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Back Analysis of a Rockfall Event and Remedial Measures along Part of a Mountainous Road, Western Saudi Arabia

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Abstract— ***Construction of the mountain roads in Saudi Arabia is one of the most difficult tasks. Many problems faced before, during and after construction of the roads. Inhomogeneous rock masses, structural settings, steep slopes, sharp cliffs and geomorphological constraints are the obvious obstacles to safe mountainous roads. Al-Hada mountain road is almost 22 km long shows many incidents of rockfalls. Rainfall took place day before and a week before rockfall. This cause a rockfall of few large blocks to take place, hit a car and break a light lamp. The height of the flying rock is about 12 m above the road level. The RocFall computer program utilized to analyze the event regarding modeling and mitigation. The necessary required rock mass parameters fed to the program. Parameters such as rock blocks size, initiation point, geomorphology and end point are the major factors determining the destructive effect of the rockfall event on the road. Remedial measures recommended according to the modeling process.***

Index Terms—***Al-Hada road, rockfalls, rainfalls, rock slopes.***

I. INTRODUCTION

The highland roads is western mountainous regions in Saudi Arabia suffer from frequent slope failures, landslides and rockfalls, especially in wet seasons. The wet seasons starts from October to June. The most difficult terrain is the Al-Hada descent (Fig. 1). Al-Hada descent lies at the upstream western part of the Arabian Shield. The highest elevation of the Al-Hada road reaches up to 2,000 m above sea level. The road alignment run along the sharp cliff edges and slopes of high rising mountains. Before the road ascent, the elevation starts from about 500 m elevation and reaches to more than 2,000 m, forming an elevation difference of about 1,500 m for 22 km road. The descent lies between longitudes 40º 16' 8.4" E and 40º 13' 22.4" E and latitudes 21º 22' 17.3" N and 21º 20' 11" N (Fig. 2). Al-Hada escarpment road starts west of Al-Taif city, runs through Al-Hada descent. The road connects the highlands, where Al-Taif city is located, to the lowlands at Na'man valley, which leads to Makkah Al-Mokarramah city. Along the road, many natural and man-made slope cuts reconstructed at 2010.

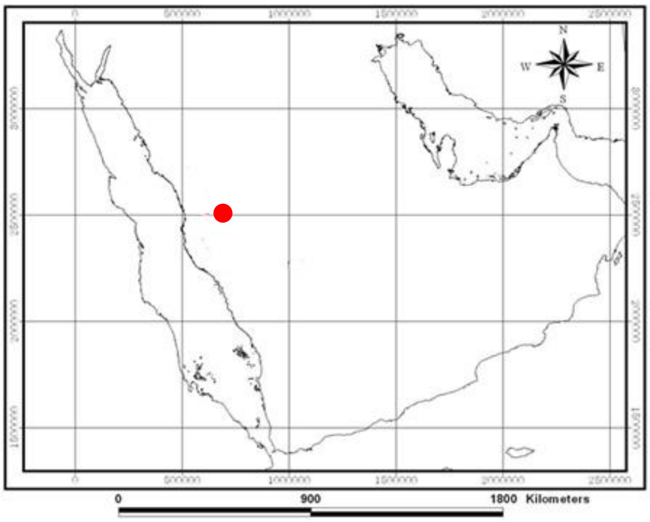

Fig. 1. Location of Al-Hada descent road in western Saudi Arabia

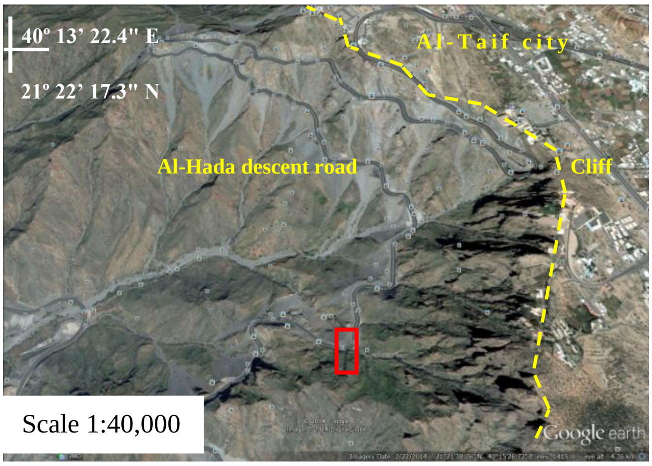

Fig. 2. Location of the study area and Al-Hada descent road

Al-Hada one-carriage road built in 1950s. Some studies done on the rock masses and road slopes [1], [2]. Due to the increase of population, the traffic density and tourism increased in turn, and then it was necessary to widen the road to be a double-carriage road. The operation of widening the road took two years, and finished almost 6 years ago, where the cut materials on the mountain side slopes. Accordingly, the man-made slope faces elevation and dip angles increased, in addition to cutting of more natural slopes.

