International Journal of Innovative Science and Modern Engineering (IJISME)
ISSN: 2319-6386, Volume-2 Issue-6, May 2014

Remedial Measures and Modeling of Rockfall Problems along Part of a Mountainous Road, Western Saudi Arabia

Bahaaeldin Sadagah

Abstract*—Construction and support of mountain roads at western Saudi Arabia are always difficult tasks, where the rock masses are inhomogeneous, high-elevation, highly fractured, structurally-controlled steep slopes, sharp cliffs, and occupied by geomorphological restrictions. Al-Hada mountain road of almost 22 km long shows many incidents of rockfalls and slope failures. The rock masses along the descent are medium quality igneous rocks such as: granite, granodiorite, and gabbro. A studied section of a mountain road lies along a man-made and natural sharp slope face cut suffers from rockfall's incidents, mainly in rainy seasons. The 40 m-height rock slope-cut along the road is unsupported. The steep man-made rock slope cut is very close to the road, forming a potential source area for rockfalls. The RocFall computer program was utilized to perform modeling and mitigation on the rock slope. Input parameters such as: block size, seeder point's locations of block's seeder points, slope angle, restitution coefficients, and slope roughness were studied to model the fallen rock blocks characteristics such as: end-point, bounce height, kinetic energies, and translational and rotational velocities along the slope and the road. The remedial measures such as rockfall barriers were proposed to prevent rockfalls from reaching the road.

***Index Terms*—mountainous road, rainfalls, rockfalls, rock slopes.**

I. INTRODUCTION

The Slope failures, landslides and rockfalls frequently occur along mountain roads in rugged terrain of western Saudi Arabia, especially in wet seasons. The most difficult terrain is the Al-Hada descent (Fig. 1). Al-Hada descent lies at the upstream region of the Arabian Shield. The highest elevation of the Al-Hada road reaches almost 2,000 m above sea level. The road alignment lies along the sharp cliff edges and slopes. Before the ascent, the road starts from about 500 m elevation and reaches to more than 2,000 m, with elevation difference is 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 in the lowlands at Na’man valley which leads to Makkah Al-Mokarramah city. Along the road, many natural and many man-made slope cuts and engineering structures are located.

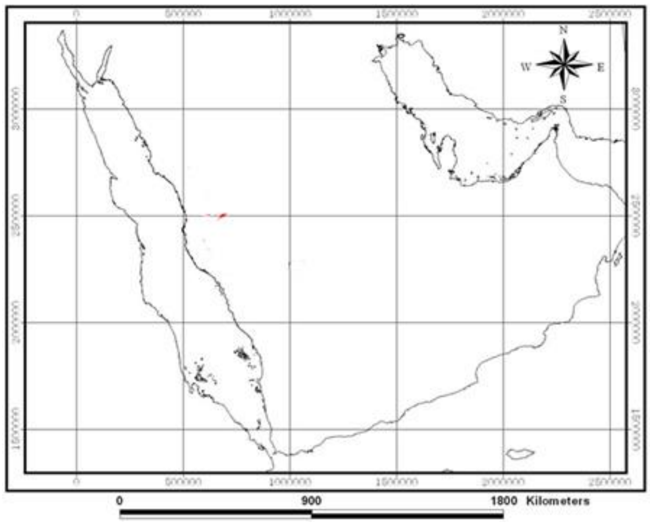


Fig. 1. Location of Al-Hada Descent Road in Western Saudi Arabia.

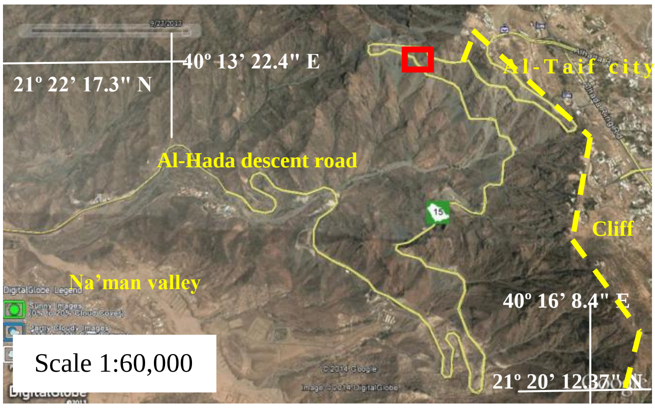


Fig. 2. Location of Al-Hada Descent Area.

