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ORIGINAL PAPER

Hazard assessment in rockfall-prone Himalayan slopes along National Highway-58, India: rating and simulation

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Abstract A massive disaster occurred in June 2013 in Kedarnath, India, due to cloudburst and extremely heavy rain along the Chorabari glacier. The resulting flash floods further aggravated the instability of natural and hill cut slopes at different places on the downstream side. The village Rambara that existed in close proximity of Kedarnath was swept away under flow of debris and water. The immediate surrounding area, which housed over a hundred and fifty shops and hotels, was completely washed away leaving no trace of civilization. This calamity in Uttarakhand is considered as India's worst natural disasters after the tsunami in December 2004. On the downstream of the affected areas lie other pilgrim destinations that witness innumerable footfalls every year. Investigation of the health of the slopes on the routes to these destinations is therefore very important to ensure minimal damage to humans and machinery. The Himalayan terrain is a tectonically active mountain belt, having a large number of unstable natural and road cut slopes. Such slopes with rugged topography lie in the high seismic vulnerability zone. Further, the instability is aggravated by natural and anthropogenic activities increasing at a rapid and uncontrollable rate. In the light of the Kedarnath tragedy, more advanced research is being conducted along the National Highways to monitor and prevent slope/structure failures. This study was conducted to evaluate the hazard potential along National Highway-58, near Saknidhar village of Devprayag district by analysing rockfall using hazard rating systems and numerical simulation. Rockfall hazard rating systems were applied to evaluate the conditions of the slopes and to identify the associated risks. Based on the field and laboratory analyses, the parameters required for numerical models were determined. The bounce height, roll-out distance, kinetic energy and speed of the detached blocks were determined by using a competent rockfall simulator. The results obtained were used to identify rockfall risk in the region. Optimization strategies were applied during investigation by modifying

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the slope angle, ditch width and ditch angle to assess the possibility of a hazard to occur in different scenarios. The simulation studies revealed that an increasing slope angle could significantly increase the kinetic energy of the rock blocks. However, an increase in the ditch angle and the ditch width reduces the energy of moving blocks. The maximum bounce height above the slope varied from 0.003 m to 0.8 m for 10-kg blocks, whereas the maximum velocity and the maximum kinetic energy under such circumstances were 7.882 m/s and 379.89 J, respectively. The barrier capacity was found to be 233.18 J for 10-kg falling blocks at a height of 10.02 m. From the optimization studies, it was found that the risk can be reduced by up to 13 % if the slope of 70° has a ditch angle of 15° while on a flat ditch, the maximum risk will be at an angle of 65°. If the ditch angle is increased, the vertical component of the falling blocks is more effective than that in case of a flat ditch. These optimization studies lay foundation for advanced research for mitigation of rockfall hazards in similar potential areas.

Keywords Rockfall hazard rating · Numerical simulation · Slope stability · Himalaya

1 Introduction

The Himalayan mountain belt comprises seismically active mountains having many unstable slopes due to adverse geological, meteorological and geotechnical conditions (Vishal et al. 2015a; Pradhan et al. 2015). The population residing in the Himalayan region are under constant threat of landslides. Increased anthropogenic activities in recent times appear to be an additional factor leading to instability in the Himalayan region. The disaster following the Gorkha earthquake of Nepal Himalaya in 2015 and that of the Kedarnath tragedy of Uttarakhand Himalaya in 2013 have reminded the need for implementation of risk-mitigation strategies and techniques in the hazard-prone regions of the Himalaya. The rockfall studies as well as slope stability investigations have earlier been carried out using different rating, numerical simulations and analysis techniques (Ahmad et al. 2013; Ansari et al. 2014; Singh et al. 2013; Vishal et al. 2010; Gupte et al. 2013; Trivedi et al. 2012). When a rockmass detaches itself from a slope face, it falls down the slope with flight trajectories that are hazardous. Rockfalls occur frequently in steep mountainous regions, quarries and mines and are much less studied and analysed than landslides. Rockfalls are generally initiated by meteorological conditions majorly rainfall, biological factors such as trees and animals and vibrations due to earthquake and blasting (Ahmad et al. 2013). Therefore, it is important to check and arrest rockfall in populated areas, especially along road cut slopes that experience dynamic loading. To minimize the effects, slope failure analysis and stabilization of slopes require in-depth understanding of the processes that govern the stability behaviour of the slopes (Monjezi and Singh 2000; Sarkar et al. 2012; Verma and Singh 2010; Singh et al. 2008; Pradhan et al. 2011, 2014; Vishal et al. 2015b).

For rockfall studies, a mathematical model coded for simulation applications and called as CADMA was designed by Azzoni et al. (1995) to predict fall trajectories and other relevant parameters (kinetic energy, bounce height, run-out distance of falling blocks). This model relies on the rigid body mechanics and applied mathematics which analyse rockfall in two-dimensional space. In the present investigation, the trajectories and kinetic energies of falling rockmass were chiefly analysed at a slope scale by simulator RocFall 4.0 by RocScience. After detachment, the key factors that dominate the flight of the rockmass are geometry and material of the slope. These factors outline the motion of the rockfall which may be classified into four types—free fall, sliding, rolling and bouncing (Ritchie 1963). According to Ritchie (1963), if the slope face is vertical or near-vertical, an easy free fall occurs (if the gradient of slope below potential falling rocks exceeds 76°). If the mean gradient decreases, the falling rock blocks collide with slope surface and cause bouncing of detached rock blocks. If the slope material is soil or talus cones, then straightforward rolling or slipping of the rockmass will be more pronounced. If the slope consists of hard rock terrain, bouncing of rockmass can be observed. Further, if the mean slope gradient is less than approximately 45°, bouncing of the rocks will gradually transform to rolling. The key property of the slope which gives rise to the present differentiation among the type of motion of the rock blocks is the restitution of the slope material. Bedrock surface has higher restitution values, whereas soil or talus cones have lower values. Rockfall mainly occurs when the downward forces acting on the rockmass changes, and that change may occur due to change in slope face geometry or morphology caused by natural or anthropogenic factors (Ahmad et al. 2013). Ansari et al. (2013) proposed the Rockfall Hazard Rating System for India (RHRSI) as a modified scheme of rockfall rating for the Indian subcontinent. In this study, the Colorado Rockfall Hazard Rating System (CRHRS) and the Rockfall Hazard Rating System for India (RHRSI) were applied and the results were correlated. The results from simulation estimating the run-out distances of the detached blocks were analysed to predict risk.