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This operation worsen the stability condition of the previous rock slopes, and increased the instabilities conditions, where a number of slope failures, rockfalls, and debris flows encountered especially at and after rainfalls; most of them were severe and frequent. This new hazardous condition comes into existence after widening operation of the road, encouraged the Ministry of Transportation to evaluate and restudy the current road condition concerning all kinds of the instabilities due to geohazards along selected dangerous parts of the road [3]. The present study is an outcome of one of the harmful rockfall cases took place along the descent road. More researches on rockfalls incidents at another location along Al-Hada road were published [4], [5], and [6].

II. GEOMORPHOLOGICAL SETTINGS

Al-Hada descent area lies west of Al-Taif city, below the edge of the plateau. It includes two distinct geomorphologic terrains: 1) a dissected upper plateau formed of low hills and mountains, and 2) a severe escarpment cliff extends north south. The study area characterized by rugged and steep terrain with steeply structurally controlled gully, and narrow crested ridges sub catchment area originated as a part of a large catchment area. Al-Hada road intersects a number of catchment areas. The most prominent of these rugged terrains is the northwesterly trending Asir or Tihama escarpment (Fig. 3), a traceable structure for some 1,500 km, extends parallel to the Red Sea coast.

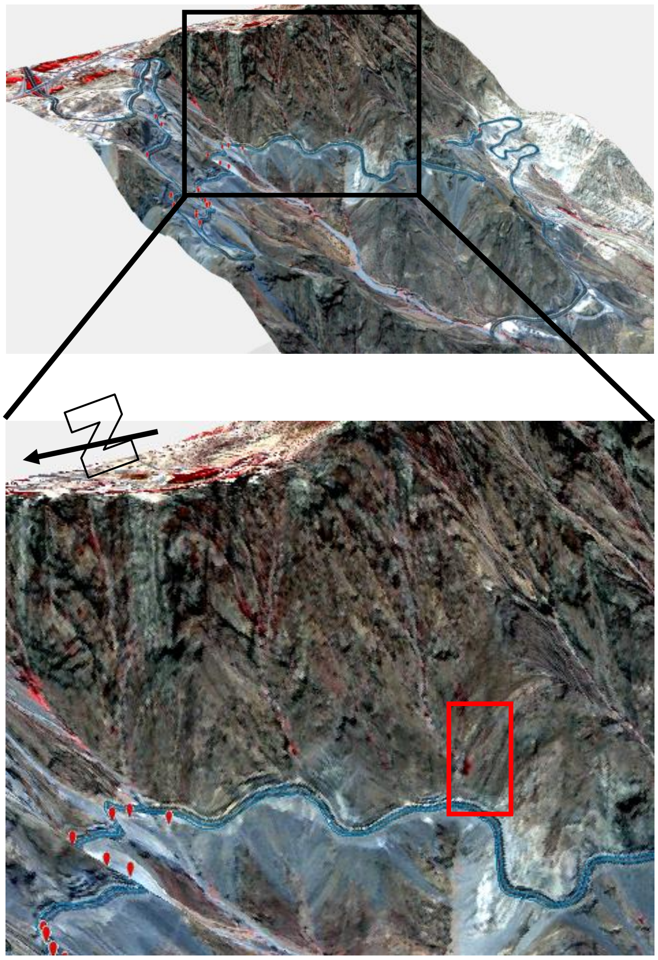

Fig. 3. Geomorphological terrain and enlarged study site

The descent road alignment at the upper part intersected by 14 very steep gullies with a slope gradient of almost 45 to 80 degrees, where it reaches the lowest and highest elevations, respectively [6]. More gullies are located, but has a different degrees of hazard to the road [7]. The gully in concern has an inclination angle overall of 42 degrees. The inclination angle decrease at lower elevation and increase close to 85 degrees close to the mountain top (Fig. 3). The highest and lowest elevation of the gully are 1672 m and 1560 m, making an elevation difference of almost 110 m. The site include gully contain debris accumulations from the fallen rock blocks due to slope failure, rockfalls from both sides of the gully and higher elevation.

III. GEOLOGICAL SETTINGS

Al-Hada region consists of a series of granitic intrusions, emplaced into amphibolite schist and quartz zofeldspathic gneiss basement [1]. These granitic intrusions belong to the younger granite [8]. The rock types projecting along the Al-Hada descent road are mainly a mix of igneous rocks such as granite, granodiorite, quartz diorite, and gabbro.

The diorite covers the central part of Al-Hada area. The granodiorite outcrops at the uppermost part of the escarpment and covers most of Al-Hada plateau. The granites are the youngest intrusions, scattered and covers the southern, southeastern and northern parts of Al-Hada area.