Al-Hada one-carriage road was built in 1950s. Some studies were made on the rock masses and road slopes [1], [2]. Due to the increase of population, traffic density, tourism, it was necessary to widen the road to be a double-carriage road in 2010. The operation of widening the road took two years, where the cut materials were on account of the mountain side slopes. Accordingly, the slope faces cuts elevation and dip angles were increased, in addition to cutting more natural slopes. This operation aggravated the stability of rock slopes, and increased the instabilities cases, where a number of slope failures, rockfalls, and debris flows were encountered; most of them were severe and frequent.

Manuscript Received on May 2014
Prof. Bahaaeldin Sadagah, Department of Engineering and Environmental Geology, King Abdulaziz University/ Faculty of Earth Sciences, Jeddah, Saudi Arabia

This new hazardous condition comes into existence after widening operation of the road, encouraged the Ministry of Transportation to restudy the current road condition concerning all kinds of the instabilities along selected dangerous parts of the road [3]. The present study is on one of the harmful rockfall cases took place along the descent road. More researches on rockfall's incidents at another location along Al-Hada road were published [4].

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. The study area is characterized by rugged and steep terrain with steeply structurally-controlled incised drainages, and narrow crested ridges originated from a number of catchment areas. The most prominent of these features 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.

The descent road alignment at the upper part is 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. All gullies contain debris accumulations formed of a mix of excessive quantities of mud, old levees and huge fallen rock blocks. A number of these debris material's contents are partially consolidated, and flows due to rainfall [5].

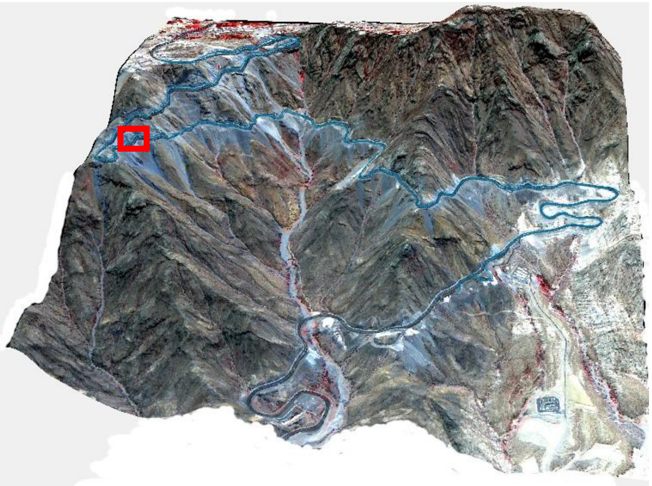


Fig. 3. Geomorphological Terrain of Al-Hada Descent Area.

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 [6]. 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 and southeastern and northern parts of Al-Hada area.

Acidic and basic dykes are intensively transverses the rocks. The igneous rocks are intersected by a large number of 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.

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

The granitic rocks at the specific study location in concern are massive, coarse grained, highly to be moderately fractured, sometimes blocky.

III. GEOTECHNICAL PROPERTIES OF THE ROCK MASS

The efforts and costs of engineering projects involving rocks depend heavily on the geotechnical characteristics of the rock mass. The rock mass rating (*RMR*) [7] is one of the several methods, or systems, available to characterize any rock mass, enjoy a world-wide acceptance [8]. 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 openings—the initial application of *RMR* values; excavated slope design [9], ground supports requirements [10], ease of excavation [11], and other applications [7].

The rock's masses geotechnical properties as measured in the study specific site (Fig. 4) are as follows: rigid, slightly to be moderately weathered [12]. The rock blocks sizes about 052 m^3. However, sizes of some fallen hanging rocks are almost 1.25 m^3, 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 more than 40 meters above the road elevation.

