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Rockfall Hazard Along Road Cut Slope in India

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ABSTRACT

Rockfall is age old problem in high hills due to complex nature of rock mass, variable heights, ingress of water, jointed rock mass and presence of favourable discontinuities. Generally, rockfall is defined as free fall of rock blocks detached from the slope. Indian hilly terrains are facing threat of rockfall in almost all regions of hilly states. In order to assess the rock fall hazard, energy of falling rock blocks is one of the important parameters to be considered. Keeping this in view, Coefficient of Restitution (COR) for different rock types have been studied. It is found that COR has larger impact while simulating the rockfall using numerical tools. In this paper, an attempt has been made to explain the methodology for determination of COR. Schmidt hammer hardness values (rebound number) of materials were observed to have proportional relationship with respective values of COR.

Keywords: Rockfall hazard; Cut slopes; Jointed rock mass; Coefficient of restitution; Schmidt hardness

1. INTRODUCTION

Rockfall is very frequent in hilly regions and every year loss of life and property are reported. The severity depends on the dimensions of the rock boulders falling from the slope as well as population in the nearby sites. Rock engineering parameters, joint roughness, and fillings accelerate the rockfall but are not able to trigger the rockfall (Ansari et al., 2012). However, earthquake, rain induced weathering and erosion, and sometimes human interventions may trigger the rockfall. Unlike landslides, rockfall does not provide enough time and signals to avoid any kind of accidents.

As compared to other parts of the world, India started late in giving proper attention to this problem. Singh et al. (2013, 2016) studied the rockfall problem of state highway No.121 which was recurrently suffered due to rockfall problem near Sawantvadi area of Maharashtra. Based on the detailed study, they have suggested approximate, economical and most scientific remedial measures. The suggested techniques were deployed including high tensile strength wire net as well as rock bolts to arrest the movement in the rock mass.

Similarly, Saptashrungi Gad where a temple is located under the basaltic cliff experienced rockfall in past and got damaged were also reported by Ansari et al. (2012, 2014). After a detailed investigation, proper remedial measures including rockfall barrier were installed.

They have done extensive geomechanical characterization of rock mass as well as numerical simulation to arrive optimum and economical remedial measures. A rockfall hazard system for Indian rock mass was also developed by Ansari et al. (2013, 2016). Actually, they have modified the earlier reported rockfall hazard rating system proposed by Wyllie (1987). Some of the relevant parameters were not considered in rating to suite Indian conditions. One of the important parameters in rockfall study is to calculate Coefficient of Restitution (COR) for different rock types which have larger impact while simulating the rockfall using numerical tools. In this paper, an attempt has been made to explain the methodology for determination of COR.

2. COEFFICIENT OF RESTITUTION (COR)

The fallen block material properties and nature of the slope surface material influence the behaviour of the bounce, which is generally defined in terms of COR of the fallen rock on the slope. There will be two COR; normal and tangential, representing the energy loss in normal and tangential directions respectively. The ratio should lie between 0 and 1, as the energy after impact will always be less than the energy before impact. A value of 0 implies there is a total loss of energy and a value of 1 implies there is no loss of energy at all. These CORs are then used to calculate the resultant velocity of a boulder after impact by reducing the velocities in the respective directions using the respective coefficients.

Newton (1999) first introduced COR while discussing the impact of two rigid bodies and described it as the ratio of the rebound and incidence velocities of two impacting bodies (or small sphere) in normal direction. This is called the kinematic definition of COR. Poisson (1817) introduced kinetic definition of COR. It is defined as the normal restitution impulse to the compression impulse at the contact point. The third definition of restitution was given by Stronge (1990) which is known as the energy coefficient of restitution and defined as the ratio of work done by the normal component of reaction forces at the contact point during the restitution phase to that during the compression phase.

Smith and Liu (1992) state that these three coefficients are of the same value in some circumstances although they are different depending upon the impact characteristics.

3. LABORATORY SETUP FOR COR

Eight different types of rock specimens were collected from different geological locations. A large number of the specimens is aimed at obtaining a large database for good statistical analysis and all specimens used for the tests are listed in Table 1. Rock slabs have been made from all the above specimens except Phyllite and Quartzite. Polished, smooth and flat slab surfaces have been prepared with a thickness greater than or equal to 5.0 cm (Fig. 1). Rock and steel slabs were tightly clamped onto a tilt test apparatus (for measurement of the accurate value of slope angle) so that a range of slope angles could easily be achieved.

