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Determination of Terrain-Specific Restitution Coefficients and Rockfall Hazard Assessment in the Chaku Bazar of Nepal

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Abstract: Many of Nepal's rapidly growing cities are located at the base of steep slopes, where rockfall hazards pose a significant threat. Rockfall issues have also been observed in Chaku Bazar, Sindhupalchowk, Bagmati Nepal, situated at km 102+000 along the Araniko Highway. The primary aims of this study were to determine the restitution coefficient of the material, stability analysis and to simulate rockfall at the steep slope in Chaku Bazar. The accuracy of rockfall simulations relies on the restitution coefficient. Initially, the normal and tangential restitution coefficients were calculated for 10 different rock boulders, varying in shape and composition using the Tracker Video analysis and modeling tool. The computed values for normal and tangential restitution coefficients were then used to simulate rockfall behavior using GeoRock 2D across four different sections, predicting rockfall trajectories and run-out distances. Geologically, the area is part of the Lakharpata Group of the Lesser Himalaya, characterized by calcareous rocks, primarily dolomite and schist. The normal restitution coefficient for vegetated rocky terrain was 0.25, while for solid rock it was 0.73. Likewise, the tangential restitution coefficient was 0.37 for grass-covered areas and 0.82 for rocky surfaces. The factor of safety of block for planar failure is 0.83, for wedge failure is 0.95 and for toppling failure is 1.35. After determining the restitution coefficients, the calculations revealed a maximum collision energy of 2576 kJ and a maximum bounce height of 4.6 meters.

Keywords: ***Block Analysis, GeoRock 2D, Hazard, Rockfall, Restitution Coefficient.***

Introduction

Rockfall is the natural downward movement of one or more detached blocks with small volumes, characterized by free fall, bouncing, rolling, and sliding (Varnes 1978) which pose threat to the environment and resulting in loss of life and property (Cruden and Varnes 1996; Bunce et al. 1997). These rock blocks can be dislodged through various processes, including natural mechanisms such as freeze-thaw cycles (McCarroll and Pawellek 1998; Matsuoka and Sakai 1999; Khatiwada and Dahal 2020), seismic events (Abebe et al., 2010), or by human activities such as slope excavation or earth-moving operations (Dorren 2003; Vijayakumar et al., 2011). The steep topography, geological variations and tectonic activity within the small belt have accelerated the soil erosion and rockfall (Tiwari et al., 2022). The Rock fall incidents, recognized as a global hazard, pose challenges due to their unpredictable nature and the lack of precise analysis.

To the mark, Nepal has experienced numerous fatal rock fall incidents, notably along the Jogimara section of Prithvi Highway and the Narayanghat-Muglin Road during the 2016 monsoon. The Araniko Highway, crucial for trade with China, has witnessed an increase in rock fall incidents since the 2015 Gorkha earthquake (Dahal 2016), which caused extensive damage, including to the Upper Bhotekoshi Hydroelectric Project's penstocks. Thus, there is a pressing need for identifying rock fall hazard zones and conducting detailed studies to mitigate risks, safeguard lives, properties, and prevent significant economic losses.

The impact of the rockfall depends upon the estimation of trajectories, bouncing heights and the kinetic energies of the unstable blocks. These elements are frequently derived through the application of kinematic modeling techniques created using numerical codes like Colorado Rockfall Simulation Program (CRSP) or RocFall (Pfeiffer and Bowen 1989). The key input parameters influencing the estimated rockfall hazard in computer simulations are the coefficients of restitution. These parameters measure the energy loss that occurs when a block impacts the slope (Sabatakakis et al. 2015). The coefficients of restitution are divided into tangential (Rt) and normal (Rn) components relative to the slope. Two primary methods are used to determine these parameters: direct measurement through experimental tests, both in situ and in the laboratory (Azzoni and de Freitas 1995; Giani et al. 2004; Chau et al. 2002), and back-analysis of natural or artificially triggered rockfalls (Evans and Hungr 1993). It has been observed that (Rn) values exceeding one have been recorded in both field tests (Bourrier et al. 2012; Spadari et al. 2012) and laboratory experiments (Asteriou et al. 2012; Buzzi et al. 2012), as well as calculated through simulations (Bourrier et al. 2009) and by back-analysis methods (Paronuzzi 2009).