The entire rock of the specific site in concern is quartz diorite for this 100 m. Some slopes are safe while others show slope instability and rockfall problems [13]. An average reading of three rock samples was taken to measure the intact rock materials in this specific studied site. Laboratory measurements were commenced following the ISRM standard methods of testing explained by Brown (1981). The quartz diorite rock material is characterized by specific gravity = 2.96 gm/cm^3, *GSI* = 65 to 80 (Hoek, 2007), *UCS* = 167 MPa. Other field properties of the granitic rock masses are marked at the data sheet of the *RMR* classification system, as well known by the *RMR* system to evaluate the rock mass (Bieniawski, 1989). All these parameter's properties were measured on a fresh rock material, both in the field and laboratory. It should be noted that the heterogeneous geotechnical rock properties of the rock type, along the road are given in details by Sadagah (2013), where the technical properties of the granite at this station causing the rockfall problem is only in concern.

The *RMR* rating was calculated as follows: 1) Strength of intact rock material = 12, 2) *RQD* = 20, 3) Spacing of discontinuities = 15, 4) Condition of discontinuity = 15 and 5) groundwater condition = 15, then the RMR_{89} = 77, 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} = 52 after adjustment, where rock mass class rating is (II), classified as fair rock.

Fig. 4 Man-Made and Natural Rock Slope Along the Road.

IV. STEREOGRAPHIC PROJECTION AND SLOPE INSTABILITY

A 100 joint attitude's readings were collected at the specific study site. The joint's distribution indicates the presence of seven joint set's attitudes of a wide scatter of the low concentration joint sets (Fig. 5). The computer program *DIPS* v.6 [14] was used to draw the stereographic projection of the prevailing joint's sets, where the kinematic graphical technique [15] was used to analyze the stability of the site.

This stability analysis shows the presence of 1) planer failure along joint set # 5; 2) wedge along the lines of intersections of discontinuity sets 4&5, 4&6, 5&6, 3&5, and 1&5, where factors of safety are 0.35, 0.28, 0.42, 2.17, and 1.54 respectively, and 3) flexural toppling failures along joint sets # 1 (20%) and # 2 (30%). At dry condition the factor of safety is <1, and naturally; it is <1 in rainy times [3].

Any falling rock block related to any of the above encountered slope failure modes from high elevation, rest on the natural/man made slope face. Some of the blocks continue falling path to reach the road, 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 prone rockfall hazard on the road. More failure incidents are liable to occur as the slope face attitude changes along the road alignment and along the upper natural slope topography.

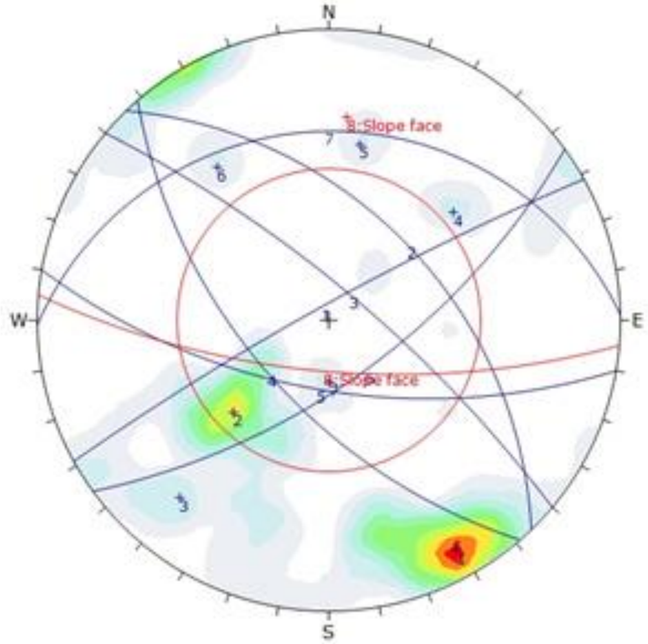


Fig. 5 Rock Slope Instability Conditions at the Stereonet.

V. ROCKFALL MODELING AND REMEDIAL MEASURES

The road of 22 km long shows many incidents of rockfalls. Each incident has its individual special features of occurrence. As the geology, geomorphology and rock mass characteristics of the area change in the road, each rockfall incident have its own field conditions are explained separately [16]-[17]. Regarding this concern, the location of the current specific unsupported rock slope face under study (Fig. 4) suffers from incidents of powerful rockfalls, as a result of failure of large rock blocks; reach to descend road and the middle road New Jersey barrier.

