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Slope Stability Hazard Assessment and Mitigation Methodology Along Eastern Desert Aswan-Cairo Highway, Egypt

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Abstract. The highway between Aswan and Cairo on the eastern bank of the Nile Valley is one of the most used highways in Egypt, connecting most of the governorates with each other. It represents the backbone of Egyptian transportation and commercial traffic. This Highway passes through a two kilometer section of rock cut located 20 km north of New Assiut city. Serious stability and rock fall issues have been recognized in this section in the past few years.

In this study the stability of the rock cuts have been evaluated using different techniques including: 1) Determining the most relevant factors affecting slope instability; 2) interpreting the discontinuity data collected from the joint surveys using stereographic projection for the assessment of the modes of failure and determining the potential unstable zones; 3) applying a rock fall simulation program(s) to evaluate the potential rollout distance for the falling rocks; 4) applying the Missouri Rock Fall Hazard Rating System (MORFH RS). Finally, the most optimum mitigation method that will decrease and minimize the consequences of slope instability was determined.

This study reveals that the cut needs to be mitigated because of the ongoing slope instability present in some areas, including planar and wedge slides and raveling rock falls. It was found that the unstable rock areas create serious safety hazards to traffic.

Keywords: Slope stability, Highway slopes, Rockfall, Slope hazards, Egypt.

Introduction

In the highly populated areas of Egypt, such as the Nile valley, highways represent an essential part of the economy. Three main highways connect the Upper Egypt governorates with Cairo, including the Western Desert, Eastern Desert, and Nile Valley Highways. Most of the traffic runs along the western and eastern desert highways. During the last decade, numerous developments have taken place all over the Egyptian territories including new urban areas, reclamation areas, and industrial zones, all of which increase the use of these highways. However, most of these highways move through rock cut zones which represent major engineering challenges in Egypt.

Transportation systems such as highways are vulnerable to rockfalls wherever they cut across or skirt along mountains, plateaus, ridges and similar topographic features (*e.g.* Bunce *et al.*, 1997; and Hungr *et al.*, 1999). In the context of highway rock slopes, potentially unstable slopes present hazards and pose risks to the traveling public, to the transportation infrastructure, to local economies and to the environment. New requirements to establish civil infrastructure across difficult terrain as population centers expand in coming decades will increase the number of rock cuts along transportation systems (Dai *et al.*, 2002). Highway systems may suffer from rockfalls on a daily basis; but these may not be considered hazardous unless rocks enter the roadway (Chau *et al.*, 2003; Chau *et al.*, 2004). Although, the public is not generally aware of rockfalls except where a particular event results in significant loss of convenience, property, or life (Budetta, 2004), rockfall remains an irritant to many transportation agencies, which are responsible for providing and maintaining safe and reliable highways and routes in an economical fashion.

Varnes, 1978 considered that both rockfall and rockslide are forms of landslides. It was updated by (Cruden & Varnes, 1996) classification systems, where the first term (rock) indicating type of material and the second term (fall or slide) indicating type of movement. The State transportation agencies and the Federal Highways Administration (FHWA) have adopted 5 simpler nomenclatures for rock slope failures affecting highways, referring to all such failures as rockfall. In general, stability assessment of rock slopes requires comprehensive information about the geology and engineering geology of the area such as geological structures, the properties of the rock mass discontinuities for the structural controlled failures as well as the characteristics of the rock cut faces for the raveling type failures. Other factors related to the traffic density and road designs are also required, because these have consequences to moving vehicles.

Different authors have developed different techniques for assessing slope instability. Some determine the engineering properties of rock and rock masses (Hoek 1977, ISRM 1981 and 1985; and Farmer 1992). Others study the effect of rolling and bouncing rocks from the rock slopes on the highways by using different simulation programs such as, CRSB (Jones *et al.*, 2000). Recently there are many authors describing rock fall hazard rating systems that have been implemented by several states in USA and Canada, including Oregon (Pierson, 1992); Utah (Pack & Boie, 2002); New Hampshire (Fish & Lane, 2002); New York (Hadjin, 2002); Washington (Ho & Norton, 1991); Tennessee (Bateman, 2002; Bellamy *et al.*, 2003; Vandewater *et al.*, 2005); and Missouri (Maerz *et al.*, 2005).

