions is the same. The same deterministic linear function is precise enough to represent the relationship between R_n, R_t, R_v, and initial velocity. The only variation is that the tangential velocity possesses recovery ability when the initial velocity exceeds 5 m/s.

4.2. The Correlations of COR and Energy Dissipation considering Slope Material. The rock energy dissipation along the slope considering four surface types is investigated. The relationship between energy loss and coefficient of restitution is demonstrated in Figure 8.

The mechanism of the surface material varies and results in the rock motion divergence. The hardness, roughness, and planeness determine the slope energy loss and also play an essential role in measuring all COR.

The relationship between normal velocity dissipation during the slope and the normal COR is illustrated. The energy loss among four surface types is sand > plastic > wood > cement. An interesting phenomenon appears at the energy dissipation for cement. Generally, more bounce equals more energy loss. Based on the moving feature, more bounces were observed. But the total slope energy dissipation is less than others, here, which is because the cement normal velocity recovery ability is better. The whole energy consumption is treated as a combination effect of motion dispersion and ability of normal energy recovery. It shows that the slope energy loss is mainly controlled by energy recovery ability, which also consisted with the value of R_n.

Considering the other three CORs, the energy loss during the slope motion differs from the normal COR. The

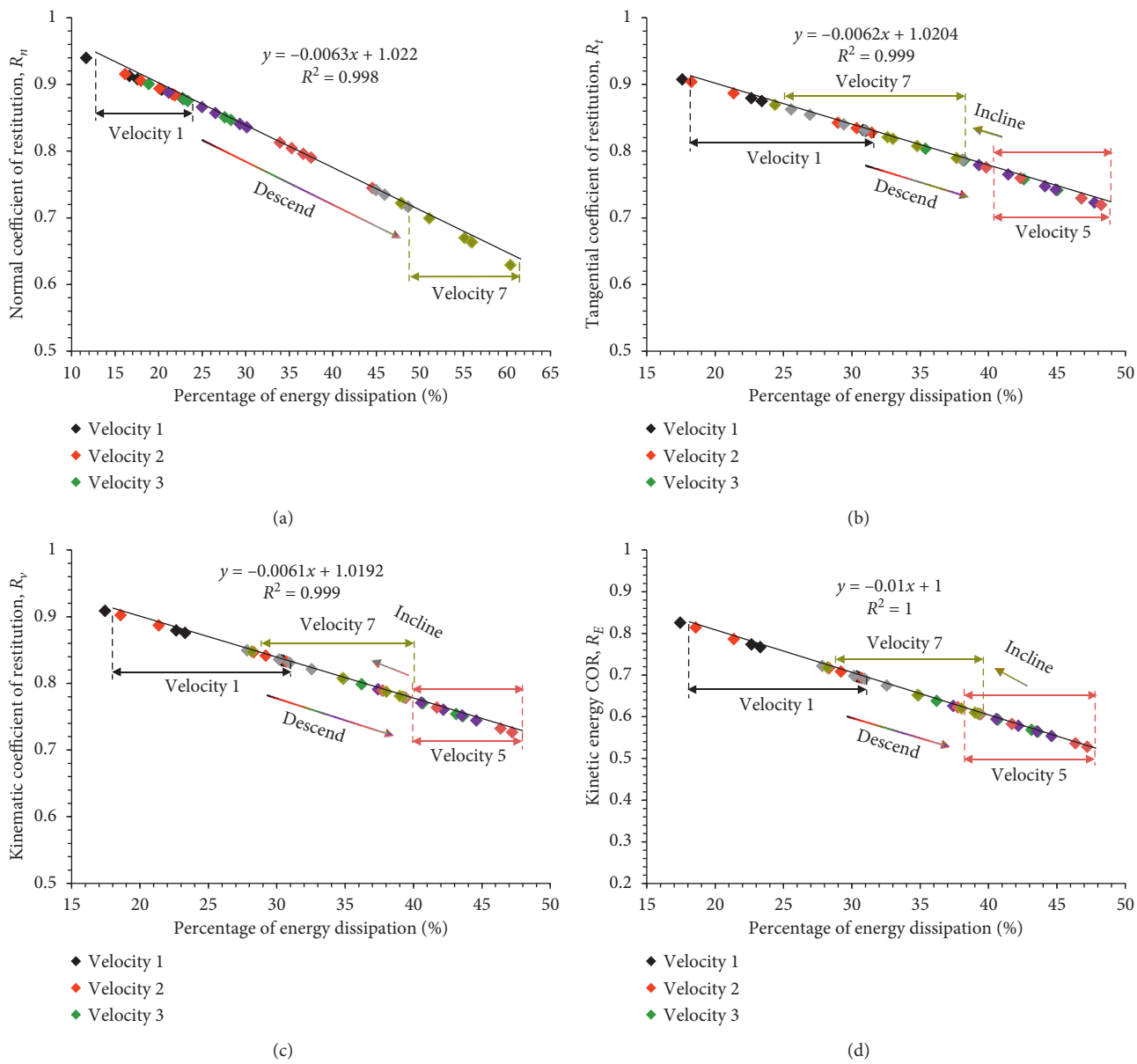


Figure 7: The correlation between four coefficients of restitution and the corresponding slope energy dissipation in terms of initial velocity.

