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# Analysis of rockfall hazards along NH-15: a case study of Al-Hada road

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## Abstract

The rock instability of granodiorite mountain rock located within a key route for the Mecca city (Al Haram) and Al-Taif (tourist place) was investigated. In this study eight, highly susceptible sites from 22 km road selected for kinematic and rockfall analysis to avoid rockfall consequences. Based on the field investigation, this mountain road is characterized by nearly vertical cut slopes with highly fractured and jointed rocks leading to the occurrences of rock instability. The kinematic results indicated that planar, wedge and toppling failure is the main reason for rock block instability. Furthermore, the rockfall movement trajectory and bounce height were modeled with their corresponding translational velocity and kinetic energy for delineating the dynamics of a falling rock block. The bounce height ranged from approximately 1.3 m to > 8 m. The energies ranged from low (< 30 kJ) to high-intensity zones (> 300 kJ) capable of causing mortality and damaging infrastructure. The present study indicates the study area is at risk of rockfalls and preventive measures are required to minimize the rockfall hazard. Study results can serve as a reference for predicting rockfall areas under similar conditions.

**Keywords:** Steep rock slope, Kinematic analysis, Rockfall, Bounce height, Kinetic energy

## Introduction

Rock slope instability is major geohazards problems for both global and local. Geohazards phenomenon is the downward movement of rock blocks, debris or/and soil in response to gravitational stresses. The failures have classified according to the type of downslope movement either slides, rotational or flow [1]. One of the major causes of rock slope failure is the construction of the transportation system without a proper understanding of geological and geotechnical consideration of natural rock slopes [2–5]. Furthermore, lack of continuous monitoring and investigations of rock slope throughout the year especially before and after the rainy season. In results, these types of geohazards have been experienced throughout history when human or nature has disturbed the delicate balance of natural rock slopes [6–8].

Like all geohazards, the rockfall is a frequent and fastest types of the landslide and common in mountainous or hilly regions, especially steep cliff terrain area. In this phenomenon, a boulder or a small group of independently moving rocks become dislodged and moves downward from the natural or manmade rock slope surfaces

[9]. A typical rockfall occurs in a jointed rock slope with a steep cliff face where joint planes loss strength due to weathering. Exfoliation weathering has been implicated for the formation and subsequent opening of fractures in the rock cliff face leading to hazardous rockfalls [10]. Other factors include seismic shock, rainfall timing, duration, and intensity, freeze–thaw, and anthropogenic activities [5, 11–14]. Rockfall incidents have been associated with large monetary losses and loss of life [15, 16]. Since the heights, inclination, topography, and slope characteristics vary considerably, rockfall behavior becomes quite erratic and difficult to predict. Therefore, it needs to understand the rockfall probability to fulfill the increasing demand for global construction projects.

The rockmass composed of a system of rock blocks and fragments separated by the presence of discontinuities [17]. The rockmass is characterized by shape and dimensions of rock blocks and fragments, by their mutual arrangement within the rockmass, as well as by joint characteristics such as joint wall conditions and possible filling [18]. Therefore, it is necessary to understand the process of slope failure by determination of the geometrical properties of both the rock material and the exposed discontinuities. There are few conventional methods (e.g. kinematic and limit equilibrium method) or computational methods (e.g. finite element and finite difference technique) can significantly be used for instability analysis of discontinuous rock slope. Formerly, the kinematic analysis is most preferable to identify the mode of slope failure (planer, wedge and/or toppling) due to the cheap and simple method [19, 20].

The specific program is commonly in use to investigate the rockfall such as the rocscience product RocFall and Colorado Rocfall Simulation Program (CRSP). Currently, RocFall (rocscience inc.) is the most widely used [15, 16, 21] to identify the assessment of slopes at risk for rockfalls. Therefore, RocFall program was used in this study because of more advantages compared to CRSP [22]. It is a statistical analysis program to assess the rockfall risk. The profile of the slope, the geomechanical properties of the rockmass and mass of detachable lumped rock are input parameters to find out energy, velocity and bounce envelopes for the entire slope. Distributions of energy, velocity and bounce height are also calculated along the slope profile.

Al Hada (NH-15) is an important mountain road link between the holy city Mecca (al-Haram) and Al-Taif city (Hill and tourist site) of western Saudi Arabia. Many commuters used this road with 93 bends on the difference of 1500 elevation in 22 km distance. However, many man-made rock cuts excavated using uncontrolled rock blasting and mechanical equipment to construct a road in steep mountain and highly fractured zone leads to frequent rock failure. Unfortunately, few studies pointed out to this phenomena although many rockfall events have been reported in the local newspaper especially after the rainy season [6, 23]. There is still requires more study to identify rockfall prone area find out after the reconnaissance site visit. Therefore, this research brings attention to the rockfall phenomenon on NH-15 to prepare the preventive and remedial measure to avoid losses of living and/or damage to properties. In this regard, selected the eight potentially hazardous sites along Al-Hada road and analyzed the rockfall hazards using a statistical tool RocFall developed by RocScience [24].

