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Discussions

Impact of rockfalls on protection measures: an experimental approach

J. Yuan[1], Y. Li[2], R. Huang[1], and X. Pei[1]

[1]State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu 610059, China
[2]Taiyuan University of Technology, Taiyuan 030024, China

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Correspondence to: Y. Li (li.dennis@hotmail.com)

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Abstract

The determination of rockfall impact force is crucial in designing the protection measures. In the present study, laboratory tests are carried out by taking the weight and shape of the falling rock fragments, drop height, incident angle, platform on the slideway and cushion layer on the protection measures as factors to investigate their influences on the impact force. The test results indicate that the impact force is positively exponential to the weight of rockfall and the instantaneous impact velocity of the rockfall approaching the protection measures. The impact velocity is found to be dominated not only by the drop height but also by the shape of rockfall as well as the length of the platform on the slideway. A great drop height and/or a short platform produce a fast impact velocity. Spherical rockfalls experience a greater impact velocity than cubic and cylindrical ones. A layer of cushion on the protection measures may reduce the impact force to a greater extent. The reduction effects are dominated by the cushion material and the thickness of the cushion layer. The thicker the cushion layer, the greater the reduction effect and the less the impact force. The stiffer the buffer material, the less the buffering effect and the greater the impact force. The present study indicates that the current standard in China for designing protection measures may overestimate the impact force by taking no consideration for the rockfall shape, platform and cushion layer.

1 Introduction

The protection measures for rockfall are mostly designed to avoid direct exposure of the protected buildings or structures to falling rock fragments. The protective flexible wire net and embankment are typical in such design (Giani et al., 2004; Labiouse, 1996; Peila et al., 1998). There is normally a strong collision behavior when the rockfall impacts the protection measures. The maximum impact force (F_m) is, therefore, crucial during designing the protection measures. In the literature, the F_m has been found to be affected by factors, such as platform on the slope, physical and mechanical properties of falling materials and incident angle when collision happens (Jean and Pascal, 2005; Azzoni et al., 1995; Tetsuya, 2004; Peila et al., 2007). Jean and Pascal (2005) carried out experiments and indicated that the drop height is the most important factor influencing the F_m. Plassiard (2009) found that the F_m has positive correlation with the impact velocity. Markus and Simone (2006) carried out field trails and found that the F_m increases with the drop height. With numerical simulation, Vilajosana et al. (2008) indicated that the signals of impact force vary with density of buffer material, incident angle, weight of rockfalls and drop height. Kishi et al. (2002) indicated that a cushion layer of sandy soil on the protection measures reduces the impact force to a great extent and the thicker the cushion layer the greater the buffering effect. The same conclusion was also made by Kawahara and Muro (2006) and Abdul and Norimitsu (2010). Kishi (1999) indicated that stiffness of the cushion layer influences the buffering effect as a cushion layer of high density absorbed less energy than that of low density, introducing higher impact forces. Pichler et al. (2005, 2006) used cone-shaped objects to simulate rockfall and indicated that the freefall penetration depth in the cushion made of gravels, the impact duration, and the impact force all were functions of the falling height. The Japan Road Association (2000) indicated that the weight of rockfalls and the drop height were the most important parameters in empirical formula of rockfall impact force.

The present study carries out laboratory tests by taking the weight and shape of rockfalls, drop height, incident angle, cushion on the protected measures and platform on the slideway as factors. The aim is to investigate and depict their influences on impact force of rockfalls.

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2 Test program

2.1 Test set-up

The test system developed in this study consists of three parts: rockfalling device, protection device and measuring unit. As shown in Fig. 1a, rockfalling device takes a bracket structure to withstand the slideway, which is a smooth steel U-shaped channel of 7 m long and 30 cm wide inside. Both ends of the slideway are placed on scaffolding brackets. An alternative device (Fig. 1b) is composed of upper slideway, lower slideway and a platform in between. The length of the platform is adjustable. During tests the inner sides of the slideway and the platform were fully lubricated with mineral oil to minimize the friction.

The protection device, being about 1.4 m high, consists of a baffle plate, a bottom plate and four lifting outriggers (Fig. 2a). The baffle plate is made of steel, being 1.2 m long, 0.8 m wide and 15 mm thick. The bottom plate is of 1.3 m long, 0.9 m wide and 10 mm thick steel plate. The inclining angle of the baffle plate can be adjusted by lifting/lowering the outriggers to mold different incident angles. The measuring device includes four force transducers, seated on the bottom plate while passing through the holes in corners of the baffle (Fig. 2a and b). During the test, the falling fragments were directed by the slideway to impact one of the transducers. As the tips of the force transducers were clear of the baffle by 5 mm (Fig. 2b), the transducer can ~~gasp~~ the full impact force without participation by the baffle. The impact forces collected by the transducer are then transmitted and stored in a data log system. In the cases where buffering effects of cushion layer were considered, the cushion materials are evenly placed on the baffle plate at a certain thickness. The test set-up was to simulate the impaction of rockfall on a protection measure as shown in Fig. 3.

2.2 Test scheme

Three types (sphere, cube and cylinder in shape) of samples are adopted in the experiments (Fig. 4). Each type of samples has three specimens with the weight of 4, 5 and 6 kg, respectively.

