

Karst Induced Geo-hazards in Egypt: Case Study Slope Stability Problems Along Some Selected Desert Highways

Ahmed M. Youssef^{1,2(✉)}, Abdel-Hamid El-Shater¹,
Mohamed H. El-Khashab¹, and Bosy A. El-Haddad¹

¹ Geology Department, Faculty of Science, Sohag University, Sohag, Egypt
bosy_abdelaziz@hotmail.com

² Geological Hazards Department, Applied Geology Sector,
Saudi Geological Survey, P.O. Box 54141, Jeddah 21514,
Kingdom of Saudi Arabia
amyoussef70@yahoo.com

Abstract. Karst environments are characterized by distinctive landforms related to dissolution characteristics. Karst terrains, frequently underlain by cavernous carbonate and/or evaporite rocks, may induce ground instability problems. Impacts and problems associated with karst are rapidly increasing as development expands upon the karst prone areas. This has led to an escalation of karst-related environmental and engineering problems such as landslides developed on rock cuts/slopes weakened by karstification features. In the current work, the effects of karstification and sinkholes on the stability of the rock cuts/slopes along some selected desert highways were evaluated. These highways represent the most used highways in Egypt, connecting most of the Governorates. They represent the backbone of Egyptian transportation and commercial traffic. Finally, the most optimum mitigation/remediation methods were summarized to decrease and minimize the consequences of slope instability.

Keywords: Slope stability · Geohazards · Karstification · Sinkholes · Egypt

1 Introduction

Highways and roads represent an essential part of the economy development in highly populated areas of Egypt, such as the Nile valley area. Many highways connect the Upper Egypt's Governorates with each other and with the capital Cairo, including western desert, eastern desert, and Nile Valley highways. Most of the traffic runs along the western and eastern desert highways. Recently, many development areas 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 rugged terrains which are characterized by karst rocks (carbonates) where a variety of different hazards (Parise 2008; Gutierrez 2010) can be presented, and involve the transportation system. Different factors can contribute to landslides (slope stability problems) such as climate, slope conditions, geological

characteristics, and construction method (Youssef et al. 2009). A landslide can be defined as a rapid disaster which may involve falling, sliding or flowing of soil and rock (Cruden and Varnes 1996). Hungr et al. (1999) indicated that the transportation systems are vulnerable to rockfalls wherever they cut across or skirt along mountains, plateaus, ridges and similar topographic features. In the context of highway rock slopes, potentially landslide zones pose risks to the traveling public, infrastructures, local economies, and the environment (Palma et al. 2012a). Rockfalls may not be considered hazardous unless rocks enter the highways (Chau et al. 2004). Rockfalls remain a serious problem to many transportation agencies, which are responsible for providing and maintaining safe and reliable highways and routes in an economical fashion. Hazards related to landslides can result in traffic accidents, blocked highways, and increased maintenance costs, as well as other hazards to the public (Bateman 2003; Palma et al. 2012a; Youssef et al. 2012). Raju et al. (1999) indicated that landslides cause the death or injury of thousands of people and significant property loss every year in India. However, prediction of landslides (slope stability problems) is very difficult because of the complexity of the factors causing these problems (Yuan and Mohd 1997).

The fundamental role played by karst in predisposing and/or favoring slope stability problems has been barely explored, largely due to the difficulty of its investigation and assessment, but in recent years several works have dealt with the issue (Parise and Gunn 2007; Parise 2008; Gutierrez 2010; De Waele et al. 2011; Gutiérrez et al. 2014). Slope movements in carbonates and evaporites are generally studied and described without paying much attention to the voids, cavities, open joints, dissolution features, and filled sinkholes produced by karst processes and their detrimental influence on the mechanical properties of the rock masses. Dunne (1990) indicated that the presence, distribution, and frequency of voids and/or caves of different sizes may have an essential impact on the slope stability and its hydrology. All types of landslides proposed by Cruden and Varnes (1996) could occur in karstified rock masses.

The environmental fragility of karst settings, together with their endemic hazardous processes, has received an increasing attention from the scientific community in the last decades (Ford and Williams 1989; Williams 1993; Gillieson 1996; Vermeulen and Whitten 1999; Barany-Kevei and Gunn 2000; Waltham et al. 2005; Parise and Gunn 2007). Concurrently, the interest of planners and decision-makers on a safe and sustainable management of karst lands is also growing. Gutiérrez et al. (2014) indicated that a correct understanding of the sinkhole typology constitutes a crucial step for a proper hazard assessment and the design of effective mitigation measures. Many examples of landslides and/or rockfalls occurred in karst rocks (carbonate and evaporate rocks) were documented by different authors (Santo et al. 2007; Prager et al. 2008; Ivy-Ochs et al. 2009; Iovine et al. 2010; Jaboyedoff et al. 2011; Parise and Lollino 2011; Gutiérrez et al. 2008a, 2012; Palma et al. 2012a; Carbonel et al. 2014. Santo et al. (2007) mentioned that there are few reported cases in which a natural cave has been involved in the formation of a slope failure. Pánek et al. (2009) proposed the role played by karstification as a preparatory factor of the development of catastrophic slope failures in mountainous areas. Jaboyedoff et al. (2009) indicated that the