Rock balls (diameter 4.0 cm to 5.0 cm) were made from all of the above rock specimens by cutting and grinding. Also, a steel plate and seven steel balls of diameter 1.5 cm, 2.0 cm, 3.0 cm, 3.5 cm, 4.0 cm, 4.5 cm and 5.0 cm were also used in the test to compare the differences between rock and steel impact and to enable comparison with the studies done by Rayudu (1997) and Richards et al., (2001).

ISRM (2007) suggested method was used to measure Schmidt hardness for rock slabs and balls. N-type Schmidt hammer with an energy of 2.207 Nm has been used. Schmidt hardness was measured before the test for both slabs and balls. The slab firmly clamped on tilt test apparatus, whereas the balls were fitted on Brazilian case which was clamped on a universal testing machine (UTM) (Fig. 1). At least 20 tests were performed for each sample, and the mean Schmidt hardness of rock slabs (N1) and rock balls (N2) are shown in Table 1. Generally, igneous rocks have a greater Schmidt hardness (granite and basalt having the greatest value of N), whereas sedimentary rocks (such as sandstone and limestone) have smaller Schmidt hardness values (rebound number). For rocks with foliation (e.g. Phyllite), values of Schmidt hardness are higher when the direction of the plunger is parallel to the foliation and smaller when the plunger is perpendicular to the foliation.

Fig. 1 - Preparation for laboratory experiment: (a) and (b) cutting and polishing of rock slab; (c) and (d) setup for measuring Schmidt hardness for slabs and balls

Table 1 - Schmidt hardness values for slabs and balls with normal COR for same type of slab and ball

Rock Types	Schmidt Hardness values (Rebound Number)				Normal COR
	Slabs (N1)		Balls (N2)		
	Average	Std. Dev.	Average	Std. Dev.	
Basalt	50.50	2.80	48.50	2.30	0.33
			49.50	2.00	
Granite	54.00	1.10	49.00	1.60	0.42
			50.00	1.30	
Sandstone	38.50	2.10	24.50	2.80	0.29
			25.00	2.40	

Limestone	42.50	2.00	27.50	3.50	0.41
			33.50	1.70	
Marble	44.50	1.30	36.50	1.50	0.43
			37.00	2.40	
Phyllite	--	--	21.00	1.70	--
			40.50	1.50	
Quartzite	--	--	39.50	2.00	--
			40.00	1.70	
Steel	47.50	1.20	43.50	1.80	0.34
			51.00	2.00	

The experimental setup used for calculation of COR between balls and rock slabs is shown in Fig. 2. The balls were released from a height of 1.0m onto the rock slab clamped on the tilt test apparatus. A digital high-speed video camera (resolution: 1280X720 and 150fps) has been used to record the bouncing tests. The camera axis has been installed perpendicular to the trajectory plane XY, so that the capture plane can be parallel to the trajectory. A reference grid has been used as a reference system for measuring rebound height and distance. The recorded videos have been analyzed with the vector analysis software, and latter data were processed by an Excel routine in order to determine COR.

Figure 3 is a digitized picture from the video record showing the process of an inclined bounce. The COR experiment involved two configurations; (a) dropping of different types of balls including steel balls onto the same type of rock slab including steel plate, (b) dropping of the same types of balls on different types of rock slab.