Acidic and basic dykes are intensively transverses the rocks. The igneous rocks intersected by many diorite dikes. The dikes intruded through group of major joint sets striking northwest and dipping southwest. The average dike’s width range between 5 to 10 m, and projected through the regional joint’s attitude, and reach to the mountains escarpment.

The area is intersected by several strike slip faults trending either NW-SE or NE-SW. Those faults appear in the northeastern part of the Al-Hada area and traceable for few 100s of kilometers. The southern faults are generally minor ones, 5-10 m long.

The rocks at the specific study in concern are granite and diorite, massive, coarse grained, highly to be moderately fractured, blocky, intersected by acidic and basic dykes.

IV. ROCK MASSES GEOTECHNICAL PROPERTIES

The rock mass rating (*RMR*) [9] is one of the several system available to characterize any rock mass, has a worldwide acceptance [10]. This acceptance has resulted, in part, from useful design/construction decision tools that are related to an assessment of the *RMR* values of a rock mass, e.g., span width and stand-up time for underground excavations—the initial application of *RMR* values; excavated slope design [11], ground supports requirements [12], ease of excavation [13], and other applications [9].

The rock’s masses geotechnical properties as encountered in the study specific site (Fig. 4) are as follows: blocky, rigid, slightly weathered [14]. The average rock blocks sizes about 0.6 m^3. However, sizes of some fallen hanging rocks are greater, as seen on the road, and inferred from the indent's sizes on the pavement. Such huge rock blocks are dropping from remote higher elevations; reach up to about 110 meters above the road elevation, as estimated from the damage it caused to the light columns along the road centerline (Fig. 5), and hitting a car on the ascending road (Fig. 6).

Fig. 4. Both man-made and natural rock slope at the study site, source of seeder points of rockfalls

The imprints of hit along the road pavement indicates the frequency of the rockfall events at this section as pointed out [15]. An average reading of three rock samples taken to measure the properties of intact rock materials in this site. Laboratory measurements commenced following the ISRM standard methods of testing [16]. The measured rock materials in the laboratory and rock masses in the field shows the diorite rock is characterized by specific gravity = 2.96 gm/cm^3, GSI = 65 to 80 [17], UCS = 167 MPa, while the granite rock properties are specific gravity = 2.67 gm/cm^3, GSI = 55 to 60 [17], UCS = 240 MPa. The heterogeneous geotechnical rock properties of the rock type, along the road given in details in a detailed study [3], where the technical properties of all rock types at this station causing the rockfall problem are only in concern.

The overall rock masses RMR rating calculated as follows: 1) Strength of intact rock material = 12, 2) RQD = 20, 3) Spacing of discontinuities = 16, 4) Condition of discontinuity = 15 and 5) groundwater condition = 13, then the RMR_{89} = 76, classified as good rock before adjustment. According to the attitudes of the prevailing joints at this specific station, the favorability of the joint sets decreased the RMR rating to RMR_{89} = 51 after adjustment, where rock mass class rating is (III), classified as fair rock.

The quality of the joint distribution in the rock mass and the man-made slope cut orientation decreased the rating of the rock mass from good to fair class.

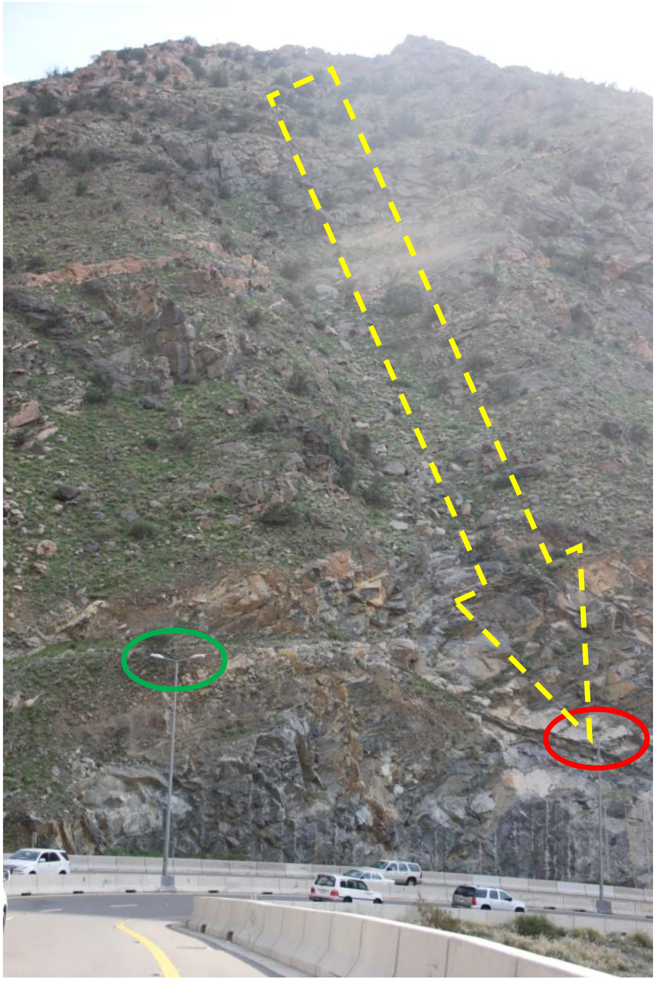

Fig. 5. The broken light lamp due to rockfall (red). The trajectory shown in yellow, while the safe light lamp shown in green

