Journal of African Earth Sciences 104 (2015) 1–5

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Correlation between Schmidt hardness and coefficient of restitution of rocks

M.K. Ansari *, M. Ahmad [1], Rajesh Singh [2], T.N. Singh [3]

Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 16 December 2014
Accepted 10 January 2015
Available online 27 January 2015

Keywords:
Landslide
Rockfall
Restitution
Schmidt hardness

ABSTRACT

Rockfall, like landslide is the disaster that could cause loss of life and property. Exact rockfall trajectories depends upon, slope geometry, slope roughness, static and dynamic friction, rolling resistance, density of rocks as well as the restitution characteristics of rocks. In all these parameters, coefficients of restitution play a vital role to control the trajectories of the rockfall. In this article, an attempt has been made to calculate the coefficient of restitution using laboratory experiments that include dropping of balls of different rock types on the same rock type slabs as well as same type of rock balls on different types of rock slab. Schmidt hardness has been also calculated for both, balls and slabs. Using these experimental results, an effort has been made to establish the relation between coefficient of restitution (COR) and Schmidt hardness.

1. Introduction

Rockfall hazard along railways, highways and roadways is one of the major problem and cost to life as well as the properties in majority of hilly or mountainous regions. Protection from rockfall started from late 60s by Ritchie (1963) and progresses as the technology improves. Nowadays, there are number of commercial rockfall simulation programs have been available that extensively can be used for the rockfall risk assessment and barrier designs. Colorado Rockfall Simulation Program (CRSP), (Pfeiffer et al., 1993) and Rocfall (Rocsciences, 2004) is two most commercial used computer programs available for rockfall analysis.

Many researchers have given information on the modeling of rockfall and suggested that the most important parameters affecting the rockfall are (i) geometry of the slope, (ii) slope roughness, (iii) sliding and rolling coefficient of restitution, (iv) rebound coefficient of restitution of rocks, (v) shape of the falling rockfalls and (vi) density of the falling rocks. (Ritchie, 1963; Azzoni et al., 1991; Chau and Lee, 1998; Richards et al., 2001; Ansari et al., 2012; Ahmad et al., 2013).

Coefficient of restitution determined either by field tests (Wu, 1985; Evans and Hungr, 1993; Azzoni and Defreitas, 1995) or, by laboratory tests (Auberger and Rinehart, 1960; Bowman, 1995; Chau and Lee, 1998; Rayudu, 1997; Richards et al., 2001). However, geoscientist also used back analysis of actual events such as impact marks or runout distance (Pfeiffer and Bowen, 1989; Fornaro et al., 1990; Budetta and Santo, 1994) to calculate COR.

In this article, an attempt has been made to determine the coefficient of restitution (COR) in laboratory and to establish a correlation between coefficient of restitution and Schmidt hardness.

2. Literature review

2.1. Background on restitution coefficient

Newton (1686) first introduced coefficient of restitution while discussing 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 can be expressed as;

$$R = \frac{V_{r1} - V_{r2}}{V_{i1} - V_{i2}} \quad (1)$$

where V_{r1} & V_{r2} = normal components of rebound velocities, and V_{i1} & V_{i2} = normal component of initial velocities.

This is called the kinematic definition of the coefficient of restitution. This coefficient has been used for more than 300 years and has been extended to 3D collisions by Brach (1991, 1997).

* Corresponding author. Mobile: +91 9326301723.
E-mail addresses: mkhalidgly97iitk@gmail.com (M.K. Ansari), masood.geo2100@gmail.com (M. Ahmad), georajeshsingh@gmail.com (R. Singh), tnsingh@iitb.ac.in (T.N. Singh).
[1] Mobile: +91 922495935.
[2] Mobile: +91 9757275271.
[3] Mobile: +91 2225767271.

http://dx.doi.org/10.1016/j.jafrearsci.2015.01.005
1464-343X/

Poisson (1817) introduced kinetic definition of the coefficient of restitution. It is defined as the normal restitution impulse to the compression impulse at the contact point as;

$$R = \frac{P_{nr}}{P_{nc}} \quad (2)$$

where P_{nr} and P_{nc} are the normal impulses in periods of restitution and compression.

The third definition of restitution was given by Stronge (1990) which is known as 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 same value in some circumstances although they are different depending upon the impact characteristics.