### Location and geology of study area

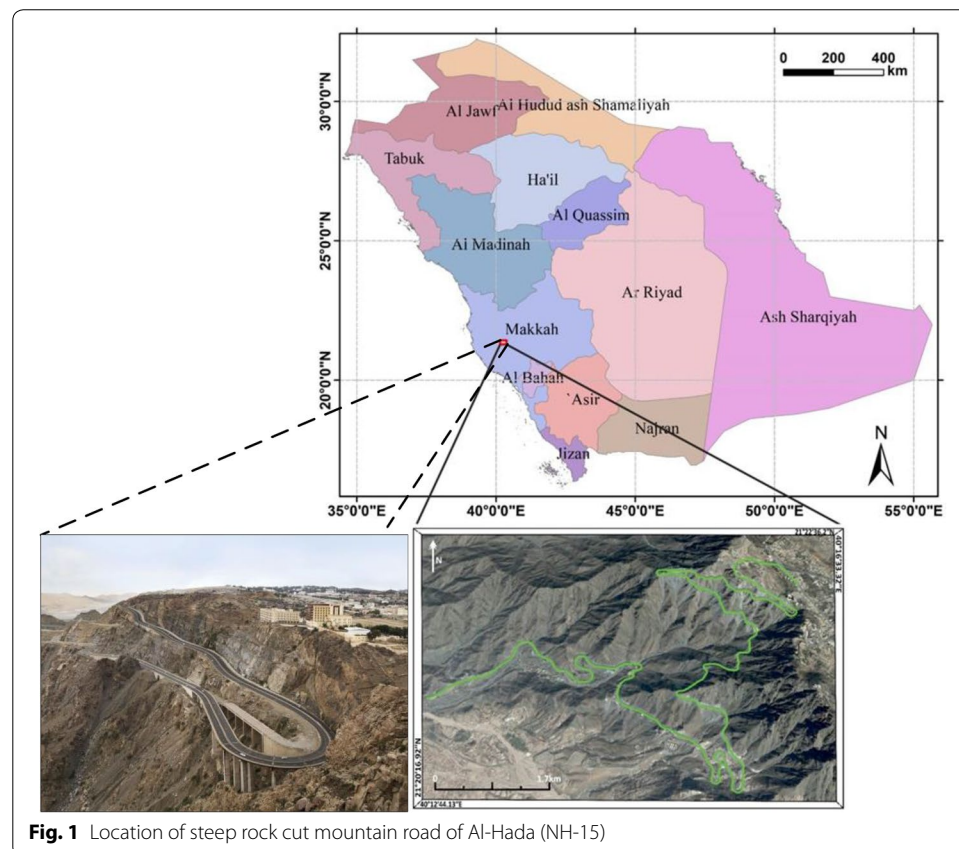
The NH-15 named Al-Hada mountain road is man-made rock cut, which is a part of Red sea scarp mountains, situated at the edge of the Hijaz plateau. The study area located to western Saudi Arabia and an important route between the Holy Mosque Mecca (Al-Haram) and Al-Taif city (Fig. 1). The study area is located between latitude  $21^{\circ}22'17.30''\text{N}$  to  $21^{\circ}20'11''\text{N}$  and longitude  $40^{\circ}16'08.40''\text{E}$  to  $40^{\circ}13'22.40''\text{E}$ . The dip angle of this steep rock cut ranges between  $55^{\circ}$  and  $88^{\circ}$ .

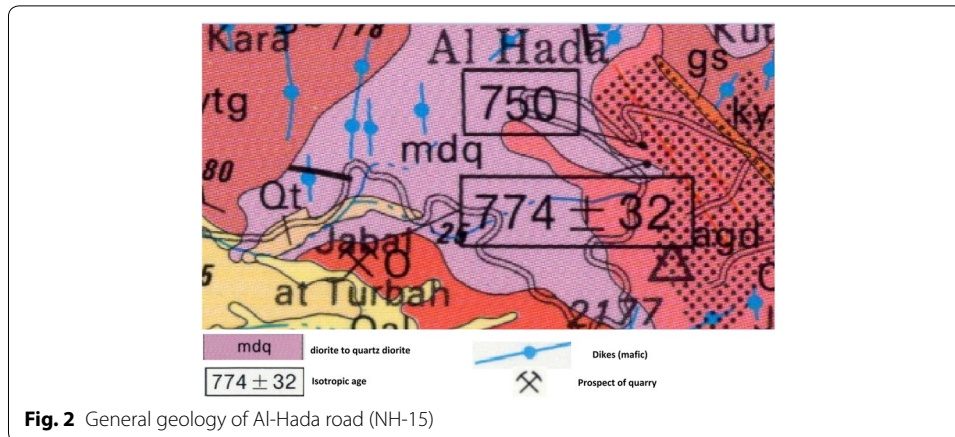
Geologically, the Al-Hada mountain rocks are principally plutonic, consisting of major diorite to quartz diorite and granodiorite [25]. The investigated rock cut is mainly composed of amphibolites and quartz feldspathic Precambrian metamorphic sequence adjacent to the plutonic rocks denoted in the map as shown in Fig. 2. The appearance and strength of the study area rockmass are varying due to the variation of the joints and weathering grade.