development of large and catastrophic translational landslides in carbonate successions is typically favored by the presence of laterally extensive and extremely planar bedding planes such as the Frank rockslide-avalanche, which destroyed the southern end of the town of Frank in southwestern Alberta, Canada. One of the most documented example of landslide in karstic rocks was the 1963 Vajont translational slide in northeastern Italy, which moved into a reservoir, thus causing a huge impulse water wave that overtopped the concrete dam leading to a sudden catastrophic flood destroying some villages and killing over 2000 people (Semenza and Ghirotti 2000; Kilburn and Petley 2003). Another situation in which karst features (differential erosions and dissolution cavities) are the main factors causing slope movements in coastal cliffs, due to deepening of coastal caves and/or notches (Delle Rose and Parise 2004; Youssef et al. 2009; Vallejo 2012).

The main objectives of this research are the assessment of the slope stability problems of the carbonate rocks due to the presence of sinkholes and karst features. Three highway sections were selected, two zones along eastern desert highway and one along the western desert highway (Fig. 1). The term slope stability problems in this work represent any type of landslides that could be registered due to the effect of karstification features, including rockfalls and rock slides of all kinds (free falling, toppling, bouncing, rolling or sliding). Field investigations were carried out in different areas along rock cuts to understand and determine the most influential karst features that have a strong impact on slope stability. The detailed objectives were to discuss: (1) the origin of karst in the study area and their classification; (2) describe the most relevant karstification features that could impact the slope stability; (3) describe the types of slope stability problems related to karstification; and (4) develop a remediation/mitigation strategy to minimize any future problems.

2 Study Area

In the recent years, the Egyptian government established many highways all over the country. This will increase the tourist activities, transportation between different areas, goods incomes and outcomes, and will contribute to open new areas for future development. Because of the nature of the terrain and population distribution along Egyptian territories, a significant number of highway projects were constructed in mountainous and/or hilly areas. These hilly areas are characterized by frequent slope stability problems (landslides). The current study deals with the eastern and western desert highways (eastern desert Sohag – Red Sea – Cairo highway, western desert Sohag – Cairo highway; and eastern desert Assuit – Cairo highway) (Fig. 1). The geology of the area is composed mainly of Eocene limestone. Generally, this limestone in the study area is dissected by many structural elements (faults and/or joints) affected by sinkholes. The general appearance of limestone is white to gray in color with weathered reddish surfaces.