The research focus of the determination of restitution coefficient of the slope material and Rockfall Simulation at Chaku Bazar, Sindhupalchock, Bagmati Nepal.

Study Area

The study area is located in Chaku Bazar, within Bhotekoshi Rural Municipality of Sindhupalchowk district (27°53'2.3" N, 85°54'48.5"E) which site on cliff with an elevation of 1216 m from mean sea level. It is easily accessible from Kathmandu via the Araniko Highway, positioned at 102+000 km along of the highway (Figure 1). The rockfall hazards in this region pose a risk to the residents of Chaku Bazar and the Araniko Highway. Geologically, the area is part of the Lakharpata Subgroup within the Lakharpata Formation, characterized by fine-grained gray limestones, dolomitic limestones, and dolomite. The boulders of these rock type were the source for rockfall.

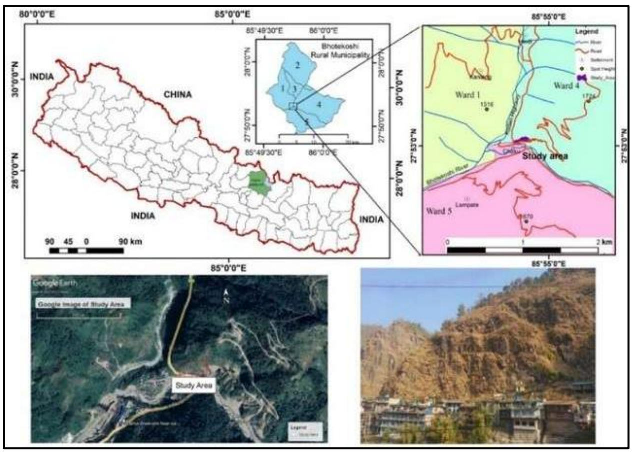


Figure 1, Location map of the study slope area.

Materials and Methods

This study experimentally evaluates the coefficient of restitution for boulders colliding with rock slopes under different impact conditions, followed by the calculation of their kinetic energy and re-bounce height at four distinct sections of the terrain. The method of data collection and interpretation is given in Figure 2 and describe as,

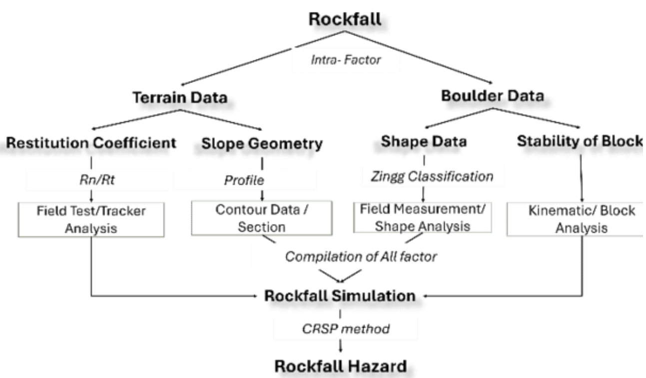


Figure 2, Methodological flow chart for the study.

Determination of restitution coefficient

Newton (1686) originally defined the coefficient of restitution (R_C) as the ratio of the rebound velocity to the incident velocity of two colliding particles (or small spheres) along the normal direction. The kinematic definition of the coefficient of restitution, has been generalized and extended to three dimensional collisions by Brach (1991, 1997).

