Remedial Measures against Combined Debris Flows and Rockfalls Hazards along Part of a Mountainous Road, Western Saudi Arabia

Bahaaeldin Sadagah

Abstract— ***Construction of the mountain roads in western Saudi Arabia is one of the most challenging missions. 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 subjected to frequent rockfalls, usually after rainfalls. A huge accumulation of debris formed due to slope failures and rockfalls through years, dropping from almost 100 m above the highway alignment. This accumulation started to move soon due to rainfall, stabilized by benches and shotcrete. The RocFall computer program utilized to analyze the event regarding modeling and mitigation. Study on the debris content properties performed. Parameters such as rock blocks size, initiation point, kinetic energy, and geomorphology are the major factors determining the destructive effect of the combined rockfall and debris flows events on the road. Debris flows barriers and rockfall meshes are the remedial measures recommended according to the site constraints and modeling process.***

Index Terms—***Al-Hada road, rockfalls, debris flows, rainfalls.***

I. INTRODUCTION

The highland roads is western mountainous regions in Saudi Arabia suffer from frequent slope failures, debris flows and rockfalls, especially in rainy seasons, which starts from October to June. One of the most difficult terrain in Saudi Arabia 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 at the valley 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. Al-Hada one-carriage road built in 1950s. Some old supported studies done on the stability of rock masses and road slopes [1], [2], and recent supported study on stability of slopes, rockfalls and debris flows [3].

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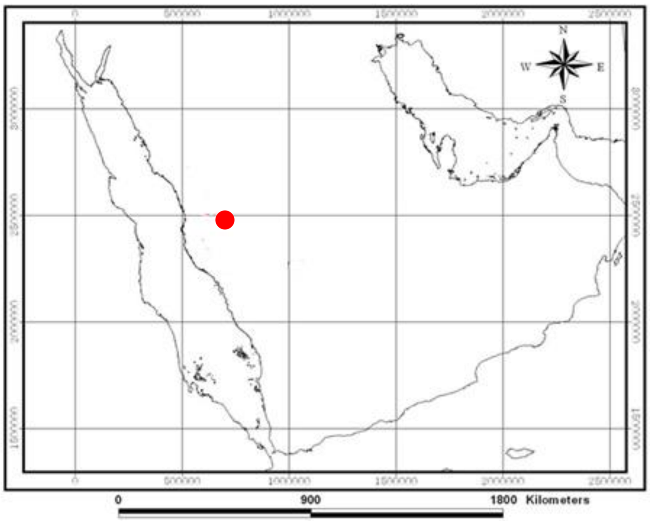

Fig. 1. Location of Al-Hada descent road in western Saudi Arabia.

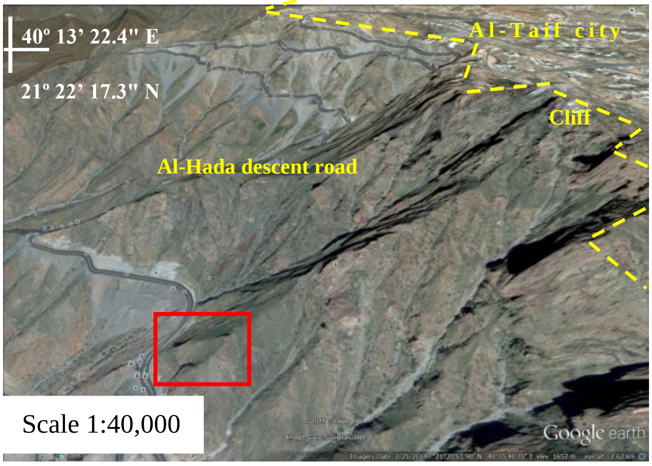

Fig. 2. Location of the study area and Al-Hada descent road.