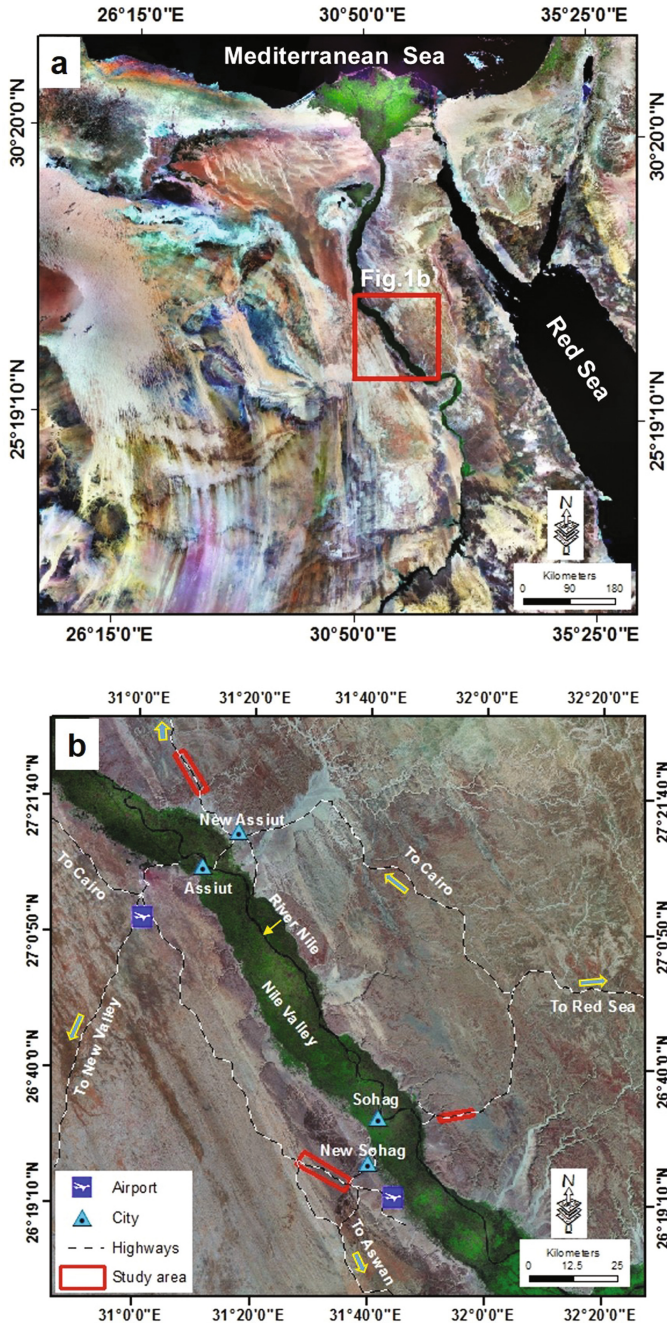


Fig. 1. (a) Study area location in Egypt map. (b) Detailed characteristics of the study area.

3 Data Collection and Methodology

Multiple field visits were carried out in the study area in order to investigate and evaluate the slope stability hazards and their relationship with karstification processes. Observations were conducted to identify potential hazard zones while considering the most influencing parameters. Later these hazard zones were located and documented with GPS coordinates. Field data collection includes (a) rock and material types (the main rock and material types at each site have been collected, identified and investigated); (b) weathering characteristics were identified by observing the degree of change in color and the rock fabric; (c) compressive strength (the strength of the intact rocks and the soil matrix in the filled sinkholes was measured using geological hammer (Burnett 1975)); (d) slop/cut face characteristics were determined (direction and slope); and (e) discontinuities characteristics were identified (fracturing degree, dip and dip direction values). Laboratory work was conducted including; (a) Jar slake test was conducted for shale samples according to Santi (1998) test procedure. The test depends on collecting samples, each sample weight 50 g which is oven-dried at 110 °C for 16 h, and allowed to cool for 20 min then immersed in distilled water for 30 min and 24 h. The results can be described according to Santi (1998) into six categories: (1) degrades to a pile of flakes or mud, (2) breaks rapidly and/or forms many chips, (3) breaks slowly and/or forms few chips, (4) breaks rapidly and/or develops several fractures, (5) breaks slowly and/or develops few fractures, and (6) no change; (b) slake durability test was carried out on marly limestone of the study area. These samples were subjected to 4 cycles of slake durability; (c) determine friction angle using tilt test; and (d) other physical properties were determined for the limestone samples such as unit weight.

4 Results and Discussions

4.1 Origin and Classification of Sinkholes

Sinkholes are depressions with internal drainage, widely regarded as one of the main diagnostic landforms of karst (Ford and Williams 2007). Sinkhole is the most common term in the international literature dealing with engineering and environmental issues (Beck 1984, 1988; Parise and Gunn 2007). Sinkholes can be distinguished in different shapes, such as cylindrical, conical, bowl- or pan shaped, and varying in size from less than a meter up to hundreds of meters across and with a depth from a few to tens of meters (Youssef et al. 2016). Sinkholes are often related to dissolution of carbonate and/or evaporite rocks/deposits (Fookes and Hawkins 1988; White 1988; Ford and Williams 2007; Palmer 2007). There are some crucial differences in sinkhole related to carbonate and evaporite rocks (Gutiérrez et al. 2008a; Gutiérrez and Cooper 2013): (1) Dreybrodt (2004) indicated that evaporites dissolve much more rapid than carbonates. Evaporites, such as gypsum and halite, have significantly lower strength and more ductile than most carbonate rocks. In the current study, the genetic classifications of sinkholes proposed by Gutiérrez et al. (2008b, 2014), and by Gutiérrez and Cooper (2013) were used. In these classifications, two terms are used, the first term referring to material type including cover (unconsolidated deposits or residual soil material),

bedrock (karst rocks), and caprock (non-karst rocks). The second term represents the subsidence mechanisms including collapse (brittle deformation of soil or rock material), sagging (ductile bending of sediments and rocks due to the absence of basal support), and suffusion (downward migration of cover deposits through voids). Complex sinkholes could be used in which different material types and several mechanisms could be detected. In the current study, according to the genetic classification, different types of sinkholes were detected in the study area as shown in Fig. 2. These types of sinkholes are the most important from a hazard and engineering