The degree and nature of the hazard risk depends in large part on the characteristics of the rock discontinuities, the height of the rock slope, rock weathering style, presence of water, and adequacy of the catchment ditch. The level of consequence depends also on the amount and speed of traffic, the decision site distance and other factors. Potential rockfalls can also create hazards with respect to ecosystems. Metamorphic or sedimentary rocks with high pyritic concentrations, for example, can create serious environmental problems if rockfall (or subsequent filtrate) enters a river or stream producing sulfuric acid (Byerly, 1989).

Objectives

The main objectives of this research are the assessment of the instability of the limestone rock cut faces, based on the field investigation. The term rockfall is used in this paper as a generic term for rockfalls and rock slides of all kinds, whether rock is free falling, toppling, bouncing, rolling or sliding. Field investigations were carried out in the rock cut area to determine the most influential geological and geotechnical characteristics of the rock material in the area and to assess the most significant factors affecting the slope stability. The detailed objectives were to:

1. Describe the most relevant factors contributing to the slope instability hazards in the site,

2. Collect discontinuity data to obtain sufficient information regarding the geological structures and discontinuity patterns and the effect of their orientation on modes of failure (planer and wedge failure analysis),

3. Determine the geometry of the rock cut in different areas to apply the rock fall simulation analysis for the impact of falling rocks on the highway.

4. Apply a rockfall hazard rating system (Maerz, *et. al*., 2005), and,

5. Develop a mitigation strategy for each section of the highway and development of alternative solutions and designs to minimize future problems.

Site Location and General Geology

The current study deals with the Eastern Desert Highway, where it moves through a zone of about 2 km of rock cut. The rock cut lies in a section between the Assuit and El-Minia governorates about 20 km north of the New Assuit city, near Wadi el-Ibrahimi (Fig. 1). The geology of the area is composed mainly of Eocene limestone. Generally, this limestone in this study area is dissected by filled sinkholes. The general appearance of limestone is white to gray in color with weathered reddish surfaces.

Analysis

Site Conditions

The rock cut, in the study area, extends about 2 km (on both sides of the road) and the highway has a width of one lane for each direction through the cut, with no ditch and a very small shoulder (Fig. 2). The limestone along the rock cut is highly fractured, and the sinkholes filled with highly weathered materials abound. These are visible in the rock cuts as well as in nearby old quarries (Fig. 2). The limestone is white to gray in color with weathered reddish surfaces. The geological map of the area shows that many joints dissect the area, trending N20W and N60E (Fig. 1b). In addition, there is major NW-SE trending fault near the road cut (Fig. 1b).

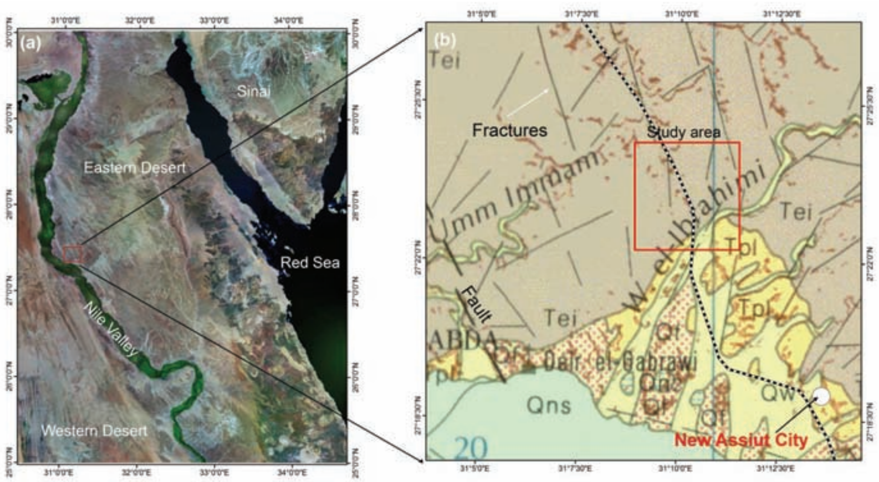

Fig. 1. **(a) Location map of the rock cut section along the Aswan-Cairo Highway, (b) Geological map of the area along the cut. Note that Qns = Nile silt; Qf = Fanglomerate; Qw = Wadi deposits; Qn2 = Pre-Nile deposits; Tpl = Pliocene deposits; and Tei = Minia Formation (Limestone).**

Fig. 2. **An overview of the desert highway along the cut section showing the horizontal and vertical curvature of the road. The road has small shoulder, with no ditch, and one traffic lane in each direction.**

Along the rock cut in the study section the shoulder width ranges from 0.5 to 2 m, and the cut face is irregular and includes joints dipping at an angle of 10 degrees toward the road. The joint system also forms potential wedge failures (Fig. 3). Debris cones form at the base of the cut. There are both horizontal and vertical curves along the rock cut (Fig. 2). The height of the rock cut ranges from 5 to 25 m, and there are no catchment ditches or benches. Most of the cliff faces are highly irregular and in some areas their reddish patches indicate highly weathered zones. On the western side of the highway, the upper parts of the cut are inclined and typically dip towards the highway (that is related to joints that dissect the study area).