### Methodology

#### Reconnaissance field visit

The design of the rock slope cut is an iterative process and there is no fix rule applicable on every site [7]. Thus, every reconnaissance survey is unique. Therefore, a reconnaissance field visit was conducted to observe the rockfall-prone area. It was found that steep rock cut slope constructed within jointed and fracture rockmass resulting prone to rock





instability. However, few areas of man-made cut slope supported by rock bolt and retaining wall within 22 km road. But there is still an adverse consequence of rock failures in the area. Accordingly, priority consideration for the safety of commuters from rock failure events, a study is highly required to avoid any probable adverse consequences. Therefore, total eight vulnerable sites selected for kinematic and rockfall analysis in this study (Fig. 3).

#### Kinematic analysis

The objective of the kinematic analysis is to define a set or sets of discontinuities which will control the stability of rock slope [7]. The orientation of geological discontinuities is the prime factor which majorly influencing rock stability. The orientation data can be collected from the exposed rock cut face with recommended terminology (dip direction/dip angle). Generally, the kinematic (stereographic projection) techniques widely used to represent the three-dimensional field orientation data to be in two dimensions [3, 8, 19, 26]. Then, the potential modes of rock failure (planer, wedge, and/or toppling) can be determined. In this study, the measured field orientation data of eight sites were interpreted by the widely used Rocscience product called DIPs to identify the potential mode of rock failure.

#### Rockfall analysis

A rockfall is a fragment of rock or a block detached by sliding, toppling, or falling, that falls along a vertical or sub-vertical cliff, proceeds downslope by bouncing and flying along trajectories or by rolling on talus or debris slopes [27]. RocFall program (Rocscience products since 1996) used in this study which is widely used in modeling the rockfall simulation problems [12, 15, 28]. The lumped mass analysis method accompanied by the software was used in this study. Table 1 depicted the presence of approximate block size and mass of every marked rockfall site. It has found that the minimum and maximum mass for site 3 and 5 is 11 kg and 4168 kg, respectively. It can be observed from Fig. 3 that site 3 is heavily jointed and weathered rockmass, whereas site 5 have large spacing block size face zone.

Block trajectory, motion, bounce height, energy, velocity, and run-out distance of falling rocks can be determined by this program, which is based on the laws of motion and collision theory [29]. However, the collision of two bodies always results in the transfer





and loss of energy, which depends on fundamental properties like mass, impact velocity, and the environment in which the collision takes place. The losses of energy during fracturing or the post-impact rebounding velocity are generally defined by the coefficient of normal restitution ( $R_n$ ) and coefficient of tangential restitution ( $R_t$ ), which are slope material properties [30–32]. It is the ratio of the relative velocity of after collision to

**Table 1 Block volume and corresponding mass at each rockfall site**

Rockfall site number	Volume (m <sup>3</sup> )	Mass (kg)
1	0.380	951
2	0.167	417
3	0.004	11
4	0.412	1029
5	1.667	4168
6	0.409	1023
7	0.346	866
8	1.548	3871

**Table 2 Used parameters for the rockfall analysis**

Parameters	Barren rock	Asphalt	Ditch
Coefficient of normal restitution ( $R_n$ )	0.4 ± 0.04	0.4	0.3
Coefficient of tangential restitution ( $R_t$ )	0.8 ± 0.04	0.9	0.8
Friction angle (°)	30 ± 2	–	–