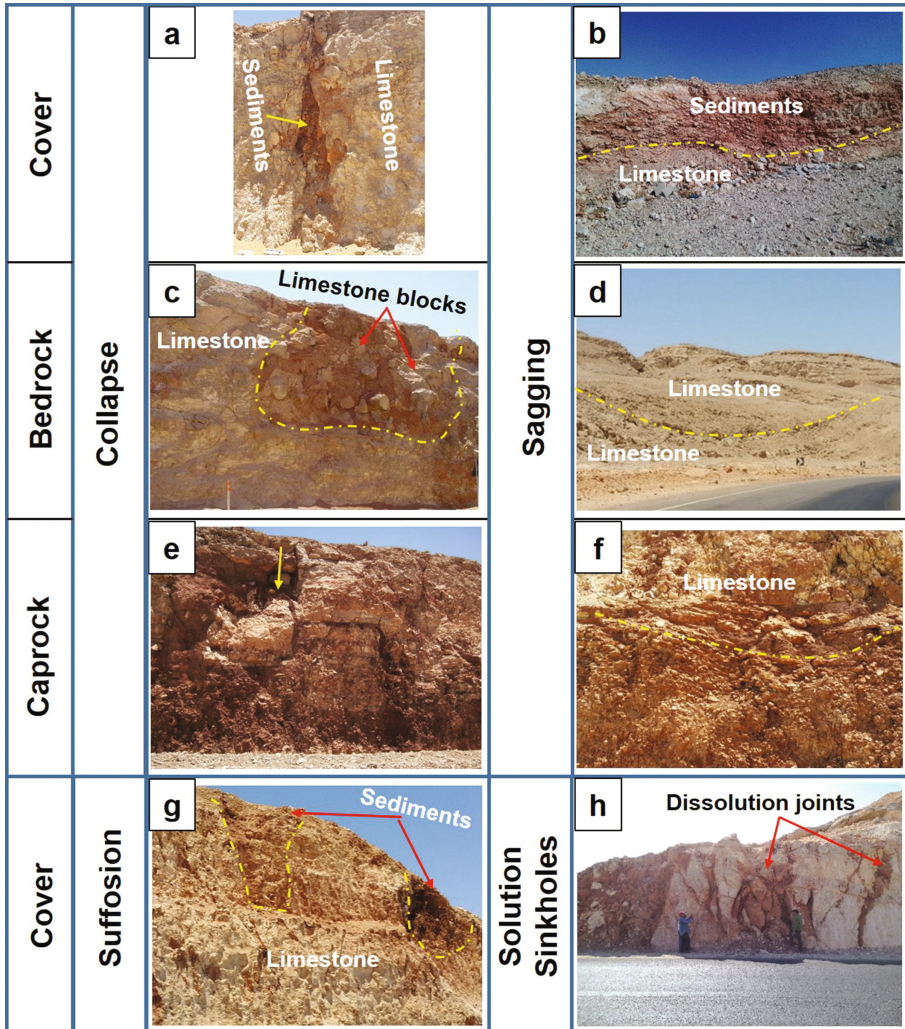


Fig. 2. Sinkholes classification in the study area (a) Cover collapse sinkhole, (b) Cover sagging sinkhole, (c) Bedrock collapse sinkhole, (d) Bedrock sagging sinkhole, (e) Caprock collapse sinkhole, (f) Caprock sagging sinkhole, (g) Cover suffusion sinkhole, (h) Solution sinkhole

perspective including; Cover collapse sinkhole (Fig. 2a), Cover sagging sinkhole (Fig. 2b), Bedrock collapse sinkhole (Fig. 2c), Bedrock sagging sinkhole (Fig. 2d), Caprock collapse sinkhole (Fig. 2e), Caprock sagging sinkhole (Fig. 2f), Cover suffusion sinkhole (Fig. 2g), and Solution sinkhole (Fig. 2h).