$$R_C = \frac{V_{1n}-V_{2n}}{U_{1n}-U_{2n}} \tag{1}$$

Where, V_{1n} & V_{2n} = normal components of rebound velocities, and U_{1n} &U_{2n} = normal component of initial velocities of two colliding bodies. The both normal and tangential component of the restitution coefficient has significant role on the velocities and trajectories of the falling block. Both normal and tangential components have determined by,

$$R_n = -\frac{V_{rn}}{V_{in}}, \tag{2}$$

$$R_t = \frac{V_{rt}}{V_{it}} \tag{3}$$

Where, V_{rn} and V_{in} are the magnitudes of the normal component of the rebounding and incoming velocities and V_{rt} and V_{it} are the magnitudes of the tangential component of the rebounding and incoming velocities. Each parameter has determined by using the following relations (Chau et al. 2002),

$$V_{rn} = \left(\frac{h}{T2} + \frac{1}{2}gT2\right) cos \propto - \frac{L}{T2} sin \propto \tag{4}$$

$$V_{in} = \left(\frac{H}{T1} + \frac{1}{2}gT1\right) cos \propto - \frac{S}{T1} sin \propto \tag{5}$$

$$V_{rt} = \left(\frac{h}{T2} - \frac{1}{2}gT2\right) sin \propto + \frac{L}{T2} Cos \propto \qquad 6)$$

$$V_{it} = \left(\frac{H}{T1} + \frac{1}{2}gT1\right) sin \propto + \frac{S}{T1} cos \propto \tag{7}$$

Where, g is the gravitational constant (i.e. 9.81 m/s^2) and H= y_1 - y_2; h= y_2 -y_3; s =x_1- x_2; L = x_2 -x_3; T_1 = t_2- t_1; T_2= t_3 -t_2.

To determine these parameters, ten blocks of varying shapes and sizes were selected and released from the top of the slope. The falling blocks were recorded on video, which was later analyzed using Tracker software to measure their velocity (Figure 3). After all the blocks had been dropped and the test area was deemed safe, the final positions of the blocks were recorded with coordinates, the impact depths were measured, and the sizes of the blocks were noted. Ranging rods and measuring tapes were used to measure and mark the distances traveled by the blocks. Data from Tracker, along with manual observations, were used to calculate the tangential and normal coefficients of restitution, with trigonometric formulas aiding in determining the blocks movement and restitution coefficients.

Kinematic Analysis

The discontinuities data were collected from the site and determined the major joint set by stereonet plot. The major joint set were used for the determination of the prominent failure type of the rock slope. After determining the prominent failure type, the block analysis for each failure type (Plane, wedge and toppling has determined. The plane failure analysis was conducted based on equations developed by Hoek and Bray (1981). Condition for calculation was external force zero ($a = T = 0$) and dry slope ($U = V = 0$).

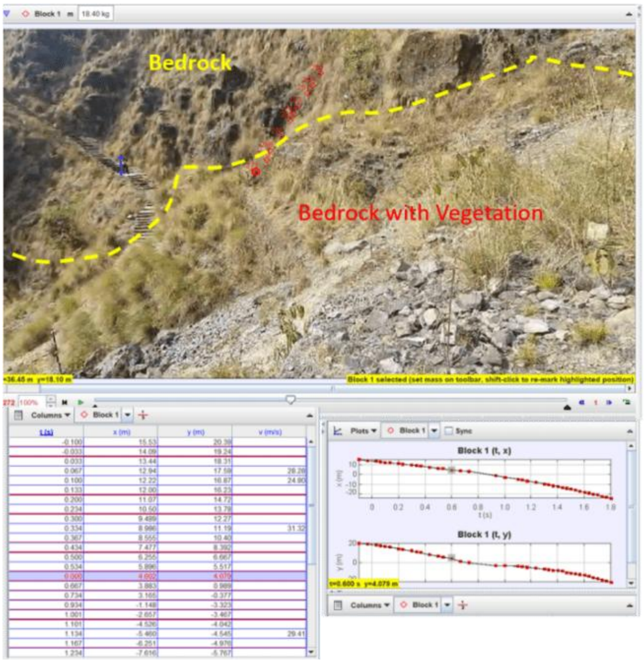


Figure 3, Tracker video analysis for determination of Restitution Coefficient (Rn and Rt).

$$FS = \frac{\{cA+[W*(\cos\Psi_p)-U-V\sin\Psi_p+T\cos\theta]\tan\phi\}}{[W(\sin\Psi_p+a\cos\Psi_p)+V\cos\Psi_p-T\sin\theta]} \quad (8)$$

Where, c = cohesive strength of failure surface; A=area of failure surface; W=weight of sliding block; Ψ_p = inclination of failure plane; a = horizontal acceleration, blast or earthquake loading; U=uplift water force; V= driving water force; T = Tension in bolts or cables; θ = inclination of bolt or cable to normal to failure plane; ϕ = friction angle of failure surfaces; Z = depth of tension crack, H = height of slope face; Ψ_f = inclination of slope face; b = distance of tension crack from slope crest; γ_r = density of rock; γ_w = density of water; Z_w = height of water in tension crack.