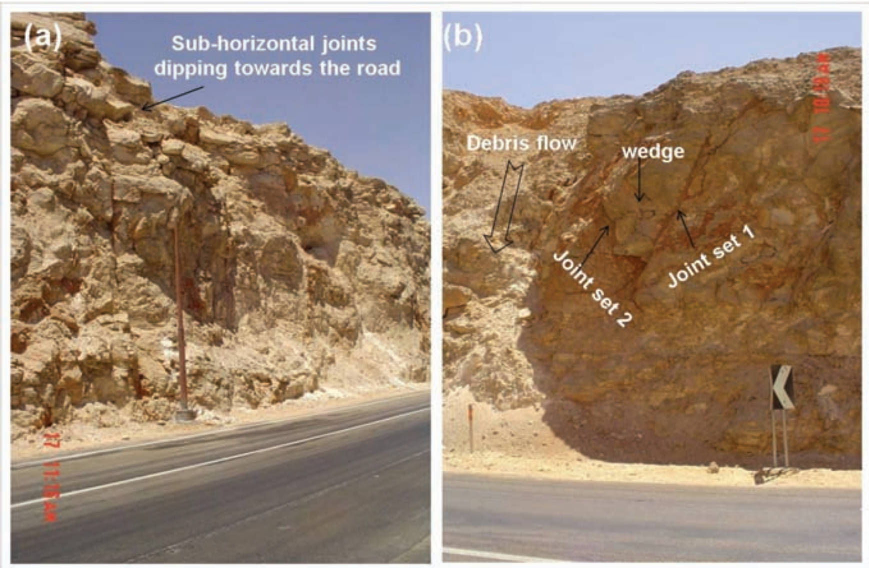

Fig. 3. (a) The narrow road shoulder and the irregular rock cut; (b) the wedge failure and the rock debris that characterized part of the road.

The limestone of the rock cut is characterized by the presence of filled sinkholes (Fig. 4). These have been found to be of importance to slope stability. The sinkholes are filled with material of a variety of block sizes ranging from 20 cm to 1 m and are weakly cemented with reddish sandy muddy materials that are easily eroded. Karst features are nearly always found to originate from solution cavities along discontinuities. This leaves cavities supported by remnant points of contact across opened discontinuities. A diminished contact area reduces the shear strength, and points of contact may break due to overstressing. The presence of these filled sinkholes during excavation, have an adverse effect on the slope stability. During blasting the explosion gases will force their way out of the rock mass via the karstic discontinuities rather than by breaking intact rock or by following discontinuities to the next borehole.

Fig. 4. Sinkhole filled with boulders of different sizes and cemented with reddish weak materials (clayey sand with a reddish matrix).

Field Tests

Simple field tests were used to acquire data on the engineering properties of the intact rock and rock mass. The term "Simple" means tests that make use of hand pressure, geological hammer, *etc.* (Burnett, 1975), have been used to determine the intact rock strength in the study area (the test classes are listed in Table 1). More than 50 locations have been tested using a geologic hammer for limestone intact rocks, weathered materials along the discontinuities, and the cemented materials filling the sinkholes. At many exposures multiple estimates of the intact rock strength were made; often more than 5 values were averaged.

For the limestones, intact strengths in the range from 12.5-50 MPa were obtained. However, the marly limestone strengths were found to be less than 1.25 MPa. The cemented materials located in the filled sinkholes were also found to be less than 1.25 MPa.

Table 1. Estimation of intact rock strength (after Burnett, 1975).

Intact rock strength	Description
< 1.25 MPa	Crumbles in hand
1.25 – 5 MPa	Thin slabs break easily in hand
5 - 12.5 MPa	Thin slabs break by heavy hand pressure
12.5 – 50 MPa	Lumps broken by light hammer blows
50 – 100 MPa	Lumps broken by heavy hammer blows
100 – 200 MPa	Lumps only chip by heavy hammer blows
> 200 MPa	Rocks ring on hammer blows. Sparks fly.