4.2 Main Characteristics of Karst Features Along the Desert Highways

In the current study, different processes can increase the slope stability problems including: active weathering processes (differential erosions); breakdown processes of the rocks that lead to increase the joints opening; weathered surfaces with the presence of reddish soil zone; and voids, cavities, and sinkholes (empty or filled). Fill materials in sinkholes include boulders (up to 1.5 m diameter) and fine grained matrix (weak and easily eroded) (Fig. 3). The rock and materials along the three selected highways are characterized by; massive limestone with flint is characterized by strong to very strong rock (50–150 MPa), low degree of fracturing, slightly weathered, and unit weight (2.4–2.5 kg/m³); bedded limestone is moderately strong to strong rock (25–75 MPa), highly jointed, slightly to moderately weathered, and unit weight (2.35–2.45 kg/m³); marly limestone is moderately weak rock (5–12.5 MPa), moderately to highly jointed, moderately to highly weathered, and unit weight (2.3–2.4 kg/m³); shale is weak rock (1.25–5 MPa), highly fractured, slightly to moderately weathered, and unit weight (1.7–1.9 kg/m³); and block-in-matrix deposits are characterized by limestone blocks embedded in weak cemented deposits (very weak material < 1.25 MPa). Several studies have postulated that differential erosion contributes to rockfalls (Hampton et al. 1693). Erosion of the weak materials (marly limestone and shale) along the rock cuts/slopes of the three selected highways causes overhanging of the massive rocks and eventually collapse. The shale layers have color ranges from green to yellow. The sensitivity of a rock type against erosion is usually described by a durability parameter (Khalily et al. 2013). In the current study, 10 jar slake tests were carried out for the green and yellow color shale layers to determine the durability degree according to Santi (Santi 1998) test procedure. The results indicated that yellow shale degrades from a pile of flakes or mud and green shale breaks to form many chips. In addition to that the slake durability test was carried out on 30 samples of the marly limestone of the study area. The marly limestone were subjected to 4 cycles of slake durability test. Results indicate that the slake durability index ranges from 97.5% (high durability) after the fourth cycle to 99% (very high durability) after the first cycle. The presence of these filled sinkholes during excavation, have an adverse effect on the slope stability. In general, during blasting the explosion gasses will force their way out of the rock mass via the karstic discontinuities rather than by breaking intact rock. There are many links between karst features and slope stability problems (landslides) such as solution enlarged discontinuities in the rock mass. The limestone along the rock cut/slope of the three selected sites is highly fractured, and sometimes sinkholes filled with highly weathered materials. The limestone of the rock cut and slopes along the three selected highways is characterized by the presence of filled sinkholes (Fig. 3b). They have a significant impact on slope stability in the study area. The sinkhole package comprises different materials ranging in size from fine matrix materials to coarse boulders as large

as 1–2 m in diameter. They are composed of angular materials cemented by reddish, sandy, mud sediments that are weak and easily eroded (by wind and/or water). The presence of these filled sinkholes during excavation, have an adverse effect on the slope stability. In general, during blasting the explosion gasses will force their way out of the rock mass via the karstic discontinuities rather than by breaking intact rock. There are many links between karst features and slope stability problems (landslides) such as solution enlarged discontinuities in the rock mass. The limestone along the rock cut/slope of the three selected sites is highly fractured, and sometimes sinkholes filled with highly weathered materials.

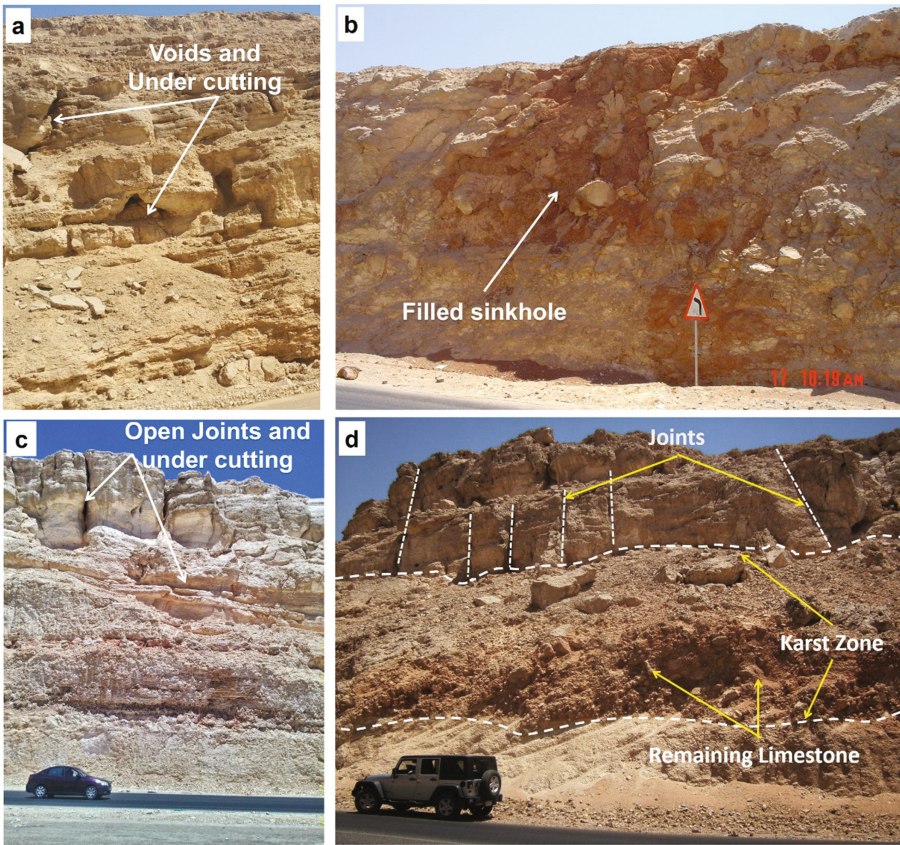


Fig. 3. (a, c) rock cut and slope along the eastern desert highway (Sohag- Cairo); (b) rock cut along the eastern desert highway (Sohag- Red Sea- Cairo); and (a, d) rock cut and slope along the western desert highway (Sohag- Cairo).