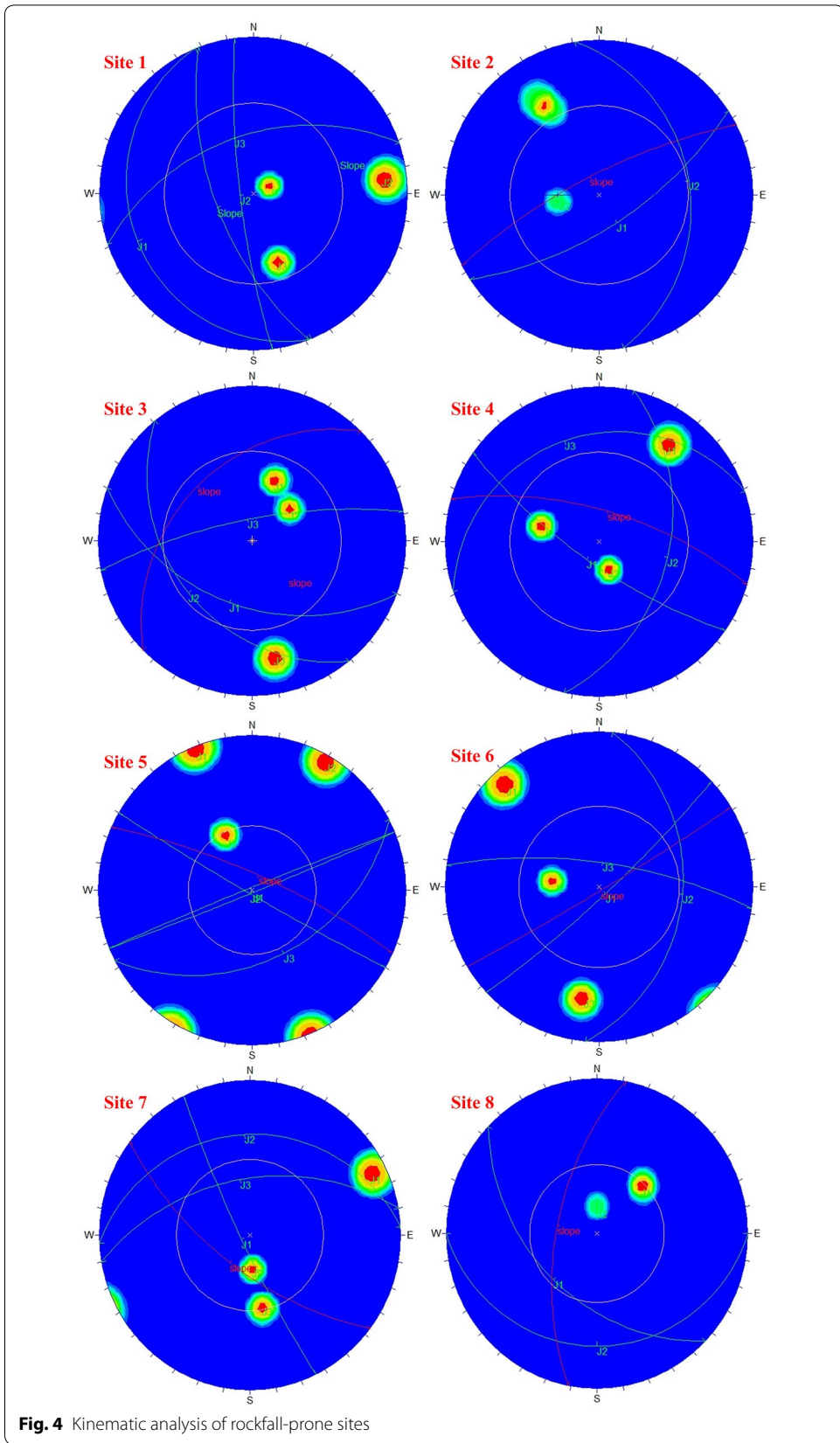
initial before collision [33]. It normally ranges from 0 to 1. The Coefficient of Restitution (COR) will be close to 0 when the rock slope contains thick vegetation with loose debris. This means that falling rock materials striking the rockmass material rebound with zero velocity, resulting to stop the falling rock more quickly. In contrast, this value will close to 1, when rockmass rebound back to falling rock at the same speed [11, 33, 34]. Table 2 shows the three different types of materials used for rockfall analysis. The tilting test used to estimate the friction angle of rock discontinuities in this study [35].

## Results and discussion

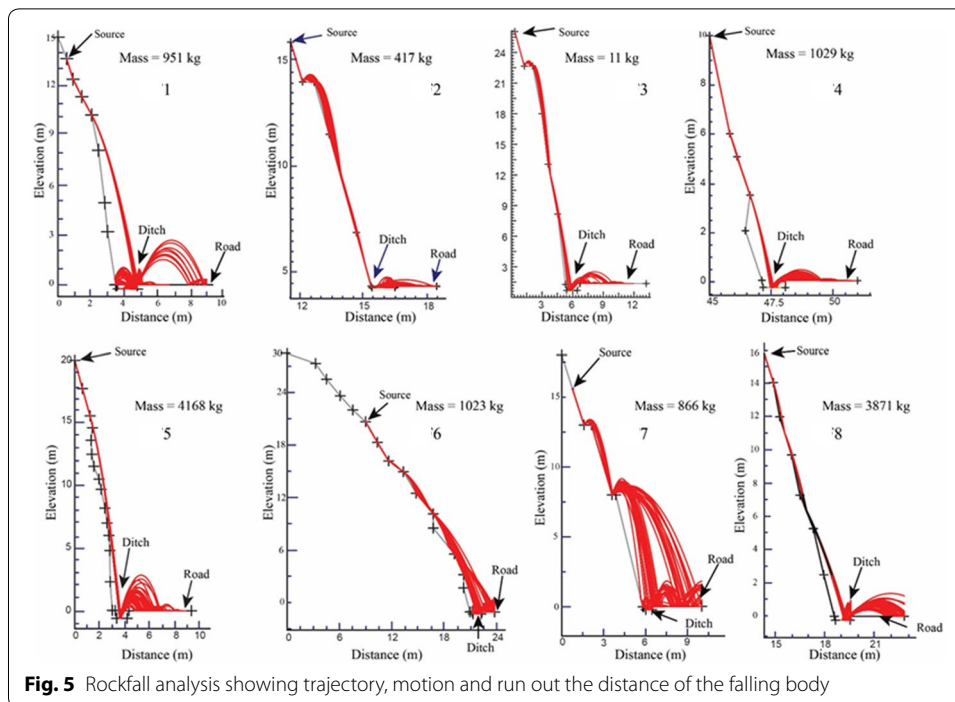
The rocks along the study area on the NH-15 (Al-Hada road) are highly jointed with variable joint spacing, which leads to the formation of variable block sizes. More than hundreds dip/dip direction measured by Brunton compass at each sites. Dominant joint set data were observed by pole density. Majorly, three sets of slightly weathered joints were observed with varying persistence and frequency at eight sites as listed in Table 3. The kinematic studies results for each site demonstrated in Fig. 4. The results showed that the predicted rockfall sites 1, 4, 6, 7 and 8 may be more prone to planar and wedge