Points A, B and C marked on the slideway are the starting points to slide (Fig. 1), representing different drop heights, i.e., 4.0, 3.5 and 3.0 m, respectively. The impact incident angles were set to be 30, 60 and 90°. The buffer platform on the slideway was adjusted to be 30, 60, 90 cm long, respectively. The cushion materials on the baffle plate were gravel, sand or clay. The physical and mechanical parameters of cushion materials are listed in Table 1.

Totally, 109 tests were conducted for encompassing the possible permutation and combination of factors listed in Table 2. A test with the identifier of S-6-4-90 denotes a spherical sample with the weight of 6 kg falling from 4 m and impacting the baffle plate at an incident angle of 90°. Similarly, a test with the identifier of C-5-3-90-2S-30 represents a cubic sample with the weight of 5 kg falling from 3 m traveling a platform of 90 cm long and impacting a sand buffer layer of 2 cm thick at an incident angle of 30°. A speedometer was employed in tests to capture the instantaneous velocity of rockfall immediately approaching the baffle.

3 Results

3.1 Drop height and incident angle

The maximum impact force (47.7 kN) occurred in the case where a 6 kg weight spherical sample falling from 4.0 m height impacts the baffle plate at the incident angle (α) of 90° (Sample no. S-6-4-90). Generally speaking, the impact force increases with incident angle, regardless of sample shape (sh) and weight (w) as well as drop height (h). The average impact force at incident angle of 90° is about 15 % higher than that at 60°,

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which in turn is about 14 % higher than that at 30°. On the other hand, the impact force increases with drop height, regardless of other factors. Averagely, the impact force of rockfall from 4 m height is about 11 % greater than that from 3.5 m height, which in turn is about 12 % greater than that from 3.0 m height. The observation here is in good agreement with what was concluded by Pichler et al. (2005) and Tetsuya et al. (2004).

3.2 Sample weight and shape

As shown in Fig. 6, the impact force increases with sample weight. The average impact force for 6 kg weight samples is about 10 % greater than that for 5 kg weight samples, which in turn is about 16 % greater than that for samples of 4 kg weight. On the other hand, sample shape is found to impose strong effects on the measured impact forces. As shown in Fig. 7, spherical samples generate greater impact forces than cubic and cylindrical samples.

3.3 Cushion layer

The embankment is often used as the protective measure against rockfalls, and it is commonly composed of core-wall and cushion layer made of buffer material. In this study, gravel, sand and clay are chosen as cushion materials, which were evenly placed on the baffle with a thickness (t) of 2 cm or 4 cm. Spherical samples with a weight of 6 kg are used as the rockfall. As shown in Fig. 8, such a thin cushion layer shows a significant effect in reducing impact forces. In general, clay cushion layers exhibit the strongest reduction effect among these three, while the effect by gravel cushion layer is the minimum, as the measured impact force reduced by a clay cushion layer is about 1/2 of that by a gravel cushion layer. On the other hand, the thickness of the cushion layer influences the extent of impact force reduction. The measured impact force after reduction by a 4 cm thick cushion layer is about half of that after reduction by a 2 cm thick cushion layer.

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In the case of right collision ($\alpha = 90^\circ$), the impact force of Sample S-6-4-2C-90 (a spherical 6 kg weight sample falling from 4.0 m height onto the 2 cm thick clay cushion layer at an incident angle of 90°) was 2.9 kN, which is only about 11 % of that from direct impact (Sample S-6-4-90, without cushion layer). The impact force is reduced down to 1.6 kN by a 4 cm thick clay cushion layer (Sample S-6-4-4C-90). On the other hand, a 2 cm thick gravel cushion layer reduces the impact force from 38 down to 5 kN, making an reduction of about 86 %. In addition, the incident angle is found to influence the reduction of impact force by cushion layer. At an incident angle of 30°, the impact force of Sample S-6-4-2C-30 is 1.4 kN, which is about half of Sample S-6-4-2C-90 at the incident angle of 90°.

3.4 Buffer platform

For simulating the reduction effects by a platform on natural slope, a set of tests were conducted with platform lengths ~~(*l*)~~ of 30, 60 and 90 cm, respectively (see Fig. 1b for test set-up). Samples of different shapes and weights fell from a certain drop height *h* of 4.0 m. The incident angle was set to be 90°.

As shown in Fig. 9, a platform of 30 cm long may reduce the impact force by about 10 %. The 60 and 90 cm platforms can even reduce the impact force by 18 and 30 %, respectively. The longer the platform, the less the impact force measured. Another observation is that the reduction effect of platform is more obvious for spherical and cylindrical rockfalls than cubic ones, as the gradient of the trendline for cubic samples ~~are~~ the least in Fig. 9.

Based on the test results, couple of findings can be drawn as follows: (1) the incident angle and drop height positively ~~effect~~ the impact force; (2) spherical rockfalls intend to introduce higher impact force than cylindrical and cubic samples; (3) the impact force increases with weight of rockfall; (4) the cushion layer made of gravel, sand or clay may significantly reduces the impact force, and the thicker the cushion layer, the greater the extent of reduction; and (5) a flat platform on the slideway can lead to a reduction of impact force, and the longer the platform, the more the impact force is reduced.