Due to the increase of population, tourism and traffic density in turn, 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 were on the mountainside slopes. Accordingly, the man-made slope faces elevation and dip angles increased, in addition of cutting more slopes that are natural. This operation aggravated 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, where no sufficient remedial measures taken to maintain stability of the rock masses. This new conditions urges the Ministry of Transportation to evaluate and restudy the current road condition concerning all kinds of the instabilities due to various types of geohazards along selected dangerous parts of the road [3]. The present study is an outcome of one of the harmful combined debris flows and rockfall cases took place and prone to take place frequently along this part of the descent road. More researches on rockfalls incidents at another location along Al-Hada road were published [4], [5], [6], [7] and [8].

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, as a whole, 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, a traceable structure for some 1,500 km, extends parallel to the Red Sea coast. 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 45 degrees. The compaction of the accumulations through years of the whole volume of the products, which formed because of rock slope failures, rockfalls and previous debris flows incidents, in addition to the falling fine materials from higher elevations and in-situ weathered materials. All these materials formed a mixture of compacted debris of well-graded materials (Figs. 3 and 4). The nearest fresh rock is almost 50 m height where the inclination angle decrease at lower elevation and increase close to the mountain top. The highest and lowest elevation of the gully are 1470 m and 1390 m, making an elevation difference of more than 80 m. The site formed of three man-made inclined terraced berms through the debris underlain by the weathered rock masses.

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 [9]. 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.

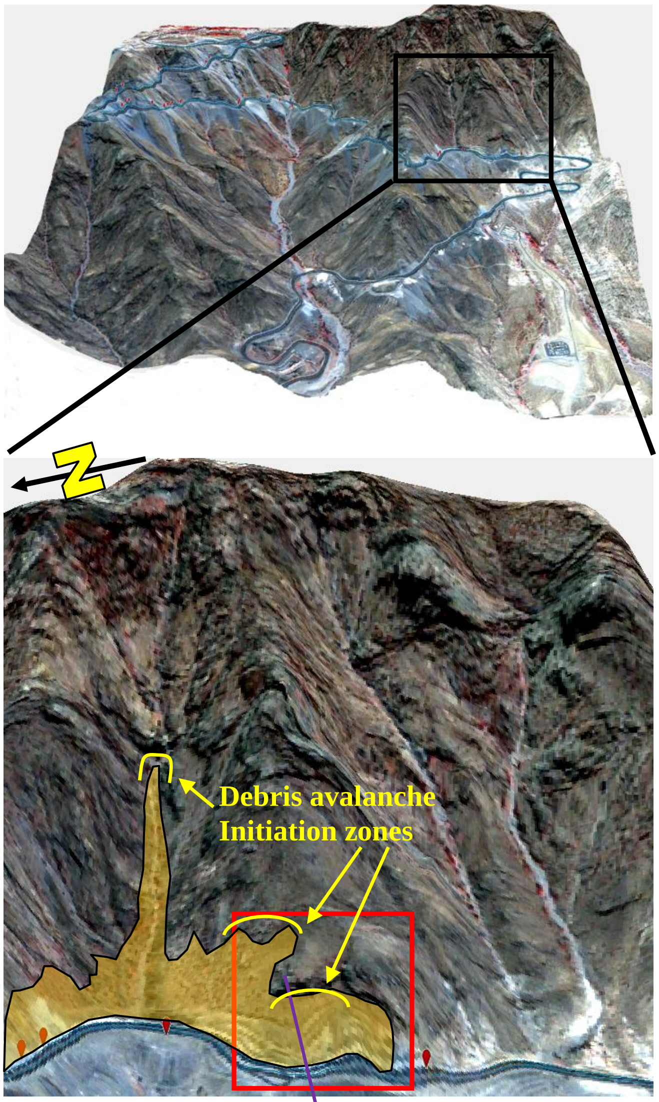

Fig. 3. Geomorphological terrain and enlarged study site.

