



# Landslide mechanisms along carbonate rock cliffs and their impact on sustainable development: a case study, Egypt

Bossy A. El-Haddad<sup>1</sup> · Ahmed M. Youssef<sup>1,2</sup>  · Abdel-Hamid El-Shater<sup>1</sup> · Mohamed H. El-Khashab<sup>1</sup>

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## Abstract

Recently, Egypt has faced unprecedented development with rapid urban and infrastructure expansion. Vast areas of Egypt are underlain by karst rocks (carbonate and evaporite). Highways and roads constructed along these karst areas are susceptible to slope stability problems. Various factors could trigger different landslides along the carbonate rock cliffs and slopes. Hence, urgent actions need to be considered to understand the landslide mechanisms that could occur along these cliffs and slopes. Carbonate rock cliffs and slopes along with some highways in Sohag-Assiut area, Egypt, were chosen as a case study in this work. Field and laboratory investigations were carried out as tools in understanding and identifying these failure mechanisms. In addition, remote sensing high-resolution images were applied to help in identifying different features, causing slope instability. Our finding indicated that five landslide mechanisms in carbonate rock cliffs and slopes were identified and categorized. These five slope instability mechanisms are including collapses of weak materials from filled caves, the breakdown of caves, instability due to differential erosions, dissolution along discontinuities, and sliding along weak surfaces. This study could help the decision-makers and planners to understand the causes of slope instability problems, to maintain the sustainability of the infrastructure, and to design appropriate prevention and remediation measures to avoid future problems.

**Keywords** Field and laboratory investigations · Slope stability · Carbonate slopes · Egypt

## Introduction

One of the most common definitions of landslides is the movement of different materials (rocks, detritus, and/or soils) by the action of gravity leading to an observable and catastrophic event (fall, slide, topple, and/or soil movement) (Cruden and Varnes 1996; De Blasio 2011). Transportation lines (roads, highways, and railways) in the different region around the world are exposed to various types of landslides (e.g., rockfalls, rockslides, debris flows, and soil slides)

wherever they cut across or skirt along mountains, posing risks to the travelers (death or injury), blocking the highway. Also, urban areas are affected by landslides, especially old buildings with inadequate foundations and new buildings that are not designed to bear displacements induced by landslides, are prone to damage and collapse (Nicodemo et al. 2017; Peduto et al. 2017). These increase the repair costs of transportation lines and the infrastructure and affected the local economies and the environment (Bateman 2003; Hungr et al. 1999; Raju et al. 1999; Ferlisi et al. 2012; Palma et al. 2012a; Youssef et al. 2012; Budetta et al. 2016, 2017). Kay et al. (2006) believed that geological structures, lithology, water, and karst are very active factors in triggering landslides. Perret et al. (2004) proved that the direction/type of discontinuities and the quantity of the overhang materials control the size, shape, and detachment position of the blocks.

Karst has a relevant role in triggering different instability phenomena, which did not receive considerable attention in previous decades. However, in recent years, several works have dealt with the different slope stability problems associated with various karst features (Ford and Williams 1989; Williams 1993; Vermeulen and Whitten 1999; Santo et al.

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✉ Ahmed M. Youssef  
amyoussef70@yahoo.com; amyoussef70@gmail.com

<sup>1</sup> Faculty of Science, Geology Department, Sohag University, Sohag 82524, Egypt

<sup>2</sup> Applied Geology Sector, Geological Hazards Department, Saudi Geological Survey, Jadah 21514, Kingdom of Saudi Arabia

2007, 2017; Gutiérrez et al. 2008, 2012, 2014; Parise 2008; Gutiérrez 2010; Parise and Lollino 2011; Ferlisi et al. 2012; Palma et al. 2012a; Feng et al. 2014; Carbonel et al. 2015). The cavities, voids, dissolution fractures, differential erosions, and filled caves are very common in carbonate rocks, which reflect directly on the geotechnical characteristics of the rock masses and have an essential impact on the slope stability (Dunne 1990; Santo et al. 2007; Youssef et al. 2009; Vallejo 2012). Many authors indicated that the development of large and catastrophic landslides in carbonate successions due to karst processes (Kilburn and Petley 2003; Jaboyedoff et al. 2009; Pánek et al. 2009). Different landslide hazards were encountered in carbonate rocks (karstified rock masses) that impacted the transportation system (Gutiérrez 2010; Gutiérrez et al. 2014; El-Haddad et al. 2017; Youssef et al. 2018). In other cases, the different karst features such as cavities dissolution and the differential weathering act as the main reasons for slope instability in coastal carbonate slopes due to deepening of coastal cavities and fissures (Mišćević et al. 2009; Youssef et al. 2009; Vallejo 2012; Mišćević and Vlastelica 2014; Santo et al. 2017; Guarino et al. 2018).