2 An overview of rockfall investigations

Roads through the mountainous regions are often hit by rockfall hazards that can cause injuries and even fatalities (Ferlisi et al. 2012). During rockfall, the rocks get detached from the cliff face and fall freely under the influence of gravity (Youssef et al. 2014). Rockfall susceptibility could be defined as a quantitative and/or qualitative assessment of the category, volume and spatial distribution of rockfall which may potentially occur in an area (Fell et al. 2008). To assess rockfall hazards, different approaches including heuristic, deterministic and statistical techniques have been applied (Dai and Lee 2002; Guzzetti et al. 2006). Rockfall hazard studies have been carried out for protection of historic sites and monuments (Topal et al. 2007; Wang et al. 2012), effects on forests (Dorren et al. 2006; Perret et al. 2004) and along road cut slopes (Budetta 2004; Ansari et al. 2016; Palma et al. 2012; Alejano et al. 2007).

Rockfall involves detachment of rock fragments and their free fall, subsequent rolling, sliding, bouncing and deposition near the foot of the slopes (Hutchinson 1988; Varnes 1978). Rapp (1960) and Whalley (1984) have classified the rockfall on the basis of size or volume. Rockfall may occur on natural or excavated slopes and the sizes of blocks may range from small pebbles to big boulders of few metres. The degree of rockfall depends upon the type of bedrock, and physical and chemical weathering (Day 1997; Schumm and Chorley 1964). Slope morphometry and potential falling rock characteristics are the most important factors determining whether a rock could fall (Dorren 2003). Frost and thaw process is one of the well-known causative factors of rockfall initiation (Coutard and Francou 1989; Grove 1972; Matsuoka and Sakai 1999; McCarroll et al. 1998). Wieczorek et al. (1995, 2000) concluded that the factors like earthquakes, rain storms, rapid snow melt, freezing and thawing cycles of water in joints and root penetration are very common in facilitating rockfall and rockslides. Anthropogenic factors also contribute in slope instability in hard rocks, although it is relatively minor as compared to the geological and other natural factors (Selby 1982). In general, coupling of topographical, geological, climatological, time and anthropogenic factors controls the occurrence and intensity of rockfall in any area.

The detached rock blocks can follow different modes of motion, viz. freefall, bouncing or rolling depending on the mean slope gradient. During free fall, the movement can be translation of centre of rock or rotation of block around its centre (Azzoni et al. 1995). The velocity of the free falling rock blocks is affected by air friction, but it has less significant effect on the motion (Bozzolo and Pamini 1986). Bouncing of falling blocks occurs as the mean slope gradient decreases, when free falling rock collides with the surface and the blocks, particularly the competent rocks, tend to break just after the first bounce (Bozzolo and Pamini 1986). As the total kinetic energy is directly proportional to the mass of the object, smaller blocks have lower kinetic energy. So, obstacles in the path such as plantation can retain smaller blocks more easily (Dorren 2003). On the basis of some quantitative studies, Jahn (1988) suggested that forest cover in rockfall-prone areas reduces probable rockfall events by three to ten times compared to slope having no forest cover. Zinggeler et al. (1991) determined the importance of trees in stopping falling rocks. They suggested that topography is important and the falling rocks loose energy by colliding with the stems of the trees. Several rockfall studies on varying geological and geomorphological conditions have been conducted in past (Caine 1976; Douglas 1980; Fahey and Lefebure 1988; Matsuoka 1990; Nyberg 1991; Rapp 1960; Sass 1998; Sommerhoff 1977). From the last couple of years, considerable progress has been made in estimating the run-out tracks of rockfall of known magnitude (Dorren 2003). However, the mechanism that determines temporal and spatial occurrence of small rockfall is not well known and still limited particularly for locations where exposure of rockfall hazard is inevitable (Krautblatter and Moser 2009).

The concept of rockfall hazard rating was introduced for the Canadian pacific railways by Brawner and Wyllie (1976). The first state wide exponential rating system for rockfall hazard rating was published by Wyllie (1987) which was later modified by Oregon Department of Transportation (DOT) and classified on the basis of the parameters: slope height, ditch catchment, average vehicle risk, decision site distance, roadway width, geological characteristics controlling rockfall, block size, quantity of rockfall, climatic conditions, role of water and rockfall history. Later the scores of these parameters were interpolated (Pierson et al. 1990; Pierson and Van Vickle 1993). Colorado's RHRS was modified from the original Oregon DOT's RHRS (Andrew 1994). Over time many modifications have been made by incorporating more precise, specific nature from several categories in CDOT's current RHRS (Santi et al. 2009). Colorado RHRS includes factors such as slope height, segment length, slope inclination, slope continuity, geological factors influencing rockfall, block size, climatic conditions rockfall history and the number of accidents caused due to rockfall. CDOT again modified the rating system by including the ditch catchment, decision site distance and average daily traffic. Many RHRS systems have been developed with time by considering different parameters and variable scores: Ohio RHRS, Mussouri's RHRS, Tennessee's RHRS, New York's RHRS, Idaho's RHRS and RHRS for Indian rockmass. The differences in parameters and scores are due to applicability to the local conditions. In the Indian context, the studies on rockfall are limited. More so in the Uttarakhand Himalaya, the rockfall phenomenon is recurrent as much as the landslides, but is understood only in little details. This study was conducted by focusing on problems of rockfall in morpho-dynamic Uttarakhand Himalayas using rockfall hazard rating and simulation technique.

3 Area of investigation

The study region is located in Uttarakhand, India, along National Highway (NH)-58 between Rishikesh and Devprayag, near the village Saknidhar. The coordinates of the village are N 30°5′9.5″ and E 78°32′52.1″. The roadways in this region allow movement of pilgrims to the important Hindu pilgrimage circuit ‘Char Dham’. The high density movement season is late spring to summers, during March to June that leads to heavy vehicular and pedestrian traffic. The road also leads to the Mana Pass that is close to the Indo-Tibetan border. A major part of the route runs along the hill cut slopes and several zones of rockfall and large scale slope failures may be encountered. The rockfall-prone slopes are on the upstream to Saknidhar and are comprised of jointed sandstone of Chakrata formation, having many blocks on slope facet that can cause damage to downstream side locality (Fig. 1). The slopes are very steep and have multiple cracks and fractures traversing through them. Nearly half of the studied slope was made of weathered bedrock. The bedrock is also massively jointed. This 5–6-km zone is marked as rockfall- and landslide-prone region (Figs. 2, 3). Some previous studies were conducted for slope mass rating and kinematic analysis by Siddique et al. (2015) along NH-58 at Rishikesh.