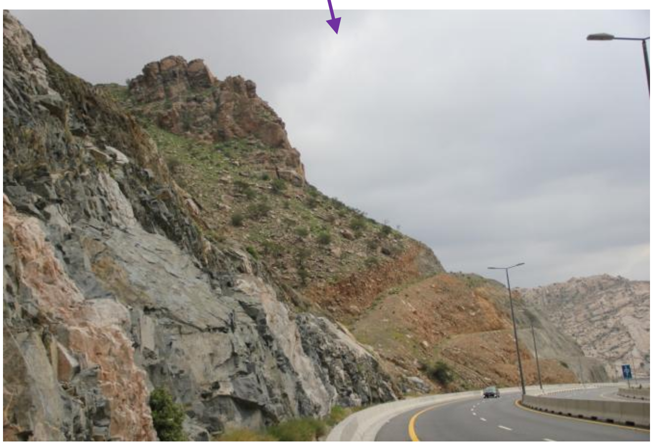

Fig. 4. An inclined slope berm cut formed of the debris accumulation.

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*) [10] is one of the several system available to characterize any rock mass, has a worldwide acceptance and applications [11]. 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 [12], ground supports requirements [13], ease of excavation [14]. The rock's masses geotechnical properties as encountered in the study specific site (Fig. 4) are as follows: blocky, rigid, slightly weathered [15]. A wide range of rock blocks are falling, where the average size about 1 m^3. However, sizes of some fallen rocks along the failure path are greater, as seen on the ditch, on the debris slope, and inferred from the indent's sizes on the highway. The seeder points of the large fallen rock blocks are dropping from higher elevations; reach up to about 80 meters above the road level, with the absence of remedial measures.

Fig. 4. Man-made and natural rock slope at the study site, where sources of seeder points of rockfalls are numerous.

Previous study shows the imprints of rockfalls along the road pavement, indicates the frequency of the rockfall events at this location [16]. Laboratory measurements commenced following the ISRM standard methods of testing [17], where an average reading of three rock samples taken to measure the properties of intact rock materials in this site. The measured rock materials in the laboratory and rock masses in the field shows the granite rock specific gravity = 2.67 gm/cm^3, *GSI* = 55 to 60 [3], *UCS* = 240 MPa. Diorite rocks covered by debris. The heterogeneous geotechnical rock mass properties shown in the field [3]. The overall rock masses *RMR* rating calculated as follows: 1) Strength of intact rock material = 15, 2) *RQD* = 20, 3) Spacing of discontinuities = 13, 4) Condition of discontinuity = 15 and 5) groundwater condition = 15, then the RMR_{89} = 82, 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} = 57 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 very good to fair class.

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 seven joint set's attitudes of a wide scatter of the low concentration joint sets (Fig. 5). The computer program *DIPS* v.6 [18] used to draw the stereographic projection of the present joint's sets utilizing the kinematic graphical technique [19], [20] and [21] used to analyze the stability of the site rock slopes.

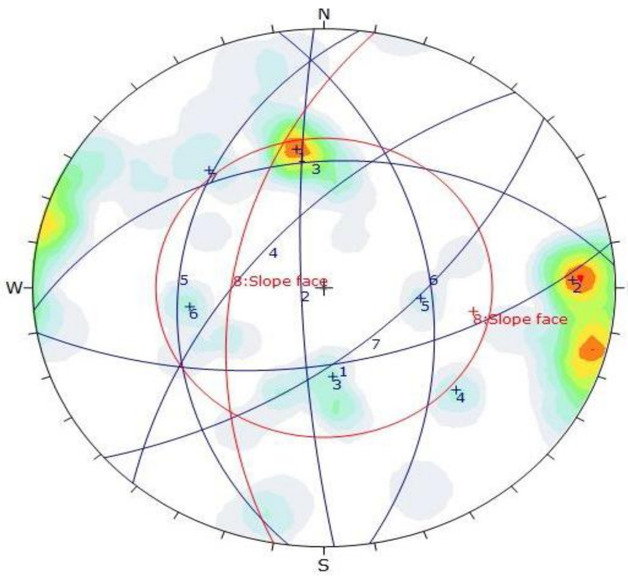

Fig. 5. Stereonet of the prevailing joints sets.