V. STEREOGRAPHIC PROJECTION AND SLOPE INSTABILITY

A 100 joint attitude's readings collected at the study site. The joint's distribution indicates the presence of five joint set's attitudes of a wide scatter of the low concentration joint sets (Fig. 7). The computer program DIPS v.6 [18] used to draw the stereographic projection of the present joint's sets applying the kinematic graphical technique [19] and [20] used to analyze the stability of the site.

This stability analysis shows the presence of 1) planer failure along joint set # 4 where the factor of safety is <1; 2) no wedge failure, and 3) flexural toppling failures along joint sets # 2 where the factor of safety is 0.85 (Fig 8). At dry condition the factor of safety is <1, and naturally; it is <1 in rainy times [3].

The used softwares are RocPlane v.3 [21], Swedge v. 6 [22], and RocTopple v. 1 [23], respectively.

Any falling rock block related to any of the above encountered slope failure modes from high elevation, rest on the natural slope face. After the rainfall event in 30 Nov., 2014 the water percolates in the joints and build pore water pressure, decreased the cohesion between the block and the surrounding blocks. As the driving forces increased and getting greater than the stabilizing forces, then the rock move down the slope in a form of a rockfall, two days after the rain event. Some of the blocks continue its falling path to reach the road, such as the problem in concern. While others stay unbalanced on the slope profile forming a number of loose blocks of variable sizes considered as rockfall seeder points, waiting for suitable conditions (decrease of soil friction angle along the slope, push from another block, earthquake, rainfall) to continue the falling process down towards the road, forming a more rockfall hazards on the road.

Fig. 6. A fallen rock block hit a car in the ascending road

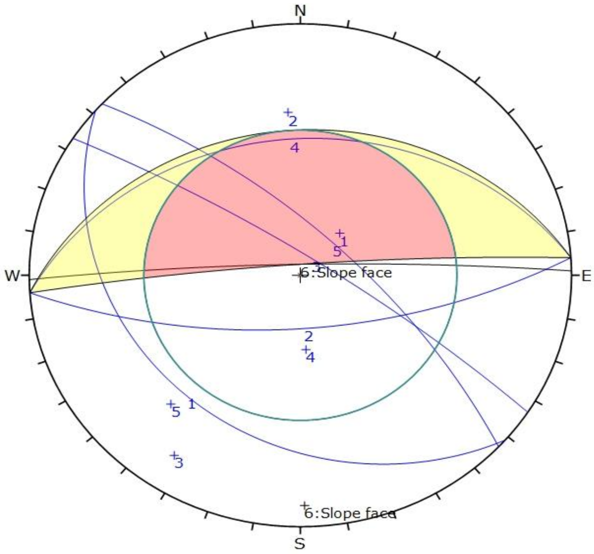

Fig. 7. Rock slope stereonet

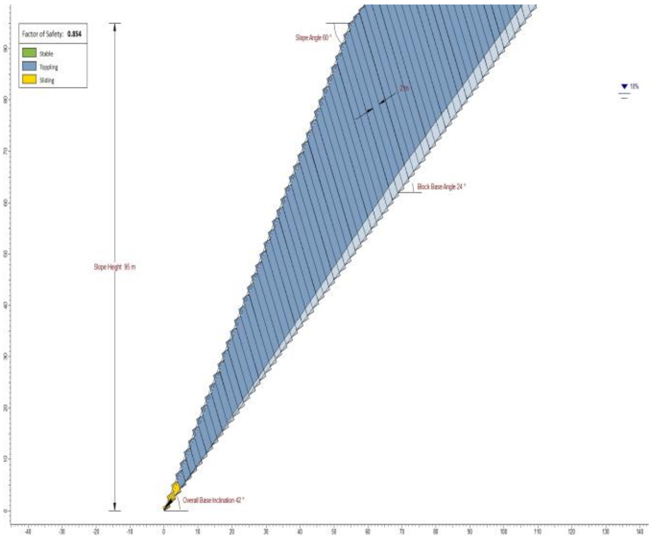

Fig. 8. Toppling failure at the study site

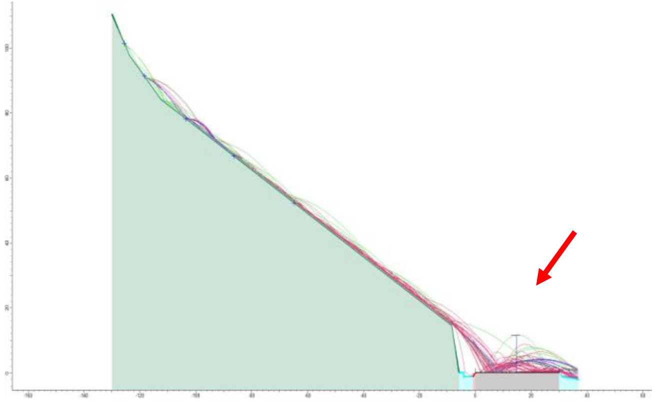

Fig. 9. Rockfall trajectories over the road break the road lamp of 12 m height shown by red arrow