4 Methodology

While landslide hazards have been studied well in the past, the focus on rockfall has not been as much and there exists the need to apply modern techniques to understand rockfall in the mountainous regions. Over the past two decades, several 2D and 3D programs such

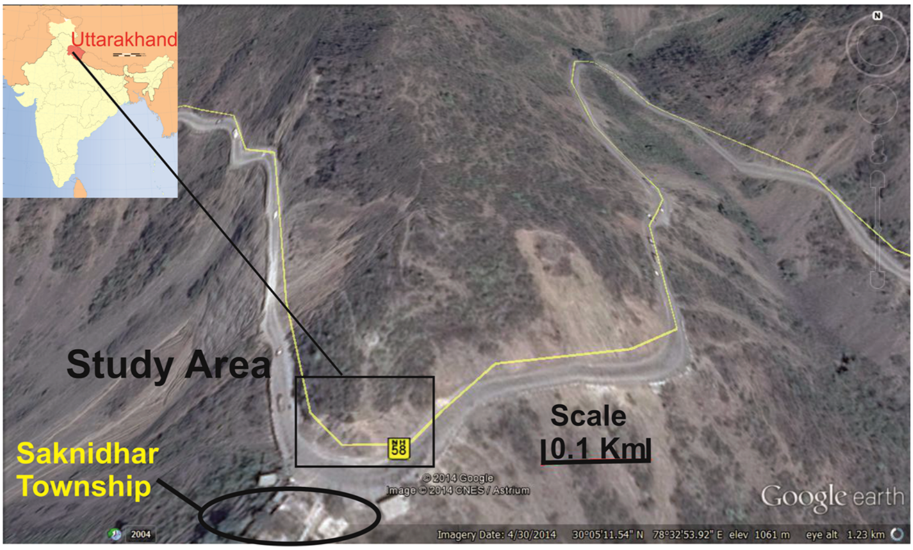

Fig. 1 Satellite imagery of study area just upstream side of Saknidhar township

Fig. 2 An overview of the cliffs, hills and roads in Uttarakhand along NH-58

Fig. 3 Investigated slope along NH-58, near Saknidhar, Uttarakhand

as CRSP by Pfeiffer and Bowen (1989) and Pfeiffer et al. (1991); RocFall by Stevens (1998); Mobyrock by Paronuzzi and Artini (1999); Eboul by Descoeudres and Zimmermann (1987) were developed using different rockfall models (Azzoni et al. 1995; Bozzolo et al. 1988; Hungr and Evans 1988; Spang and Rautenstrauch 1988). RocFall 4.0 has been designed to develop 2D slopes for studying rockfall phenomenon and its alternative attributes. Rockfall trajectories can be simulated using rigorous and lumped model. Rigorous models are given by rolling the rocks deliberately down a given slope, and the rockfall trajectory can be established. The lump model simulates rockfall trajectories in which different types of motion of a rock can be traced throughout its fall. The coefficient of restitution can be estimated from field tests (Evans and Hungr 1993; Robotham et al.

1995), by back analysis (Evans and Hungr 1993; Fornaro et al. 1990; Pfeiffer and Bowen 1989; Kobayashi et al. 1990; Paronuzzi 1989; Descoeudres and Zimmermann 1987; Budetta and Santo 1994) or by theoretical estimation (Kobayashi et al. 1990; Bozzolo and Pamini 1986). The motion of rockmass depends on the slope face, i.e. vertical or nearly vertical and on slope material such as soil, vegetation, talus cones or hard bedrock. Further, optimization of slope by numerical methods provides better understanding of slope stability as well as rockfall pattern.

In this study, detailed field work was performed on NH-58 and based on the field inputs, the two rockfall hazard rating systems were implemented and the results analysed. Due to the differences in the weightage of parameters in each system, different rating scores were achieved (discussed in Sect. 5). During field work, the rock samples were collected and transported to the laboratory. The samples were tested to obtain the required geomechanical characteristics. The parameters were together used to develop efficient numerical models using RocFall 4.0. For simplifying the study, the slope roughness was reduced during simulation. Further, certain parameters like the shape of the blocks, mechanical characteristics of the overall slope and local slope angles at impacts are not uniquely defined and can assume random values, in accordance with Azzoni et al. (1995). Suitably, the statistical analysis was performed by taking the obtained values. The numerical study was extended to optimize various parameters such as slope angle, ditch angle and ditch width.

5 Results and discussions

5.1 Rockfall hazard rating

Rockfall hazard rating schemes provide qualitative assessment of rockfall hazards which can be applied during preliminary stages of investigations. Major factors considered in RHRS are slope, climate, geology, traffic and rockfall frequency which includes several internal parameters and scores are assigned to each. Different rockfall schemes have been developed under different conditions. An attempt was made to classify the road cut slopes using two different rating schemes and the results were co-related. Rockfall Hazard Rating System for Indian Rockmass and modified Colorado Rockfall Hazard Rating System (CRHRS) were employed, and the results bear good co-relation. Such rating systems provide good initial assessment in rockfall studies. They essentially are qualitative methods for prioritizing the rockfall-prone zones in a given area to address with remedial measures.

The RHRSI method is a modification of Pierson et al. (2005) by Ansari et al. (2013) and includes five major classes (28 parameters). The algebraic sum of score for each parameter gives final hazard rating which enables to determine the hazard potential for rockfall to occur. Each parameter comprises a set of sub-parameters based on the vulnerability of slopes, triggering mechanisms and causes, and frequency of rockfall events to happen. In case of each parameter, the rating criteria points increase exponentially from 3 to 81 points. Once the scores are computed, a comparative chart is drawn and the slopes with maximum total scores are estimated to pose maximum risk and addressed on a priority basis. While the major factors in both classifications systems are similar, the weightage are not of the same values. While in case of RHRSI, vegetation contributes 50 points to the hazard score, it is a mere 27 in case of CRHRS. Similarly, the ditch catchment scores are 60 and 24 in case of RHRSI and CRHRS, respectively, leading to large variations in the cumulative score for the slope factor. However, some parameters provide comparable or same scores too, for instance, the annual precipitation provided 94 and 98 points to the total score in RHRSI and CRHRS, respectively. The cumulative scores were obtained as 539 and 466 in RHRSI and CRHRS, respectively. The score in each category and the final computed scores are given in Tables 1 and 2. The slopes have high values as indicated by both the methods, and it is understood that they need attention to prevent any damage due to rockfall. It is also interesting to note that both the systems do not incorporate or recommend the scores for involvement of mitigation conditions or methods.