This stability analysis shows the presence of 1) planer failure along joint set # 5 where the factor of safety is <1; 2) wedge failure took place along the intersection between joints sets # 3&5, 4&5, 1&5, and 1&4, and 3) flexural toppling failures along joint sets # 6 where the factor of safety is <1 (Fig. 5). The used utilized softwares for analyses are *RocPlane* v.3 [22], *Swedge* v. 6 [23], and *RocTopple* v. 1 [24], respectively. At this environment elevation dry condition, the factor of safety is <1, and naturally; it getting worse in rainy times [3], where the falling rock block from higher elevations related to any of the above encountered slope failure modes from high elevation, rest on the natural slope face forming debris accumulation of huge size (Figs. 3 and 4).

VI. ROCKFALL MODELING AND REMEDIAL MEASURES

After the rainfall event in 30 Nov. 2014 the water percolates in the joints and debris particles, then increase pore water pressure, decreased the cohesion between the blocks and debris particles. 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 ditch and the road. While other blocks stay unbalanced on the slope profile forming a 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 path process down towards the road, forming a more rockfall hazards on the road. Al-Hada road suffers from rockfall incidents encountered along the road and studied separately [3], [25], [26] and [27]. The slope in concern is unsupported against geohazards, such as rockfalls, debris flows and rock slope instability. Therefore, after the rainfall event a rock block fall from higher elevation and damage the road pavement. Utilizing the damage on the road and using the trial and error method, the possible locations of the seeder points of rock blocks, as observed from the field study (Fig. 6), were defined and modeled using the *RocFall* program v6 [28].

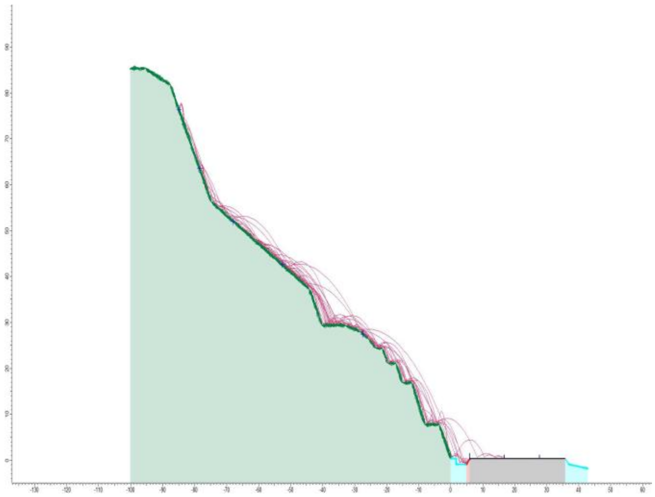

Fig. 6. Rockfall trajectories along the study site.

The fallen rock blocks are emerging from six possible point seeders. The end point and bounce height could reach up to 6-8 m on the road surface (Figs. 7 and 8). The total kinetic energy, translational velocity given (Figs. 9 and 10). This rockfall incident damage provoke a quick study to control this problem at this site. Modeling process show that it is necessary to place three inclined rockfall barriers of strength 8500 kJ of 8 m height and 30 m length along the berm to stop the rocks from falling again at this location (Fig. 11).

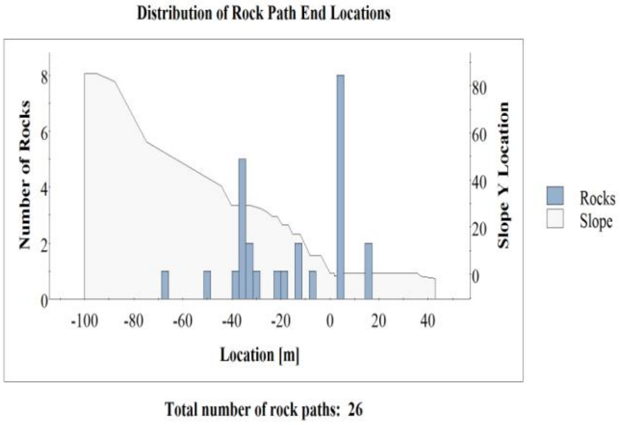

Fig. 7. End point of the fallen rock blocks.