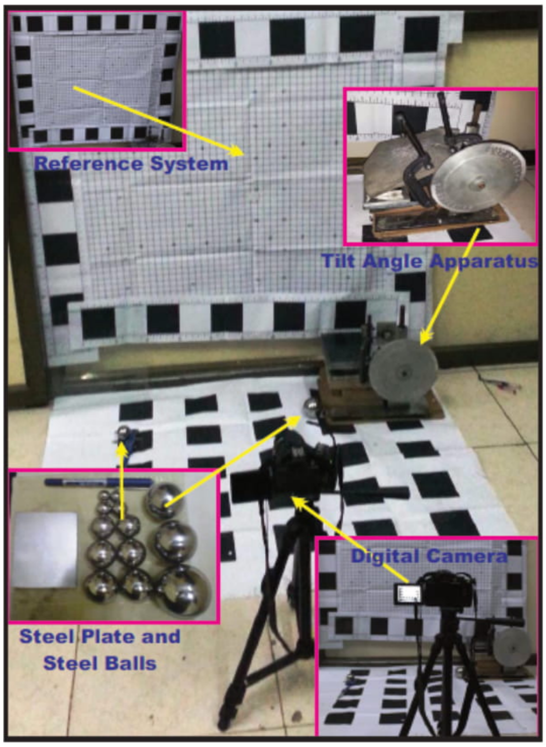


Fig. 2 - COR experiment setup-tilt test apparatus, digital camera, slabs and balls

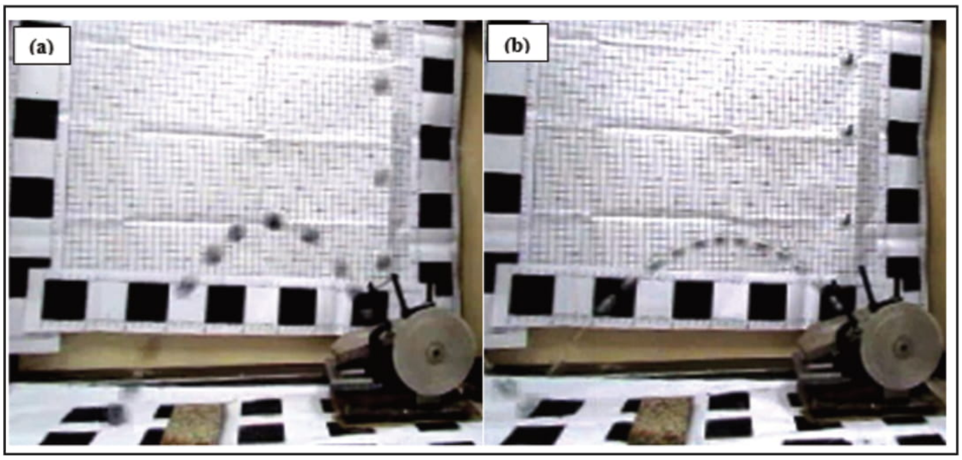


Fig. 3 - Digitized video pictures showing the process of inclined bounces in laboratory experiments for (a) basalt and (b) steel ball impacting on basalt slab

4. CALCULATION OF NORMAL AND TANGENTIAL COR

The bouncing tests were carried out with slabs set to level. The test was done for a combination of a particular slab and a rock ball. The ball was bounced five times, and the mean value of the restitution coefficient was calculated for each test according to Eq. 1,

$$R = \sqrt{\frac{h}{H}} \quad (1)$$

where

R = rebound coefficient,
H = height of drop (m), and
h = height of rebound (m).

Generally, a rock slab was tested once with a rock ball from the same sample.

In inclined bounce, the angles of the tilt test apparatus were set to 10°, 20°, 40° and 55° from the horizontal to calculate both normal and tangential COR as per the relation shown in Fig. 4 and given in Eq. 2 & 3 mentioned below:

$$R_n = \frac{V_{rn}}{V_{in}} \quad (2)$$

$$R_t = \frac{V_{rt}}{V_{it}} \quad (3)$$

where

V_{in} = V_i*cosA

V_{it} = V_i*sinA. F

For upward bounce,

$$V_{rn} = V_{rx}*\sin A + V_{ry}*\cos A$$

$$V_{rt} = V_{rx}*\cos A - V_{ry}*\sin A$$

$$V_{ry} = (h + 0.5g*t^2 / t)$$

and for downward bounce,

$$V_{rn} = V_{rx}*\sin A - V_{ry}*\cos A$$

$$V_{rt} = V_{rx}*\cos A + V_{ry}*\sin A$$

$$V_{ry} = (h - 0.5g*t^2 / t)$$

$$V_{rx} = S / t$$

where

R_n and R_t = normal and tangential coefficient of restitution,
V_{rn} and V_{rt} = normal and tangential components of rebound velocity,
V_{in} and V_{it} = normal and tangential components of impact velocity,
V_{rx} and V_{ry} = horizontal and vertical components of rebound velocity, and
A = tilt angle from horizontal.