Different factors could cause landslides in carbonate cliffs and slopes, including karstic features (open joints, cavities, and filled caves), weathering and erosion features (undercutting, differential erosions, weathering materials along discontinuities), human activities (poor excavations, face irregularities, and overhanging), material types, and geological structure (direction/type of discontinuities). The different karst features and weathering effects have an essential role in these slope instability mechanisms. The dissolution process works on widening fractures and joints, sediments motion, growing of cavities, and the decreasing of strength (Fookes and Hawkins 1988; Ford and Williams 2007; Palmer 2007; White 1988). The discontinuities (e.g., fractures, cleavages, faults, and joints) work on extending and widening to the deep of rock mass because of the constant dissolution and disgregation of groundwater (Santo et al. 2007). The weathering effect can turn the rock into a soil-like material (Mišćević et al. 2009). The resistance of the various rock types against weathering processes can be defined as rock durability. Different standard tests could be applied to measure the degree of rock durability, such as jar durability test (for shale and clay rocks) and slake durability index (for soft rocks, such as shale, clay, conglomerates, marls, and sandstones with weak cementing material) (Franklin and Chandra 1972; Sabatakakis et al. 1993; Santi 1998; Erguer and Ulusay 2009). The degree of rock units durability has a substantial role in the formation of different slope instability features leading to high disintegration rate of rock units and slope failures (Fookes et al. 1988; Anagnostopoulos et al. 1991; Maekawa and Miyakita 1991; Johnston and Novello 1994; Frydman et al. 2007; Athmania et al. 2010; Hornig 2010).

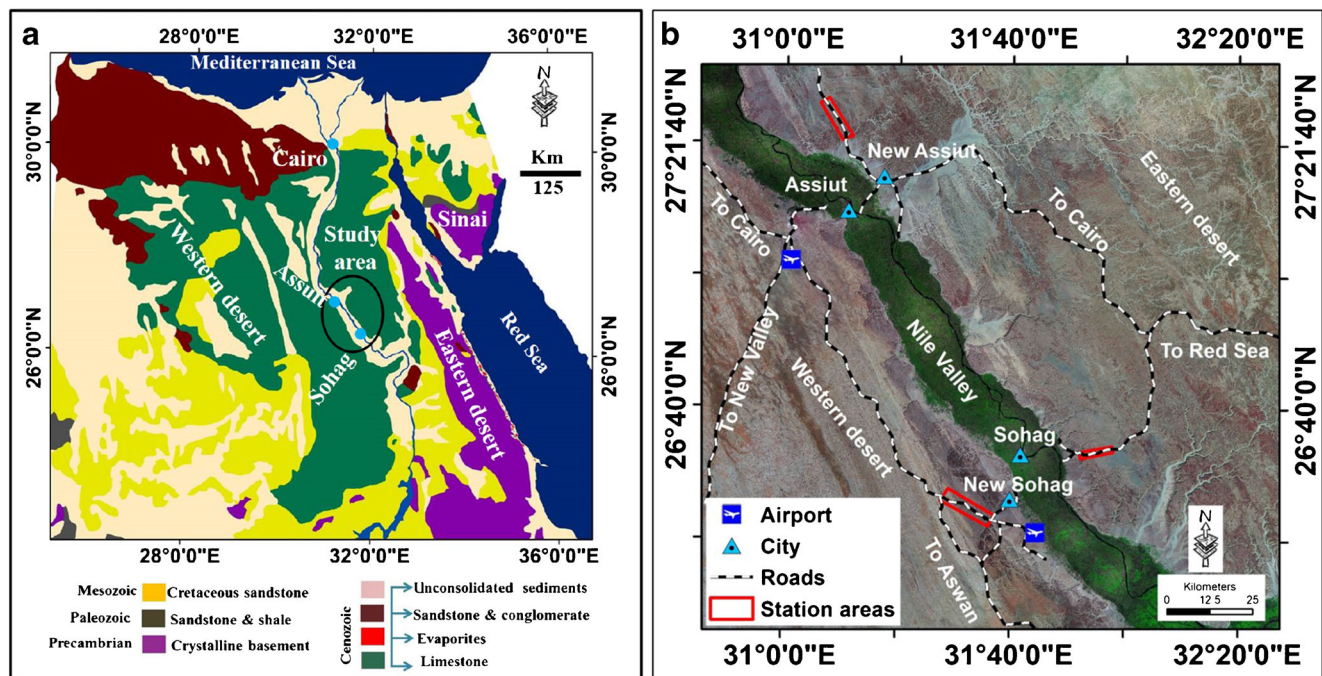
Recently, different types of landslides/slope instability areas and slow landslide movements were mapped using various methods, including historical records, field investigations, repetitive geodetic surveys, hydrogeological monitoring, and remote sensing (Käab 2000; Laprade et al. 2000; Wait 2001; Birk et al. 2003; Huggel et al. 2004; Troost et al. 2005; Di Crescenzo and Santo 2007; Schulz 2007; Macfarlane 2009; Youssef et al. 2009, 2012; De Vita et al. 2013; García-Davalillo et al. 2014; Grana and Tommasi 2014; El-Haddad et al. 2017). These studies captured the interest of the decision-makers and the planner of new cities to achieve safe and sustainable management of karst lands. Gutiérrez et al. (2014) indicated that a correct evaluation of the karst typology constitutes a crucial step for a proper hazard assessment and the design of effective mitigation measures.