**Table 3 Dominant joint set data at eight rockfall sites**

Rockfall site number	Joint set ( $J_1$ ), °	Joint set ( $J_2$ ), °	Joint set ( $J_3$ ), °	Slope, °
1	50/340	81/264	13/245	62/249
2	64/150	72/147	30/81	75/333
3	75/349	35/230	45/201	37/315
4	42/105	75/216	22/340	67/016
5	89/158	87/210	43/154	78/024
6	34/097	72/009	84/137	87/149
7	84/244	51/350	25/355	65/217
8	48/222	45/227	20/180	60/281



**Fig. 4** Kinematic analysis of rockfall-prone sites



failure, whereas sites 2, 3, and 5 are most likely to undergo toppling failure. These failure blocks triggered to rockfall due to steep rock slope face, reaching the road and causing undesirable consequences.

The results of RocFall program of eight sites analyzed and interpreted in terms of trajectory, motion, runout distance, bounce heights with translation velocity and total kinetic energy. The falling trajectories and their endpoints are shown in Fig. 5. Some slopes (i.e., sites 2, 3 and 7) have benches on which detached rock blocks first bounce. Their trajectories are decided by the characteristics of the benches. A great amount of energy is lost after the first impact, causing fragmentation of blocks into smaller pieces on impact. Additional slope characteristics determine the position of the detached blocks: some may stop at first impact, some may travel farther downslope, and some may even travel hundreds of meters to reach the valley floor. The analysis results showed the starting falling rock with X (m) and Y (m), the mass of falling rock (kg), first hit point and run out the distance of falling rock. The slope height is more than 15 m in all study locations except site 4, which allows the blocks to attain higher velocity and even higher momentum. Therefore, rock motion begins with sliding in all cases and is generally observed in the final stages of rockfall as well.

If the slope gradient remains constant in the sliding zone, the blocks stop because of energy loss due to friction. Several case studies have shown that this type of motion seldom occurs in mountainous areas because cliff faces are near vertical. It can be noticed that site 4 has the highest run out distance (51 m), whereas site 5 covered the less distance (5 m). Furthermore, it can be clearly observed that falling rock hits the rock slope and ditches material then bounce and roll a few times along



