STOCHASTIC ANALYSIS OF ROCKFALL ALONG A HIMALAYAN SLOPE

Kaustav Chatterjee[1] and Arindam Dey[1]

[1] Civil Engineering Department, IIT Guwahati, Guwahati – 781039

chatterj@iitg.ac.in; arindamdeyiitg16@gmail.com

Abstract. Rockfall is a geological hazard for highways and areas located in mountainous terrain. Analysis of rockfall is of major importance due to its effect on the transportation system, buildings, and various other infrastructure facilities. It is caused in the regions of high seismic activity or heavy rainfall. Determination of bounce height, kinetic energy, and translational velocity of a falling rock are necessary for the design of mitigation systems. This research work is carried out using numerical simulation program Rocfall 6.0 to determine the effect of rock-falls at four different sites in the Theng slope situated in Sikkim. The deterministic analysis is not able to incorporate the wide variability of the different geotechnical properties. Hence, considering the pitfalls of deterministic analysis, a stochastic analysis is implemented using Monte-Carlo simulation technique, considering the velocity of the moving block and coefficient of restitution as its input parameter. In this simulation technique, the truncated normal distribution is used and the coefficient of variation is considered approximately 10%. Finally, a sensitivity analysis of barrier system is performed. From this sensitivity analysis, the location, height, and inclination of the barrier are obtained.

Keywords: Rockfall; Stochastic analysis; Monte-Carlo simulation; Barrier

1 Introduction

Rockfalls are one of the natural hazards along highways and railroads situated in hilly areas. The effect of rockfalls on life, properties, and different infrastructure facilities can be catastrophic and it can cause an interruption in transportation facilities. The event of rockfalls generally occur during the periods of heavy rainfall or during the periods of major seismic events, in which rock masses of different sizes are detached from slope faces and move down the slopes.

The risk involved in the event of a rockfall is arduous to estimate. The various factors due which difficulty arises in calculating risk are: lacking accurate data, site-specific nature of the hazard, difficulty in modeling spatial variation of rockfall, assessing the heterogeneous nature of vulnerability of elements at risk and variations in temporal vulnerability [1 - 4].

The risks associated with the event of rockfalls can be obtained from conventional methods of analysis like deterministic rockfall analysis; however, the same approach does not take into account the uncertainties arising due to the variation of different geotechnical parameters and variation of natural forces. Due to these unavoidable shortcomings of deterministic analysis, stochastic analysis of rockfall should be performed considering the variation in geotechnical properties as well as natural forces.

In this study, four different sections of the Theng slope, located in Himalayan Sikkim, are investigated. The site has experienced numerous events of rockfall in the past, and earlier studies have shown the area to be susceptible to rockfall hazard [5]. Numerical modeling has been carried out using RocFall 6.0 to predict the height of bounce, kinetic energy, and velocity of translation of a falling rock mass. Monte-Carlo simulation is implemented to perform the stochastic analysis of rock slopes. The result obtained from Monte-Carlo simulation is used for designing mitigation measures.

2 Description of the study area

The location of the Theng slope is along the North Sikkim Highway that connects Chungtang town to Tung, and other different parts of the state. A study based on slope mass rating suggested the risk of slope failure at different sections [6]. In this study, four different sections of the slope, named as RS1, RS2, RS3 and RS4, with different morphological features are studied for determining the various parameters that contribute to the hazard of rockfall, as indicated in Table 1.

Table 1. Morphological features of different slope sections considered in the study [as per 5]

Slope Designation	Height of the slope (m)	Angle of the slope (°)	Friction angle (°)
RS1	141	35-60	35
RS2	346	45-75	30
RS3	258	50-80	30
RS4	244	45-65	35

Table 2. Geotechnical properties adopted in the present study

Parameters	Value
Tangential restitution	0.65
Friction angle	30°
Slope roughness	0
Number of rocks thrown	500
Vertical velocity	0
Rotational velocity	0
Initial Rotation	0