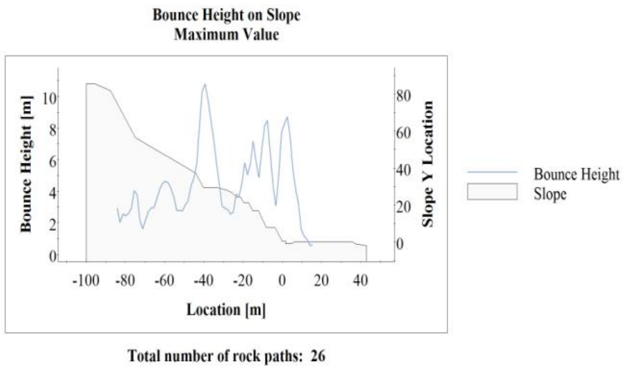

Fig. 8. Bounce height of the rockfalls.

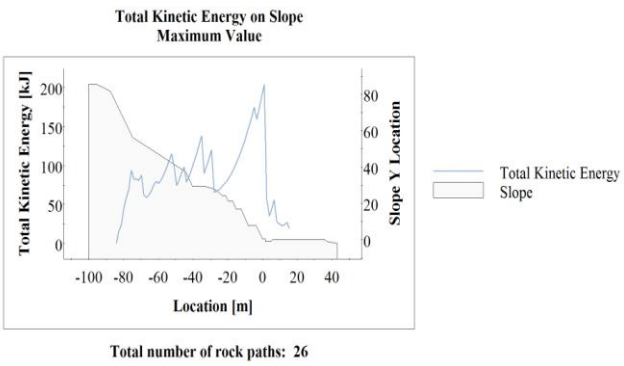

Fig. 9. Total kinetic energy of the rockfall.

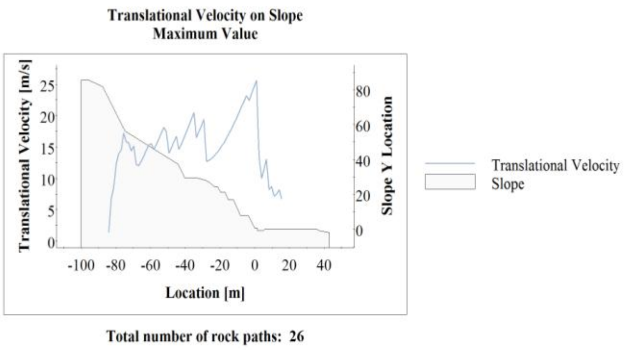

Fig. 10. Translational velocity of the rockfall.

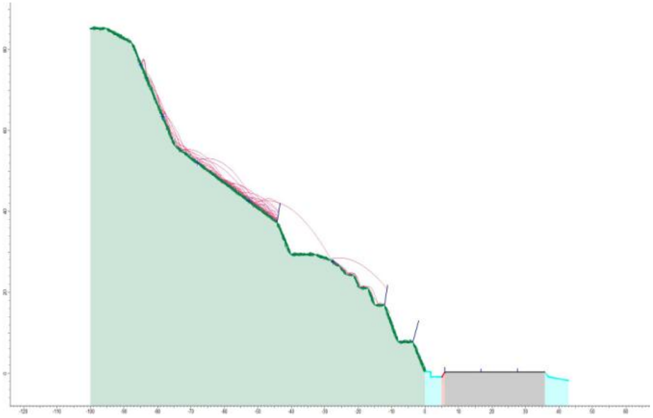

Fig. 11. Locations of rockfall barriers.

The placement of the barriers highly reduced the end point, bounce height, kinetic energy and velocity along the natural rock slope (Figs. 12 to 15).

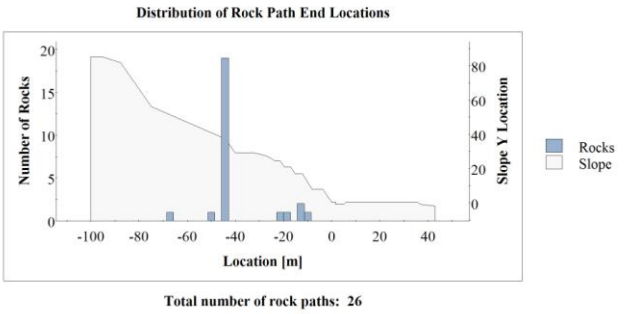

Fig. 12. The end point after installation of rockfall barriers.