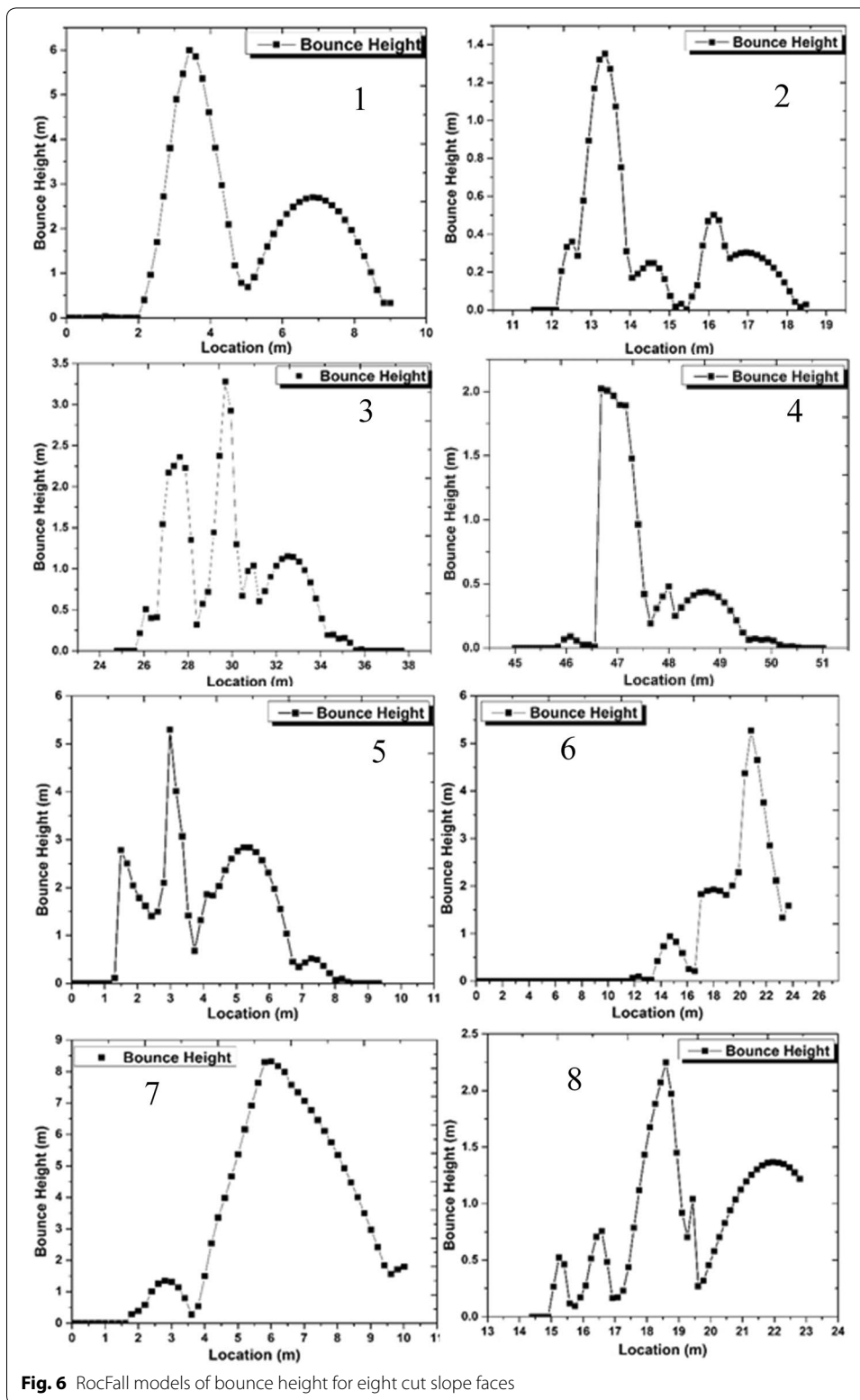
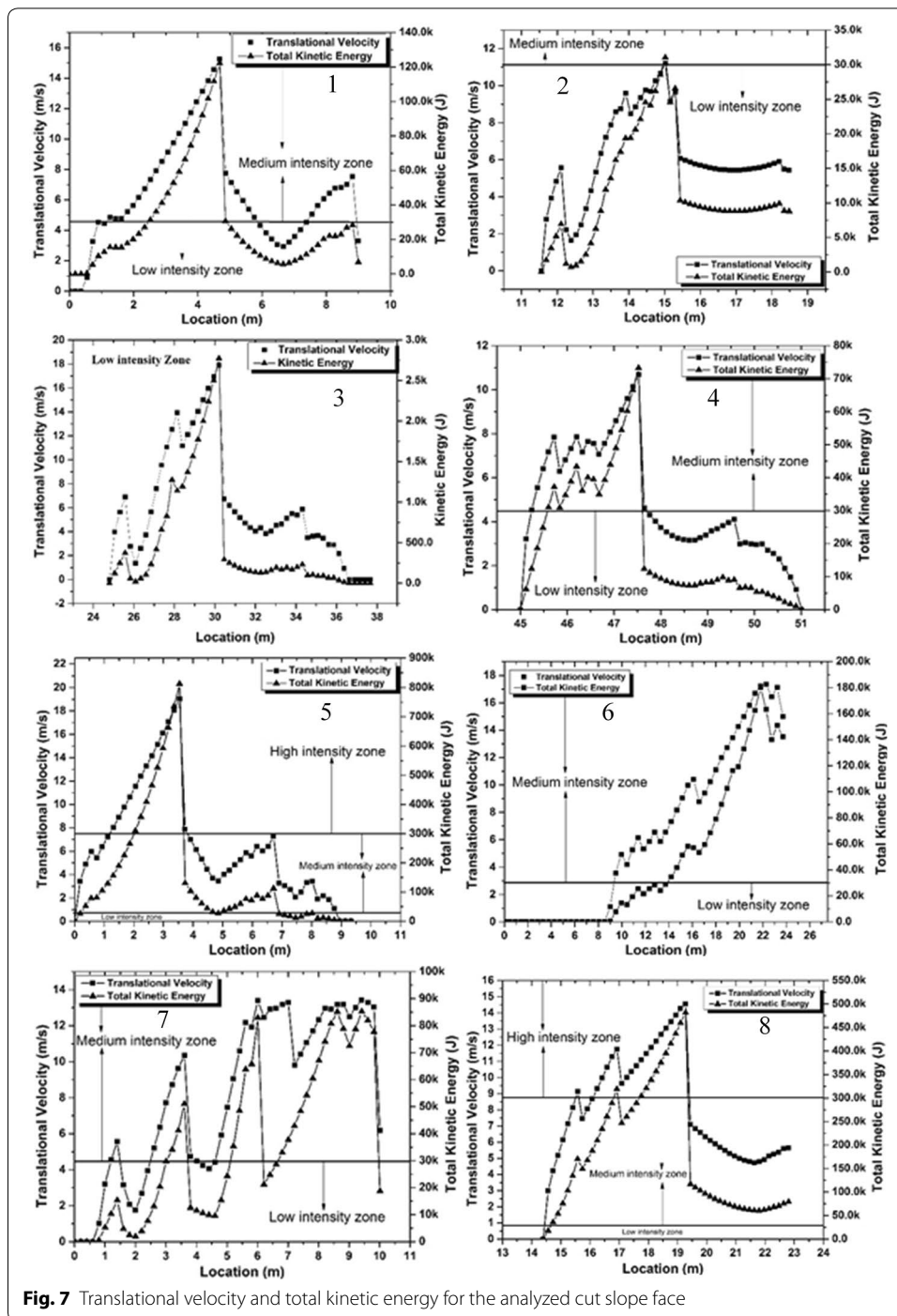


Fig. 6 RocFall models of bounce height for eight cut slope faces

its trajectory before stopping or resting the asphalt. Therefore, it is a high probability to hit the commuters on a mountain road. The estimated maximum bounce