The slope face is currently not supported against rock slope instability or rockfall's hazards. Rockfalls caused the incident in concern of breaking Jerseys. This case led to the necessity of modeling the unstable slope face. In addition of using *DIPS* program, the program *RocFall* was also utilized as a statistical analysis program designed to assist with a rockfall risk assessment along this slope. Velocity and bounce-height envelopes for the entire slope are determined by the program as is the location of rock endpoints [18].

The source area is located at almost 20 to 60 m above the road elevation, just below the upper road twist, which is formed of natural rock slopes formed of jointed rocks and detached fallen rock blocks resting on the slopes, in addition to fallen rock's blocks due to slope failures at the man-made rock slope faces. As nobody witnessed the rockfall path(s) during the moments of rock's blocks dropping from above elevations, the contour line's distribution can give suggested probable paths of the fallen blocks (Fig. 6).

The location of the rock slope face (Fig. 6) suffers from some incidents of rockfalls caused by all modes of failure, as the measured joint's attitudes are prevailing in this location. The slope face shows that the support by small nails on the man-made slope cut is installed in random order and not effective for rockfalls.

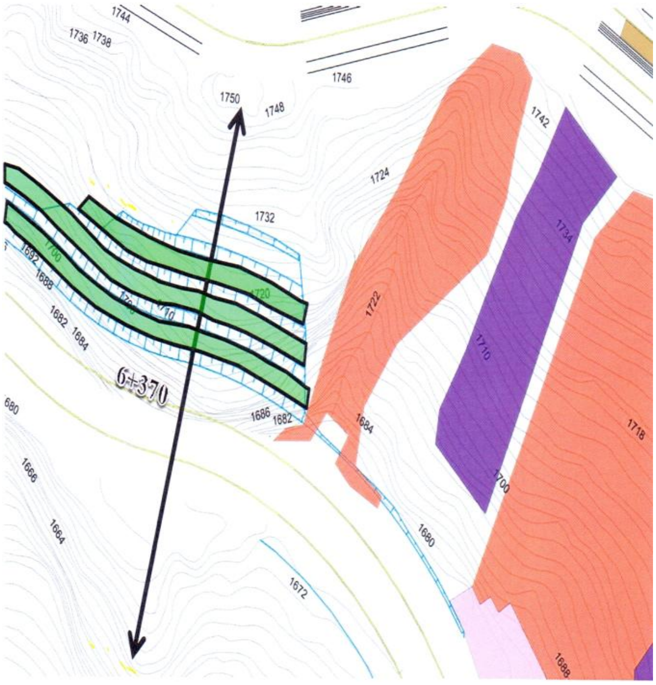
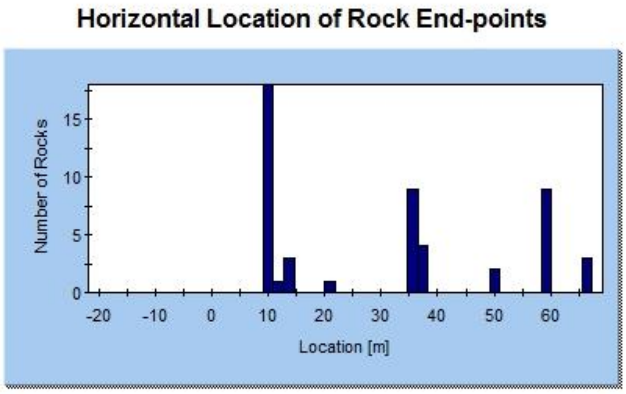


Fig. 6 The morphology of the site and location of the rockfalls catch meshes.

Modeling of the rockfall's trajectories (Fig. 7), indicates that a number of rockfalls reach the closest New Jerseys and partially break them, and may reach the lower-level road 100's m below, following trajectory's paths (Fig. 7). These loose rock blocks are falling down from 4 possible point seeders, according to field investigation and the slope geometry, from higher elevations at 14 m, 25 m, 36 m, and 36 m of about 15 m, 30 m, 39 m, and 48 m behind the slope face cut foot, respectively (Fig. 7). The horizontal location of end-points is 10 m (Fig. 8) for 17 rock blocks. The bounce height is 3.5 m (Fig. 9). The given envelope's values of the total kinetic energy are >500 kJ (Fig. 10), indicates that rock blocks would reach the road with a tremendous harmful force, hence the wire meshes must be installed.