mainly difference focuses on wood surface. Due to the distinctive mechanism on normal and tangential velocity, the most consuming surface is wood. Except for hardness, roughness, and planeness effect, the tangential velocity is more easily to be influenced by rotation. The combination of these two results in the variation among four CORs in case of surface type. The energy dissipation for R_t, R_v, and R_E is wood > sand > plastic > cement, where the overlap space among different surfaces is larger than R_t. Therefore, the surface effect on normal velocity is more clear and obvious than tangential velocity.

All CORs present linear decreasing trend, but each surface is affected differently. The linear functions for R_n, R_t, and R_v are almost the same with tiny difference. Thus, a deterministic linear function could demonstrate the corresponding energy dissipation with the relevant COR.

4.3. The Correlations of COR and Energy Dissipation considering Slope Angle. Due to the essential role of slope motion, the energy dissipation in normal and tangential direction before the bottom impact is identified. The correlation between coefficient of restitution and slope angles is developed as in Figure 9.

Based on the test results, the effect of slope angle still explores different mechanisms on $R_n$and R_t. Regarding the normal velocity influence, the big slope angle induces much slope energy loss as plotted. When the slope angle increases, the value of R_n and the remaining energy decrease. According to the moving status, big angle slope presents more bounces and consumes more energy, which also meets the results. As a combination effect of bounce time and angle variation, the effect on R_n complies with big angle corresponding to great consumption.