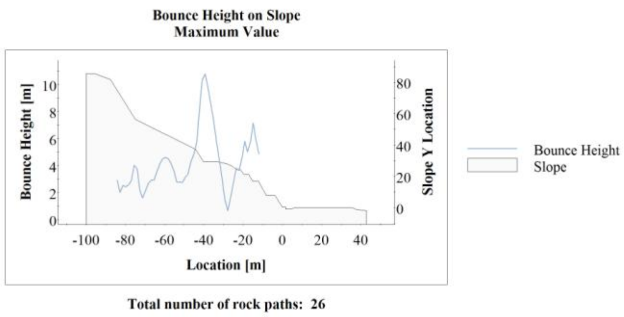

Fig. 13. The bounce heights after installation of rockfall barriers.

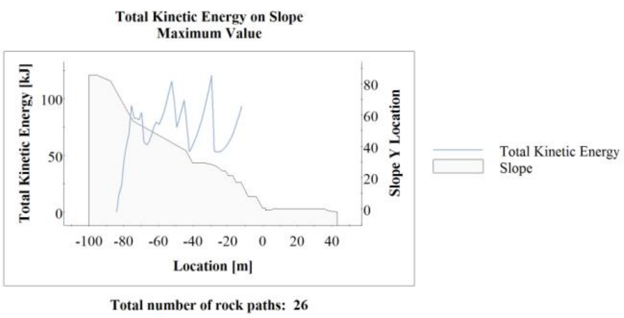

Fig. 14. Total kinetic energy after installation of rockfall barriers.

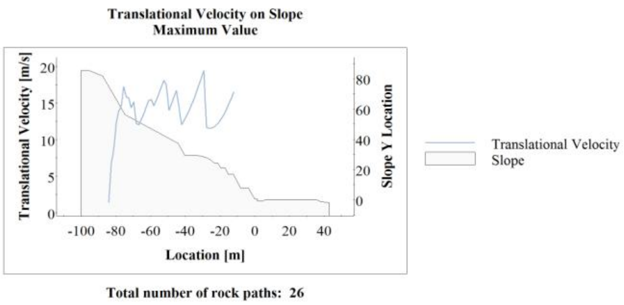

Fig. 15. Translational velocity after installation of rockfall barriers.

VII. DEBRIS FLOWS AND REMEDIAL MEASURES

The other mode of geohazard is the debris accumulations, which are located along the gulley starting from the higher elevation down to the ditch. In situ measurement of the infiltration rate of the debris shows that it is almost 2.5 cm/hr (Fig. 17). The shear strength of the debris were tested at 0%, 10% 20% water content of the soil. Three samples tested for each water content ratio. The samples tested under three stress levels 100, 200, 300 kPa (Figs. 18, 19, and 20). The results shows a general decrease of the cohesion and friction angle as the water content increase. The maximum and minimum obtained friction angle are 30º and 13º, respectively. As the water content increase in the soil, which is representing the intensity of the rain, the friction angle decrease, which cause a debris flows at this particular debris accumulation at the site.

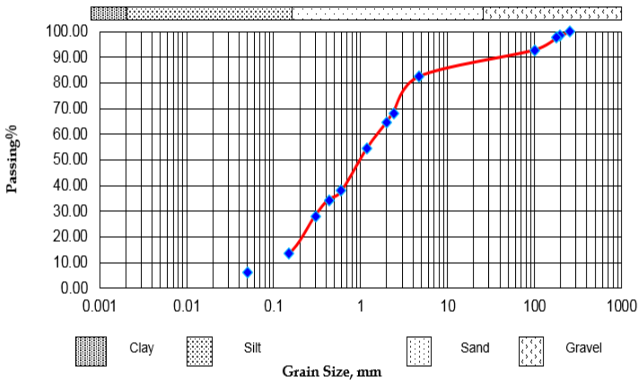

Fig. 16. Grain size analysis of the debris accumulations, excluding large rock blocks more than 10 mm diameter.