Results

Determination of the Most Relevant Factors that Contribute to Slope Instability

By surveying the rock cut zone it was found that there are different factors which have a significant role in the stability problems in the area. These factors include:

1. Discontinuity orientations which could form wedge and planer failures (Fig. 3b).

2. Low strength of intact rocks and rock mass.

3. Filled sinkholes composed of angular materials cemented by a very weak, easily erodable matrix (Fig. 4).

4. Irregular unstable faces (Fig. 5).

5. Loose faces prone to rock falls on the upper part of the cut (Fig. 5).

6. Only one single traveling lane in each direction, without an adequate shoulder, which does not have enough space for the driver to swerve to avoid any fallen materials (Fig. 2).

7. No ditches to retain any fallen materials, allowing the material to spill out onto the traveling lanes (Fig. 5).

8. A high degree of road curvature resulting in a small decision sight distance.

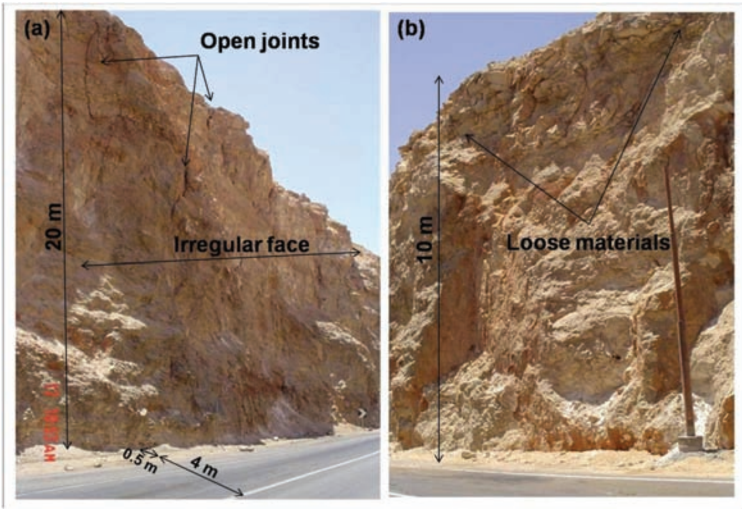

Fig. 5. (a) 20 m height rock cut is characterized by high face irregularity, open vertical joints, (b) 10 m height with face looseness at the top portion. Note the lane width is 4 m with a shoulder less than 0.5 m and no catchment ditch.

The results show that these factors can be classified into three main groups that will increase the possibility of slope instability as follows:

1. Group (I): Geologic factors, including rock types, the strength of the intact rock, strength of the weathered materials along the discontinuities, presence of sinkholes, strength of the cemented materials in sinkholes, and presence of adversely oriented discontinuities orientations, are the main geological factors with a large influence on the rock cut stability in the study area.

2. Group (II): Method of excavation factors, which reflect the effect of the engineering method used to cut the slope. This has a considerable influence on the parameters measured or observed in the exposure. For example, the face irregularity and looseness are the result of poor blasting technique.

3. Group (III): Road design factors including the absence of shoulders and catchment benches and ditches which increases the amount of falling rock that reaches the road, either blocking the highway or creating a hazard for moving vehicles. In addition, the limited number of lanes (one in each direction) reduces the ability of drivers to avoid the fallen materials.

Discontinuities Controlling the Slope Failures

In order to assess the potential mode of failures and the stability of slope faces in the limestone road cut section, the data obtained from the geological mapping were used. Field investigation was done to understand the structural control on slope stability and mapping the discontinuity orientation distributions in the area including strike and dip, as well as defining the friction angle along the joints. In this study the rock cut adjacent to the northbound lane has been used for discontinuities mapping. Two main methods were undertaken including:

1. Field surveying the site and measuring about 100 discontinuity orientations along the cut and,

2. Determination of the rock mass properties, especially the friction angles along the discontinuities.

The field data collected from the discontinuities were statistically analyzed (Fig. 6). The data results show that the distribution of the subvertical discontinuities have a strike azimuths of 65, 90, and 320º.

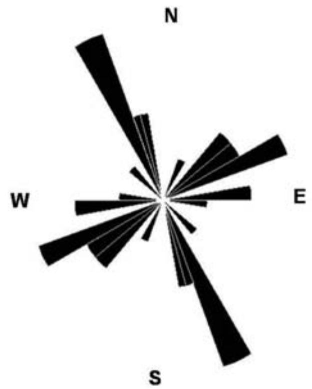

Fig. 6. Rose diagram showing the trend of 100 measurements of joints in the rock cut.