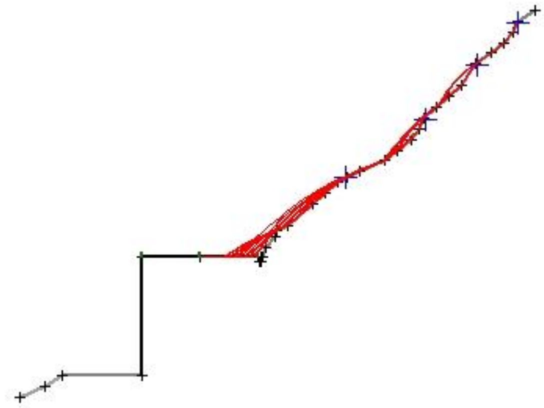


Fig. 7 Modeling of the Current Rockfalls Trajectories. Seeder Points are Shown as + Shape Along the Profile.

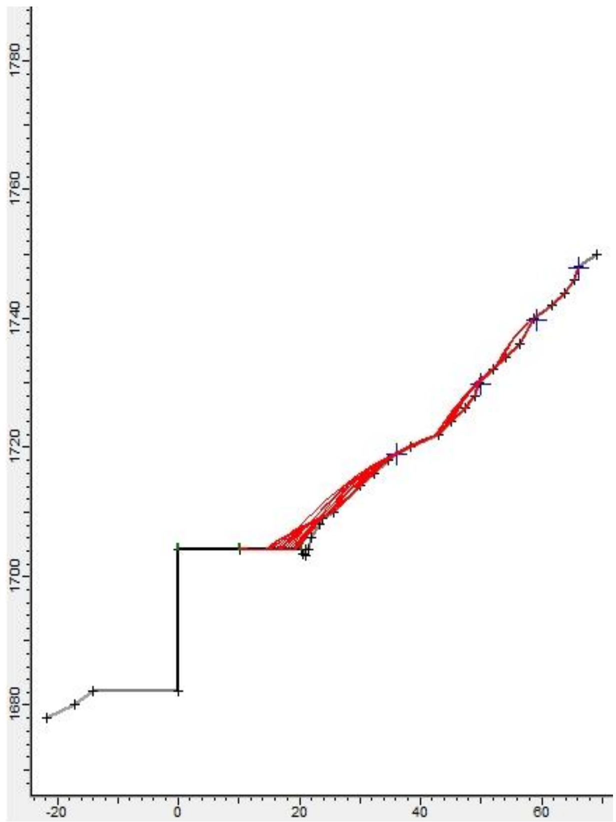


Fig. 8 The end-points of the falling rock blocks.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

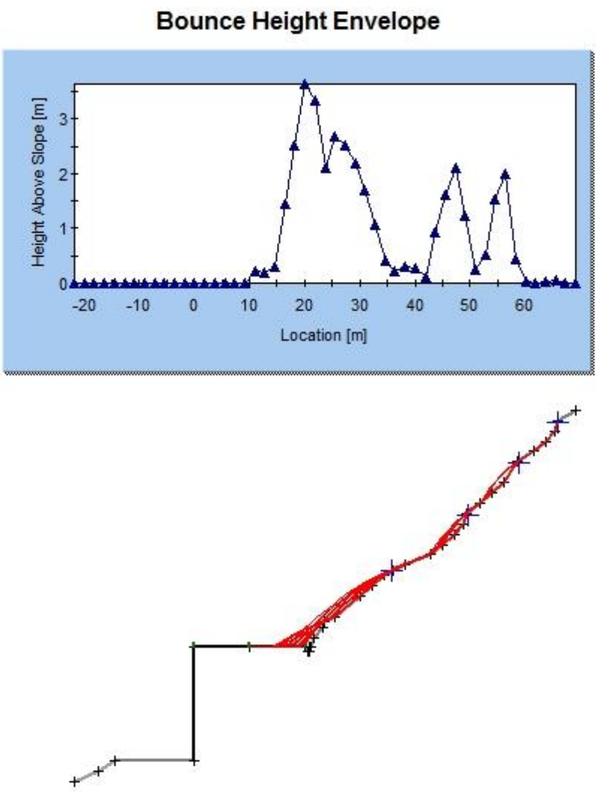


Fig. 9 The bounce height and number of the falling rock blocks.