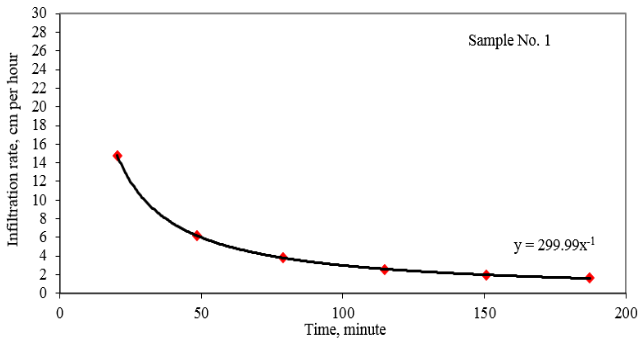

Fig. 17. The infiltration rate of the debris accumulation at the site.

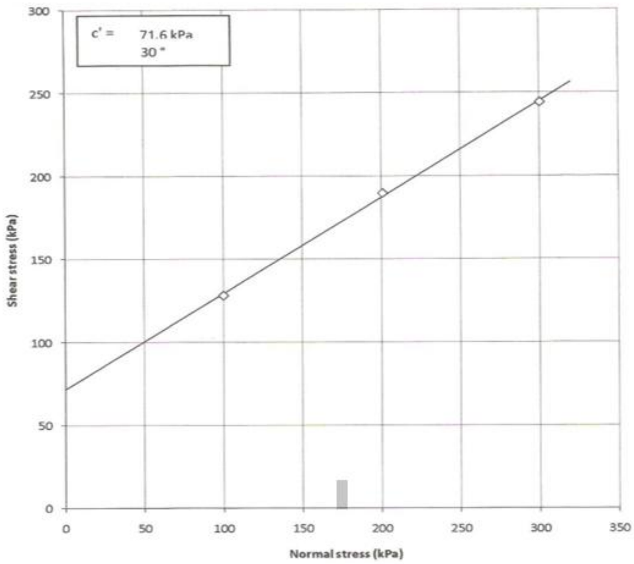

Fig. 18. Shear strength of debris soil at 0% water content.

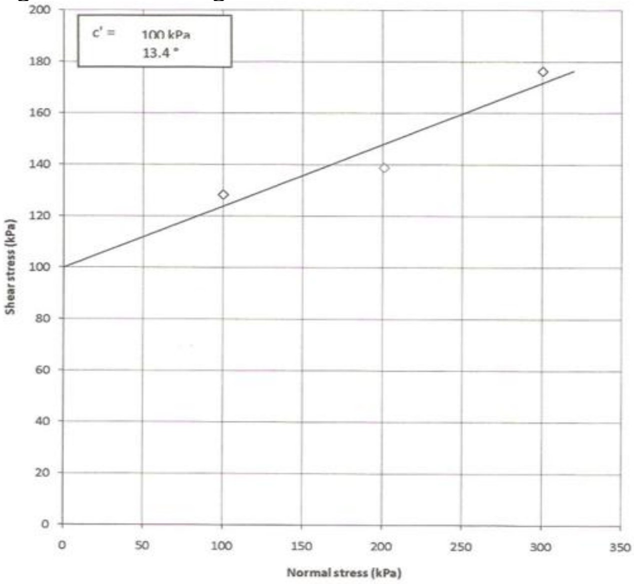

Fig. 19. Shear strength of debris soil at 10% water content.