VI. ROCKFALL MODELING AND REMEDIAL MEASURES

Many rockfall incidents encountered along the road and studied separately [3], [24] and [25]. The slope in concern is unsupported against either rock slope instability (Fig. 4) or rockfall (Fig. 5) incidents. Therefore, after the rainfall event a rock block fall from higher elevation and break the lamp of the post at the road centerline (Fig. 5), and hit a car at the middle of the ascending road (Fig. 6). Utilizing the damage on the road and using the trial and error method, back analysis of the seeder points of rock blocks were modeled using the RocFall program v6 [26]. Figure 9 show the way light lamp damaged due to the jump of the rock block as it falls on the asphalt surface and hit the lamp of 12 m above the asphalt surface.

The fallen rock blocks are emerging from five possible point seeders. The location of the seeders s determined during field investigations (Fig. 9). The bounce height could reach up to 16 m either directly rebounding from the rock mass or after rebound from the asphalt surface which could hit all the road and reach behind the far New Jersey (Figs. 10 and 11).

The total, translational and rotational kinetic energies result from the fallen rocks show that the translational kinetic energy is much larger than the rotational kinetic energy (Figs. 12, 13, and 14) which indicated the jumping behavior of the rockfall over the high natural slope angle. Whereas, the translational is much larger than the rotational velocity (Figs. 15 and 16).