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4 Discussion

4.1 Impact velocity of rockfall

According to the theorem of momentum, the rockfall impact force can come out from the following equation (Johnson, 1985; Han et al., 2004):

$$F = mv/\Delta t \tag{1}$$

where, m is the mass of rockfall (kg), v is the instantaneous velocity of rockfall immediately approaching the baffle ($\mathrm{m\,s^{-1}}$), F is the impact force (N) and Δt is the time duration of the impact process (s). As the time duration (Δt) is instant and Δts are nearly consistent for all tests, Eq. (1) indicates positive correlation between weight and instantaneous velocity of rockfall and the impact force. This is consistent with the observation from Fig. 6, where the measured impact force increases with weight of rockfall.

The instantaneous velocity (v) of rockfall immediately approaching the baffle plate was measured by means of a speedometer for all tests. As shown in Fig. 10, the measured impact velocity (v) increases with drop height (h) for a certain shape of rockfalls. The average impact velocity of 6 kg weight spherical samples falling from 4 m height is about 1.3 times as much as that from 3.0 m height. In addition, the impact velocity (v) is found to be influenced by the shape of rockfalls. The impact velocity of 6 kg weight spherical rockfalls falling form 4.0 m height was 6.36 $\mathrm{m\,s^{-1}}$, while that of cubic and cylindrical rockfalls from the same height was 3.71, 3.48 $\mathrm{m\,s^{-1}}$, respectively. According to the regression of test results (Fig. 10), relationships between impact velocity (v) and drop height (h) are obtained as follows for different shapes of rockfall:

$$\begin{aligned}
&\text{Spherical:} && v = 2.186h^{0.778} && (R = 0.92)\\
&\text{Cubic:} && v = 0.958h^{1.031} && (R = 0.93)\\
&\text{Cylindrical:} && v = 0.636h^{1.164} && (R = 0.96)
\end{aligned} \tag{2}$$

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The above equations indicate a positive exponential correlation between drop height and impact velocity of rockfalls, which is consistent with the theoretical formula deriving falling velocity (v_o) of a object from a certain height (h):

$$v_o = \sqrt{2gh} = 4.43h^{0.5} \tag{3}$$

where, g is the gravity acceleration.

Figure 11 shows the normalized velocity (λ), which is defined here as the ratio of impact velocity (v) by Eq. (2) to falling velocity (v_o) by Eq. (3). It is found that with increase in drop height, the impact velocity (v) is approaching the theoretical falling velocity (v_o), regardless of the shape of rockfalls. However, at small drop heights, there are big differences between them. In addition, spherical rockfall exhibits the highest normalized velocity, indicating its approximation of the theoretical values, especially at a big drop height. In the cases of cubic and cylindrical rockfalls, the low values of λ indicate the influences of shape of rockfall on the impact velocity. Among the considered three types, the cylindrical shape contributes the most to reduction of impact velocity.

On the other hand, the instantaneous impact velocity is significantly reduced by a buffer platform on the slideway. The impact velocity of 6 kg spherical rockfalls falling form 4.0 m height was 5.19, 4.68 and 4.11 $\mathrm{m\,s^{-1}}$ in the case where the buffer platform is 30, 60 and 90 cm long, respectively. It is found from Fig. 12 that the longer the buffer platform, the lower the impact velocity. This is in good agreements with previous researches. Huang et al. (2010) and Yoichi (2000), for instance, carried out field trials of rockfall travelling through a slideway with platform of different lengths, and indicated that the platform length reduces the impact force of rockfalls.

Figure 13 demonstrates the change process of rockfall velocity during the falling process. At Point O (the start point), the velocity (v) is equal to zero. It gets greater when the rockfall runs towards Point A due to the gravity. At Point A, the component in vertical direction (v_y) becomes zero due to the upward counterforce by the platform, leaving the component in horizontal direction (v_x) alone. v_x may get smaller due to energy dissipation by friction along the platform. After Point B v_y starts increasing from

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zero due to the gravity acceleration, leading to increase in v and v_x. The process above indicates that the platform works as a barrier to eliminate the vertical component v_y of the rockfall velocity v and dissipate the kinetic energy of rockfall by friction, which lead to an overall reduction of rockfall velocity.

Regression analysis taking the measured impact velocity (v) and weight of rockfall (w) as independent variables and the measured impact force as dependent gives the following nonlinear relationship (Eq. 4):

$$F = 11.2w^{0.216}v^{0.502} \quad (R = 0.87) \tag{4}$$

The above exponential equation indicates that the impact force is positive to weight and impact velocity of rockfall. As the foregoing discussion, the impact velocity is dependent not only upon the drop height but also upon the shape of rockfall and the platform length. However, in the present engineering practice, both rockfall shape and the platform are not taken into account during designing of protection meansures, instead an equivalent spherical object is normally used. This is thought to overestimate the impact force.

4.2 Cushion layer

According to the law of energy conservation, the kinetic energy ($\bar{E}$) of the rockfall, which is equal to $1/2mv^2$, is transferred into the strain energy (U) of the buffer layer during the impacting process. The strain energy can be calculated according to the fallowing theoretical formula:

$$\bar{E} = U = \iiint_V u_0\left(\varepsilon_{ij}\right) \mathrm{d}V \tag{5}$$

where, $u_0(\varepsilon_{ij})$ is the density of strain energy, i.e., the strain energy per unit volume.