Carbonate rocks represent a significant portion of the Egyptian territory. Different highways were constructed through these rocks to connect different cities, reclamation lands, and new industrial cities with each other. Karst features are widespread in carbonate rocks. The presence of karst features characterizes the carbonate rocks and intercalated with weak materials (weak sandstone, shale, marl, and marly limestone) that are eroded easily by water and wind actions (El-Haddad et al. 2017; Youssef et al. 2018).

This study aimed at categorizing, understanding, and identifying the different mechanisms of landslides along the karst-prone rocks (carbonate slopes) using field and laboratory investigations. It also will discuss the negative impact of karst features, weathering, and erosion factors on landslide mechanisms. This approach is rarely used in Egypt and will be very useful in rock cuts and slopes that move through carbonate and weak rocks.

## Study area characteristics

Part of Egypt territory is covered by karst prone areas (carbonate and evaporate rocks) (Fig. 1a). The Nile Valley and its surroundings are occupied by a buried canyon that has been carved during the Late Miocene desiccation of the Mediterranean and subsequently filled with sediments and overlooked from west and east by the limestone plateaus (western and eastern limestone plateaus) (Fig. 1a). Nowadays, Egypt faces unprecedented development, especially in infrastructures (roads and highways) and urban expansions. Many roads and highways have been established all over the Egyptian territory making an adequate road network to facilitate transportation activities for people and goods between different cities. A significant number of these roads and highways are cutting through and moving above Egyptian carbonate rocks (e.g., Eastern Sohag-Assiut-Cairo-Red Sea road, which cut through eastern limestone plateau; western Sohag-Assiut-Cairo highway moves through western



**Fig. 1** a Generalized geological map of Egypt showing the distribution of karst-prone areas (carbonate and evaporite rocks) (<http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt>). b Close up view of the

area surrounds Sohag-Assiut cites showing different highways run through limestone plateaus

limestone plateau; Ain Sokhna–Zafrana highway cut through Al-Galaah Plateau; and many small segments that connect the cites in the Nile floodplain with the western and eastern Highways move through limestone rocks). These roads and highways are subjected to landslides frequently (El Haddad et al. 2019). The current study aims at understanding and identifying the different landslide mechanisms along the karst-prone rocks (carbonate rocks), case study the highways surrounding Sohag-Assiut area (Egypt). These highways move through the western and eastern limestone plateaus (Fig. 1b). Results of the current approach can apply to all roads and highways that cut and run through limestone and weak rock units.