Similarly for wedge failure, the empirical relation developed by Hoek and Bray (1981), has applied,

$$FS = \frac{3}{\gamma_r H}(c_a X + c_b Y) + A\tan\phi_a + B\tan\phi_b \quad (9)$$

Where, c_a and c_b are the cohesive strengths of planes a and b, ϕ_a and ϕ_b are the angles of friction on planes a and b; γ_r is the unit weight of the rock; H is the total height of the wedge; X, Y, A and B are dimensionless factors which depend upon the geometry of the wedge.

The toppling failure analysis was conducted by using empirical relations formulated by Hoek and Bray (1981).

$$FOS = \frac{w\cos\theta.\left(\frac{t}{2}\right)}{w\sin\theta,\left(\frac{h}{2}\right)} = \frac{\frac{t}{h}}{\tan\theta} \quad (10)$$

Where, weight of the block, θ = inclination of slope, h= height of block and t is the thickness of block.

Rockfall simulation

The rockfall simulation has followed by CRSP method in GeoRock 2D Software which is easily available and widely used in the simulation of rock fall problems. The parameter required for the rockfall simulation were restitution coefficient of slope material, slope geometry and the boulder data. For the rockfall simulation, the restitution coefficient was used from previously determined values after field tests and tracker analysis.

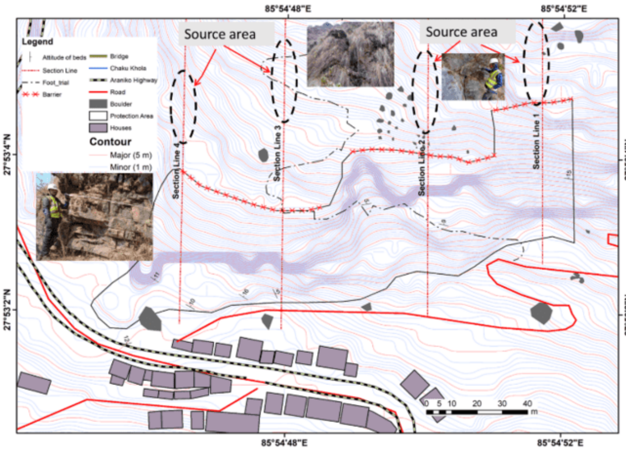


Figure 4, Slope geometry section line with source of loose rock boulders.

The cross-sectional profile of the slope, as shown in Figure 4 was developed based on contour data generated from a total station survey. The source area was determined based on field investigations and kinematic analysis to identify the mode of failure at the source. Boulder data, including the shape of the boulders, was determined through block analysis using major discontinuities and field measurements.

The rigid body approach of CRSP analyzes the impulse reaction of the rock during its brief contact with the slope to identify critical events such as slipping, sticking, and reversal behavior during both the compression and restitution phases. The normal coefficient of restitution is applied during these two contact phases to calculate the terminal impulse. Using this terminal impulse, the outgoing velocities at the contact point can also be determined.

Result and Discussion

Restitution coefficient

The normal and tangential coefficients of restitution were determined for ten different rock boulders, each varying in shape and lithology, to account for the diversity in rockfall behavior associated with different physical and material characteristics. The tangential coefficient of restitution for the bedrock varies from 0.77 to 0.87, which is in the range of standard values in dolomitic terrain. Similarly, the average normal coefficient for bedrock is 0.73. The average normal and tangential coefficient of restitution for bedrock with vegetation is 0.25 and 0.37 respectively (Figure 5).