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According to the Green formula:

$$\frac{\partial u_{0(\varepsilon_{ij})}}{\partial \varepsilon_{ij}} = \sigma_{ij} \tag{6}$$

by integral, there ~~is~~:

$$\int_0^u (\varepsilon)\mathrm{d}u_0 = \int_0^\varepsilon \sigma_{ij}\mathrm{d}\varepsilon_{ij} = u_0\left(\varepsilon_{ij}\right) - u_0(0) \tag{7}$$

where $u_0(\varepsilon_{ij})$ and $u_0(0)$ is the strain energy density after and before the deformation, respectively. Taking $u_0(0)$ as zero, there is:

$$u_0 = \int_0^\varepsilon \sigma_{ij}\mathrm{d}\varepsilon_{ij} \tag{8}$$

Considering $\bar{\sigma}$ as the average stress of cushion material during deformation by impaction of rockfall, Eq. (8) can be simplified and reformed as:

$$u_0 = \frac{1}{2}\bar{\sigma}\varepsilon = \frac{\bar{\sigma}^2}{2E} \tag{9}$$

where, ε and E are the strain and elastic modulus of cushion material, respectively.

The total strain energy (Eq. 5) of the cushion layer is therefore can be expressed as Eq. (10):

$$U = h \cdot S \cdot \frac{\bar{\sigma}^2}{2E} \tag{10}$$

where, h is the thickness of the cushion layer and S is the rockfall-cushion layer contact area.

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Combining Eqs. (5) and (10) gives:

$$\bar{\sigma} = \sqrt{\frac{2EU}{hS}} = \sqrt{\frac{2E\bar{E}}{hS}} = \sqrt{\frac{Emv^2}{hS}} \tag{11}$$

According to Eq. (11), for a certain impaction, a thick cushion layer made of material with low elastic modulus would introduce a relatively low stress in the cushion layer. The above derivation explains the greater buffering effect by a layer of clay than that of gravel and explains the contribution of cushion layer thickness (Fig. 8). On the other hand, the contact area changes with the shape of rockfall. A spherical rockfall minimizes the contact area, which maximizes the stress and therefore the measured impact force.

5 Conclusions

According to the foregoing discussion, main conclusions can be drawn as follows:

The impact force is positively exponential to the weight of rockfall and instantaneous impact velocity of the rockfall approaching the protective measures. The impact velocity is in turn dominated not only by the drop height but also by the shape of rockfall as well as platform on the slideway. A platform reduces the impact velocity by eliminating the vertical component of falling velocity and minimizing the horizontal component. A spherical rockfall may introduce an impact velocity close to that from theoretical calculation.

A layer of cushion material on the protection measures may reduce the impact force to a greater extent. The reduction effects are dominated by the cushion material and the thickness of the cushion layer. The thicker the cushion layer, the greater the reduction effect and therefore the less the impact force. The stiffer the cushion material, the less the reduction effect and the greater the impact force.

The determination of impact force is crucial in designing protection measures for rockfalls. The present study depicts the influences of drop height and weight of rockfall,

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platform on the slideway and buffer layer on the protection measures, which indicate that the the impact force may be misestimated by taking no consideration for rockfall shape, platform and buffer layer. Due to the limitation of the experiments, the bouncing and rolling behavior of rockfalls was not considered in this study. Further investigation is desired to verify and improve the relationships derived from this study in order to cover a broader natural situation.

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References

Abdul, Q. B. and Norimitsu, K.: Impact response of RC rock-shed girder with sand cushion under falling load, J. Nuclear Eng. Design, 240, 2626–2632, 2010.

Azzoni, A., Barbera, G., and Zaninetti, A.: Analysis and prediction of rockfalls using a mathmatical model, Int. J. Rock Mech. and Mining Sciences, 32, 709–725, 1995.

Compilation by Japan Road Association: Handbook for rockfall measures, 20–23, 2000.

Giani, G., Giacomini, A., and Migliazza, M.: Experimental and theoretical studies to improve rock fall analysis and protection work design, Int. J. Rock Mech. and Rock Engineering, 37, 369–389, 2004.

Han, W., Jin, D. P., and Hu, H. Y.: Dynamics of an oblique-impact vibrating system of two degrees of freedom, J. Sound Vibration, 275, 795–822, 2004.

Huang, R. Q., Liu, W. H., Zhou, J. P., and Pei, X. J.: Experimental field study of movement charateristics of rock blocks falling down a slope, J. Earth Sci., 21, 330–339, 2010.

Jean, P. M. and Pascal, P.: Rock fall impact on reinforced concrete slab: an experimental approach, Int. J. Impact Eng., 31, 169–183, 2005.

Johnson, K. L.: Contact mechanics, Cambridge University Press, London, England, 399–409, 1985.