**Fig. 7** Translational velocity and total kinetic energy for the analyzed cut slope face

heights were plotted with run out distance Fig. 6. The results showed that site 2 have attended the 1.4 m bounce height which is minimum as compare to another site. In contrast, site 7 attended the maximum bounce height which is 8.5 m. Researchers have used translational velocity and kinetic energy values obtained from rock-fall analysis to characterize the damage capacity of rockfalls as high (> 300 kJ), medium (30–300 kJ), and low intensity (< 30 kJ). The hazard zoning of rockfall is

**Table 4 Results of RocFall program simulation for eight site of NH-15**

Rockfall station number	X (m)	Y (m)	Mass (kg)	First hit point from X (m)	End point (m)	Max bounce height (m)	Max translation velocity (m/s)	Max total kinetic energy (J)	Max intensity level zone
1	0.5	13	951	5	9	6	15	120	Medium
2	11.5	16	417	12.5	18.5	1.4	11	29.5	Low
3	0	26	11	2	11	3.3	18	2.75	Low
4	45	10	1029	47.5	51	2	11	70	Medium
5	0	20	4168	3.5	9	5.5	21	800	High
6	9	21	1023	21.5	24	5.5	17	180	Medium
7	1.5	15	866	6	10	8.5	13	90	Medium
8	15	16	3871	19.5	23	2.25	15	500	High

not an absolute scale but usually attained using a qualitative estimate of hazard in terms of the intensity of the considered phenomenon (e.g. kinetic energy for rock-falls). Therefore, an attempt to refine rockfall hazard zoning based on the kinetic energy for this study to classify the intensity level zone. The results showed that site 5 and 8 at the high-intensity level zone, which contains the highest kinetic energy of 800 J and 500 J, respectively (Fig. 7). On the other side, site 2 and 3 marked at low-intensity level with the value of 29.5 J and 2.75 J, respectively. The results of RocFall program of each site tabulated in Table 4.

## Conclusion

The NH-15 (Al-Hada) road of western Saudi Arabia is not only a very important route for commuters but also highly susceptible to rockfalls, which might risks to humans and led to large monetary losses. The different mode of rock failures identified from the kinematic analysis which was the sources of rockfall block under steep rock slope face. The eight study sites were highly jointed, with variable block size and jointing pattern giving way to planar, wedge, and toppling mode failure. Rockfall analysis with RocFall was used to model the trajectory, endpoint, velocity, and maximum impact energy. Block detachment was the most common mode of motion from joints plane in the initial stage which followed by bouncing and freefall. The bounce height ranged from 1.3 to >8 m among the eight sites. The damage capacity was classified as high at two sites (site 5, and 8) and low to medium at the other sites. The blocks have the sufficient energy and velocity to travel very far from the slope face and consequently, there is a high probability to create extensive risks to commuters if they fall.

## Authors' contributions

The author read and approved the final manuscript.

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## Competing interests

The author declares that he/she has no competing interest.