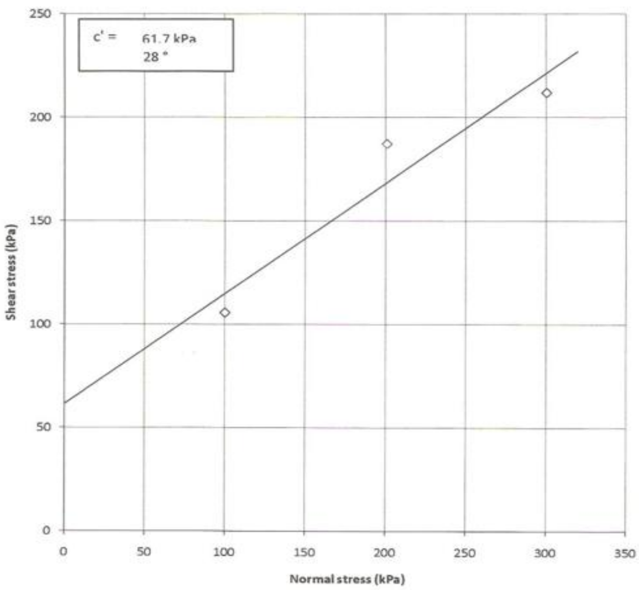

Fig. 20. Shear strength of debris soil at 20% water content.

The remedial measures for this debris at the site is to build a series of check dams across the debris avalanche path, of type sabo/slit barrier [29]. This type is capable to prevent the debris flows blocks to reach the road, where it could pass the water and the fine sediments to pass through the openings and directed towards the culvert.

VIII. CONCLUSION

1. The unsupported man-made slope cut endanger the commuters along the road.
2. As the fresh rocks are at high elevations, it is economic to prevent the negative results as rockfalls by placing rockfall meshes across the direction of failures.
3. Modeling of rockfall barriers energy, location, height and location is necessary before placement of the rockfall meshes along the slopes.
4. Trial and error method in case of rockfalls is essential to perform back-analysis method, where the observation of the imprints on the road declares the possible location of the seeder points along the natural rock slopes.
5. The check dams are a suitable type of dams to decrease the harm of the debris flows on the road.

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, 2013, 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, “Rockfall modeling analysis and mitigation at mountainous road, Saudi Arabia,” *GeoShanghai* 2014, 26-28, May, 2014, Shanghai, P.R.China, 2014.
6. B.H. Sadagah, “Remedial measures and modeling of rockfall problems along part of a mountainous road, western Saudi Arabia,” International Journal of Innovative Science and Modern Engineering™ (IJISME), Vol. 2, Issue 6, pp: 23-29, 2014.
7. 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.
8. B.H. Sadagah, “Back analysis of a rockfall event and remedial measures along part of a mountainous road, western Saudi Arabia” International Journal of Innovative Science and Modern Engineering™ (IJISME), Vol. 3, Issue 2, pp: 1-7, 2015.
9. 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.
10. Z.T. Bieniawski, “*Engineering rock mass classification*”. John Wiley and Sons, New York, USA. 1989, 251p.
11. 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.
12. 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.

13. 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.
14. 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.
15. 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.
16. 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.
17. E.T. Brown, “Rock characterization testing & monitoring. ISRM Suggested Methods”. Commission of testing methods, International Society for Rock Mechanics. Pergamon Press. 211p, 1981.
18. Rocscience, “DIPS User’s manual,” Rocscience Inc., 2013.
19. E. Hoek, “Practical rock engineering”, internet edition, 2007.
20. E. Hoek, and W. Bray, “*Rock slope engineering”*. Institute of Mining and Metallurgy. 1980.
21. D.C Wyllie and C.W. Mah, “*Rock slope engineering civil and mining*” 4th ed... Taylor and Francis, 431p., 2005.
22. Rocscience, “RocPlane v. 3 User’s guide,” 2014.
23. Rocscience, “Swedge v. 6 User’s guide,” 2014.
24. Rocscience, “RocTopple v.1 User’s guide,” 2014.
25. B.H. Sadagah, “Rockfall Modeling Analysis and Mitigation at Mountainous Road, Saudi Arabia,” GeoShanghai 2014, 26-28 May, 2014, Shanghai, P.R.China.
26. 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.
27. B.H. Sadagah, “Back analysis of a rockfall event and remedial measures along part of a mountainous road, western Saudi Arabia. IJISME: vol. 3, Issue 2, pp. 1-7.
28. Rocscience, “RocFall v. 6 User’s guide,” 2014.
29. M. Jacob and O. Hunger “Debris-flow hazards and related phenomena” Springer, 739p, 2005.

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