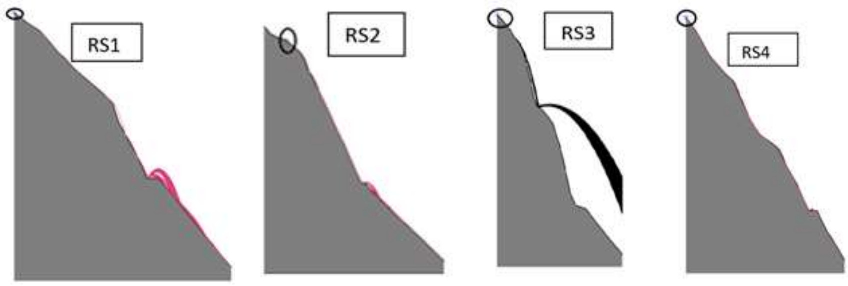

Fig. 1. Various section along Theng slope indicating the origin of falling rock

3 Rockfall analysis

In the event of rockfall, a rock mass undergoes four types of motion namely sliding, rolling, bouncing and freefall [7]. In this research, numerical simulation of rockfall is carried out in RocFall 6.0. In the numerical simulation, the blocks of rock are modeled using lumped mass approach and the slope roughness is neglected for mathematical convenience in the numerical study. The weight of each rock mass is assumed consistently 500 kg. The rockfall is assumed to originate from pre-defined points on the rock slope as indicated in Fig. 1. The geotechnical properties used in this numerical analysis is listed in Table 2. Some of these geotechnical parameters are assumed for mathematical simplicity and some of them are adopted from published literature [6].

In this study, the horizontal velocity of rock mass and the coefficient of restitution along the hill slope are considered as stochastic parameters and are modeled using 'truncated normal distribution' with a coefficient of variation of 10%. The horizontal velocity of a rock mass, at its time of separation from the hill slope, may vary due to the variation of the influencing seismic force. Similarly, the coefficient of restitution can vary along the rock slope owing to the variation in the stiffness of soil or rock along the slope surface. As a result, both the above-stated parameters are modeled stochastically. The horizontal velocity is assumed 0.1 m/s and the coefficient of normal restitution is assumed to 0.5. The maximum and minimum values, type of distribution and the standard deviation of the stochastic parameters are indicated in Table 3.

Table 3. Stochastic parameters and their characteristics

Stochastic parameters	Horizontal velocity (m/s)	Coefficient of restitution
Types of distribution	Truncated normal	Truncated normal
Mean	0.1	0.5
Standard deviation	0.01	0.05
Maximum value	0.11	0.55
Minimum value	0.9	0.45

4 Parameters obtained from numerical simulation

In this research, the bounce height and the total kinetic energy of rock mass are obtained for four different sections of the rock slope. Monte-Carlo simulation technique has been used while considering the stochastic parameters mentioned in Table 3. From the numerical simulation, values of different parameters are obtained at their mean, 75 percentile, 95 percentile, and the maximum. From the numerical simulation, it can be concluded that the location of the maximum bounce height, maximum kinetic energy, and the maximum translational velocity entirely depends on the geometry of the slope.

For the rock slope section RS1, the location of maximum bounce height is at 53 m from the bottom of the slope, while the location of maximum total kinetic energy is at 59 m from the bottom of the slope. Therefore, for rock slope section RS1, the location of maximum bounce height and maximum total kinetic energy is at 0.37H and 0.41H from the bottom of the slope, respectively, where H is the total height of the slope section. Table 4 illustrates the location of maximum bounce height and maximum kinetic energy as function of the total height of slopes. Figure 2 depicts the variation of the bounce height and total kinetic energy along the slope section RS1. Similarly, Fig. 3-5 indicates similar variations for slope sections RS2, RS3 and RS4, respectively.

Probabilistic analysis is performed to find out the values of a particular parameter at a slope section with different levels of risk. These parameters in-turn will be used for the design of mitigation system. It can be inferred from Figs. 2-5 that at a particular slope section, four different values of a particular parameter are obtained. Depending on the importance of a particular infrastructure facility, a particular value of parameter can be chosen for designing the mitigation system. For instance, if an infrastructure of very high importance is in the vicinity of a rockfall site, then maximum value of bounce height and total kinetic energy should be chosen for designing mitigation system.

Table 4. Location of maximum bounce and kinetic energy as a function of height of slope

Rock slope section	Location of maximum bounce height	Location of maximum kinetic energy
RS1	0.37H	0.41H
RS2	0.3H	0.72H
RS3	0.3H	0
RS4	0.69H	0.55H

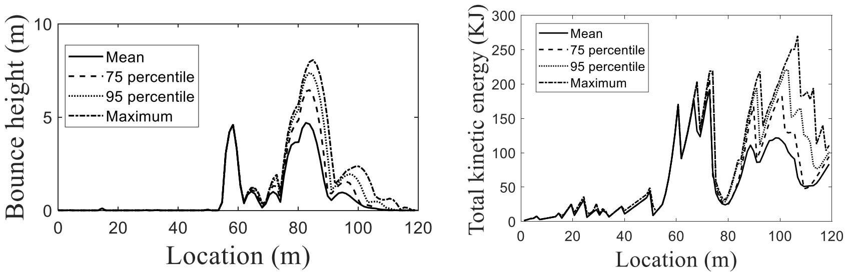

Fig. 2. Variations of bounce height and total kinetic energy at mean, 75 percentile, 95 percentile and maximum obtained for rock slope RS1.