The results obtained from both the methods were correlated (Fig. 4). Due to variations in slope parameters, small differences exist in the points while climate, geology and traffic scores are almost same due to similar ratings and weightage in both classifications. However, the total score from either scheme is very high indicating that the slope under investigation is under critical situation and needs proper treatment to reduce fatalities and obstruction in traffic along NH-58, Saknidhar.

Table 1 Rockfall hazard rating system for Indian rockmass

Parameters	Category	Points
Slope	Slope height	4
	Average slope angle score	14
	Vegetation	50
	Launching features	9
	Ditch catchment	60
Climate	Annual precipitation	94
	Annual freeze/thaw cycles	3
	Seepage/water	3
	Slope aspect	9
Geology	Sedimentary rock	
	Degree of undercutting	3
	SDI	27
	Degree of inter-bedding	9
	Discontinuities	
	Block size/volume	9
	Block Shape	9
	Number of sets	9
	Persistence/orientation	81
	Aperture	9
	Weathering condition	27
	Friction	27
	Infilling material	27
Traffic	Percentage decision sight distance	5
	Average vehicle risk	4
	Road width including paved shoulder	17
	Number of accidents	27
	Rockfall history/frequency	3
	Total score	539

Table 2 Modified Colorado rockfall hazard rating system

Parameters	Category	Points
Slope	Slope height	3
	Rockfall frequency	8
	Average slope angle score	13
	Launching features	8
	Ditch catchment	24
Climate	Annual precipitation	98
	Annual freeze/thaw cycles	3
	Seepage/water	3
	Slope aspect	27
Geology	Sedimentary rock	
	Degree of undercutting	3
	Jar slake	18
	Degree of inter-bedding	9
	Discontinuities	
	Block size/volume	15
	Number of sets	9
	Persistence, orientation	81
	Aperture	9
	Weathering condition	27
	Friction	27
	Block in material	
	Block size (×3)	9
	Block shape (×3)	9
	Vegetation	27
Total hazard score		430
Traffic	Sight distance	5
	Average vehicle risk	4
	Number of accidents	27
	Total risk score	36
Total score		466

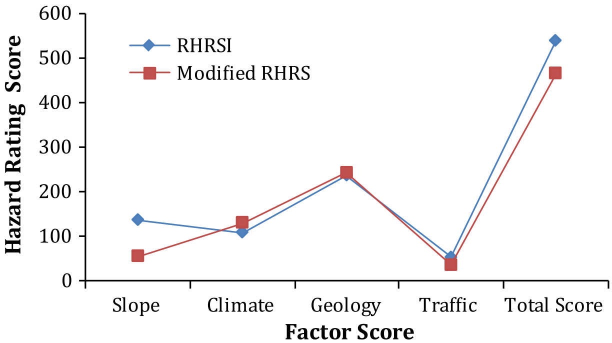

Fig. 4 A comparison between the scores of Rockfall Hazard Rating System for Indian rockmass and modified rockfall hazard rating system

5.2 Numerical simulation

Numerical models using RocFall 4.0 were developed for one of the slopes along which recurrent failures are reported, as well as observed during the fieldwork. The slope geometry was constructed to the best possible approximation to represent the road cut slope. The overall geometry of the slope was created by including the benches on the slope which guide the pattern of rockfall trajectories during simulation (Fig. 5a). Simulations were conducted without considering any barrier in front of the slope as per the field conditions. The slope height, width of ditch and width of road were estimated as 10.02, 2.28 and 7.1 m, respectively (Table 3). The gradient of the cliff was steep—upper part comprised of massively jointed sandstone while the outer lower part of the slope was covered by weathered debris. Due to variable slope angles along the cliff, different types of rockfall motions were observed. The coefficients of normal and tangential restitution for the field lithology were taken as 0.35 and 0.85, respectively. The rock material making the slope was different; thus, the portion of the slope below fresh sandstone was categorized as weathered rockmass, and consequently, the coefficients of normal and tangential restitution were taken as 0.47 and 0.55.

The rockfall trajectories depend on many factors like slope geometry, friction, roughness of slope face, density and restitution of rock. As observed in this case, as the initial slope from the top is steep, thus, the detached rock block experiences free fall. It bounces on all benches after detachment. The middle part of the slope is weathered rock with very less tangential restitution that inhibits bouncing and the rock blocks undergo rolling or sliding motion. On the lower bench, the blocks bounce up to greater heights, some fall into the valley while some fall on the road. Through simulation, the rockfall trajectories were obtained for 10-kg falling blocks through 100 simulations (Fig. 5b).

The results show that the bounce height of rock blocks from the surface of the slope is high at the initial trajectory zone with a value as high as 1.2 m (Fig. 6a). However, the maximum kinetic energy of nearly 380 J was observed at approximately the middle level of the slope (Fig. 6b). This is due to the high velocity of free falling blocks from the head of the cliff. Another peak bounce height was observed at around 8 m and this corresponds to the impact of high kinetic energy of the moving blocks. The translational velocity and the total kinetic energy follows similar pattern on falling rock blocks of 10 kg (Fig. 6c). The input values and the output results of simulation are listed in Table 4.