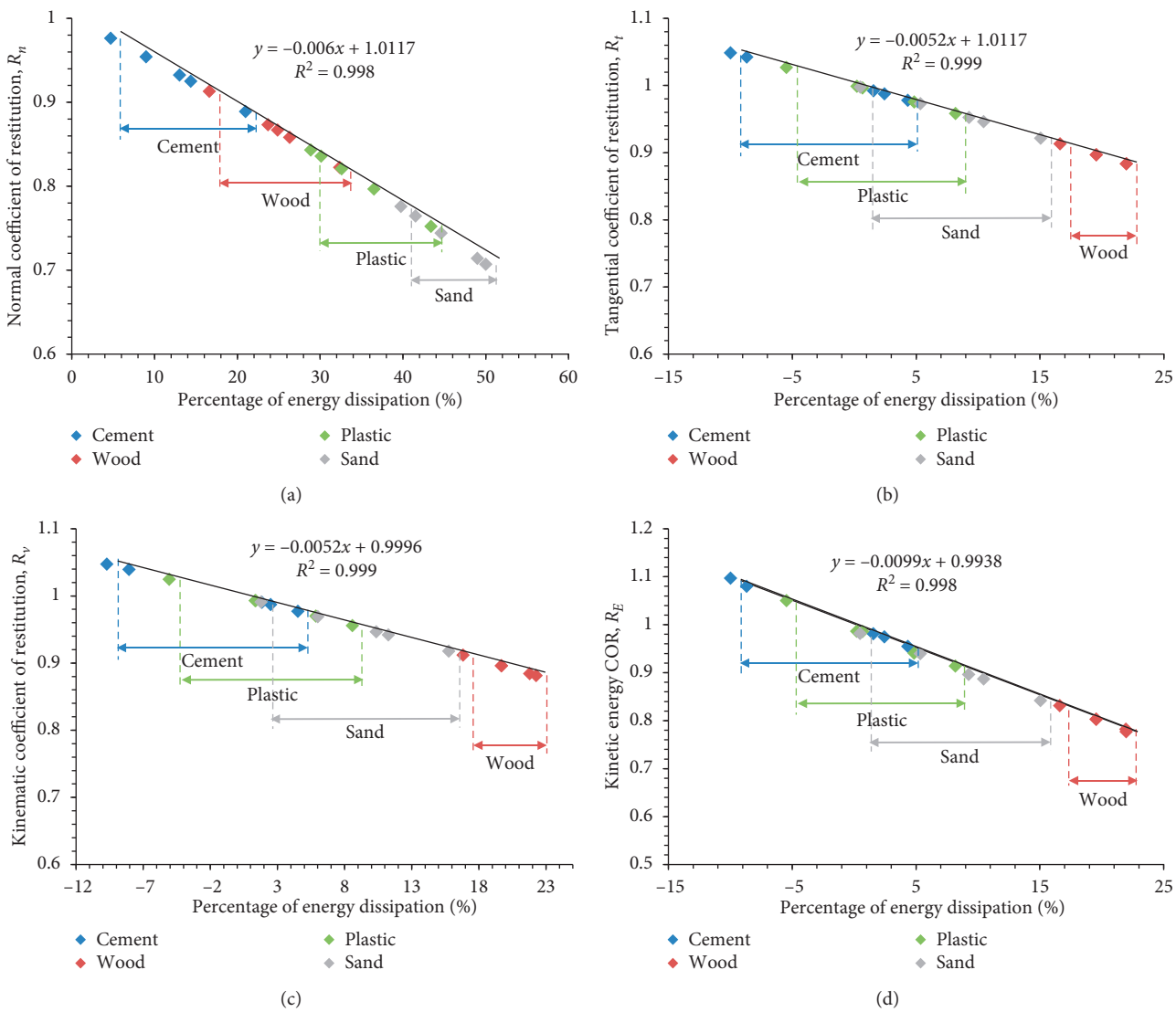


Figure 8: The correlation between four coefficients of restitution and the corresponding slope energy dissipation in terms of surface type.

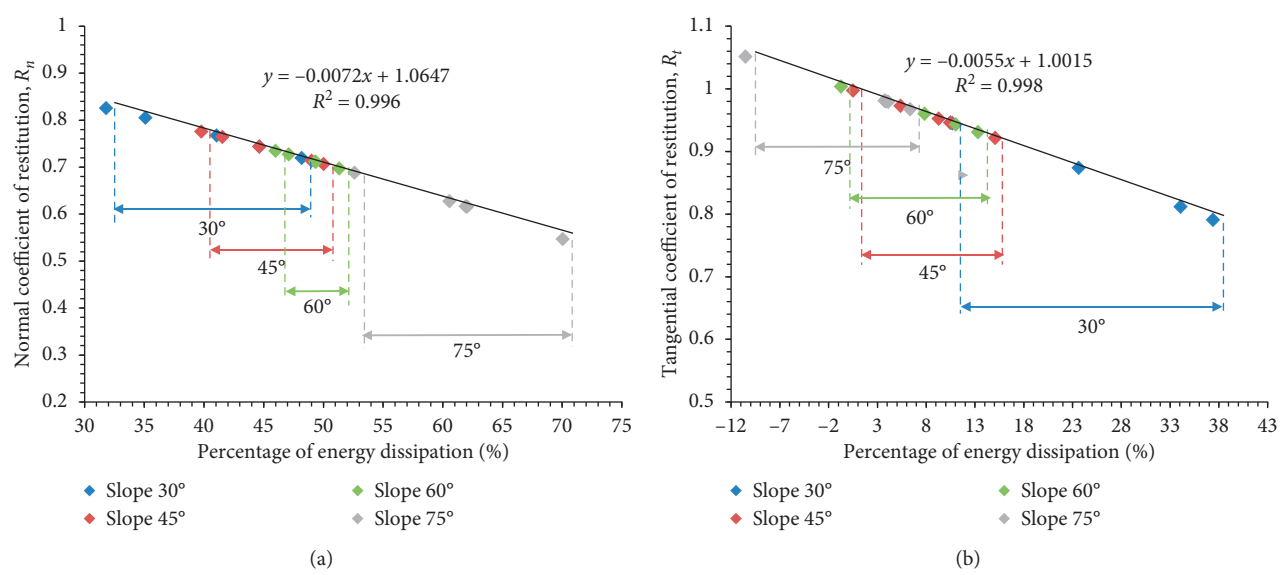


Figure 9: Continued.