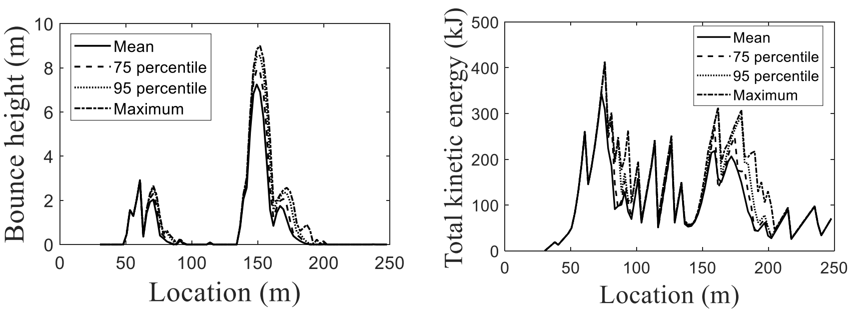

Fig. 3. Variations of bounce height and total kinetic energy at mean, 75 percentile, 95 percentile and maximum obtained for rock slope RS2.

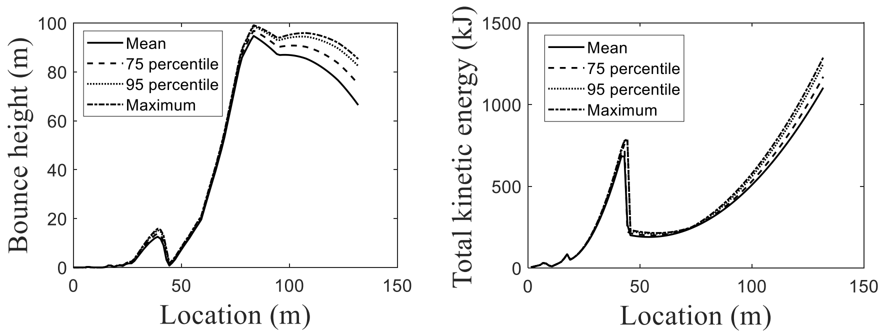

Fig. 4. Variations of bounce height and total kinetic energy at mean, 75 percentile, 95 percentile and maximum obtained for rock slope RS3.

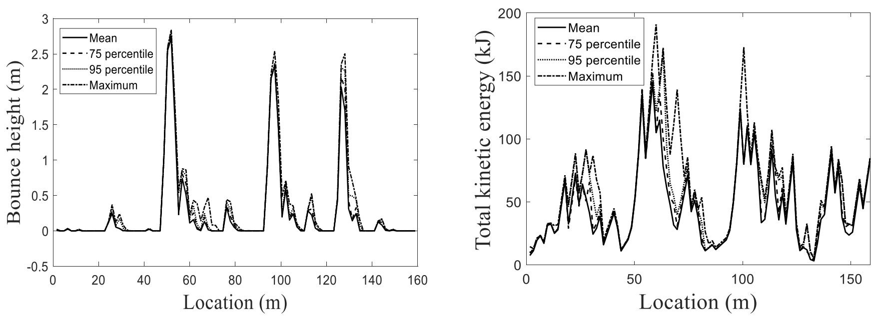

Fig. 5. Variations of bounce height and total kinetic energy at mean, 75 percentile, 95 percentile and maximum obtained for rock slope RS4.