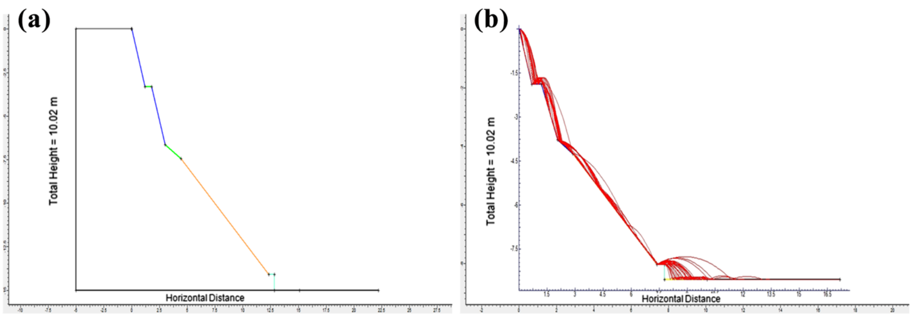

Fig. 5 **a** Geometry of slope under investigation; **b** Rockfall trajectory of 100 blocks of 10 kg falling from top of the slope

Table 3 Field data collected from the area of investigation

Location: Saknidhar, Devprayag	Coordinates: N 30°5′9.5″ E 78°32′52.1″
Slope parameters	
Parameters	Value
Slope direction	N207°/SE
Slope height	10.02 m
Slope angle	40°–70°
Ditch width	2.28 m
Road width	7.1 m

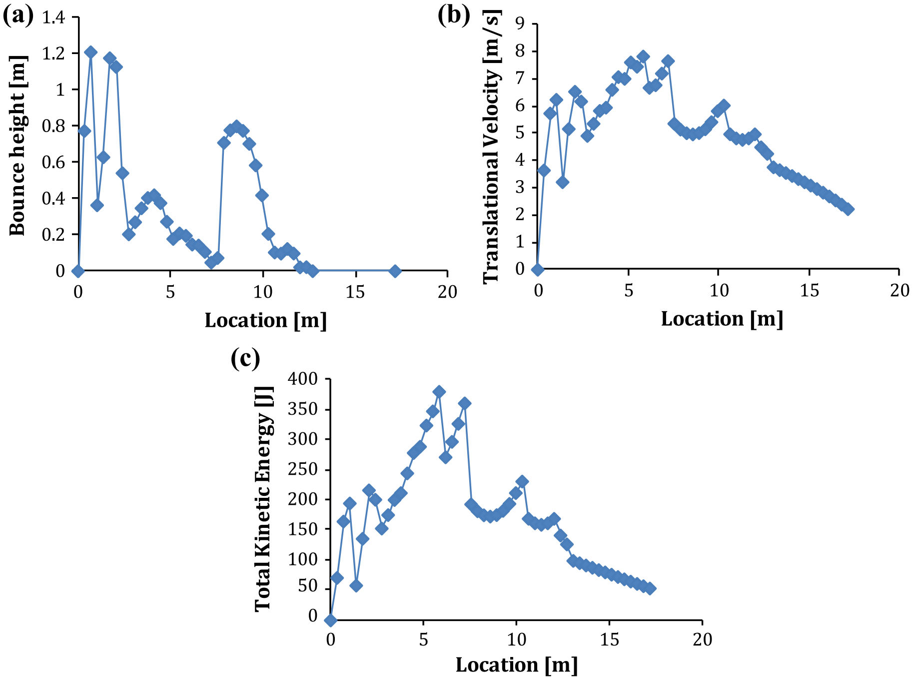

Fig. 6 **a** Plot of bounce height envelope at varying locations; **b** plot of translational velocity envelope at varying locations; **c** plot of total kinetic energy envelope at varying locations for 10-kg blocks

5.3 Optimization

After simulation of the vulnerable cliff, an attempt was made to optimize the slope parameters along with the ditch geometry. It is important to note that while the overall slope angle has a strong influence on the trajectory of the rock block, the ditch geometry (width and slope) controls the final energy of the fallen rock blocks. During optimization studies, the overall slope angle was changed from 40° to 65° with an interval of 5° and the resulting rockfall trajectories were obtained. The angle of the slope when varied from 40°

Table 4 Input and output parameters of simulation

<table>
<tr><td>Sr. No.</td><td colspan="4">Input</td></tr>
<tr><td>1.</td><td colspan="4">Coefficient of restitution</td></tr>
<tr><td></td><td>Colour</td><td>Slope property</td><td>Coefficient of restitution (normal)</td><td>Coefficient of restitution (tangential)</td></tr>
<tr><td></td><td>(blue)</td><td>Bedrock covered by blocks (sandstone)</td><td>0.35</td><td>0.85</td></tr>
<tr><td></td><td>(pink)</td><td>Weathered rock</td><td>0.47</td><td>0.55</td></tr>
<tr><td></td><td>(light blue)</td><td>Hard paving</td><td>0.40</td><td>0.90</td></tr>
<tr><td></td><td>(purple)</td><td>Soil</td><td>0.39</td><td>0.57</td></tr>
<tr><td></td><td>(black)</td><td>Asphalt roadway</td><td>0.40</td><td>0.90</td></tr>
<tr><td></td><td colspan="2">Parameters</td><td colspan="2">Value</td></tr>
<tr><td>2.</td><td colspan="2">Minimum cut off velocity (m/s)</td><td colspan="2">0</td></tr>
<tr><td>3.</td><td colspan="2">Slope roughness</td><td colspan="2">0</td></tr>
<tr><td>4.</td><td colspan="2">Friction angle</td><td colspan="2">30°</td></tr>
<tr><td>5.</td><td colspan="2">Initial velocity (m/s)</td><td colspan="2">0.5 m/s</td></tr>
<tr><td>6.</td><td colspan="2">Number of falling blocks considered</td><td colspan="2">100</td></tr>
<tr><td>7.</td><td colspan="2">Average weight of the blocks</td><td colspan="2">10 kg</td></tr>
<tr><td colspan="5">Output</td></tr>
<tr><td rowspan="2">Sr. No.</td><td colspan="2" rowspan="2">Parameters</td><td colspan="2">Value</td></tr>
<tr><td>Max</td><td>Min</td></tr>
<tr><td>1.</td><td colspan="2">Run out distance (m)</td><td>9.21</td><td>0.25</td></tr>
<tr><td>2.</td><td colspan="2">Bounce height (m)</td><td>1.2</td><td>0.003</td></tr>
<tr><td>3.</td><td colspan="2">Kinetic energy (J)</td><td>379.89</td><td>53.05</td></tr>
<tr><td>4.</td><td colspan="2">Velocity of falling blocks (m/s)</td><td>7.882</td><td>2.222</td></tr>
</table>

to 50° showed a rise in the number of blocks crossing over to the road. Further, a significant change in the ditch width was observed and that led to the change in the energy configurations of the falling rock blocks. The comparison charts for the number of rock blocks crossing the road and the most probable kinetic energy with respect to the slope angle is shown in Fig. 7.