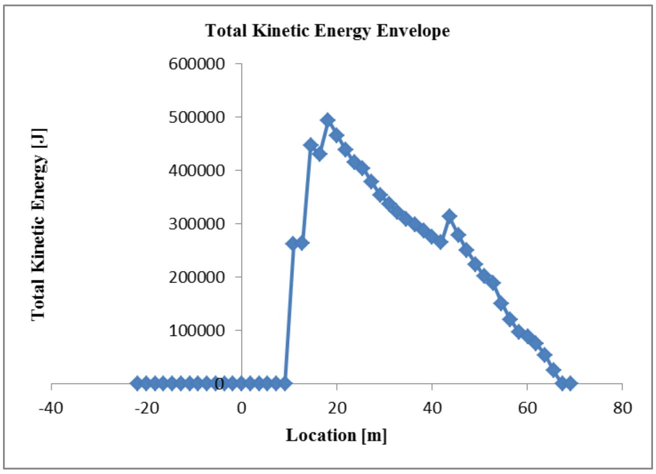


Fig. 10 The total kinetic energy envelope along the rock slope face.

The computer program was used to model and indicate the necessity to install 3 vertical seven m-high and one inclined seven m-high rockfall barriers along and above the slope benches (Fig. 11). This will decrease the end-point distance (Fig. 12), bounce height (Fig. 13), and rockfall total kinetic energy to 50 kJ above the slope face and to zero at the slope face (Fig. 14) before reaching the slope face.

The catch barriers should be 100 m long and a capacity of >500 kJ (Fig. 6) higher than the modeled kinetic energy of the falling rock blocks in order to stop the rockfalls from reaching the road.

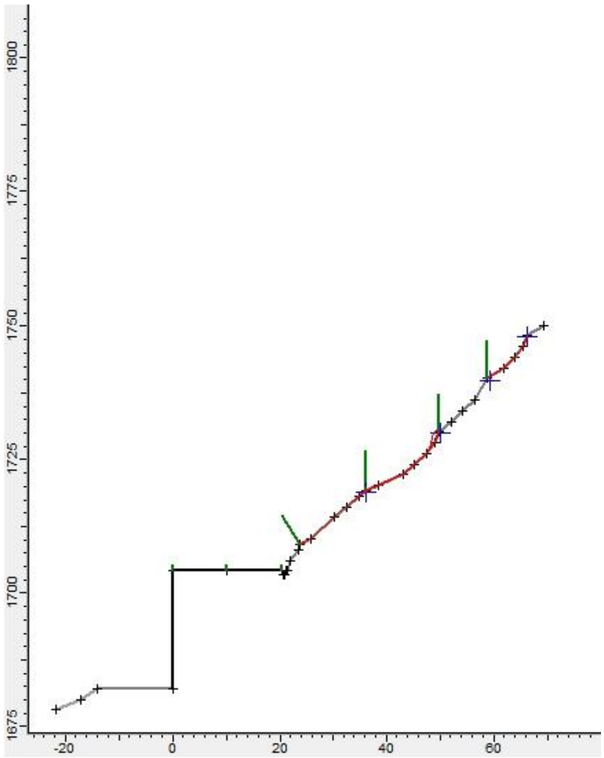


Fig. 11 Modeling of the suggested rockfalls catch barriers location to prevent the falling rock blocks from reaching the road.