In order to assess the potential modes of failure, the friction angle has been calculated according to two methods: 1) In the field using matched discontinuity surfaces and 2) using the RockData program (RockScience group) in which the empirical estimation of rock mass modulus could be calculated (Hoek and Diederichs, 2006). For the field test, the friction angle has been determined using a tilt test, in which two contiguous blocks are extracted from the exposure, and the upper is laid upon the lower as it was in the rock mass. Both are tilted, and the angle at which sliding occurs is recorded. The results of tilt testing of different blocks in the study area showed that, the value of the tilted angle ranges from 18º-24º. To estimate the friction angle, this formula has been used where the friction angle ranges from 20º-27º. To be conservative a friction angle with a 20º has been used in this study.

$$\phi_b = \tan^{-1}(1.55\tan\alpha)$$

Where alpha (α) is the tilting angle and $Ø_b$ is the friction angle

The field test data was confirmed by the RockData program in which the characteristics of the rock were determined as follows: The uniaxial compressive strength ranges from 12.5 to 50 MPa as determined by geological hammer, geological strength index (GSI) = 29 for blocky limestone with poor condition discontinuity, material constant (mi) = 7 for limestone, Disturbance factor = 1 for poor blasting, average unit weight for limestone = 0.023 MN/m^3, slope height = 25 m. The result of the program shows that, according to change of the uniaxial compressive strength, the friction angle ranges from 17º to 25º. It was found that the RockData program results are very close to the field determined values. It should be noted that the calculated friction angle is only related to the limestone with weathered surfaces.

Consequently when the lower hemisphere equal-area stereographic projection method was used to analyze the discontinuity data, a friction cone of 20º was incorporated into the analysis. Figure 7 shows that there are four major joint sets including F1, F2, F3, and F4. The rock cut strike has two azimuth values, 170º (Fig. 7a) and 30º (Fig. 7b).

For the first section, a kinematic analysis shows that there are two main possible modes of failures, including planer and wedge failures (Fig. 7a). Wedge failures can occur between joints F1F2, F1F3, F1F4, F2F3, and F2F4, while, planer failure could occur along joint F1.

For section 2, a stereographic projection of the major discontinuity shows that there are two main modes of failures including planer and wedge failures (Fig. 7b). Wedge failures can occur between joints F1F2, F1F3, F1F4, F2F3, and F2F4, while, planer failure can occur along joints F3 and F4.

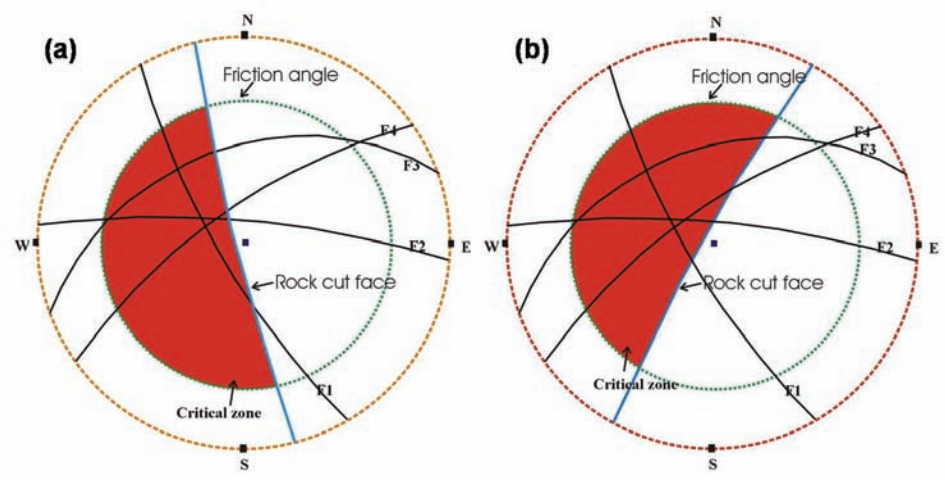

Fig. 7. Lower hemisphere stereographic projection of dominant discontinuity planes in the study area: a) Northern section of the road, and b) Southern section of the road.