The stratigraphic setting of the study area had been carried out by many authors (e.g., Said 1960, 1971; Mostafa 1979; Omer and Issawi 1998) (Table 1). The various rock units distributed in the Nile Valley and the surrounding plateau are composed of sedimentary succession ranging from Lower Eocene to Recent. Most of the karst phenomenon is located in the limestone plateau, which is distinguished mainly by Eocene limestone. It includes Thebes Formation (lower part) and Drunka Formation (upper part) (El-Naggar 1970; Keheila et al. 1991; Said 1961). Figure 2 shows a lithological section that was generated of a slope cut along Sohag-Red Sea Highway. It is located at lat.  $26^{\circ} 32' 52.68''$  N and long.  $31^{\circ} 52' 52.26''$  E. The exposed section is composed of Thebes and Drunka formations (karst prone rocks).

Thebes Formation represents the main part of carbonate rock in the study area. Keheila et al. (1990) divided the

Thebes Formation in Sohag-Qena stretch into lower, middle, and upper lithofacies. In the study area, the Thebes Formation is represented by the middle and upper lithofacies. The upper lithofacies of Thebes Formation, reaches 56 m in thickness, is characterized by dark gray, thinly banded, and laminated micritic limestone intercalated with burrowed and mud supported limestone. Numerous chert bands and concretions are intercalated and arranged in a rhythmic manner. Several flint nodules, either arranged in certain horizons or randomly distributed within the succession, are also recorded. The middle lithofacies is mainly characterized by yellowish-white thinly laminated, rhythmic pure lime mudstones, and wackestones rich in chert nodules and bands. This lithofacies is intercalated with two remarkable gray to yellowish-green calcareous shale horizons (reach 1.5 m in thickness) with abundant Nummulites, Assilines, and Operculines. The lower shale bed is  $\sim 1\text{--}1.5$  m of yellowish-green calcareous shale, and the second bed is  $\sim 1.5\text{--}2$  m whitish-gray calcareous shale. According to X-ray diffraction and microscopic examination of the Thebes carbonates, it was demonstrated that there is an extensive occurrence of dolomitized limestones sharing the composition of the sequence. Evaporite minerals such as gypsum, anhydrite, and halite show a parallel occurrence with dolomites (Keheila et al. 1991). Hafez et al. (2017) classified the mineralogy of the Thebes Formation into two main parts: the carbonate minerals and the non-carbonate minerals. The carbonate minerals were represented mainly by calcite as the major carbonate mineral in the bulk samples of this formation. This calcite was recorded as micrite or recrystallized calcite

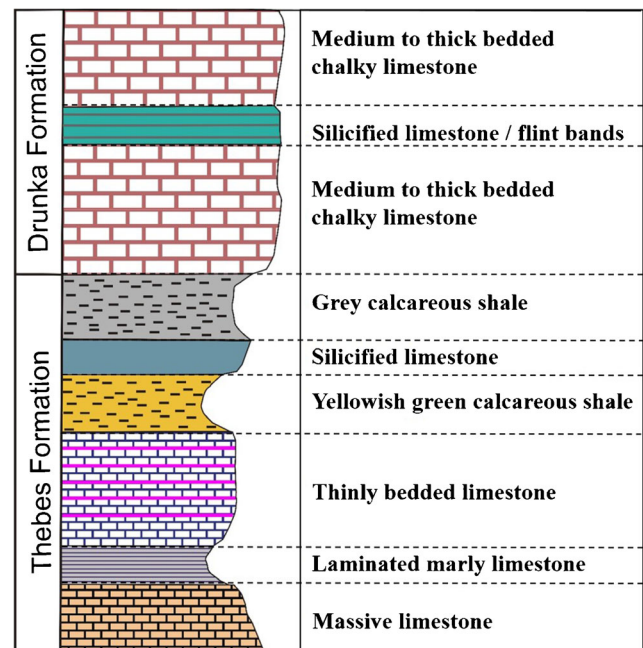
**Table 1** A stratigraphic column of the study area. Note that karst prone rocks are Thebes and Drunka Formations (lower Eocene rocks)