4.3 Landslide Types and Their Mechanisms in Karst Zones

Rockfall mechanisms are controlled by different factors including geological characteristics of the area, climate conditions, and weathering processes (differential erosions). Kay et al. (2006) believed that water, lithology, geological structure, and karstification are important factors in triggering rockslides. Perret et al. (2004) indicated that direction/type of discontinuities and the volume of the overhang materials play an important role in the size, shape, and the detachment place of the blocks. In the study areas, fallen boulders and blocks of different sizes and shapes were recognized. These rockfall events are triggered by different factors including discontinuities, wind action, surface water, human activities, and differential erosion among the different rock units. Based on the detailed field investigations, different slope stability models were explained that represent the slope stability problems along the selected highways.

Rockfall and Raveling Model

Two models were proposed for the rockfall activity in the study area including: (1) The first model (Fig. 4a, b) is related to (a) the karstic effect along tectonic fractures and/or faults can slowly widen the width to create open fractures and empty caves that can be some tens of meters long and more than 1 m wide. These might favor the start of rock falls especially along the upper part of the limestone cliffs in the three selected sites. (b) Rockfalls are also associated with the presence of overhanging, the result of erosion of the shale and marly limestone beds separating massive limestone beddings. The shale and marly limestone layers have low resistance to erosion processes. This will leave a large volume of rocks overhanging. Due to the weight of overhanging blocks, tension cracks will appear at the top of the slope. These tension cracks represent an evidence of a deformation on the rock mass. (2) The second rockfall model is particularly problematic in the filled sinkholes where large blocks embedded in weak materials. The fill materials in these sinkholes consist of large boulders (up to 2 m diameter) embedded in fine weakly matrix. The fine materials (matrix) are weak (1.25–5 MPa) and easily eroded by seepage water and wind action. The rockfalls are associated with the presence of overhanging of the large blocks (boulders) due to the erosion of fine materials (Fig. 4c, d).

Sliding Type Models

Adverse geologic structures including open joints, shear zones, and empty cavities exist along the study area. In order to assess the potential mode of failures and the stability of slope faces in the selected highways along limestone rocks, field investigations were performed to map discontinuity distributions (dip direction and dip angle), to calculate the friction angle along the sliding planes, and to determine the main characteristics of the rock masses (Harrison et al. 2002; Waltham 2002; Parise 2008; De Waele et al. 2011; Parise and Lollino 2011; Gueguen et al. 2012; Palma et al. 2012a, 2012b; Pepe and Parise 2014; Andriani and Parise 2015). Field data of discontinuities were