Kawahara, S. and Muro, T.: Effects of dry density and thickness of sandy soil on impact response due to rockfall, J. Terramechanics, 43, 329–340, 2006.
Kishi, N.: Absorbing performance of sand cushion and three-layered absorbing system, Proceedings of Third SILOS, Singapore, 51–56, 1999.
Kishi, N., Konno, H., and Ikeda, K.: Prototype impact tests on ultimate impact resistance of PC rock-sheds. Int. J. Impact Eng., 27, 969–985, 2002.
Labiouse, V.: Experimental study of rock sheds impacted by rock blocks[J], J. Struct. Eng. Int., 3, 171–175, 1996.
~~Markus, S~~. and ~~Simone, P~~.: Reconstructing past rockfall activity with tree rings, J. Dendrochronologia, 24, 1–15, 2006.
Peila, D., Oggeri, C., and Castiglia, C.: Ground reinforced embankments for rockfall protection:design and evaluation of full scale tests, J. Landslides, 4, 255–265, 2007.
Peila, D., Polizza, S., and Sassudelli, S.: Evaluation of behaviour of rockfall retaining nets by full scale tests, Int. J. Rock Mech. and Rock Engineering, 31, 1–24, 1998.
Pichler, B., Hellmich, C., and Mang, H. A.: Impact of rocks onto gravel design and evaluation of experiments, Int. J. Impact Eng., 31, 560–578, 2005.
Pichler, B., Hellmich, C., and Mang, H. A.: Loading of a gravel-buried steel pipe subjected to rockfall, J. Geotec. Geoenviron. Eng., 11, 1465–1473, 2006.
Plassiard, J. and Donze, F.: Rockfall impact parameters on embankments: A discrete element method analysis, J. Struct. Eng. Int., 19, 333–341, 2009.
Tetsuya, S., Naoki, S., and Yozo, O.: The effect of rockfall simulation due to impact angle, Proceedings of the Symposium on Rock Mech., 33, 337–342, 2004.
Vilajosana, I., Suriñach, E., Abellán, A., Khazaradze, G., Garcia, D., and Llosa, J.: Rockfall induced seismic signals: case study in Montserrat, Catalonia, Nat. Hazards Earth Syst. Sci., 8, 805–812, doi:10.5194/nhess-8-805-2008, 2008
Okura, Y., Kitahara, H., Sammori, H., and Kawanami, A.: The effects of rockfall volume on runout distance, J. Eng. Geol., 58, 109–124, 2000.

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Table 1. Physical and mechanical parameters of the cushion materials.

Cushion material	Water content (%)	Density ($g\,cm^{-3}$)	Elastic modulus (MPa)	Poisson's ratio
Gravel	–	2.12	50	0.17
Sand	7.8	1.56	13	0.25
Clay	21.7	1.27	5	0.36

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Table 2. Test conditions.

Factor		Values		
Rockfall shape		Spherical	Cubic	Cylindrical
Weight (kg)		6	5	4
Drop height (m)		4.0	3.5	3.0
Incident angle (°)		90	60	30
Buffer materials	2 cm thick 4 cm thick	Gravel	Sand	Clay
Platform length (cm)		90	60	30

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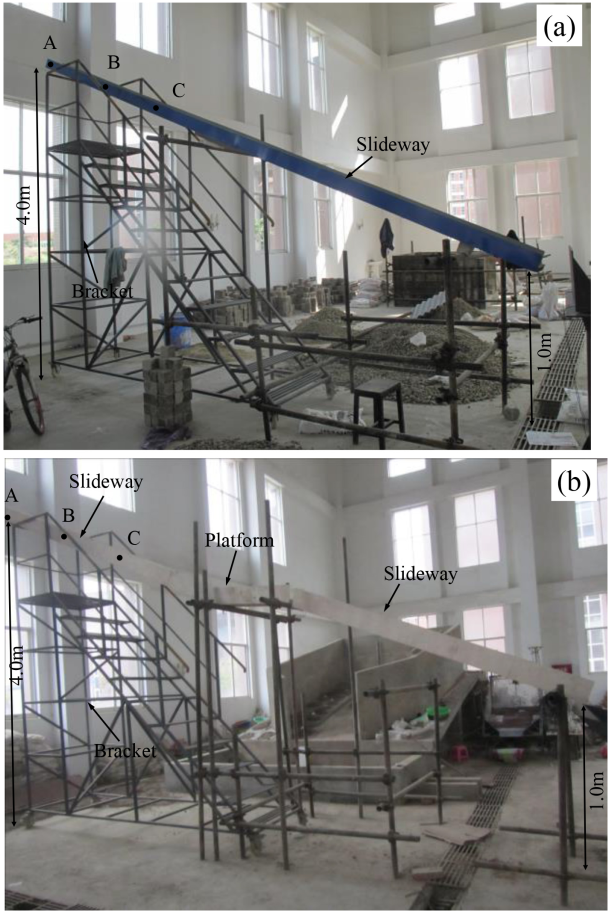

Figure 1. The rockfalling devices: **(a)** slideway without platform; and **(b)** slideway with a platform.