Age	Formation	Description	
Neogene and quaternary	Recent (Holocene)	Wadi deposits Disintegrated product of the nearby Eocene carbonate, in addition to the reworked material from the pre-existing sediments	
	Pleistocene	Alluvial deposits (Nile floodplain)	Clays and silts with sandstone intercalations
		Dandara	Fluviatile fine sand-silt intercalations and accumulated at low-energy environment (Omer and Issawi 1998)
		Ghawanim	Nile sandy sediments exhibiting the first appearance of the heavy mineral of ithyupian origin
		Kom Ombo	Sand and gravel sediments containing abundant coarse fragments of igneous and metamorphic parentage
	Qena	Quartzose sands and gravels lacking igneous and metamorphic fragments (Said 1981)	
	Late Pliocene/Early Pleistocene	Issawia	Clastic facies at the lake margins and carbonate facies in the central zones (Said 1971)
Early Pliocene	Muneiha	Bedded brown and gray clays intercalated with thin beds and lenses of silt and fine sand, and fluviatile-dominated sediments made up of sand, silt, and mud intercalations (Omer and Issawi 1998)	
Lower Eocene	Drunka	Medium to thick-bedded succession of limestone, which is highly bio-turbated in some horizons, with siliceous concretions of variable sizes (Mostafa 1979)	
	Thebes	Massive to laminated limestone with flint bands or nodules and marl rich with Nummulites and planktonic foraminifera (Said 1960)	

(sparite). Also, dolomite is associated with calcite in dolomitized limestone facies. The dolomite rhombs, as revealed from the microscopic investigations, are scattered throughout the micritic matrix and sparit groundmass. The non-carbonate minerals form the minor contents in these carbonate rocks and include quartz, halite, iron oxides (hematite), iron sulfide (pyrite), and clay minerals.

Drunka Formation represents the upper part of the carbonate succession in the study area. Generally, the thickness of Drunka Formation increases northward and westward with a total thickness up to 186 m. Drunka Formation was described by Said (1990) as gray to snow white, massive, hard, mainly crystalline-algal limestone and divided into three units: the lower bed made of chalky limestone, the middle one composed of massive silicified limestone, and the upper bed composed of gray to yellowish limestone. Petrographically, Drunka Formation in the study area is characterized by three types: lime mud, wackestone, and a few packstone. Drunka Formation is mainly composed of 30–50% sand-sized fossils with random orientation, rare peloids, intraclasts, and sparry calcite embedded in a micritic matrix. Echinoids and bryozons algae are present locally (McBride et al. 1999). Most of the fossils and part of the micrite matrix have been replaced by spar. All forms of calcite, including spar filled fractures, are non-luminescent. Also, the results of

the scanning electron microscope showed that sparry calcite is nearly stoichiometrically pure calcite except for 0.5% mol Mg in some samples. All other minor elements



**Fig. 2** Simplified lithological section along Thebes and Drunka Formations east of Sohag area shows different lithology units (not to scale)

were below the detection limit (Khalifa et al. 2004). The uppermost part of Drunka Formation in the study area shows different sizes and shapes of open and fill cavities and very dense bioturbation zones.

## Methodology

Several field studies were carried out in the area around Sohag City including the Sohag-Assiut asphaltic road and Sohag-Red Sea road. These investigations were enabling us to understand and identify different rock unit characteristics and karst features that could have an essential role in different mechanisms of slope instability. Karst features were detected and investigated in detail in the Thebes and Drunka limestone formations. The limestone formations in the study area are characterized by bioturbation, joints, fissures, and fractures, which facilitate the process of dissolution of limestone and trigger the formation of cavities, sinkholes, and collapsed caves. Field investigations were conducted along 100 stations along the study area in order to (a) identify different slope stability features; (b) understand weathering and erosion characteristics; (c) investigate large- versus small-scale features, filled/collapsed caves versus empty caves, and different depositional facies associated with filled caves; (d) determine compressive strength using a geological hammer (Burnett 1975); and (e) collecting samples to perform laboratory analysis of different rock units (massive limestone, bedded limestone, marly limestone, and shale).

According to the distribution of different rock units and the accessibility to reach these materials and collect samples, some tests were conducted to acquire physical and geotechnical characteristics of these rock units as follows: (1) sixteen samples (4 samples for each rock unit) were used to conduct uniaxial compressive strength (UCS) (according to ASTM D653), density, and water absorption (according to ASTM D792, ISO 1183, and ASTM D-570 respectively); (2) six samples from yellowish-green shale and gray shale were used for the Jar slake test (three samples each shale type) (according to Santi 1998); (3) five samples of marly limestone were used to conduct the slake durability tests (according to IS-10050-1981); (4) four samples from yellowish-green shale and gray shale were used for the free swelling test (two samples each shale type) (according to ASTM D 4546); and (5) 20 samples from yellowish-green shale and gray shale (ten samples each shale type) were used to conduct liquid limit (according to ASTM D-4318).