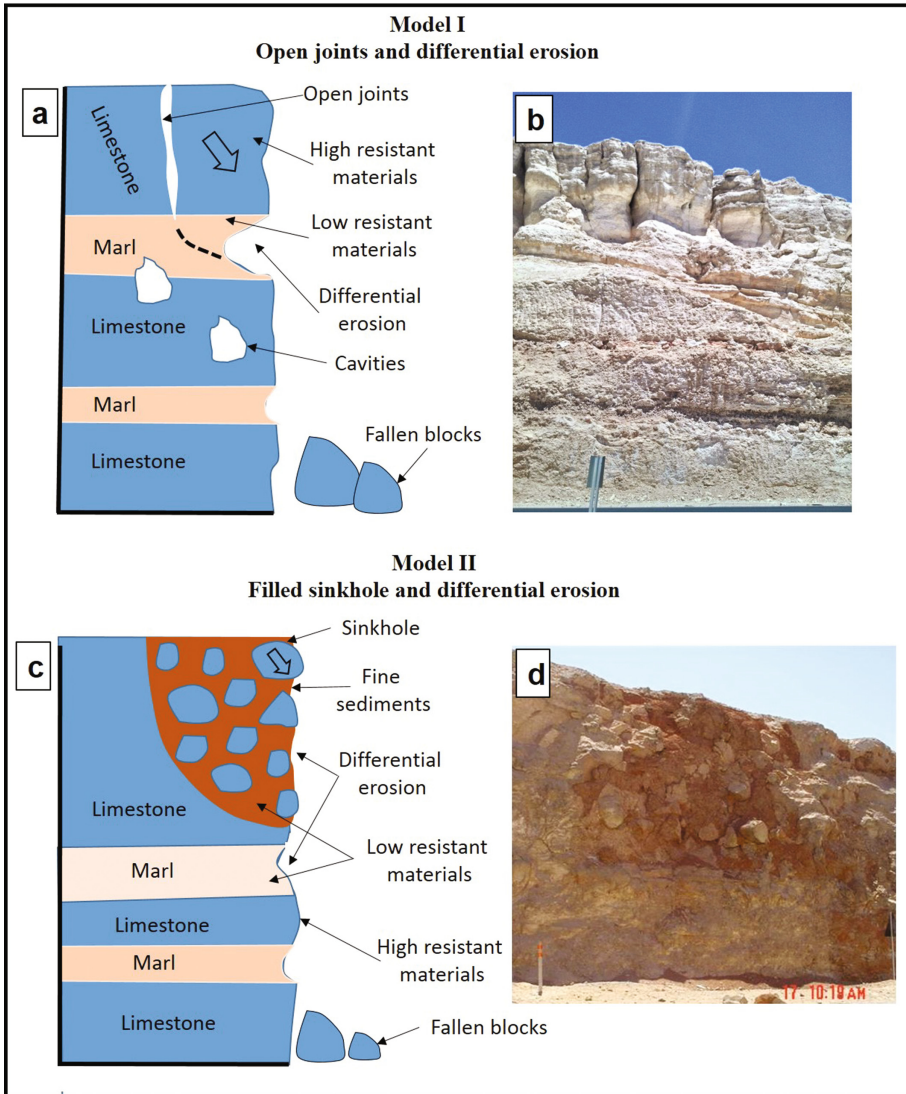


Fig. 4. Models of rockfall and raveling (a, b) due to open joints and differential erosions, (c, d) due to sinkhole and differential erosion.

statistically analyzed for the three selected highways. For the field method, friction angle has been measured using a tilt test, 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 was recorded. The results of tilt test of different blocks for the three selected highways in the study area showed that, the value of the tilted angle ranges from 19°–28°. To estimate the friction angle Eq. (1) was used.

The final friction angle for the three selected highways ranges from 22° to 33°. To be conservative a friction angle of 22° has been used in this study.

$$\phi_b = \tan^{-1}(1.155 \tan \alpha) \tag{1}$$

Where alpha (α) is the tilting angle and ϕ_b is the friction angle

The calculated friction angle is related to the limestone with weathered surfaces. Consequently, the kinematic method using stereographic projection method was used (Markland 1972), a friction angle of 22° was incorporated into the analysis. The markland test compares the orientation of the rock cut with the orientation of the discontinuities and the friction angle. Results of the test, along the three selected highway zones, indicate that most of the potential failures are of the planar, wedge and circular types (Fig. 5a, b, c, d, e). Planar, wedge and circular failure types are associated chiefly with the presence of joint systems. Weathering effect and karstification features play an important role in these stability mechanisms. Karstic dissolution play fundamental roles in the processes of joint widening, clastic movement, increase of the