The most optimum ditch angle was found by varying the cliff slope between 40° and 70° by taking an interval of 5° and testing all the variations in ditch angle. 10,000 possible rock trajectories were taken to estimate the risk. It was found that for each given slope angle, as the ditch angle was increased, the number of rocks stopped by the ditch also increased (Fig. 8). The change in number of rocks is minimum for 40° slope while it is maximum for 70° slope. It was found that for a 70° slope, the risk can be reduced by up to 13 % with a ditch angle of 15° while on a flat ditch; the maximum risk will be at an angle of 65°. With an increase in the ditch angle, the vertical component of the falling blocks becomes more effective.

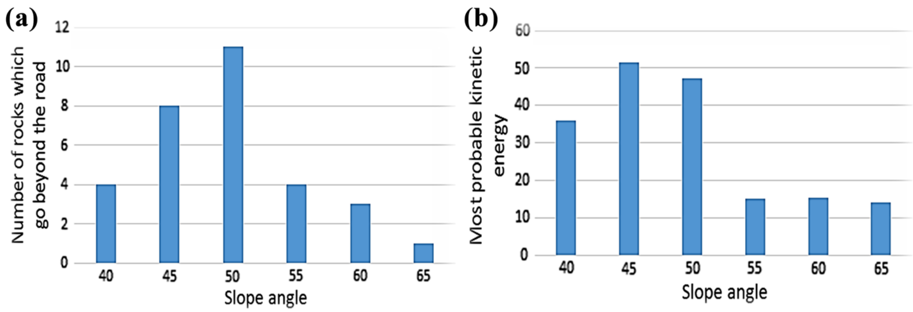

Fig. 7 **a** Number of blocks crossing road and **b** most probable kinetic energy with varying slope angle

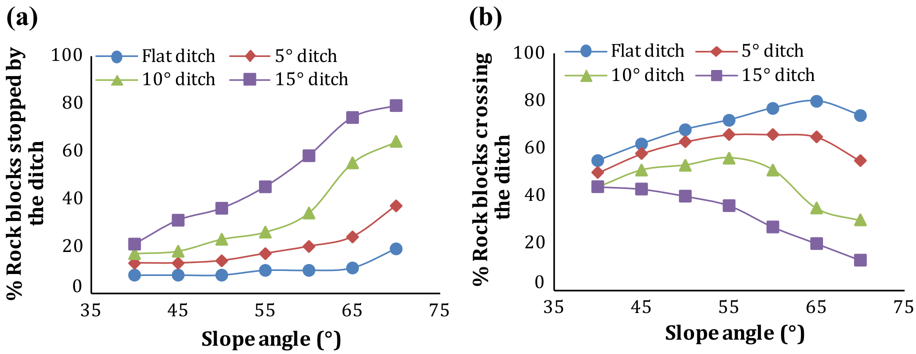

Fig. 8 **a** Percentage rock blocks stopped in the ditch on varying slope angle; **b** percentage rock blocks that move beyond the ditch on varying slope angle

6 Conclusions

The rockfall hazard study along NH-58 near Saknidhar, Uttarakhand reveals that the studied slope is under critical threat of rockfall which needs proper attention and protection. Recurrent rockfall leads to loss of property and affect the safety and the lives of people residing in the downstream locality. According to the rock hazard rating systems, slopes having less than 300 score can be assigned as low priority while those having a total score above 500 need urgent remedial action. In this study that implemented different hazard rating schemes, the slopes were found to have total scores of 539 and 466 and need immediate treatment to reduce fatalities along the highway. Special attention must be given to the hanging blocks and the vulnerable slopes along the highway.

The bounce height, maximum kinetic energy and run-out distance of the falling rock blocks were determined using the simulation studies. The maximum kinetic energy was found to be 379.89 J for only 10-kg rock block. The kinetic energy is directly proportional to mass of the falling blocks. A heavier rock block will have a higher kinetic energy during fall and can have serious consequences when hitting a vehicle, human or an establishment. The maximum run-out distance for the rockfall blocks was calculated as 9.21 m and this may be severe to cause obstructions in the transport. The maximum translational velocity was found to be 7.882 m/s and the barrier capacity was 233.18 J for only 10-kg blocks from the height of 10.02 m. To understand these numbers better, optimization studies were conducted to have more scenarios before any implementation works are done. To minimize the hazard risk, the ditch width can be increased or the angle of ditch inclination can be changed to retain falling blocks more efficiently. Initially when the ditch width was increased, the number of rocks retained in ditch reduced. Additionally, with the increase in ditch width, the slope angle was modified giving more energy to the falling rock block. On increasing the ditch angle in the direction opposite to the rock block motion, a reduction in kinetic energy of the moving block was observed. As high ditch angles are not safe enough for traffic, angles up to 15° only were considered and recommended. From these results, it can clearly be inferred that lesser the angle between the slope profile and the ditch, more the number of rocks retained in the ditch. Thus, appropriate slope profiles which minimize the risk hazard may be obtained through detailed field and laboratory investigation.

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References

Ahmad M, Umrao RK, Ansari MK, Singh R, Singh TN (2013) Assessment of rockfall hazard along the road cut slopes of state highway-72, Maharashtra, India. Geomaterials 3:15–23

Alejano LR, Pons B, Bastante FG, Alonso E, Stockhausen HW (2007) Slope geometry design as a means for controlling rockfalls in quarries. Int J Rock Mech Min Sci 44:903–921

Andrew RD (1994) The Colorado rockfall hazard rating system. Colorado Department of Transportation; Report # CTI-CDOT-2-94

Ansari MK, Ahmad M, Singh R, Singh TN (2013) Rockfall hazard rating system for Indian rock mass. Int J Earth Sci Eng 06(01):18–27

Ansari MK, Ahmad M, Singh TN (2014) Rockfall risk assessment for pilgrims along the circumambulatory pathway, Saptashrungi Gad Temple, Vani, Nashik Maharashtra, India. Geomat Nat Hazard Risk 5(1):81–92

Ansari MK, Ahmad M, Singh R, Singh TN (2016) Rockfall hazard rating system along SH-72: a case study of Poladpur-Mahabaleshwar road (Western India), Mahabaleshwar, India. Geomat Nat Hazards Risk 7(2):649–666

Azzoni A, Barbera GL, Zaninetti A (1995) Analysis and prediction of rockfalls using a mathematical model. Int J Rock Mech Min Sci Geomech Abstr 32(7):709–724