Two durability tests were applied to indicate the erosion rates of shale and marly limestone layers including Jar slake and slake durability tests. Jar slake test was applied for shale samples, according to Santi (1998). The analysis was performed using 50 g of each sample. These samples were oven-dried at 110 °C for 16 hours, then cooled for 20 min, and finally immersed in distilled water for 30 min and 24 h.

Santi (1998) created six categories to describe the result of this test, including (1) degrades to a pile of flakes, (2) could break quickly and/or forms several chips, (3) cracks slowly and/or builds few chips, (4) disintegrates rapidly and/or develops many cracks, (5) disintegrates gradually and/or develops few fractures, and (6) there is no change detected. The second test, the slake durability test, was applied to marly limestone samples of the area under study. Four cycles of slake durability tests were suggested to give good results according to Koncagul and Santa (1999) and Lashkaripour and Ghafoori (2003). Franklin and Chandra (1972) introduced a classification for the slake durability tests using the slake index value as follows: 0–25% very low durability, 25–50% low durability, 50–75% medium durability, 75–90% high durability, 90–95% very high durability, and 95–100% extremely high durability.

In addition, visual interpretation of high-resolution satellite images (QuickBird images of June 2015 and Professional Google Earth images) was used to map the instability features. QuickBird was launched in 2001 with a meter to sub-meter spatial resolution (0.61 m for the panchromatic band). Corrected images were used to build the 3D model to extract different features that could accelerate the slope instability phenomena.

## Results and discussions

### Laboratory analysis results

Various tests, including compressive strength, density, and water absorption of massive limestone; bedded limestone; marly limestone; shale; and block-in-matrix deposit, were conducted in this study. The results are shown in Table 2. Results showed that the uniaxial compressive strength (UCS) (according to ASTM D653) of massive limestone ranges from 51 to 54 MPa with an average of 52.6 MPa, for bedded limestone from 27 to 29.7 MPa with an average of 27.4 MPa, for marly limestone ranges from 10.9 to 12.3 MPa with an average of 11.5 MPa, and for shale from 1.3 to 2.1 MPa with an average of 1.8 MPa. For filled cave materials, the geologic hammer (Burnett 1975) indicated that these materials are very weak < 1.25 MPa. According to the density test, results showed that the density of massive limestone ranges from 2.4 to 2.5 g/cm<sup>3</sup>, for bedded limestone from 2.35 to 2.45 g/cm<sup>3</sup>, for marly limestone ranges from 2.3 to 2.4 g/cm<sup>3</sup>, and for shale ranges from 1.7 to 1.9 g/cm<sup>3</sup>. Water absorption results indicated that massive limestone has the lowest values, which ranges from 2.5 to 2.9%, for bedded limestone from 6.1 to 7.9%, and for marly limestone from 10.3 to 12.6%; however, shale rocks give high absorption values, gray shale from 25.1 to 30.2%, and yellowish-green shale from 60.9 to 73.9%.

Jar slake test result indicated that yellowish-green shale samples degraded to form a pile of flakes and that gray shale samples broke to form chips. The free swell test indicated that the yellowish-green shale had an average free swell value of

**Table 2** Laboratory tests results

Rock types	Compressive strength and (average) (MPa)	Density (g/cm <sup>3</sup> )	Water absorption (%)	Free swell/ liquid limit %	Slake durability 4 to 1 cycles %	Jar slake test
Massive limestone	5154 (52.6)	2.4–2.5	2.5–2.9	-	-	-
Bedded limestone	26.1–29.7 (27.4)	2.35–2.45	6.1–7.9	-	-	-
Marl limestone	10.9–12.3 (11.5)	2.3–2.4	10.3–12.6	-	88 to 99%	-
Gray shale	1.3–2.1 (1.8)	1.7–1.9	25.1–30.2	11.4/26–28.5	-	Chips
Yellowish-green shale			60.9–73.9	17.5/32–36	-	Pile of flakes
block-in-matrix deposit	< 1.25	-	-	-	-	-

17.5% with a high liquid limit ranging from 32 to 36% and that the gray shale had an average free swell value of 11.4% with a liquid limit varying from 26 to 28.5%. For the slake durability test, the marly limestone samples were subjected to 4 cycles of slake durability test. The findings demonstrated that the slake durability index ranges from 88% (high durability) after the fourth cycle to 99% (very high durability) after the first cycle.