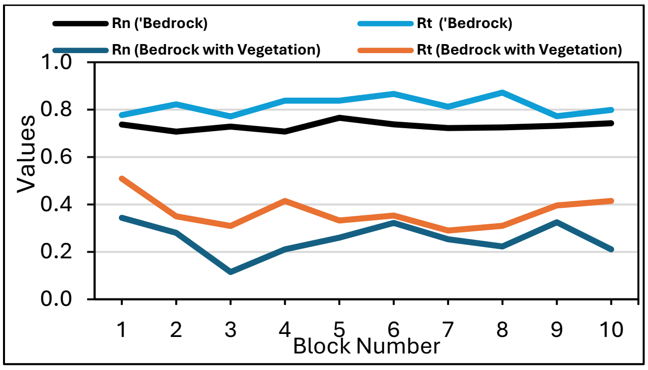


Figure 5, Result showing restitution coefficient of the bed rock terrain and grass with bedrock terrain.

Kinematic Analysis

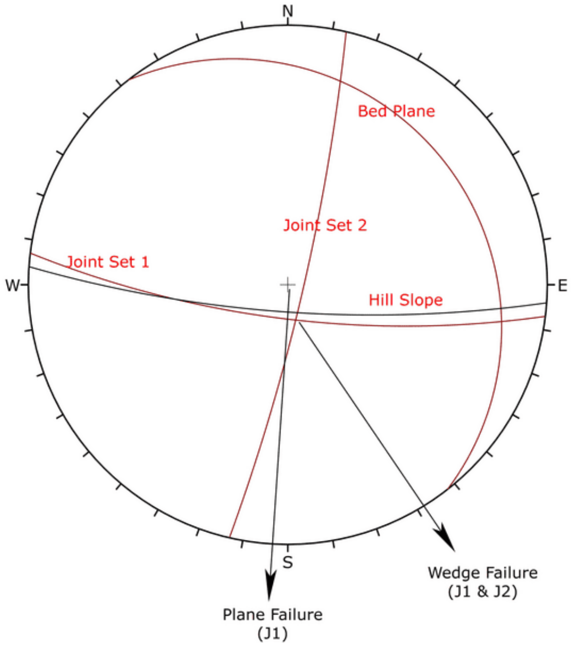
The kinematic analysis of discontinuities data shows that the predominant type of slope failure of slope are wedge failure and plane failure. Block analysis, using the modified Hoek and Bray (1981) method, was conducted on a representative slope section to determine the factor of safety for a typical vulnerable block. The factor of safety of block for plane failure is 0.83, for wedge failure is 0.95, and for toppling failure is 1.35, which is given in Table 1 and Figure 7 which implies that the slope instability has created by the blocks.

Table 1, The determination of factor of safety of block with respect to prominent failure.

Plane Failure		Wedge Failure						Toppling Failure	
b	0.94	Өna*2	89.11	φb	71			d	0.08
c	1.49	Өnb*1	85.89	Phi	17.72			γ	26
γ	26	Өna*nb	58.87	H	54.98			W	2.04
H	41	φi	46	γ	26			θ	85
z	8.67	Ө24	72.85	C	0.517			t	0.5
φp	74	Ө45	67.83	X	1.41			H	2.11
φf	85	Ө35	50.11	Y	-1			**FOS**	**1.35**
ϕ	30	Ө13	50.34	A	0.28				
A	1109.8	φa	70	B	0.28				
W	2442.3			**FOS**	**0.95**				
ROS	**0.83**								

Rockfall Hazard

The field measurement and discontinuities plot show that the size of the boulder is 2.4 m on average. The Zingg classification of the boulder data shows that the shape of the boulder is "disc" (Figure 8) which is used for the rockfall hazard simulation. The result shows that there is possibility of the rock slope failure. On varying the shape and size of the block, the factor of safety has increased. The rockfall simulation result shows that the rockfall hazard can be of maximum energy 15000 kJ to the settlement area of Chaku Bazar and Araniko Highway (Table 2).



Bed Plane (15°/052°) J1 (75°/187°) J2 (83°/103°)

Figure 6, Stereonet plot of discontinuities data for kinematic analysis in the Dips software.