Bozzolo D, Pamini R (1986) Simulation of rock falls down a valley side. Acta Mech 63:113–130

Bozzolo D, Pamini R, Hutter K (1988) Rockfall analysis—a mathematical model and its test with field data. In: 5th international symposium on landslides; Balkema, Rotterdamm, Lausanne, Switzerland

Brawner CO, Wyllie D (1976) Rock slope stability on railway projects. Am Railw Eng Assoc Bull 656:449–474

Budetta P (2004) Assessment of rockfall risk along roads. Nat Hazards Earth Syst Sci 4:71–81

Budetta P, Santo A (1994) Morphostructural evolution and related kinematics of rockfalls in Campania (southern Italy): a case study. Eng Geol 36:197–210

Caine N (1976) The influence of snow and increased snowfall on contemporary geomorphic processes in alpine areas. In: Steinoff HW, Ives JD (eds) Ecological impacts of snowpack augmentation in the San Juan Mountains, Colorado. Final report of the San Juan Ecology Project. prepared for the Division of Atmospheric Water Resources Management, Bureau of Reclamation, U.S. Department of Interior, Denver, Colorado, by Colorado State University, Fort Collins, Colorado. Report No. CSU-FNR-7052-1, Contract No. 14-06-D-7052, pp 21–38

Coutard JP, Francou B (1989) Rock temperature measurements in two alpine environments: implications for frost shattering. Arct Alp Res 21:399–416

Dai FC, Lee CF (2002) Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Geomorphology 42:213–228

Day RW (1997) Case studies of rockfall in soft versus hard rock. Environ Eng Geosci 3(1):133–140

Descoeudres F, Zimmermann T (1987) Three-dimensional dynamic calculation of rockfalls. In: Herget G, Vongpaisal S (eds) Proceedings of the 6th international congress on rock mechanics, Montreal. Balkema, Rotterdam, pp 337–342

Dorren LKA (2003) A review of rockfall mechanics and modelling approaches. Prog Phys Geogr 27(1):69–87

Dorren LKA, Berger F, Putters US (2006) Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes. Nat Hazards Earth Syst Sci 6:145–153

Douglas GR (1980) Magnitude frequency study of rockfall in Co., Antrim, North Ireland. Earth Surf Process Landf 5:123–129

Evans SG, Hungr O (1993) The assessment of rockfall hazard at the base of talus slopes. Can Geotech J 30:620–636

Fahey BD, Lefebure TH (1988) The freeze-thaw weathering regime at a section of the Niagara escarpment on Bruce Peninsula, Canada. Earth Surf Process 13:293–304

Fell R, Corominas J, Bonnard C, Cascini L, Leroi E, Savage WZ (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Eng Geol 102:99–111

Ferlisi S, Cascini L, Corominas J, Matano F (2012) Rockfall risk assessment to persons travelling in vehicles along a road: the case study of the Amalfi coastal road (southern Italy). Nat Hazards 62:691–721

Fornaro M, Peila D, Nebbia M (1990) Block falls on rock slopes application of a numerical simulation program to some real cases. In: Price DG (ed) Proceedings of the sixth international congress IAEG, Amsterdam. Balkema, Rotterdam, pp 2173–2180

Grove JM (1972) The incidence of landslides, avalanches and floods in western Norway during the Little Ice Age. Arct Alp Res 4:131–138

Gupte SS, Singh R, Vishal V, Singh TN (2013) Detail investigation of stability of in-pit dump slope and its capacity optimization. Int J Earth Sci Eng 6(2):146–159

Guzzetti F, Reichenbach P, Ardizzone F, Cardinali M, Galli M (2006) Estimating the quality of landslide susceptibility models. Geomorphology 81:166–184

Hungr O, Evans S (1988) Engineering evaluation of fragmental rockfall hazards. In: 5th international symposium on landslides. Balkema, Rotterdamm, Lausanne, Switzerland

Hutchinson JN (1988) General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Bonnard C (ed) Proceedings of the 5th international symposium on landslides. Balkema, Rotterdam, pp 3–35

Jahn J (1988) Entwaldung und Steinschlag. In: Proceedings of the international congress interpraevent 1988, Bnd 1, Graz, pp 185–198

Kobayashi Y, Harp EL, Kagawa T (1990) Simulation of rockfalls triggered by earthquakes. Rock Mech Rock Eng 23:1–20

Krautblatter M, Moser M (2009) A nonlinear model coupling rockfall and rainfall intensity based \newline on a four year measurement in a high Alpine rock wall (Reintal, German Alps). Nat Hazards Earth Syst Sci 9:1425–1432

Matsuoka N (1990) The rate of bedrock weathering by frost action: field measurements and a predictive model. Earth Surf Process Landf 15:73–90

Matsuoka N, Sakai H (1999) Rockfall activity from an alpine cliff during thawing periods. Geomorphology 28:309–328

McCarroll D, Shakesby RA, Matthews JA (1998) Spatial and temporal patterns of late Holocene rockfall activity on a Norwegian talus slope: a lichenometric and simulation modeling approach. Arct Alp Res 30(1):51–60

Monjezi M, Singh TN (2000) Slope instability in an open cast mine. Coal Int 8:145–147

Nyberg R (1991) Geomorphic processes at snowpatch sites in the Abisko Mountains, northern Sweden. Z Geomorphol 35:321–343

Palma B, Parise M, Reichenbach P, Guzzetti F (2012) Rock-fall hazard assessment along a road in the Sorrento Peninsula, Campania, southern Italy. Nat Hazards 61:187–201

Paronuzzi P (1989) Probabilistic approach for design optimization of rockfall protective barriers. Quarternary J Eng Geol 22:175–183

Paronuzzi P, Artini E (1999) Un nuovo programma in ambiente windows per la modellazione della caduta massi. Geol Tech Ambient 1(99):13–24

Perret S, Dolf F, Kienholz H (2004) Rockfalls into forests: analysis and simulation of rockfall trajectories-considerations with respect to mountainous forests in Switzerland. Landslides 1:123–130

Pfeiffer TJ, Bowen TD (1989) Computer simulation of rockfalls. Bull Assoc Eng Geol 26(1):135–146

Pfeiffer TJ, Higgins JD, Schultz R, Andrew RD (1991) Colorado rockfall simulation program users manual for version 2.1. Colorado Department of Transformation, Denver, p 127