2.2. Restitution coefficient in rockfall simulation

The restitution coefficient has been used to calculate rebound velocity in rockfall simulation; however, different researchers used different definitions of restitution as explained above. Azzoni and Defreitas (1995) used energetic coefficient of restitution, whereas Wu (1985), Pfeiffer and Bowen (1989), and Hungr and Evans (1988) used kinematic (velocity) coefficient. The restitution coefficient used to model the rockfall problem defines the manner in which rockfall behavior is changed when a block impacts onto the slope. Both programs, Rocfall (Rocsciences, 2004) and CRSP (Pfeiffer et al., 1993) use velocity loss in each of the normal and tangential direction to the slope to define the coefficients of restitution. So, the normal and tangential COR according to the above definition are as follows;

$$R_n = \frac{V_{rn}}{V_{in}} \quad (3)$$

$$R_t = \frac{V_{rt}}{V_{it}} \quad (4)$$

where R_n and R_t are the normal COR and tangential COR, V_{rn} is normal components of rebound velocity, V_{rt} is tangential components of rebound velocity, V_{in} is normal component of impact velocity, and V_{it} is tangential component of impact velocity.

2.3. Experimental studies

Wu (1985) performed an *in-situ* test on an inclined wooden platform and on rock slope. The results indicate that both the mean values and standard deviation of normal COR increases linearly with slope angle while those for tangential COR decreases with slope angle. Azzoni et al. (1991) carried out rockfall experiments at four quarry sites and one on natural slope. They used tabular to spheroid boulders of different size ranged between $5.0 * 10^5\ cm^3$ to $3.0 * 10^6\ cm^3$. The calculated value of R_n and R_t varies from 0.45–0.85 and 0.45–0.75 respectively.

Rayudu (1997) used steel ball of diameter 4.0 cm that dropped onto 14 different rock slabs and found a linear relationship between the normal COR and Schmidt hardness. However as the experiment used only steel balls, it cannot be used in rockfall simulation. Chau and Lee (1998) carried out laboratory experiments with granite boulders impacting on different types of slope and found out that both normal and tangential COR increases with slope angle and decreases with impact energy. They also encountered that the angularity of the boulders affect the normal COR only as it increases with angularity. Richards et al. (2001) performed drop tests for various types of rocks. They have also given correlation between the normal COR and Schmidt hardness along with slope angle. From the correlation, it was observed that normal COR increases with slope angle. Chau et al. (2002) modelled balls and slope from plaster material for the experiment. Results of experiment show that Normal COR increase with slope, however tangential COR did not show any correlation with slope angle. The findings of the experiment suggested that COR depends also on block characteristics (weight, geometry) and kinematics (impact velocity and angle) along with ground characteristics (material, slope angle). Asteriou et al. (2012) conducted a laboratory and field experiment to determine parameters affect the trajectories of falling rock blocks. They used kinematic definition to calculate COR and suggested that kinematic COR is more suitable parameter as compare to normal COR. They also proposed a correlation between Schmidt hardness rebound hardness and kinematic COR.

3. Laboratory investigation

Eight different types of rock specimens were collected from different geological locations. The large number of 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 thickness greater than or equal to 5.0 cm (Fig. 1). Rock and steel slabs were tightly clamped on to 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 (dia. 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,

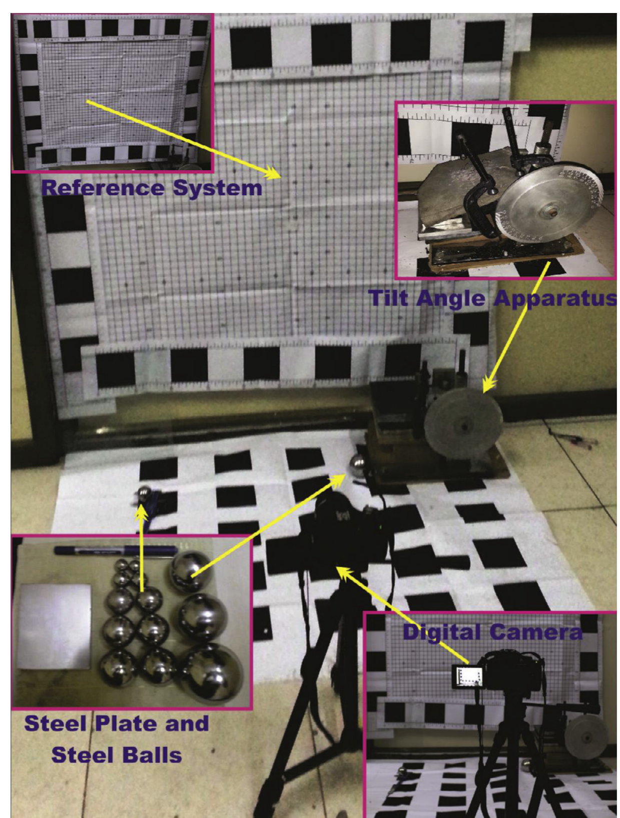

Fig. 1. Rockfall experiment setup – tilt test apparatus, digital camera and steel and rock slabs and balls.