For each angle, different combinations of the slabs and balls were tested. Generally, one slab was tested once with one rock sphere from the same sample due to the limited number of specimens.

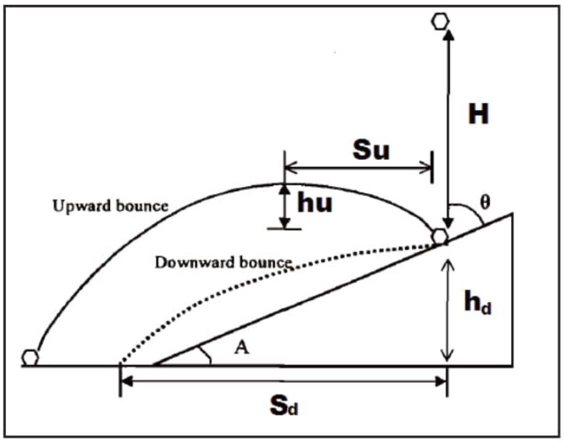


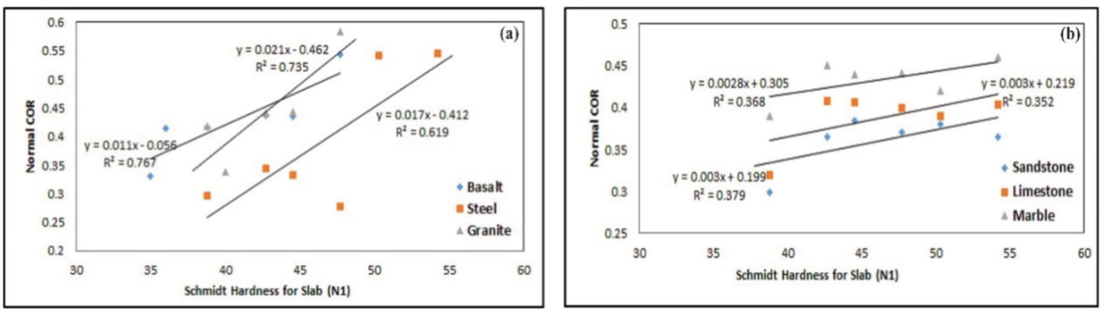
Fig. 4 - Parameter relationships in inclined bounce.

The values of tangential COR (R_t) range from 0.56 to 0.84 (basalt) and mentioned in Table 2. R_t seems to be independent of the Schmidt hardness, indicating that the Schmidt hardness is not a factor affecting the value of R_t. Also, the Schmidt hammer test measures the impact property in the normal direction with the plunger normal to the surface, however, the impact property in the tangential direction is affected mainly by friction. It was observed from the tests that the shape of rock ball plays an important role in the rebound trajectory and thus the tangential COR. The trajectory of a perfect sphere will follow a theoretical parabola as assumed in the calculation of the COR. However, when an irregular shape is involved, rotation of the rock sphere takes place, and the resulting trajectory will be different from the theoretical parabola assumed in the calculation of the COR (Fig. 3), which will affect the values of the calculated COR (R_n and R_t) significantly. Due to the poor correlation of Schmidt hardness with tangential COR, no further experiments have been performed.

Table 1 shows that the normal COR (R_n) ranges from 0.29 (sandstone) to 0.43 (marble), generally rocks with higher Schmidt hardness have higher values of R_n, indicating a possible correlation between R_n and Schmidt hardness of rocks. However, the values of R_n for steel on steel impact are smaller than those of some rocks (e.g. basalt and granite) whose Schmidt hardness is higher, indicating that the Schmidt hardness is a better parameter (than compressive strength or the modulus of elasticity) in the analysis of the COR.