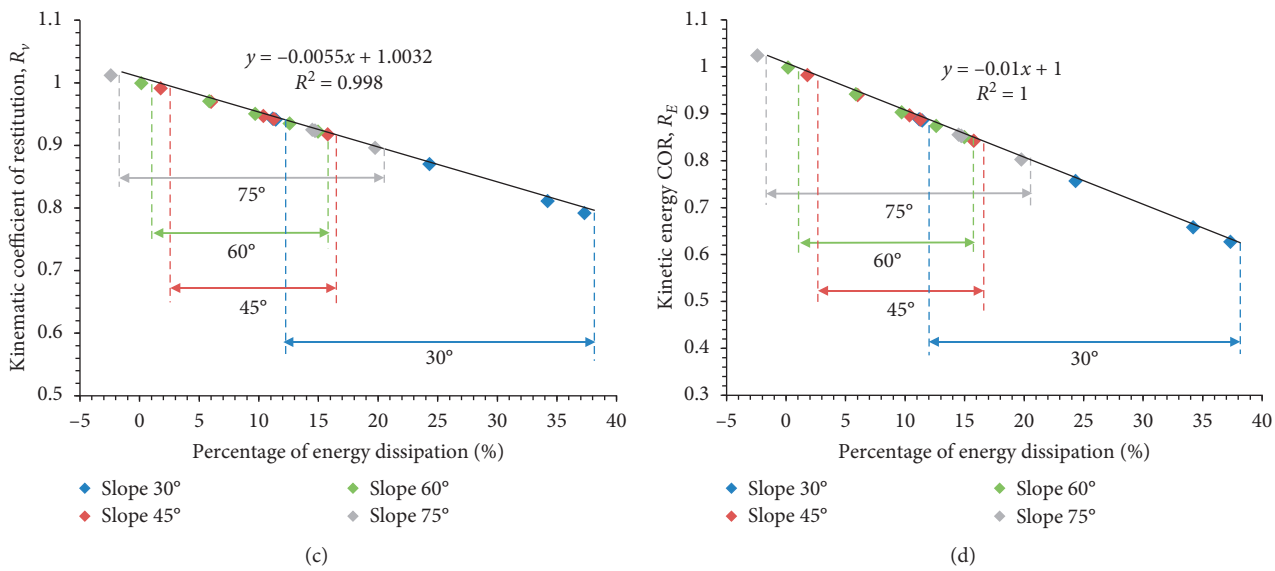


Figure 9: The correlation between four coefficients of restitution and the corresponding slope energy dissipation in terms of slope angle.

R_t, R_v, and R_E effects happen to be the opposite. When the impact angle inclines, the tangential and total velocity dissipation reduce. It could be told that the mechanism on normal and tangential direction are different from each other. In general, the total velocity composed of normal and tangential effect follows the same rule as the R_t. Additionally, all CORs meet the linear decreasing trend. The functions for R_t and R_v are almost the same, and a deterministic linear function could be applied to express this rule.

5. Conclusion

On the basis of the medium-scale tests, the effects of initial velocity, surface type, and slope angle on rockfall behaviors in terms of COR and energy dissipation are verified. Generally, small-scale laboratory tests were carried out, in which tests explored only monitoring of the temporary colliding moment before and after the impact without discussing the slope and rock interaction; hence, no preimpact interactions are developed. In this study, a medium-scale artificial slope is shaped, and it is compact to adopt the experiment. The coefficient of restitution is evaluated to reveal the effect of initial velocity, surface material, and slope angle. Due to the significant role of interactions between rock and slope, energy dissipation regarding the three key factors is carried out. The correlations among energy consumption and COR are demonstrated.

(1) Boulders with high initial velocity pretended to own a higher rebound height with a larger kinematic energy, which obeys the moving feature. The initial velocity influences R_n in a decreasing effect, which reveals that big initial velocity leads to more reduction of normal velocity. A linear function could match the changing rule of R_n and the corresponding energy loss regarding the variation of initial velocity.