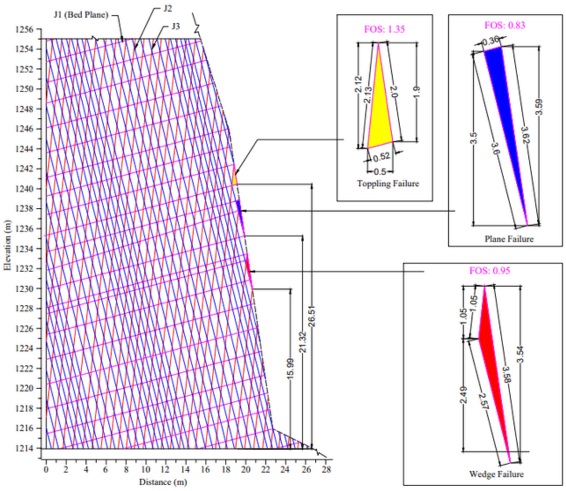


Figure 7, Rockfall analysis by stability of block at section of study slope.

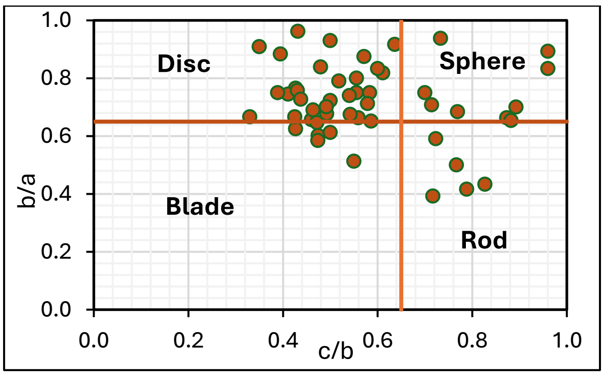


Figure 8, Zingg classification of the boulder data.

Similarly, the maximum run-out distance is estimated to be 160 meters, with a rebound height of up to 30 meters, due to the extremely steep terrain with slopes exceeding 80° (Table 2). The slope area is divided into three zones according to kinetic energy (Figure 9). The red zone implies high-energy zone while green zone indicates the low energy zone.

Table 2, Section wise rockfall simulation result.

Section	Energy	Max. Height	Run out
1	14000 kJ	24 m	140 m
2	15000 kJ	25 m	160 m
3	7000 kJ	30 m	160 m
4	6900	30 m	160 m

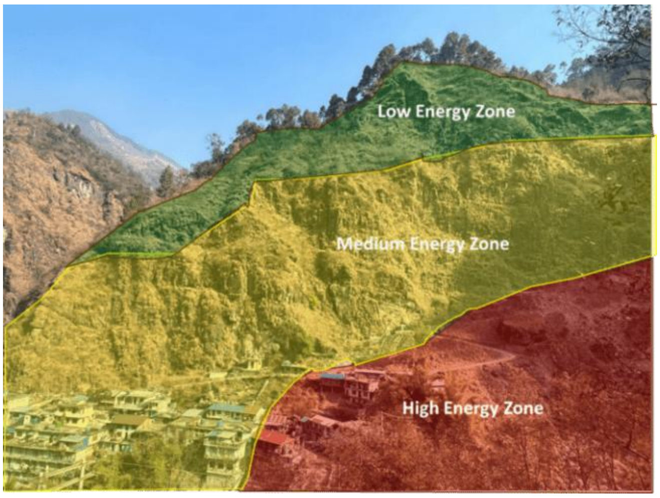


Figure 9, Hazard map of the studied slope according to rockfall and kinetic energy.

Conclusion

In this research, rockfall hazard assessment was carried out using field tests and simulations, leading to recommendations for significant stabilization measures. Kinematic analysis indicated a high likelihood of planar failure occurring at rock slope of Chaku Bazar in which factor of safety is less than 1, with notable chances of wedge and toppling failure. The analysis implies that the rock fall is significantly dependent on restitution coefficient and this value should be site specific. The findings highlight the elevated risk, particularly at the toe of the slope, where the highway road is the primary element exposed to danger.

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