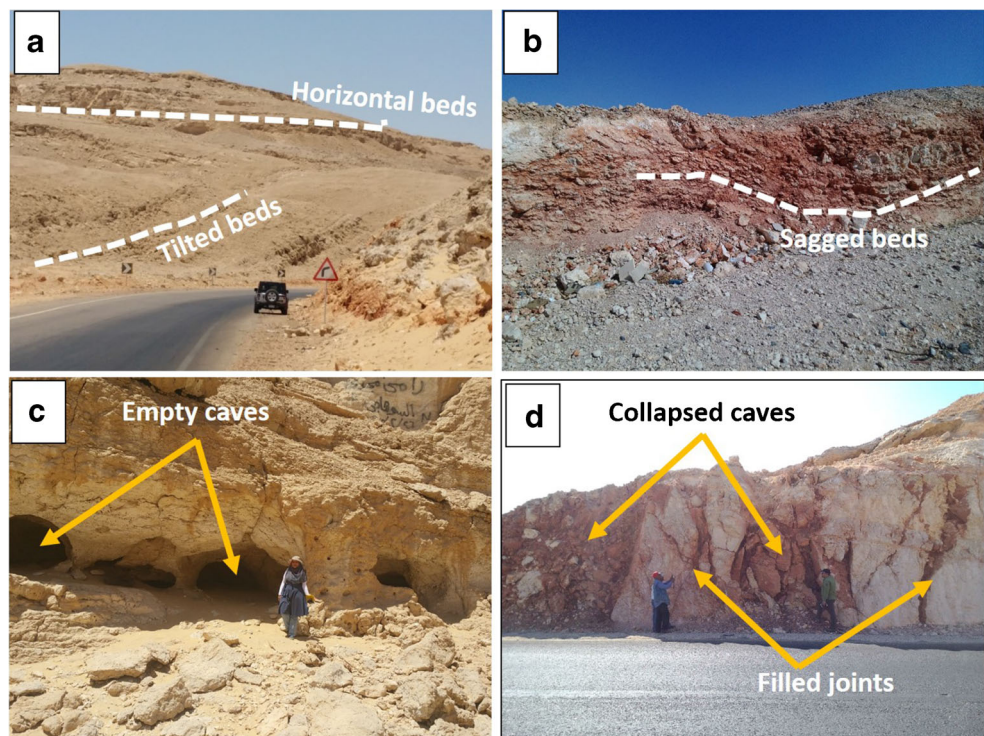
Our results indicated that strength decreases dramatically from massive limestone to shale rocks, density decreases with decreasing strength, and water absorption increases with decreasing density and strength. Our finding indicated that the study area includes many weak materials that are very susceptible to weathering and deterioration (e.g., marly limestone and filled caves materials), and other materials show swelling properties (e.g., shale layers). Consequently, the swelling mechanism of the shale layers could lead to the absorption

of water during rainy events and then will shrink when dried. Thus, the repetition of expansion and shrinkage of these swellable shale bands are considered as instability and triggering factors that cause landslides in the study area.

### Field investigation along the study area

Field investigation indicated that the dissolution features of the limestone in the area surrounding Sohag–Assiut cities are common. Many large and small-scale karst features along the study area were encountered, such as subsidence, tilting, and sagging of the limestone beds (Fig. 3a). In addition, small-scale features were detected that were located inside the filled and collapsed caves (Fig. 3b). These features include tilting of the laminated limestone beds and sagging of the beds due to the loading effect of the massive limestone. Other features were detected in the

**Fig. 3** **a** Large-scale karstification features. **b** Small-scale karstification features inside the filling caves materials. **c** Open caves. **d** Filled collapsed caves and dissolution joints filled with red sediments



areas, which include the passages of water and fine soils, which happened mostly along fractures and joints.

Also, field investigations indicated that there are many main joints that have major impacts on the formation of these empty and filled caves (Fig. 3c). These joints represent the main conduits of water and play a major role in dissolution characteristics and cave formations (Grosch et al. 1987). Sometimes, carrying fine materials to fill these caves time water moving through these joints wash away the fine materials from the caves. These joints help in accelerating the karst phenomena in the study area.