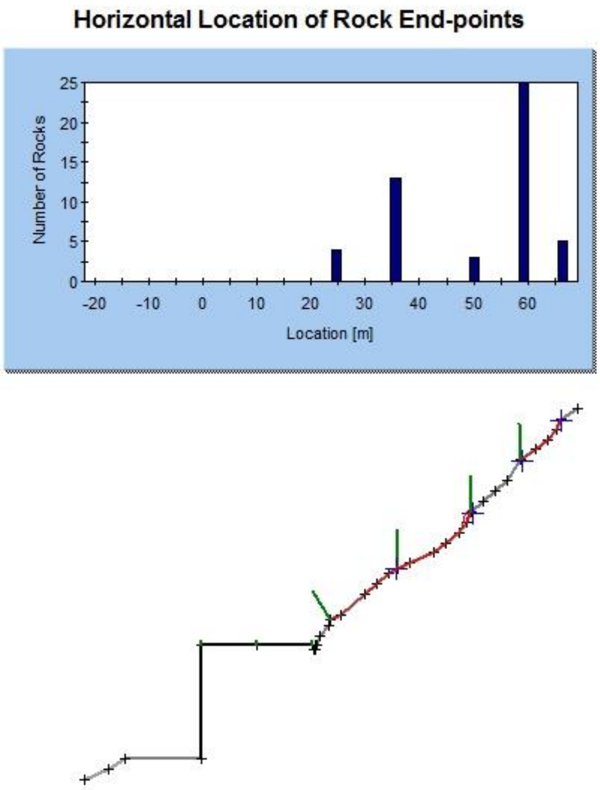


Fig. 12 The end-points of the falling rock blocks, after installing the barriers.

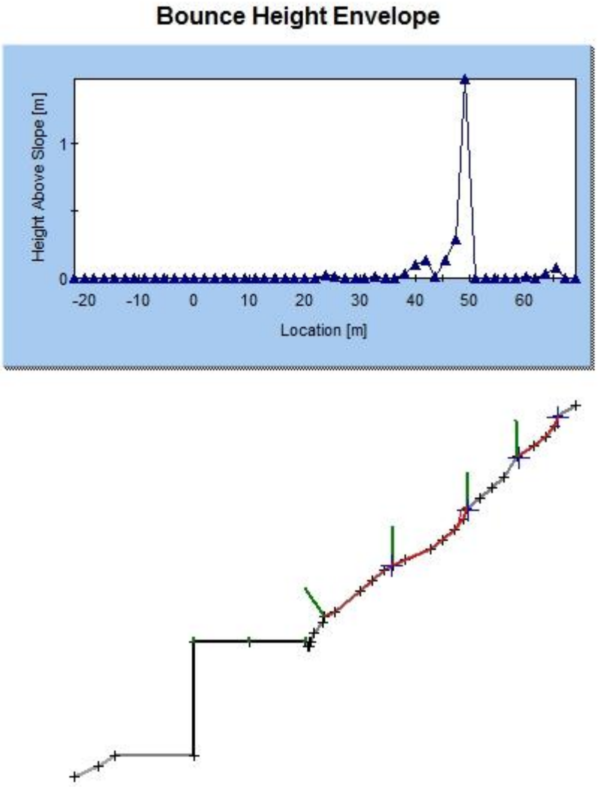


Fig. 13 The bounce height and number of the falling rock blocks, after installing the barriers.

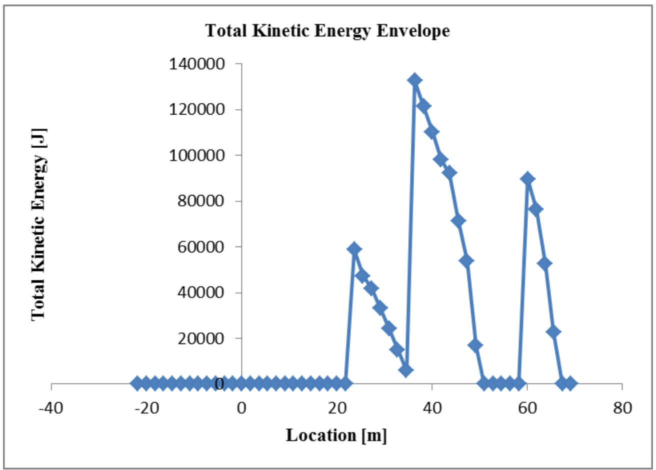


Fig. 14 The total kinetic energy after installing the remedial measures.

The computer program *RocFall* was used to model and indicate the necessity to install 3 vertical and 1 inclined seven m-high rockfall barriers along and above the slope bench (Figs. 11 to 13). A barrier in *RocFall* program is a line segment with one end on the slope surface, which can be placed anywhere along the slope in order to alter the paths of the rocks as they travel down the slope [18]. Modeling of the barriers was commenced on elastic state, as recommended by the program manual.