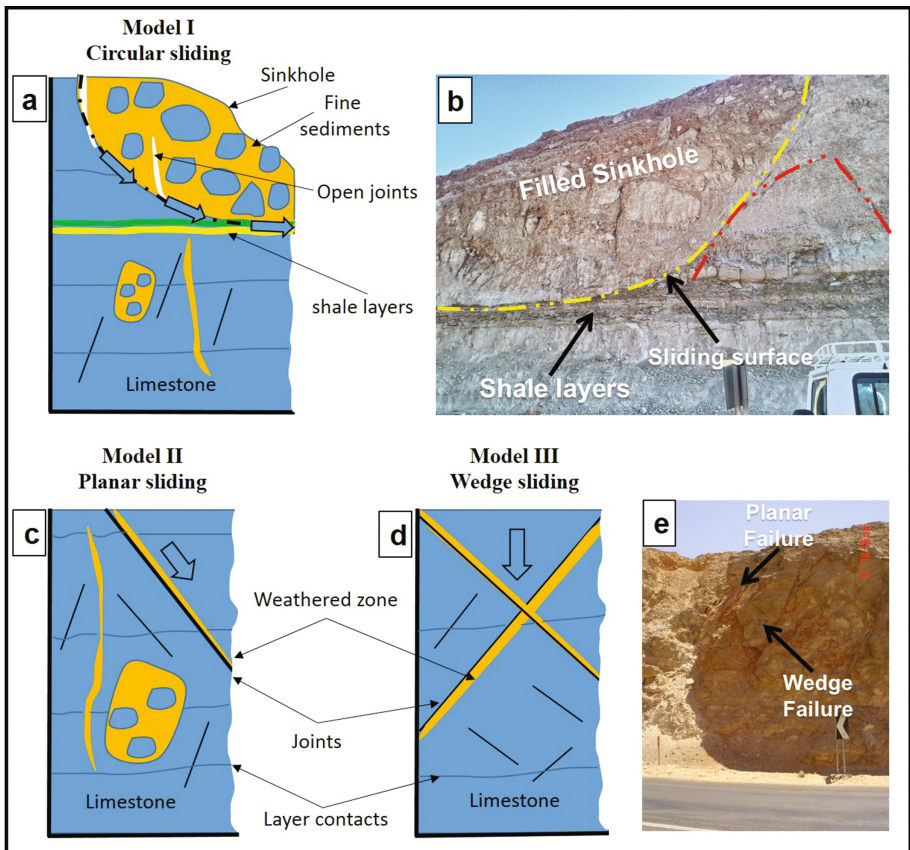


Fig. 5. Models of sliding (a, b) Circular sliding, (c, d, e) planar and wedge sliding.

voids and the reduction of cohesive strength (Fookes and Hawkins 1988; White 1988; Ford and Williams 2007; Palmer 2007). Discontinuities keep widening and extending to the deep of rock mass by constant dissolution and disgregation of underground water (Santo et al. Santo et al. 2007). This leaves cavities supported by remnant points of contact across opened discontinuities leading to decrease in the shear strength, and points of contact may breakdown due to overstressing. The failure potential increases due to the weathering materials along the joint surfaces due to dissolution (clay materials) (Fig. 5e). Another type of failure includes the circular failure along the contact between filled sinkholes and massive rocks (Fig. 5b). The presence of shale layers under the filled sinkhole will accelerate the circular failure to occur. This is related to the rapid disintegration of shale due to water effect. The jar slake tests, of the green and yellow color shale samples, indicate that the shale samples degrades from a pile of flakes or mud (for yellow shale) to form many chips (for green shale).

5 Remediation/Mitigation Options and Recommendations

Many authors suggested different methods that will help in preventing rockfalls or minimizing their impacts (Fookes and Sweeney 1976; Peckover and Kerr 1977; Hoek 1977, 2001; Hoek and Bray 1980). These methods are used to stabilize the rocks in place, to protect the road from moving rocks, and/or to provide adequate warning system to vehicles. Two methods are mainly used to increase the safety at a single site including remediation and mitigation options.

Remediation methods are applying a physical restraint to landslides. They consist of the application of rock bolting and/or shotcrete, or building a metal, concrete or stone retaining wall. These methods are very costly; especially the retaining walls, and tend to be used in very small areas. For the bolted or shotcrete solutions, further deterioration of the rock will make these efforts unpractical over time.

Mitigation Options of landslides consist of methods that allow rock to fail but minimize the damages by containing the fallen rock and not allowing it to impact the vehicles and highways. The mitigation methods include different types such as catchment benches and ditches, berms and/or fences, draped wire mesh, or rock shed structures.

For the current study, the remediation options were considered to be not adequate methods due to the presence of filled sinkholes all over the carbonate rock cuts. However, mitigation methods will be suitable. For the karstic zones along the three selected highways, the following mitigation methods could be used including: (1) catch benches and ditches, which act as traps of fallen rock, represent the most effective solutions. These work adequately in catching rockfalls if there is sufficient space at the toe of the slope to accommodate the trapped rocks. (2) Retreating the rock cuts in narrow roads by blasting to create ditches and benches is also not an option in the current study, because of the cost and disruption due to the presence of filled sinkholes. (3) Berms are a very effective means of catching rockfalls but also need space. (4) Wire mesh is a good alternative. Draping wire mesh 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 creates significant damage if the draped mesh is not routinely inspected and maintained. (5) Catch fences or barrier fences are effective way to increase the ditch capacity (volume and width) if the current ditches are inadequate. Fences and barriers such as jersey barriers are ideal solutions for this situation since they occupy small space. (6) Line the ditch with an energy damping material such as gravel or sand. It requires also routine inspection and maintenance (remove of fallen rock).

6 Conclusions

In the current study, three different highway zones were selected to study karst induced slope stability problems. The study reveal that, there is a crucial impact of the karst features on the slope instability phenomena. Many sections of the rock cuts along these selected highways are not stable and may endanger the traffic safety if the rocks are not stabilized. It was found that different karst features contribute the slope stability problems such as differential erosions, open joints, empty cavities, filled sinkholes, and weathering effect along discontinuities. Different landslides types were detected in the study area including rockfalls due to differential erosions and filled sinkholes, planar, wedge, and circular failures. It was found that mitigation methods are most effective to increase the rock stability.

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