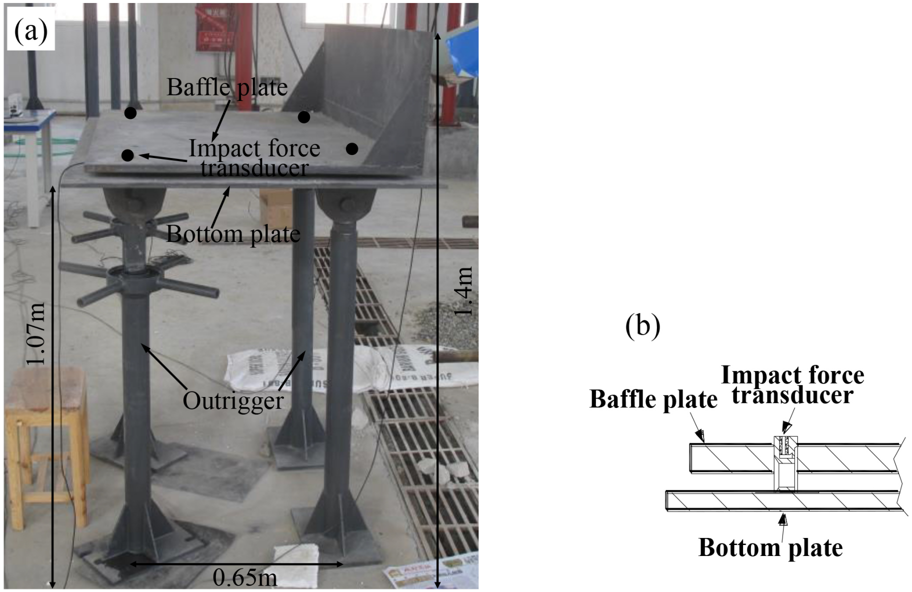

Figure 2. The protection device: **(a)** an overview; and **(b)** configuration of force transducer.

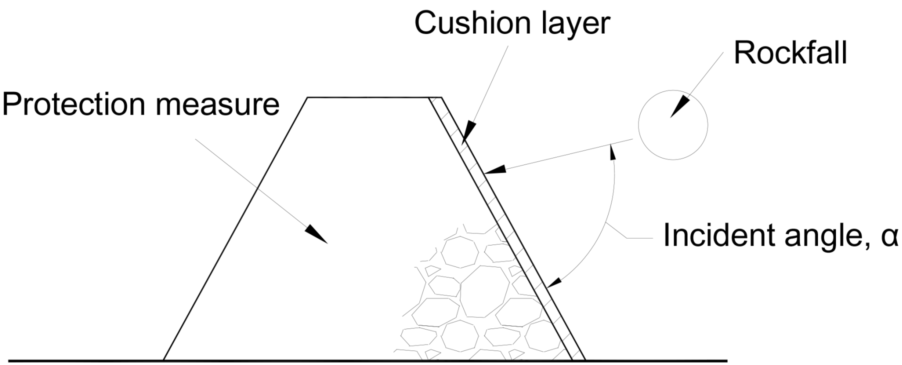

Figure 3. Schematic diagram of rockfall impacts.

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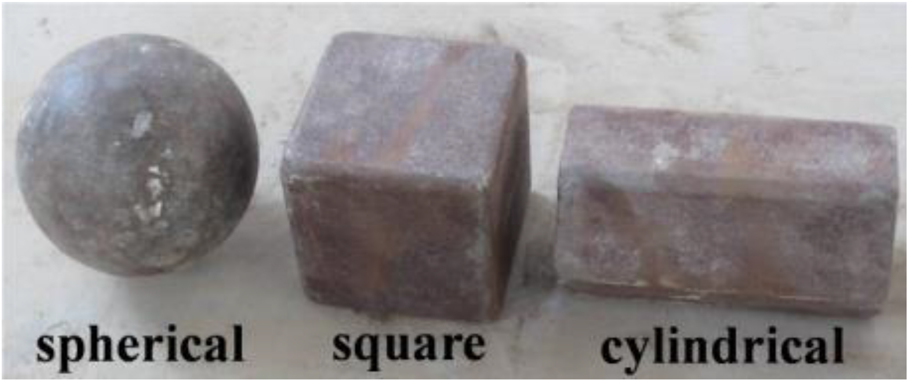

Figure 4. Shapes of falling specimens.

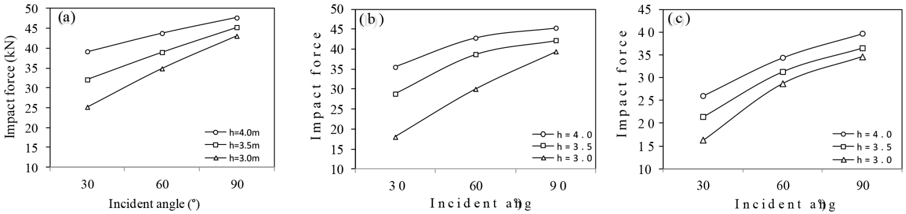

Figure 5. Measured impact force vs. incident angle for samples of different weights: **(a)** sample weight = 6 kg; **(b)** 5 kg; and **(c)** 4 kg.

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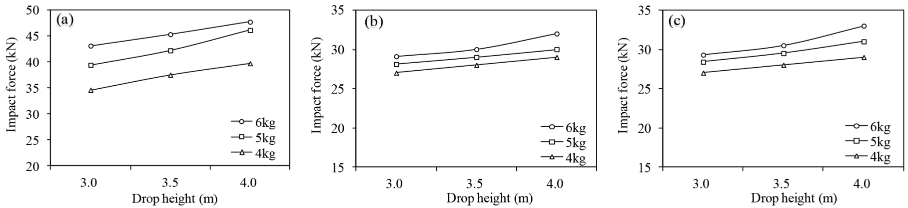

Figure 6. Impact force vs. drop height for samples of different shapes: **(a)** spherical; **(b)** cubic; and **(c)** cylindrical.