VI. CONCLUSIONS

The attitudes of the structural setting of the rock masses with regard to the orientation of man-made or natural the slope face, indicates that the modes of failures are the main sources of rockfall's incidents.

The rock slope profile indicates the path and location of the fallen rock blocks hit location on the road.

A one rockfall barrier is not enough to stop the rockfalls from reaching the road, while three levels of rockfall seven m-barriers, as utilized by modeling, are active tools to stop the falling rocks from reaching the road, as indicated by the bounce height, end-point and kinetic energy along the slope profile.

Redesign the rock profile, and making benches could be another solution to the rockfall problems.

Factors such as block size, specific gravity, slope profile, strength, coefficients of restitution and height are also input parameters and the most sensitive factors for solving the rockfall problems.

REFERENCES

1. F. Marzouki, "Petrogenesis of Al-Hada plutonic rocks, Kingdom of Saudi Arabia," Ph.D. Thesis. University of Western Ontario, London, 1977, unpublished.
2. Y.E. Abou-Seadah, "Preliminary evaluation of the stability of Al-Hada rock slopes," Unpublished M.Sc. Thesis, Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia, 1982, unpublished.
3. B.H. Sadagah, "Study of the failures, rockfalls and debris flows occurred along Al-Kar/Al-Hada descent road," 1213p, unpublished.
4. B.H. Sadagah, M.S. Aazam, A. Al-Amri, O. Al-Hoseiny, and A. Al-Harbi, "Powerful rockfall incidents at Al-Hada descent and remedial measures," in *Slope Stability 2013, Proc. of The 2013 Intnl. Symp. on Slope Stability in Open Pit Mining and Civil Engineering*, 25-27 Sept., 2013, Brisbane, Australia, 783-791pp.
5. B.H. Sadagah, "A vigorous debris flow incident at Al-Hada descent and remedial measures". *World Landslide Forum*, 2-6 Jun., 2014, Beijing, P.R.China.
6. G.F. Brown, R.G. Bouge, and W.H. Maclean, "Geologic map of the Southern Hijaz Quadrangle, Kingdom of Saudi Arabia," U.S. Geol. Survey, Misc. Geol. Map I-210 A, 1962.
7. Z.T. Bieniawski, "*Engineering rock mass classification*". John Wiley and Sons, New York, USA. 1989, 251p.
8. D. Banks, "Rock mass ratings (RMRs) predicted from slope angles of natural rock outcrops," Technical note. *Intnl. J. Rock Mech. Min. Sci.* 2005 (42): 440-449.
9. C.M. Orr, "Assessment of rock slope stability using the rock mass rating (RMR) system," *Australia Inst. Min. Metall. Proc., 1992,* 297(2):25–29.
10. C.M. Orr, "Use of rock mass rating (RMR) system in assessing the stability of rock slopes," in *Milestones in rock engineering: the Bieniawski jubilee collection*, 1966.
11. O.M. Abdullatif, and D.M. Cruden, "The relationship between rock mass quality and ease of excavation," *Bull. Int. Assoc. Eng. Geol*.; 1983, 28:183–187.
12. Geological Society of London, "The description of rock masses for engineering purpose," Geological Society, Engineering Group Working Party. *Q. J. Eng. Geology*, 1977, Vol. 10, pp. 335-389.
13. B.H. Sadagah, and Y.E. Abou-Seadah, "The remedial measures on the rock slopes to prevent rockfalls and to protect the commuters along Al-Hada descent road," King Abdulaziz City for Science and Technology, supported project No. 14-25, 2011, 626 p.
14. Rocscience, "*DIPS User's manual*," Rocscience Inc., 2013.
15. E. Hoek, and W. Bray, *Rock slope engineering*. Institute of Mining and Metallurgy. 1980.
16. B.H. Sadagah, "Rockfall Modeling Analysis and Mitigation at Mountainous Road, Saudi Arabia," *GeoShanghai 2014*, 26-28 May, 2014, Shanghai, P.R.China.
17. B.H. Sadagah, "Rockfall analysis, modeling and mitigation of a critical section along Al-Hada descent road, Saudi Arabia." *IAEG XII Congress*, Torino, Italy, 15-19 Sept., 2014.
18. Rocscience, "*RocFall User's guide*," 2012, 59p.

AUTHORS PROFILE

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 48 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.