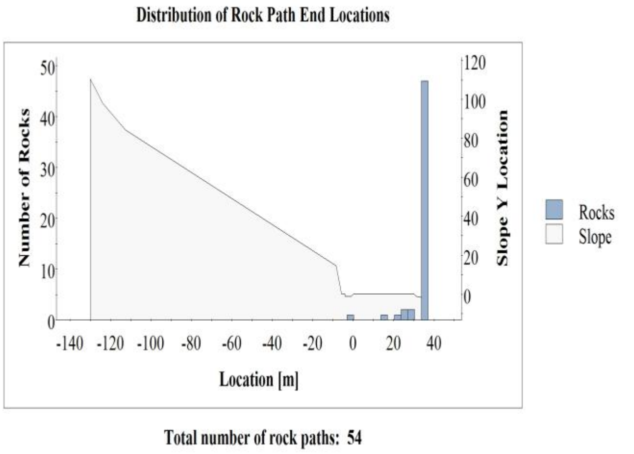

Fig. 10. End point of the fallen rock blocks

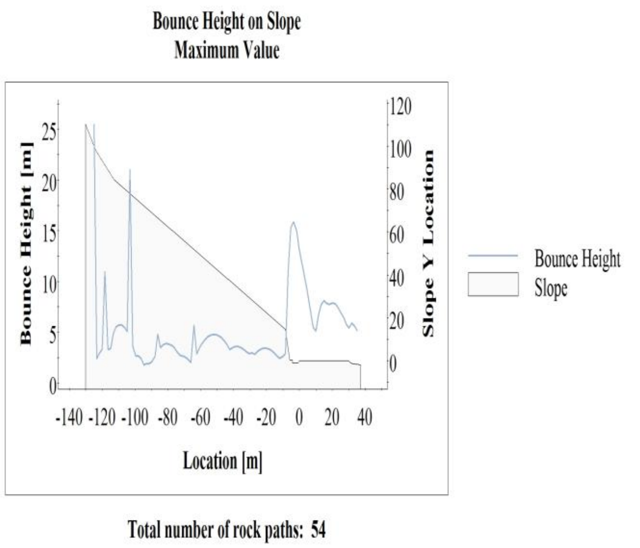

Fig. 11. Bounce height of the rockfalls

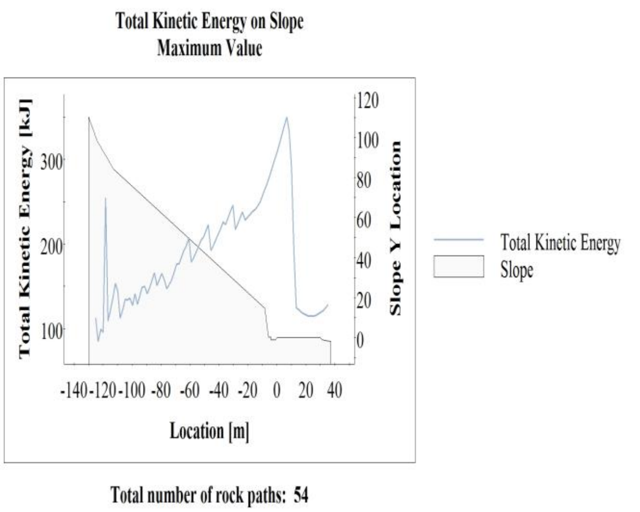

Fig. 12. Total kinetic energy of the rockfall

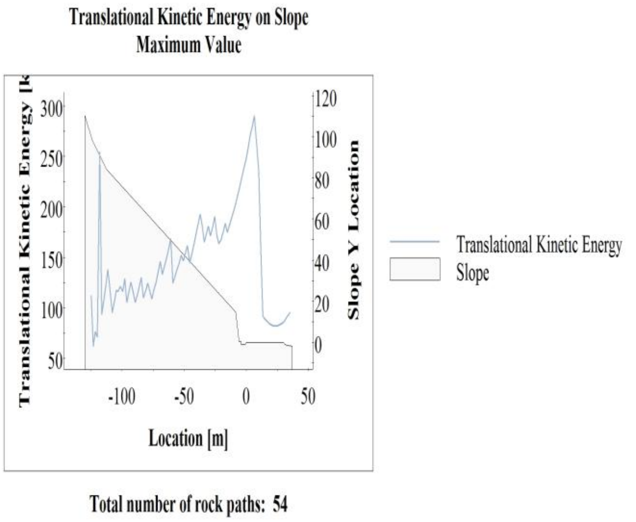

Fig. 13. Translational kinetic energy of the rockfall

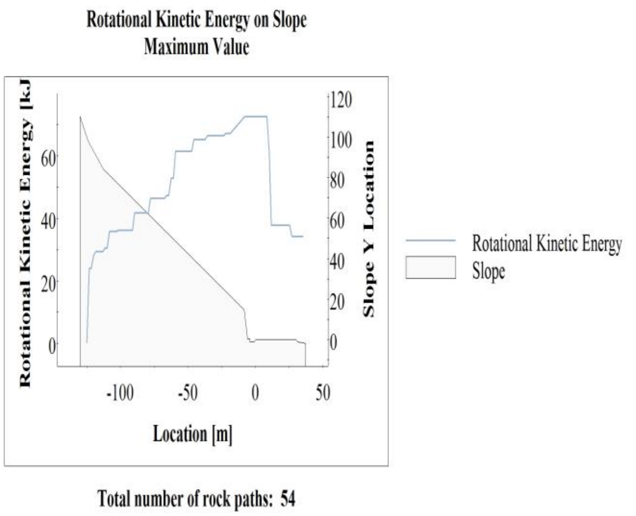

Fig. 14. Rotational kinetic energy of the rockfall

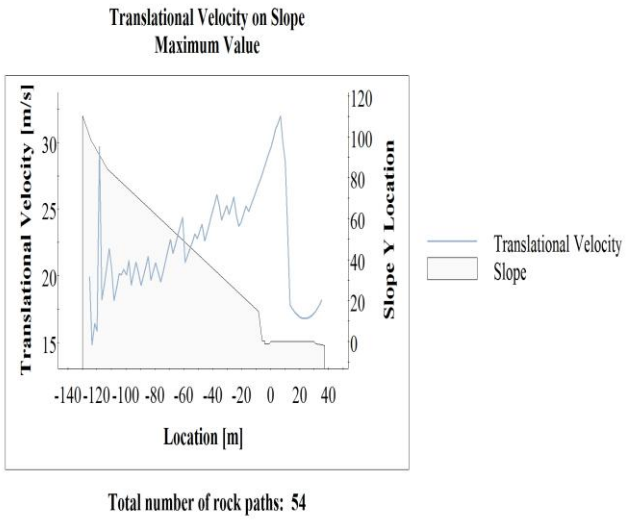

Fig. 15. Translational velocity of the rockfall

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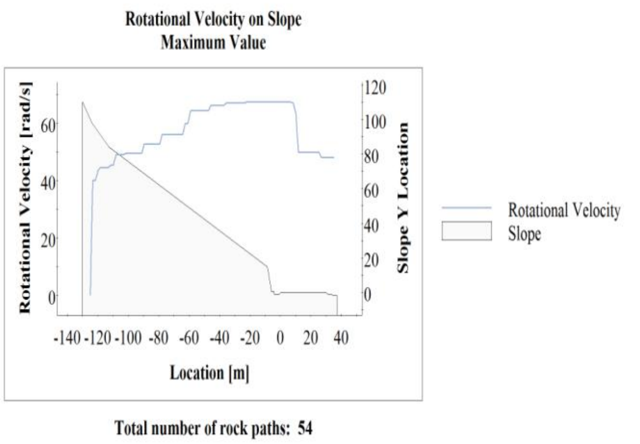

Fig. 16. Rotational velocity of the rockfall

This rockfall incident damage provoke a quick study to control this problem at this site. Modeling process of the show that it is necessary to place two rockfall barriers of strength 8500 kJ of 8 m height and 30 m length along the valley to stop the rocks from falling again at this location (Fig. 17).