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## References

- Sarkar K, Sazid M, Khandelwal M, Singh TN (2009) Stability analysis of soil slope in Luhri area, Himachal Pradesh. *Min Eng J* 10:21–27
- Kainthola A, Singh PK, Wasnik AB et al (2012) Finite element analysis of road cut slopes using Hoek and Brown failure criterion. *Int J Earth Sci Eng* 5:1100–1109
- Singh PK, Kainthola A, Panthee S, Singh TN (2016) Rockfall analysis along transportation corridors in high hill slopes. *Environ Earth Sci* 75:1–11. <https://doi.org/10.1007/s12665-016-5489-5>
- Singh PK, Wasnik AB, Kainthola A et al (2013) The stability of road cut cliff face along SH-121: a case study. *Nat Hazards* 68:497–507. <https://doi.org/10.1007/s11069-013-0627-9>
- Ansari MK, Ahmad M, Singh R, Singh TN (2012) Rockfall assessment near Saptashrungi Gad temple, Nashik, Maharashtra, India. *Int J Disaster Risk Reduct* 2:77–83. <https://doi.org/10.1016/j.ijdrr.2012.09.002>
- Youssef AM, Pradhan B, Maerz NH (2014) Debris flow impact assessment caused by 14 April 2012 rainfall along the Al-Hada Highway, Kingdom of Saudi Arabia using high-resolution satellite imagery. *Arab J Geosci* 7:2591–2601. <https://doi.org/10.1007/s12517-013-0935-0>
- Wyllie DC, Mah C (2004) *Rock slope engineering: fourth edition*. Rock Slope Eng
- Ahmad M, Umrao RK, Ansari MK et al (2013) Assessment of rockfall hazard along the road cut slopes of state Highway-72, Maharashtra, India. *Geomaterials* 3:15–23. <https://doi.org/10.4236/gm.2013.31002>
- Kliche CA (2003) *Rock slope stability*, 2nd ed. Society for Mining, Metallurgy, and Exploration, Colorado
- Collins BD, Stock GM (2016) Rockfall triggering by cyclic thermal stressing of exfoliation fractures. *Nat Geosci* 9:395–400. <https://doi.org/10.1038/ngeo2686>
- Asteriou P, Saroglou H, Tsiambaos G (2012) Geotechnical and kinematic parameters affecting the coefficients of restitution for rock fall analysis. *Int J Rock Mech Min Sci* 54:103–113. <https://doi.org/10.1016/j.ijrmms.2012.05.029>
- Dorren L, Berger F, Jonsson M et al (2007) State of the art in rockfall–forest interactions. *Schweizerische Zeitschrift für Forstwes* 158:128–141. <https://doi.org/10.3188/szf.2007.0128>
- Agliardi F, Crosta GB (2003) High resolution three-dimensional numerical modelling of rockfalls. *Int J Rock Mech Min Sci* 40:455–471. [https://doi.org/10.1016/S1365-1609\(03\)00021-2](https://doi.org/10.1016/S1365-1609(03)00021-2)
- Dorren LKA (2003) A review of rockfall mechanics and modelling approaches. *Prog Phys Geogr*. <https://doi.org/10.1191/0309133303pp359ra>
- Ansari MK, Ahmad M, Singh R, Singh TN (2018) 2D and 3D rockfall hazard analysis and protection measures for Saptashrungi Gad Temple, Vani, Nashik, Maharashtra—a case study. *J Geol Soc India*. <https://doi.org/10.1007/s12594-018-0819-8>
- Mineo S, Pappalardo G, Mangiameli M et al (2018) Rockfall analysis for preliminary hazard assessment of the cliff of taormina Saracen Castle (Sicily). *Sustain*. <https://doi.org/10.3390/su10020417>
- Hudson J, Harrison J, Popescu M (2002) *Engineering rock mechanics: an introduction to the principles*. Appl Mech Rev. 45:67. <https://doi.org/10.1115/1.1451165>
- Hoek E (2007) Rock mass properties. In: *Practical Rock Engineering*
- Yoon W, Jeong U, Kim J (2002) Kinematic analysis for sliding failure of multi-faced rock slopes. *Eng Geol* 67:51–61. [https://doi.org/10.1016/S0013-7952\(02\)00144-8](https://doi.org/10.1016/S0013-7952(02)00144-8)
- 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), Maharashtra, India. *Geomaterials Nat Hazards Risk* 7:649–666. <https://doi.org/10.1080/19475705.2014.1003416>
- Volkwein A, Brügger L, Gees F et al (2018) Repetitive rockfall trajectory testing. *Geosciences*. 56:78. <https://doi.org/10.3390/geosciences8030088>
- E'bayat A, Mariam S (2017) Assessment of rockfall rollout risk along varying slope geometries using the Rockfall and CRSP software
- Youssef AM, Maerz NH (2013) Overview of some geological hazards in the Saudi Arabia. *Environ Earth Sci* 70:3115–3130. <https://doi.org/10.1007/s12665-013-2373-4>
- Rocsciences I (2017) Risk analysis of falling rocks on steep slopes
- Marzouki F (1977) *Petrogenesis of Al-Hada plutonic rocks, Kingdom of Saudi Arabia*. University of Western Ontario, London
- Markland JT (1972) A useful technique for estimating the stability of rock slopes when the rigid wedge slide type of failure is expected. *Imp. Coll. Rock Mech. Res. Imprints* 10
- Varnes DJ (1978) Slope movement types and processes. In: *Special report 176: landslides: analysis and control*
- Aqeel A, Zaman H, Abd El Aal A (2018) Slope stability analysis of a rock cut in a residential area, Madinah, Saudi Arabia: a case study. *Geotech Geol Eng*. <https://doi.org/10.1007/s10706-018-0720-7>
- Keskin İ (2013) Evaluation of rock falls in an urban area: the case of Boğaziçi (Erzincan/Turkey). *Environ Earth Sci* 70:1619–1628. <https://doi.org/10.1007/s12665-013-2247-9>
- Buzzi O, Giacomini A, Spadari M (2012) Laboratory investigation on high values of restitution coefficients. *Rock Mech Rock Eng* 45:35–43. <https://doi.org/10.1007/s00603-011-0183-0>
- Chau KT, Wong RHC, Wu JJ (2002) Coefficient of restitution and rotational motions of rockfall impacts. *Int J Rock Mech Min Sci* 39:69–77. [https://doi.org/10.1016/S1365-1609\(02\)00016-3](https://doi.org/10.1016/S1365-1609(02)00016-3)



32. Ansari MK, Ahmad M, Singh R, Singh TN (2015) Correlation between Schmidt hardness and coefficient of restitution of rocks. *J Afr Earth Sci* 104:1–5. <https://doi.org/10.1016/j.jafrearsci.2015.01.005>
33. Imre B, Rábsamen S, Springman SM (2008) A coefficient of restitution of rock materials. *Comput Geosci* 34:339–350. <https://doi.org/10.1016/j.cageo.2007.04.004>
34. Asteriou P, Saroglou H, Tsiambaos G (2013) Rockfalls : influence of rock hardness on the trajectory of falling rock blocks. In: Proceedings of the 13th international congress, Chania, Sept. 2013. pp 1684–1693
35. Bruce IG, Cruden DM, Eaton TM (1989) Use of a tilting table to determine the basic friction angle of hard rock samples. *Can Geotech J* 26:474–479. <https://doi.org/10.1139/t89-060>

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