5 Design of mitigation systems

Barriers are the mitigation measures that are usually constructed adjacent to transportation facilities in mountainous regions, where rockfall is one the predominant hazard. In this study, the mitigation systems are assumed located near the roads to mitigate rockfall hazard. Therefore, for obtaining the optimum location of barriers, a two variable sensitivity analysis is implemented in the software Rocfall 6.0. The input variables for the sensitivity analysis are location of barriers, and their inclination with the horizontal. The assumed values of mechanical properties of barrier installed at various rock slope sections are listed in Table 5. For each of the rock slope sections, the sensitivity analysis study provides the information for the optimum location of the barrier, optimum angle of inclination, and the energy of impact on the barrier, and the same is listed in Table 6. The optimum inclination of barrier generally depends on the slope geometry, and from the sensitivity analysis, the energy of impact on the barrier can be obtained. By varying the two input parameters over a range, the point of first impact of the boulder on the barrier gets varied, and finally, the point is obtained where the boulder will strike the barrier with maximum impact energy. For the rock slope section, RS2 and RS4, the optimum horizontal inclination is varying from 30° to 90°, and for these cases, a suitable angle of horizontal inclination can be chosen in the field. In case of rock section RS2, the barrier inhibited the boulder while it was still rolling on the ground. Therefore, in this particular case, varying the angle of inclination of barrier will not change the striking point, as under any circumstances, the boulder would always strike the bottommost point of the barrier. Therefore, in this case, the angle of inclination can vary in the range of 30º to 90º, while maintaining the same impact energy. A schematic representation of barrier installed on the rock slope section RS1 is depicted in Fig. 6.

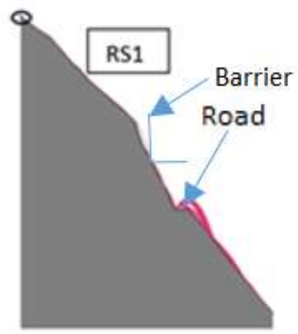

Fig. 6. Slope section RS1 with barrier at an angle of 90° with horizontal.

Table 5. Assumed values of physical and mechanical parameters of barrier for different rock slope sections

Rock slope section	Height of barrier (m)	Capacity of barrier (kJ)
RS1	10	250

RS2	10	350
RS3	20	400
RS4	10	100

Table 6. Optimum barrier characteristics from sensitivity analysis

Rock slope section	Optimal location of barrier from left side of slope section (m)	Optimum inclination of barrier	Impact energy on barrier (kJ)
RS1	64	90°	124
RS2	129.35	30° to 90°	73.91
RS3	50.38	50°	214.16
RS4	120.35	30° to 90°	43.78

6 Conclusion

Analysis of rock slopes undergoing rockfall hazard is a stochastic problem due to uncertainties in geotechnical properties and natural forces. In this article, the numerical analysis of rockfall is performed considering the horizontal velocity of detached rock mass and coefficient of normal restitution as the stochastic parameters. From the numerical analysis, it can be concluded that the bounce height, total kinetic energy and the translational velocity at a particular location depends on the geometry of a rock slope for a fixed value of the horizontal velocity of rock mass and coefficient of restitution of rock slope surface. The numerical value of these parameters is required for efficient design of mitigation systems.

In this research, the bounce height, total kinetic energy, and the translational velocity are obtained at the mean, 75 percentile, 95 percentile, and the maximum. It can be inferred that depending on the importance of the facility near the rockfall site, the bounce height, total kinetic energy, and the translational velocity can be selected.

The position and angle of inclination of a mitigation system are obtained by implementing two-variable sensitivity analysis. From the result of the sensitivity analysis, the optimum location and optimum inclination of the barrier are selected corresponding to the lowest impact energy.

References

1. Crosta, G. B., & Agliardi, F. (2004). Parametric evaluation of 3D dispersion of rockfall trajectories. *Natural Hazards and Earth System Science*, *4*(4), 583-598.
2. Frattini, P., Crosta, G., Carrara, A., & Agliardi, F. (2008). Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. *Geomorphology*, *94*(3-4), 419-437.
3. Glade, T. (2003). Vulnerability assessment in landslide risk analysis. *Erde*, *134*(2), 123-146.
4. Michoud, C., Derron, M. H., Horton, P., Jaboyedoff, M., Baillifard, F. J., Loye, A., ... & Queyrel, A. (2012). Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps. *Natural Hazards & Earth System Sciences*, *12*(3), 615-629.
5. Mithresh, K. P., & Murali Krishna, A. (2017) Rock fall analysis along a Himalayan rock slope. *Sixth Indian Young Geotechnical Engineers Conference*, 10-11 March 2017, NIT Trichy, India.
6. Ghosh, S., Kumar, A., & Bora, A. (2014). Analyzing the stability of a failing rock slope for suggesting suitable mitigation measure: a case study from the Theng rockslide, Sikkim Himalayas, India. *Bulletin of Engineering Geology and the Environment*, *73*(4), 931-945.
7. Crosta, G. B., Agliardi, F., Frattini, P., & Lari, S. (2015). Key issues in rock fall modeling, hazard and risk assessment for rockfall protection. In *Engineering Geology for Society and Territory-Volume 2* (pp. 43-58). Springer, Cham.