Pierson LA, Van Vickle R (1993) Rockfall hazard rating system. Participant's Manual Federal Highway Administration Publication, SA-93-057

Pierson LA, Davis SA, Van Vickle R (1990) Rockfall hazard rating system–implementation manual, Federal Highway Administration (FHWA), Report FHWA-OR-EG-90–01, FHWA, U.S. Dep. of Transp

Pierson LA, Beckstrand DL, Black BA (2005) Rockfall hazard classification and mitigation system. Report FHWA/MT-05-011/8174, State of Montana Department of Transportation Research Programs

Pradhan SP, Vishal V, Singh TN (2011) Stability of slope in an open cast mine in Jharia coalfield, India—a slope mass rating approach. Min Eng J 12(10):36–40

Pradhan SP, Vishal V, Singh TN, Singh VK (2014) Optimisation of dump slope geometry vis-à-vis flyash utilisation using numerical simulation. Am J Min Metall 2(1):1–7

Pradhan SP, Vishal V, Singh TN (2015) Study of slopes along River Teesta in Darjeeling Himalayan region. In: Lollino G et al (eds) Engineering geology for society and territory. Springer, Berlin, pp 517–520. ISBN: 978-3-319-09299-7

Rapp A (1960) Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. Geogr Ann 42:65–200

Ritchie (1963) Evaluation of rockfall and its control. Highway research record 17

Robotham ME, Wang H, Walton G (1995) Assessment of risk from rockfall from active and abandoned quarry slopes. Trans Inst Min Metall 104(1–4):A25–A33

Santi PM, Russell CP, Higgins JD, Spriet JI (2009) Modification and statistical analysis of the Colorado rockfall hazard rating system. Eng Geol 104:55–65

Sarkar K, Singh TN, Verma AK (2012) A numerical simulation of landslide-prone slope in Himalayan region—a case study. Arabian J Geosci 5:73–81

Sass O (1998) Die Steuerung von Steinschlagmenge durch Mikroklima; Gesteinsfeuchte und Gesteinseigenschaften im westlichen Karwendelgebirge, Munchner Geogr. Abh. Reihe B, 29

Schumm SA, Chorley RJ (1964) The fall of endangering rock. Am J Sci 262:1041–1054

Selby MJ (1982) Controls on the stability and inclinations of hillslopes formed on hard rock. Earth Surf Process Landf 7:449–467

Siddique T, Alam MM, Mondal MEA, Vishal V (2015) Slope mass rating and kinematic analysis of slopes along the national highway-58 near Jonk, Rishikesh, India. J Rock Mech Geotech Eng 7(5):600–606

Singh TN, Gulati A, Dontha L, Bhardwaj V (2008) Evaluating cut slope failure by numerical analysis—a case study. Nat Hazards 47:263–279

Singh TN, Pradhan SP, Vishal V (2013) Stability of slope in a fire prone opencast mine in Jharia coalfield, India. Arabian J Geosci 6:419–427

Sommerhoff G (1977) Zur spat- und postglazialen Morphodynamik im oberen Rißbachtal, Karwendel. Mitt Geogr Ges Munch 62:89–102

Spang RM, Rautenstrauch RW (1988) Empirical and mathematical approaches to rockfall protection and their practical applications. In: Proceedings of 5th international symposium. Landslides, Lausanne

Stevens W (1998) RocFall: a tool for probabilistic analysis, design of remedial measures and prediction of rockfalls. M.A.Sc. Thesis, Department of Civil Engineering, University of Toronto, Onatario, Cannada

Topal T, Akin M, Ozden AU (2007) Assessment of rockfall hazard around Afyon Castle. Environ Geol 53(1):191–200

Trivedi R, Vishal V, Pradhan SP, Singh TN, Jhanwar JC (2012) Slope stability analysis in limestone mines. Int J Earth Sci Eng 5(4):759–766

Varnes DJ (1978) Slope movements: types and processes. In: Schuster RL, Krizek RJ (eds) Landslide analysis and control. Transportation Research Board, Special Report 176, Washington, pp 11–33

Verma AK, Singh TN (2010) Assessment of tunnel instability—a numerical approach. Arabian J Geosci 3(2):181–192

Vishal V, Pradhan SP, Singh TN (2010) Instability analysis of mine slope by finite element method approach. Int J Earth Sci Eng 3(6):11–23

Vishal V, Pradhan SP, Singh TN (2015a) Analysis of stability of slopes in Himalayan terrane along National Highway: 109, India. In: Lollino G et al (eds) Engineering geology for society and territory. Springer, Berlin, pp 511–516. ISBN: 978-3-319-09299-7

Vishal V, Pradhan SP, Singh TN (2015b) An investigation on stability of mine slopes using two dimensional numerical modeling. J Rock Mech Tunn Technol 21(1):49–56

Wang XL, Zhang LQ, Wang SJ, Agliarid F, Frattini P, Crosta GB, Yang ZF (2012) Field investigation and rockfall hazard zonation at the Shjing Mountains Sutra caves cultural heritage (China). Environ Earth Sci 66:1897–1908

Whalley WB (1984) Rockfalls. In: Brundsden D, Prior DB (eds) Slope instability. Wiley, London, pp 217–256

Wieczorek GF, Nishenkod SP, Varnes DJ (1995) Analysis of rockfalls in the Yosemite Valley, California. In: Daemen JJK, Schultz RA (eds) Rock mechanics: proceedings of the 35th US symposium. Balkema, Rotterdam, pp 85–89

Wieczorek GF, Snyder JB, Waitt RB, Morrissey MM, Uhrhammer R, Harp EL, Norris RD, Bursik MI, Finewood LG (2000) The unusual air blast and dense sandy cloud triggered by the July 10, 1996, rock fall at Happy Isles, Yosemite National Park, California. Geol Soc Am Bull 112(1):75–85

Wyllie DC (1987) Rock slope inventory system. In: Proceedings Federal Highway Administration

Youssef AM, Al-kathery M, Pradhan B, Elsahly T (2014) Debris flow impact assessment along the Al-Raith Road, Kingdom of Saudi Arabia, using remote sensing data and field investigations. Geomat Nat Hazards Risk. doi:10.1080/19475705.2014.933130

Zinggeler A, Krummenacher B, Kienholz H (1991) Steinschlagsimulation in Gebirgswäldern; Berichte und Forschungen 3. Geographisches Institut der Universität Freiburg, pp 61–70