Rockfall Simulation Analysis

A critical component of the hazard assessment was estimate how far the falling rocks will roll in the highway. Rockfall hazard assessments in other areas have used field and modeling-based approaches to assess rock-fall runout distances. Evans and Hungr (1993) used the angle formed between the top of talus deposits and the distance limit of rock-fall runout to estimate rock-fall runout zones or "rockfall shadows". Guzzetti, *et. al*., (2003) used a computer program STONE, (Guzzetti, *et. al*., 2002) to estimate rock-fall runout in Yosemite National Park. Maerz *et al.* (2005) indicates that larger boulders that roll down low angle slopes, and smaller blocks that bounce down steeper slopes are the most likely to reach the highway. At the study area the CRSP program (Jones *et al.*, 2000), was used for estimating runout. The simulations have been done for about 5 sections with differing geometries. The location of the unstable rocks were visually determined in the cuts, and input into the simulation.

Rockfall simulation analysis shows that most of the falling rocks will bounce and roll far enough to reach the highway. This may cause a serious hazard for the vehicles especially with the presence of horizontal and vertical curves which do not allow enough time for the driver to reacts. An interesting example shown in Fig. 8a and b, is demonstrating the falling materials that will hit the rock cut or the pavement area and bounce to the roadway. The data of the 5 sections indicate that most or all the falling rocks will reach the highway especially in the areas where there is no ditch (Fig. 8c).

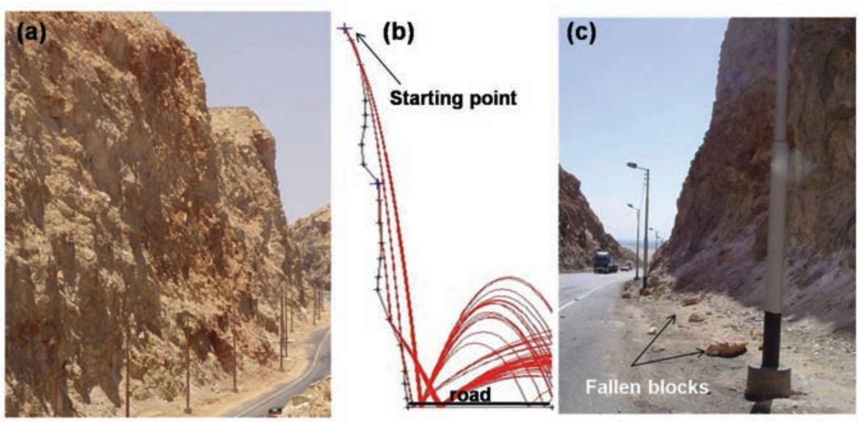

Fig. 8. a) A rock cut example of the cliff used for rock fall simulation, b) CRSP simulation example for 100 blocks 0.4 ft in diameter bouncing and rolling down a slope to a roadbed, and c) The falling rocks reach the road way.

Application of the MORFH RS

The Missouri Rock Fall Hazard Rating system (MORFH RS) (Maerz *et al.* 2005) was designed for Missouri highways, which are in many ways similar to rock cut of the present study in terms of rock types and the presence of filled sinkholes. The MORFH RS system classifies the rock cuts into two classes based on; risk and consequence of failure. The system consists of 23 factors, 11 for the risk, and 12 for the consequence (Table 2). The calculation of an individual factor in risk class, for example is independent from the other factors of the consequence class. Three factors (out of the 23) are considered “adjustment factors”, two from the risk side (OED and KE) and one for consequence side (DCE).

The factors of the risk (with the single exception of weathering) are rated in a scale of 0 to 12, the weathering factor is rated in a scale of 0 to 24. The scale rating of the consequence factors are form 0 to 12, only the adjustment factor (DCE) is from 0 to 15. It is to be noted that two factors (Slope Angle and Block Size) appear both in the risk and consequence rating side, but each have quite different rating criteria on each side. The factors rating from both sides are calculated based on the formulas described in Maerz *et al.* (2005).

Table 2. The risk and consequences factors of the MORFH RS system.

Risk	Consequences
1. Slope Height (SH). 2. Slope Angle (SA). 3. Rockfall Instability (RFI). 4. Strength of Intact Rock (SOIR). 5. Face Irregularity (FI). 6. Face Looseness (FL). 7. Block Size (BS). 8. Water on Face (WOF). 9. Weathering Factor (WF). 10. Dip Angle of Discontinuities (AOD). 11. Karst Effect (KE).	1. Ditch Width (DW). 2. Ditch shape (DS). 3. Ditch Volume (DV). 4. Expected Rock Fall Quantities (ERFQ). 5. Slope Angle (SA). 6. Shoulder Width, (SW). 7. Number of Lanes (NOL). 8. Average Daily Traffic (ADT). 9. Average Vehicle Risk (AVR). 10. Decision Sight Distance (DSD). 11. Block Size (BS). 12. Ditch Capacity Accidence (DCE).