Table 2 - Tangential COR for basalt ball impacting on the different slab at 40° slope angle

Slab Label	Ball Label	Tangential COR
Basalt	Basalt	0.75
Granite		0.84
Sandstone		0.56
Limestone		0.59
Marble		0.62
Steel		0.76



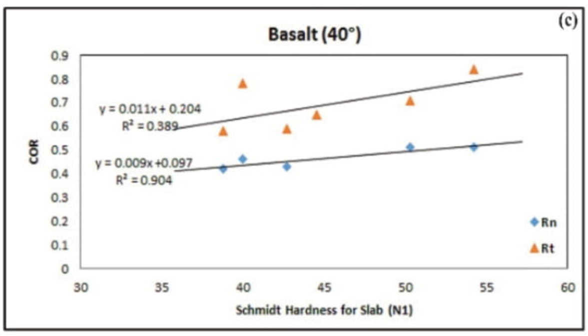


Fig. 5 - Graph for Schmidt hardness verses normal COR when the same type of ball impacting on different types of rock slabs. (a) and (b) Plots of normal COR against Schmidt hardness for slabs (N1); (c) Plot of normal and tangential COR of basalt ball impacting on a different type of rock slabs

The coefficient of restitution obtained from impact of the same ball on different slabs have been plotted against the Schmidt hardness of the slabs (N1) (Fig. 5), which shows that a linear correlation exists between the normal coefficient of restitution (R_n) and the Schmidt hardness of the slabs (N1) for most of the situations. A good correlation (R^2 greater than 0.60) is found in rock balls with higher values of Schmidt hardness (such as granite, basalt and steel ball), while for rock balls with low value of Schmidt hardness (such as sandstone, marble and limestone) the correlation is not as good as the former (R^2 generally less than 0.38). That is possibly because of the anisotropy of the sedimentary and metamorphic rocks, and because other factors such as the shape effect becomes more important when the Schmidt hardness is small. Also, as the strength of rock decreases, large destructive deformation occur, which is affected by variations of rock materials such as grain bounding and defect, and thus the results of the coefficient of restitution are more diverse. Moreover, irregular shape of rock ball causes the ball to bounce in directions other than the normal theoretical direction (inclined slab) as achieved by a perfect sphere (such as a steel ball) due to the momentum generated at impact.

The results of the restitution coefficients of different slope angles show that both the normal and tangential COR increases slightly with slope angle. Figure 6, a plot of the average values of restitution coefficient against slope angle shows good correlation (R^2 0.94 for R_n and 0.81 for R_t).

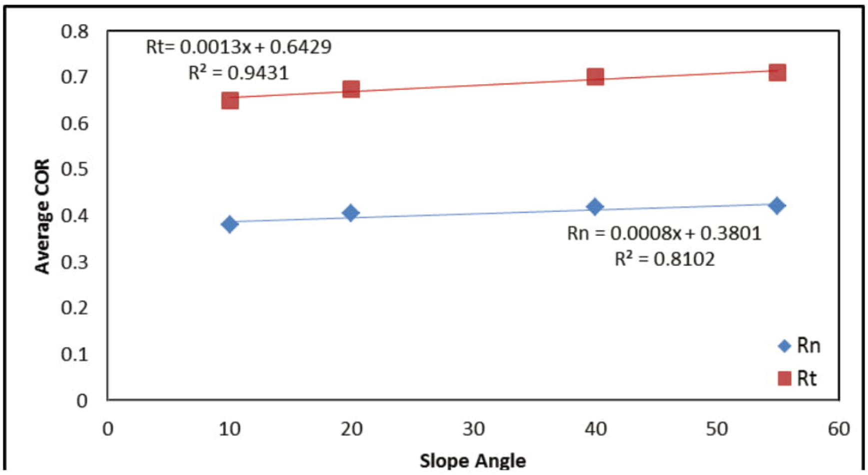
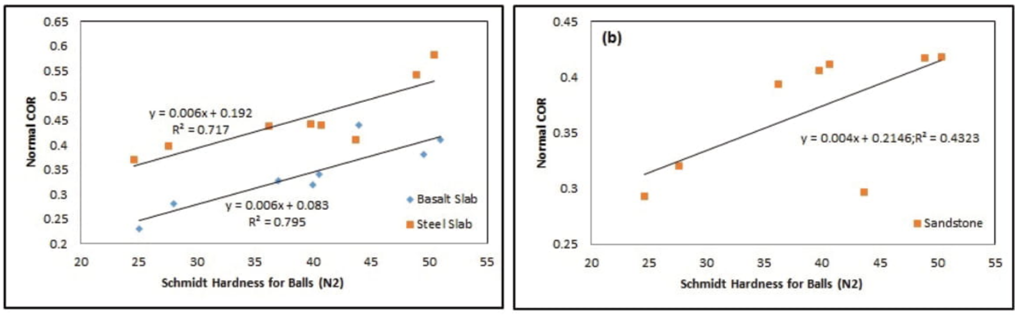