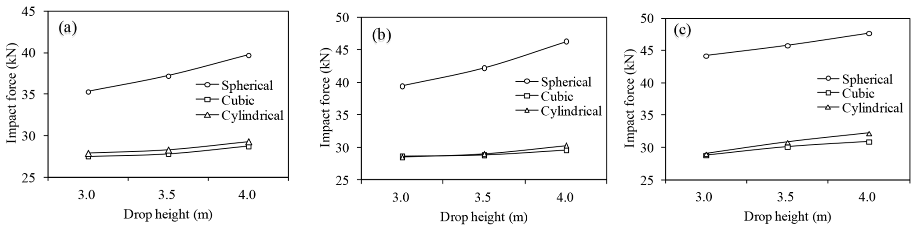

Figure 7. Impact force vs. drop height for samples with different weights: **(a)** sample weight = 6 kg; **(b)** 5 kg; and **(c)** 4 kg.

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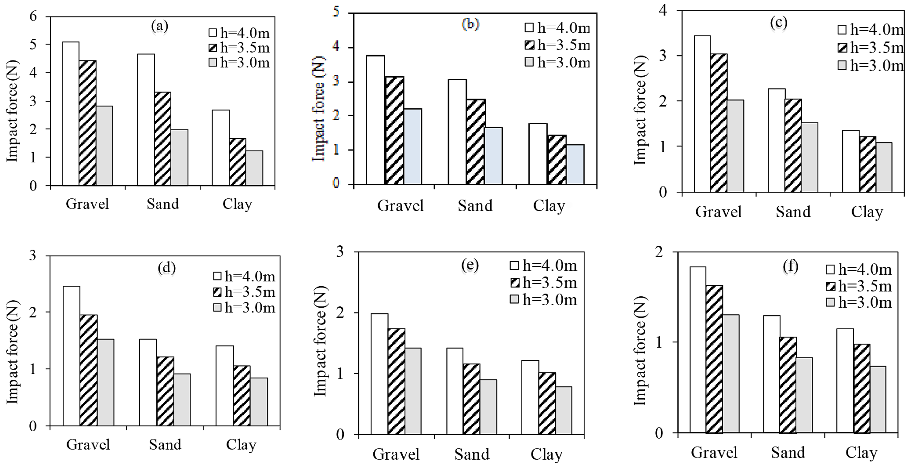

Figure 8. Influence of cushion layer on the impact force: **(a)** incident angle $\alpha = 90^{\circ}$, thickness of cushion layer $t = 2\,\text{cm}$; **(b)** $\alpha = 60^{\circ}$, $t = 2\,\text{cm}$; **(c)** $\alpha = 30^{\circ}$, $t = 2\,\text{cm}$; **(d)** $\alpha = 90^{\circ}$, $t = 4\,\text{cm}$; **(e)** $\alpha = 60^{\circ}$, $t = 4\,\text{cm}$; and **(f)** $\alpha = 30^{\circ}$, $t = 4\,\text{cm}$.

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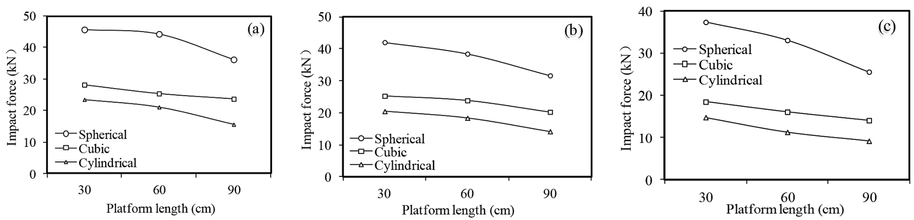

Figure 9. Influence of platform length on the impact force by different shapes of rockfalls. **(a)** 6 kg; **(b)** 5 kg; **(c)** 4 kg.

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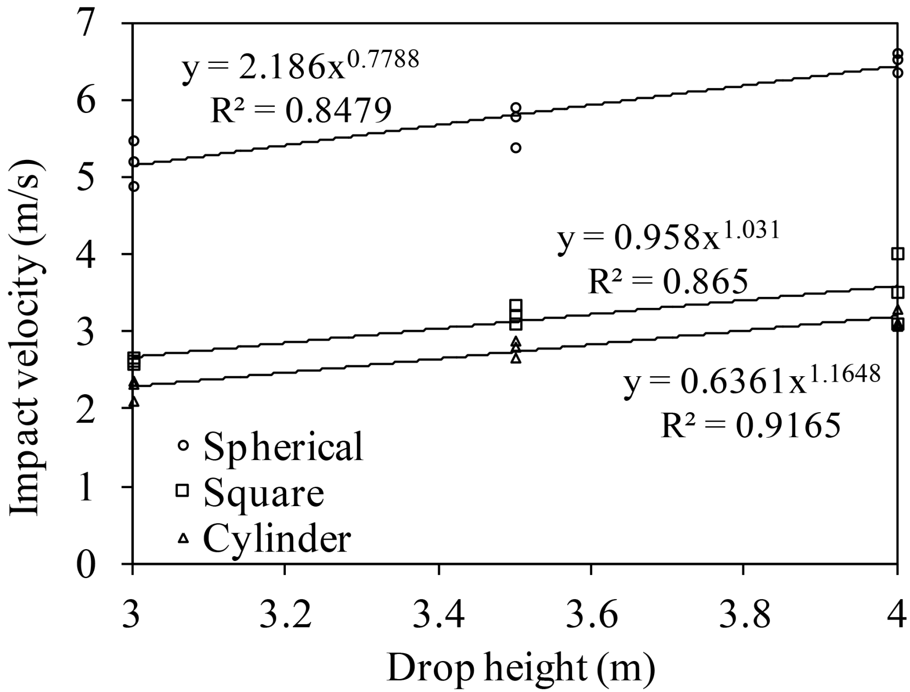