The values of the risk and the consequence parameters were summed and normalized to produce a risk or consequence rating on a scale of 0-100 for each. The adjustment factors of each rock class (if not equal to zero) are added separately to the risk side (scale of 0 to 12) or the consequence side (scale of 0 to 15). The maximum risk or consequence rating is 100 (Maerz *et al.*, 2005).

The field investigation and measurements for 10 stations across the two rock cut sections (section 1 on the east side and section 2 on the west side) of the study area indicate that these cut stations have both high risk and high consequence rating values. The results of the risk and consequence values for the 10 stations are shown in Table 3 and Fig. 9. Figure 9 also shows that all data are located in zone A, which represents high hazard and requires immediate remediation.

Table 3. Rating values (MORFH RS) of the investigated rock cuts.

Stations number	Cut section	Risk	Consequence	Description
1	1	96	78.0	High hazard high consequence
2	1	94	80.0	High hazard high consequence
3	1	88	90.0	High hazard high consequence
4	1	90	95.0	High hazard high consequence
5	1	78	85.0	High hazard high consequence
6	2	90	87.0	High hazard high consequence
7	2	75	88.0	High hazard high consequence
8	2	80	75.0	High hazard high consequence
9	2	95	90.0	High hazard high consequence
10	2	100	82.0	High hazard high consequence

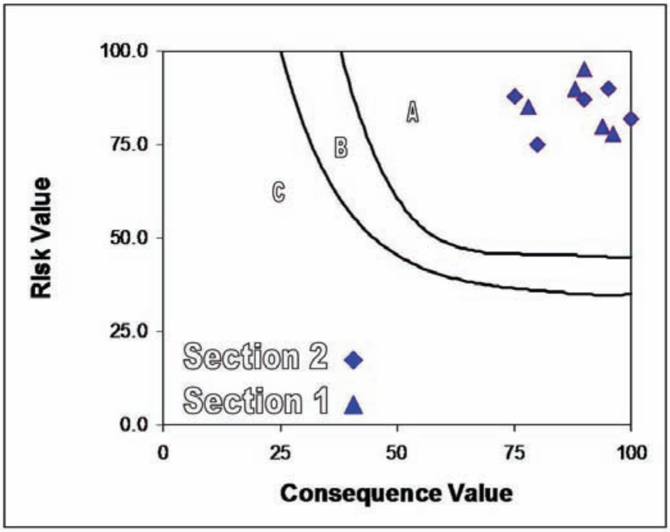

Fig. 9. Plotted risk and consequence values for the studied area on the risk-consequence diagram (after Maerz, *et. al.*, 2005). Zone A represents high hazard and immediate remediation is recommended; zone B represents moderate hazard where remediation is optional; and zone C represents low hazard where remediation is not required.

Remediation/Mitigation Options and Recommendations

Fookes and Sweeney (1976), Peckover and Kerr (1977), and Hoek (2000) suggested different methods for preventing rockfalls (remediation) or minimizing their effects (mitigation). The methods are either to stabilize the rocks in place or protect the road from moving rocks, or to provide adequate warning system to protect motorists. Various methods can frequently be combined to increase the safety at a single site.

Remediation Options

Physical restraint of rockfalls typically consists of a program of rock bolting and or shortcrete application, or building a metal, concrete or stone retaining wall. These techniques are typically very costly; especially the retaining walls, and tends to be used only locally in very small sections. For the bolted or shortcrete solutions, further deterioration of the rock will make these efforts unpractical in the long run.

For this project, especially because of the sheer volume of rock that needed to be treated, the remediation option was considered to be far too costly.

Mitigation Options

Mitigation of rockfalls consists of methods that allow rock to fall but minimized the damages by containing the fallen rock and not allowing it to affect the traffic in any way. These include catchment benches and ditches, berms or fences, draped wire mesh, or rock shed structures.

The most cost effective solutions in this study are catch benches and ditches which act as traps to contain fallen rock. Rock traps work well in catching rockfalls provided that there is sufficient room at the toe of the slope to accommodate these rock traps. The studied sites have very narrow roads and retreating the rock cuts in these parts by blasting to create ditches and benches is also not an option, because of the cost and disruption. Berms are a very effective means of catching rockfalls but could not be applied for the same reason.