(2) The normal coefficient of restitution owns obvious slope surface effect. It presents a declining trend with a fixed order of material sequence. For the decreasing rule of R_n, it is combined with cement, wood, plastic, and sand. This is as a result of the material hardness and rebound resilience ability. According to the effect of slope and rock interactions, a linear decreasing function could be acquired to represent the relationship between energy dissipation and the COR.

(3) Effect of slope angle on rock is dominated by the interaction procedure, which is mainly different from bounce times. Thus, the efforts that focused on slope rock interactions are necessary. Instead of targeting the final collision at slope foot, the effects of preimpact status on energy dissipation are investigated. The angle effect on R_n appears to descend as the angle inclines. Here, lower angle presents more bounces with more energy losses and results in smaller impact velocity at the slope foot, but a higher recovery at the normal direction.

Although several general rules considering the effect of initial velocity, slope surface, and slope angle on COR are confirmed, the correlations between coefficients of restitution and energy dissipation are verified. Still the credible formula that could predict the rockfall behaviors lacks. Besides, only specimen of spherical rock is adopted, whether the conclusions for samples with other shapes need to be done in the further study.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C. O. Brawner and D. Wyllie, "Rock slope stability on railway projects," *American Railway Engineering*, vol. 656, pp. 449–474, 1976.

[2] P. Budetta and A. Santo, "Morphostructural evolution and related kinematics of rockfalls in Campania (southern Italy): a case study," *Engineering Geology*, vol. 36, no. 3-4, pp. 197–210, 1994.

[3] C. M. Bunce, D. M. Cruden, and N. R. Morgenstern, "Assessment of the hazard from rock fall on a highway," *Canadian Geotechnical Journal*, vol. 34, no. 3, pp. 344–356, 1997.

[4] V. Labiouse, F. Descoeudres, and S. Montani, "Experimental study of rock sheds impacted by rock blocks," *Structural Engineering International*, vol. 6, no. 3, 1996.

[5] B. Pichler, C. Hellmich, and H. A. Mang, "Impact of rocks onto gravel design and evaluation of experiments," *International Journal of Impact Engineering*, vol. 31, no. 5, pp. 559–578, 2005.

[6] S. Kawahara and T. Muro, "Effects of dry density and thickness of sandy soil on impact response due to rockfall," *Journal of Terramechanics*, vol. 43, no. 3, pp. 329–340, 2006.

[7] A. M. Ritchie, "Evaluation of rockfall and its control," *Highway Research Record*, vol. 17, pp. 13–28, 1963.

[8] P. G. Fookes and M. Sweeney, "Stabilization and control of local rock falls and degrading rock slopes," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 9, no. 1, pp. 37–55, 1976.

[9] P. Whiteside, *Discussion on "Rockfall and its Control"*, Hong Kong Engineer, Hong Kong, 1984.

[10] J. C. Flageollet, "The time dimension in the study of mass movements," *Geomorphology*, vol. 15, no. 3-4, pp. 185–190, 1996.

[11] M. Jaboyedoff and V. Labiouse, "Technical note: preliminary estimation of rockfall runout zones," *Natural Hazards and Earth System Sciences*, vol. 11, no. 3, pp. 819–828, 2011.

[12] Y. T. Yang, W. Wu, and H. Zheng, "Stability analysis of slopes using the vector sum numerical manifold method," *Bulletin of Engineering Geology and the Environment*, vol. 80, no. 1, pp. 345–352, 2021.

[13] Y. T. Yang, D. D. Xu, F. Liu, and H. Zheng, "Modeling the entire progressive failure process of rock slopes using a strength-based criterion," *Computers and Geotechnics*, vol. 126, p. 103726, 2020.

[14] F. Agliardi, G. B. Crosta, and P. Frattini, "Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques," *Natural Hazards and Earth System Sciences*, vol. 9, no. 4, pp. 1059–1073, 2009.

[15] L. Pantelidis and A. Kokkalis, "Designing passive rockfall measures based on computer simulation and field experience to enhance highway safety," *International Journal of Rock Mechanics and Mining Sciences*, vol. 48, no. 8, pp. 1369–1375, 2011.

[16] F. Bourrier, S. Lambert, and J. Baroth, "A reliability-based approach for the design of rockfall protection fences," *Rock Mechanics & Rock Engineering*, vol. 48, no. 1, 2015.