Figure 10. Positive exponential correlation between impact velocity (v) and drop height (h).

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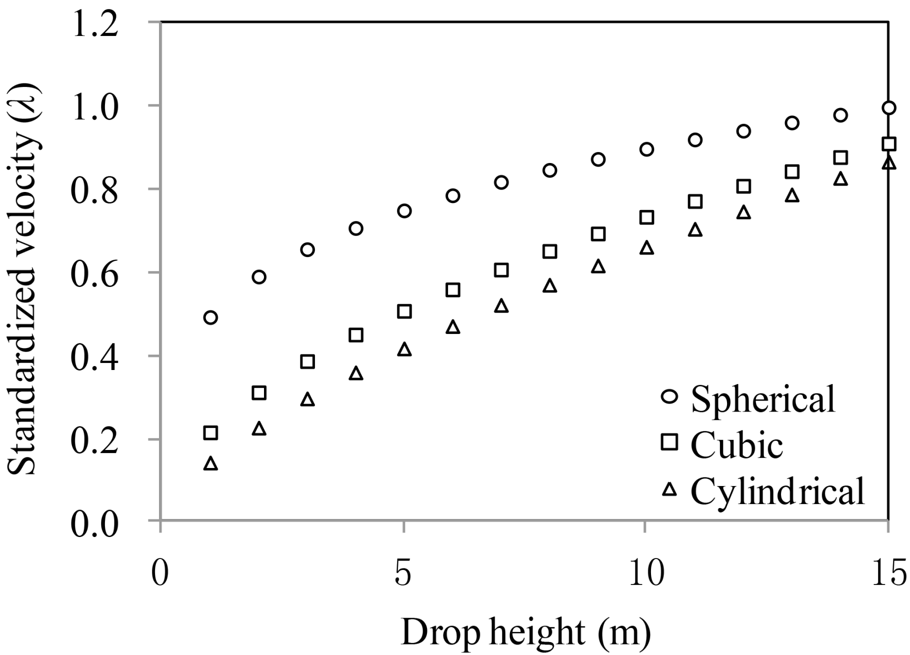

Figure 11. Normalized velocity (λ) of rockfalls of different shapes.

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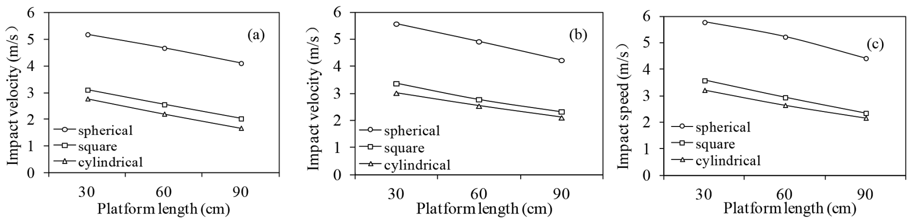

Figure 12. Influence of platform length on the impact velocity of rockfalls of different shapes and weights: **(a)** 6 kg; **(b)** 5 kg; and **(c)** 4 kg.

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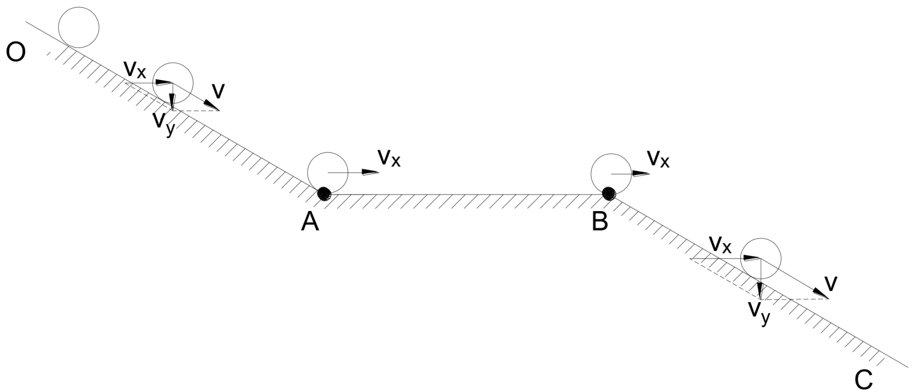

Figure 13. Change of rockfall velocity along a slideway with a platform (length of the vector indicates the absolute velocity values).

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