Wire mesh is a good alternative. Draping wire over the face will serve to keep small rocks from falling, while releasing larger rock slowly down the face with low enough kinetic energy to keep the rock from bouncing out onto the highway. Draped mesh is a good economical option, but larger rock failure can create significant damage if the draped mesh is not routinely inspected and maintained.

Catch fences or barrier fences are effective way to increase the ditch capacity (volume and width) if the current ditches are inadequate. Fences in common use are estimated to have an energy absorption capacity of 100 kNm, which is equivalent to a 250 kg rock moving at about 20 m/s. Fences and barriers such as jersey barriers are ideal solutions for this situation since they occupy small space. Care must be taken to line the ditch with an energy damping material such as gravel or sand. It requires also routine inspection and maintenance (removal of fallen rock). Analysis of the effectiveness can be conducted with a CRSP analysis as in Fig. 8.

Conclusions

Some sections of the rock cuts along Aswan – Cairo highway north of New City of Assiut are not stable and may endanger the traffic safety if the rocks are not stabilized. The main findings are:

1. The rock movement is in the form of structural control failures (planer and wedge slides) and raveling rock falls,
2. The application of the Missouri rock fall hazard rating system (MORFH RS) and the Rock fall simulation program (CRSP) were effective to rate the degree of hazards and determine the impact of falling rocks on the highway,
3. It was found that the most effective mitigation strategy to increase the rock stability in this study are mesh draped over the face,
4. The rock stability is improved further by catch or barrier fences and scaling of roadside and rock faces to remove loose rocks,
5. Long term, highway works such as modifications to the horizontal or vertical alignments, and blasting back the rock faces would provide the best most permanent solution.

Recommendations

Based on the analysis and finding of this study it is recommended:

1. To scale and trim the roadside and rock faces to remove loose rock as a useful method in the short term,
2. To divert the surface water from the top of the cut especially along the weathering sections.

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تقييم مخاطر ثباتية المنحدر ووسائل التخفيف على طول الطريق السريع القاهرة – أسوان بالصحراء الشرقية، مصر

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المستخلص. الطريق السريع بين أسوان و القاهرة، تقييم مخاطر ثباتية المنحدر ووسائل التخفيف على الضفة الشرقية من وادي النيل، يعتبر واحدًا من أكثر الطرق المستخدمة في مصر، والذي يربط معظم المحافظات مع بعضها البعض. ويمثل هذا الطريق العمود الفقري للنقل والملاحة التجارية في مصر، ويمر جزء منه عبر نطاق يبلغ طوله كيلومترين من القطع الصخرية، والذي يقع على بعد ٢٠ كيلومترا إلى الشمال من مدينة أسيوط الجديدة. تم التعرف علي العديد من المناطق الخطرة من حيث الثباتية، والتساقط الصخري في هذا النطاق في السنوات القليلة الماضية.

تم تقييم استقرارية القطوعات الصخرية في الدراسة الحالية باستخدام تقنيات مختلفة منها: (١) تحديد أهم العوامل التي تؤثر على عدم استقرار المنحدرات، و (٢) تفسير البيانات التي جمعت من مسح الفواصل باستخدام الإسقاط الاستريوجرافي لتقييم طبيعة الانهيار، وإمكانية تحديد النطاقات غير المستقرة، و (٣) استخدام برنامج محاكاة التساقط الصخري لتقييم مسافة السقوط والجريان المحتملة للصخور الساقطة، و (٤) تطبيق نظام مخاطر التساقط الصخري بولاية ميسوري (MORFH RS). وأخيرًا، تم تحديد الطرق المثلى للحد أوالتخفيف من آثار عدم الاستقرار للمنحدر.

وتستنتج هذه الدراسة أن القطع الصخري بحاجة إلى الحماية بسبب استمرار عدم الاستقرار في هذا الانحدار في بعض المناطق، والتي تشتمل على انزلاق على مستوى واحد أو على مستويين (إسفين) والأخرى المرتبطة بالانهيار الناتجة من اتحاد عوامل عدة (Raveling). وقد تبين أن عدم استقرار المناطق الصخرية تسبب مخاطر شديدة لسلامة المرور.

الكلمات المفتاحية: استقرار المنحدرات، منحدرات الطرق السريعة، الصخور المتساقطة، أخطار المنحدر، مصر.