[17] K. T. Chau, R. H. C. Wong, and C. F. Lee, "Rockfall problems in Hong Kong and some new experimental results for coefficients of restitution," *International Journal of Rock Mechanics and Mining Sciences*, vol. 35, no. 4-5, pp. 662-663, 1998.

[18] R. Fell, K. K. S. Ho, S. Lacasse et al., "A framework for landslide risk assessment and management," in *Proceedings, International Conference on Landslide Risk Management*, Vancouver, Canada, May 2005.

[19] O. Buzzi, A. Giacomini, and M. Spadari, "Laboratory investigation on high values of restitution coefficients," *Rock Mechanics and Rock Engineering*, vol. 45, no. 1, pp. 35–43, 2012.

[20] D. Peila, S. Pelizza, and F. Sassudelli, "Evaluation of behaviour of rockfall restraining nets by full scale tests," *Rock Mechanics and Rock Engineering*, vol. 31, no. 1, pp. 1–24, 1998.

[21] F. Guzzetti, G. Crosta, R. Detti, and F. Agliardid, "STONE: a computer program for the three-dimensional simulation of rock-falls," *Computers & Geosciences*, vol. 28, no. 9, pp. 1079–1093, 2002.

[22] G. P. Agliardi, A. Giacomini, M. Migliazza, A. Segalini, and S. Tagliavini, "Rock fall in situ observations, analysis and protection works," in *Proceedings of the International Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage*, Kyoto, Japan, 2005.

[23] K. T. Chau, R. H. C. Wong, and J. J. Wu, "Coefficient of restitution and rotational motions of rockfall impacts," *International Journal of Rock Mechanics and Mining Sciences*, vol. 39, no. 1, pp. 69–77, 2002.

[24] F. Agliardi and G. B. Crosta, "High resolution three-dimensional numerical modelling of rockfalls," *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, no. 4, pp. 455–471, 2003.

[25] L. K. A. Dorren, F. Berger, and U. S. Putters, "Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes," *Natural Hazards and Earth System Sciences*, vol. 6, no. 1, pp. 145–153, 2006.

[26] P. Asteriou, H. Saroglou, and G. Tsiambaos, "Geotechnical and kinematic parameters affecting the coefficients of restitution for rock fall analysis," *International Journal of Rock Mechanics and Mining Sciences*, vol. 54, pp. 103–113, 2012.

[27] M. Spadari, A. Giacomini, O. Buzzi, S. Fityus, and G. P. Giani, "In situ rockfall testing in New South Wales, Australia," *International Journal of Rock Mechanics and Mining Sciences*, vol. 49, no. 2, pp. 84–93, 2012.

[28] J. L. Falcetta, "Un nouveau modèle de calcul de trajectoires de blocs rocheux," *Revue Française de Géotechnique*, vol. 30, no. 30, pp. 11–17, 1985.

[29] O. Hungr and S. G. Evans, "Engineering evaluation of fragmental rockfall hazards," in *Proceedings of the 5th International Symposium on Landslides*, Lausanne, Switzerland, 1988.

[30] A. Azzoni, G. La Barbera, and A. Zaninetti, "Analysis and prediction of rockfalls using a mathematical model," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 32, no. 7, pp. 709–724, 1995.

[31] T. Ushiro, S. Shinohara, K. Tanida, and N. Yagi, "A study on the motion of rockfalls on slopes," in *Proceedings of the 5th Symposium on Impact Problems in Civil Engineering*, Japan Society of Civil Engineers, Tokyo, Japan, June 2000.

[32] T. J. Pfeiffer and T. D. Bowen, "Computer simulation of rockfalls," *Environmental & Engineering Geoscience*, vol. 26, no. 1, pp. 135–146, 1989.

[33] M. Fornaro, D. Peila, and M. Nebbia, "Block falls on rock slopes application of a numerical simulation program to some real cases," in *Proceedings of the 6th International IAEG Congress*, Amsterdam, Netherlands, August 1990.

[34] G. Urciuoli, "Sperimentazione sulla caduta di blocchi lungo un pendio nella formazione calcareo-dolomitica della Penisola Sorrentina," in *Proceedings of the Convengo Cartografia e Monitoraggio dei Movimenti Franosi*, Bologna, Italy, 1988.

[35] V. Labiouse and B. Heidenreich, "Half-scale experimental study of rockfall impacts on sandy slopes," *Natural Hazards and Earth System Ences*, vol. 9, no. 6, 2009.