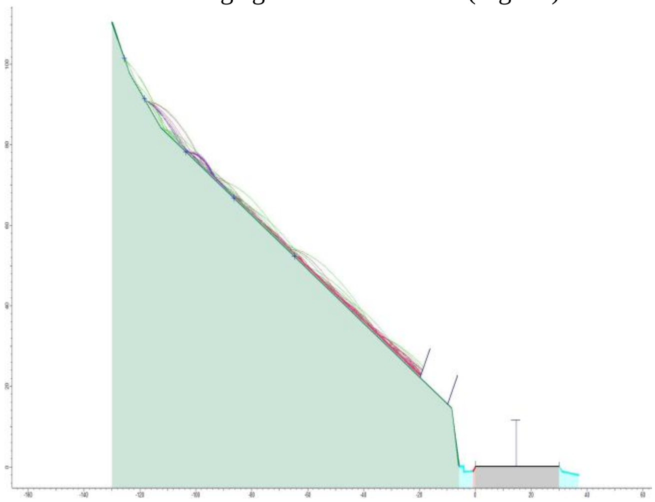

Fig. 17. Locations of rockfall barriers

The placement of the barriers highly reduced the bounce height, kinetic energies and velocities along the gully and the natural rock slope (Figs. 18 to 23).

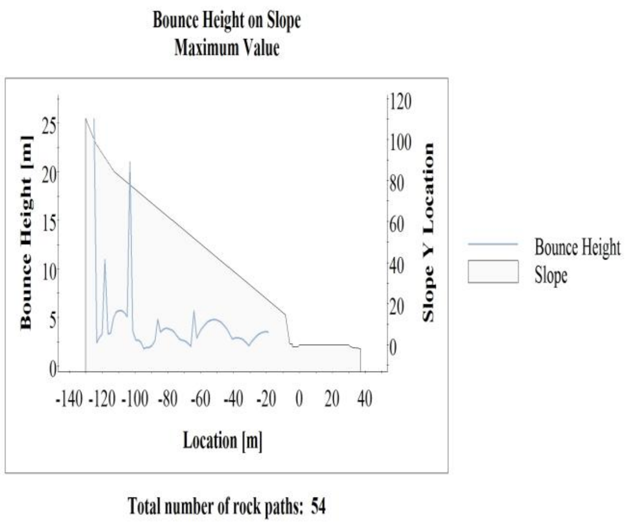

Fig. 18. The bounce heights after installation of rockfall barriers

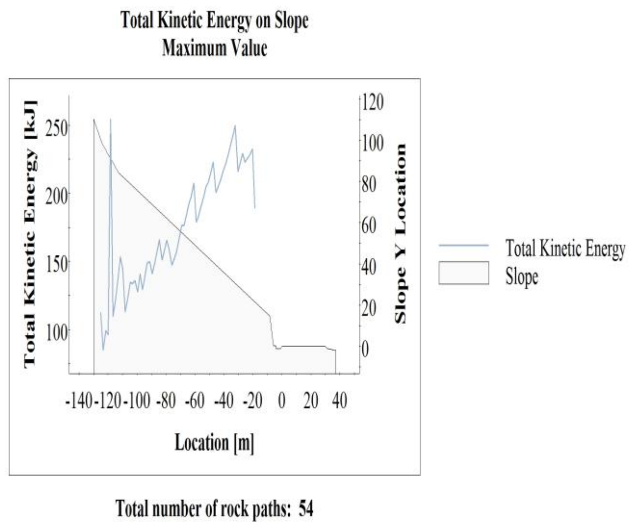

Fig. 19. Total kinetic energy after installation of rockfall barriers

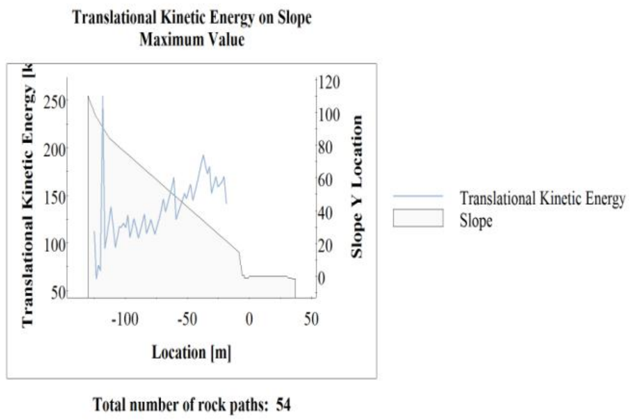

Fig. 20. Translational kinetic energy after installation of rockfall barriers

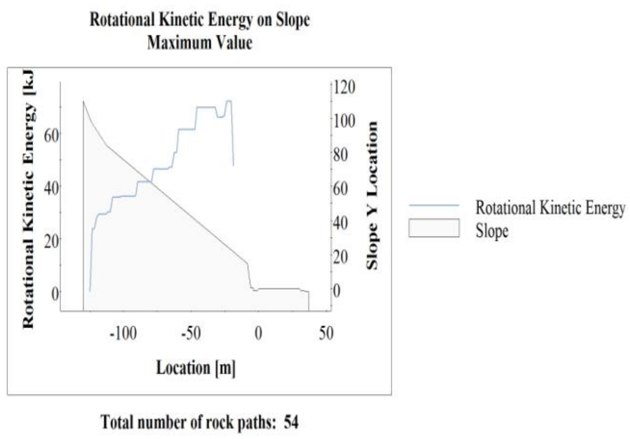

Fig. 21. Rotational kinetic energy after installation of rockfall barriers

VII. CONCLUSION

1. The new man-made slope cut and design without making any support to all slopes is endanger the commuters along the road.

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2. Modeling of rockfall barriers energy, location, height and location is necessary before placement along the slopes.
3. Trial and error method is essential to perform back-analysis method, where the observation of the rockfall imprints events declares the location of eh seeder points along the natural rock slopes.

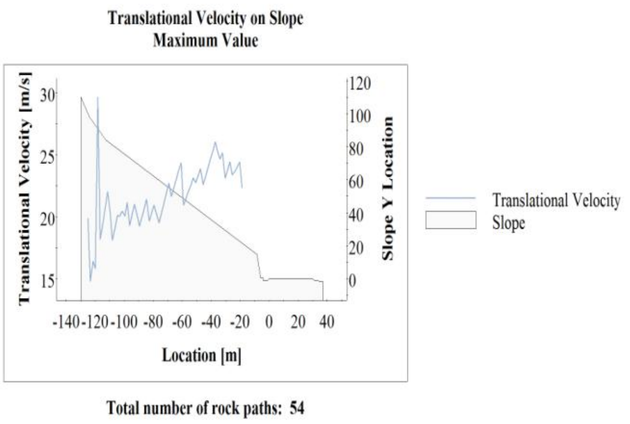

Fig. 22. Translational velocity after installation of rockfall barriers

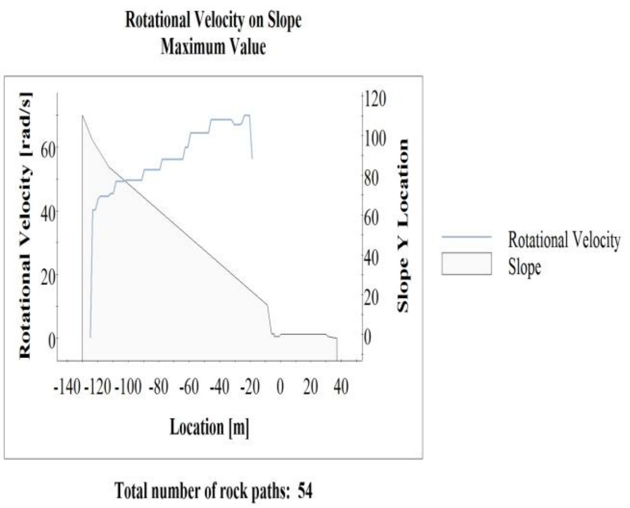

Fig. 23. Rotational kinetic energy after installation of rockfall barriers

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Prof. Bahaaeldin Sadagah, Bahaa has more than 37 years industry and research experience in the rock mechanics, slope stability and site investigation of the mountainous roads. He graduated as a geologist from Cairo University in 1976 and obtained a High Diploma and Master's degree in engineering geology, both from the King Abdulaziz University of Saudi Arabia in 1981. He completed a PhD and DIC in engineering geology at Imperial College, University of London in 1989, and then he joined the King Abdulaziz University where he became a professor of engineering and environmental geology in 2006. He serves as the head of the engineering geology department for four years. He is the principal investigator of six supported scientific projects from KACST and Ministry of Transportation. He published 52 scientific articles, and translated the Internet version books of E. Hoek "Practical rock engineering" 2001 and 2007 editions into Arabic. He is the founder of House of Experience Geotechnology, which involved in many consultancy projects in slope stability, rockfalls and debris flow problems. His research interests are the rock slope stability; rockfall, debris flow, engineering geological maps, and solid and liquid wastes disposal sites. He serves on the Editorial Board of two international journals in fields related to geology.