Fig. 6 - Plot shows a correlation between restitution coefficient and slope angle

The COR for the impact of different balls impacting on the same slabs have been plotted against Schmidt hardness of rock balls (N2) (Fig. 7). Results show that a linear correlation exists between the normal coefficient of restitution (R_n) and the Schmidt hardness of rock balls (N2) for most of the situations (similarly in case of rock slabs). For rock slabs with a higher value of Schmidt hardness (such as basalt and steel), a better correlation is found with R^2 greater than 0.79, while for rock slabs with a low Schmidt hardness (such as sandstone) correlation is not as good as the former (R^2 less than 0.43). The above results show that the Schmidt hardness of the falling rock (N2) is also a factor affecting the normal coefficient of restitution (R_n) and could be used to determine the normal COR for rockfall analysis.



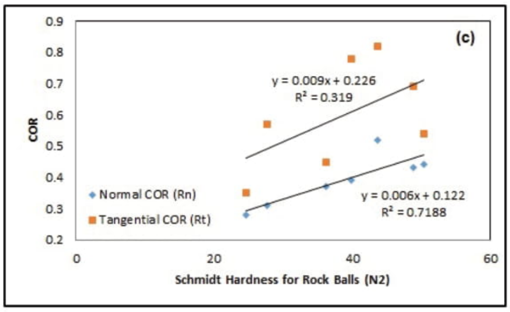


Fig. 7 - Plot shows the relation between normal COR and Schmidt hardness for rock balls (N2). (a) Different rock balls impacting on basalt and steel slab; (b) Different rock balls impacting on sandstone slab; (c) Plots showing the relationship between normal and tangential COR and Schmidt hardness for rock balls for 40° slope angle

An empirical equation was established between normal COR and N1, N2 for normal bounce (Eq. 4). The validity of the equation was examined using correlation coefficient, which is 0.80 (Fig. 8).

Normal bounce: $$R_n = -0.215 + 0.0183*N1-0.007*N2 \quad (4)$$

From this analysis, it can be easily seen that the Schmidt hardness for the slab (N1) is 2.5 times as compare to a hardness value of the ball (N2).

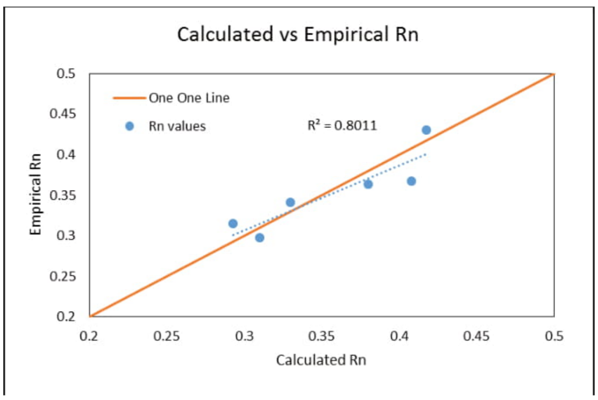


Fig. 8 - Graph between calculated and empirical values of R_n

5. CONCLUDING REMARKS

Rockfall is a key geotechnical issue and owing to its importance has attracted the importance of geotechnical communities for several decades. The problem of rockfall is very pertinent to any mountainous and hilly regions. It poses a big threat to the safety of man and machinery in the hilly region. A thorough investigation is required prior to numerical simulations with appropriate and reliable data from the site. The laboratory experiment was performed to identify COR for eight rock types, and the imperical equation has been proposed with Schmidt hammer and COR. The results suggest that the hardness of the rock is directly proportional to the COR. These equations would save the time and effort of the fellow geo-scientists while analysing the rockfall studies in particular areas.

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