The most common karst features in the study area are the presence of filled and collapsed caves (Fig. 3d). These features could be utilized to understand the development stages of these filled and collapsed caves. Ford and Williams (1989) indicated that the clastic stream sediments are carried into these caves from allogenic surface sources. It was found that there are wall and roof collapses into the caves. This feature represents the essential role in modifying and contributing to the cave enlargement processes. White (1988) indicated that cave roof collapse occurs where the passage widths exceed the stable span, which is dictated by the local bed thickness and fracture density. Large numbers of these caves can be seen along the different road cuts along the Sohag-Red Sea road, where collapsed caves were detected mainly inside Thebes Formation. Our results indicated that karst features in this area are of various types, such as pockets, networks that are parallel to the bedding plains or along joints, and empty caves (ranges from few centimeters to tens of meters). Investigating of the caves filling materials indicated that depositional facies were encountered, including (a) presence of original bedding planes of limestone deformed boulders inside the caves filling materials (Fig. 3b); (b) basal breccia, which includes blocks of chalk, limestone, and chert (up to 1 m diameter) derived from the surrounding country rocks (Fig. 3d); (c) presence microcrystalline and well-crystalline gray calcite which forms large masses up to few meters in with and length; and (d) some caves filled totally with red sands associated with mud matrix. There are massive limestones that form the roof of the empty and filled caves.

Results indicated that both Thebes and Drunka Formations are characterized by karst features (e.g., filled and empty caves, collapsed caves, and dissolution joints). The Thebes Formation in this area is dominated by the presence of filled and collapsed caves. The Drunka limestone in this area is characterized by the domination of open cavities and open dissolution joints and fractures trending N, NE, and NW. The discontinuities (joints, fractures, faults, and bedding planes) represent the pathways of solution that increase the slope instability of limestone cliffs.

### Landslide mechanisms along carbonate rocks

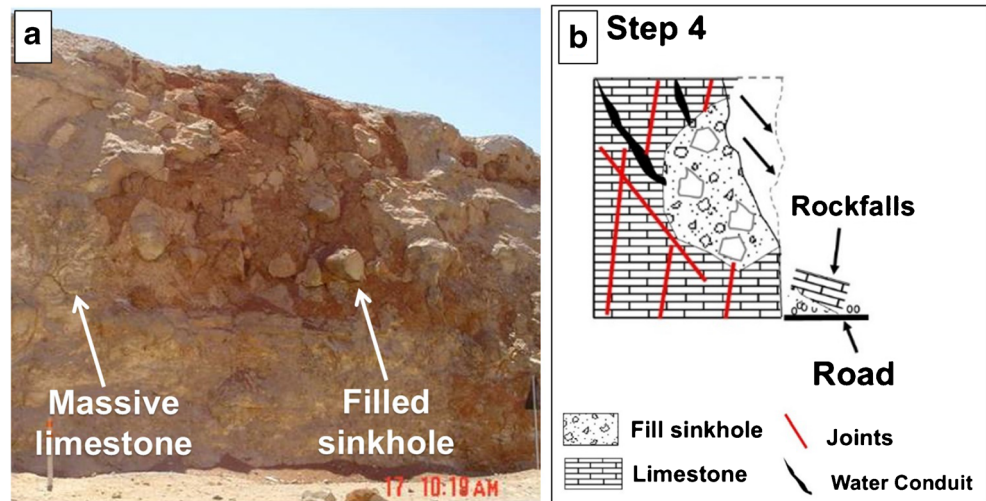
There are several factors controlling the landslide mechanisms along the carbonate rock slopes in the study area. These

factors include the geological properties (lithology type and discontinuities), karstic conditions (filled caves, cavities, and dissolutions along open joints), weathering and erosion processes (due to wind and water actions), human activities (bad excavations, face irregularities, and overhanging blocks), and climate conditions (rainfall). In the area under study, fallen blocks and boulders of different sizes and shapes were recognized. Based on the remote sensing analysis, detailed field, and laboratory investigations, different landslide mechanisms were examined and proposed in the area under study.

### Landslides due to removing the filling detrital materials from caves

Karst is termed a particular type of landscape and could be considered as a hydrogeological system. It develops predominantly by the dissolution of rock and has particular geomorphological features like dolines, karren, and caves. Karst as a hydrogeological system is a self-regulated underground dewatering system, which optimizes its discharge by the dissolution of the rock mass and develops a drainage system (karst conduits). The carbonate massifs are distinguished by the occurrence of filled caves with different diameters (few meters to several tens of meters). Red fill material found within the caves that are exposed along the road cuts in the study area has traditionally been called paleofill. It is believed that a paleokarst topography had developed in the study area during the early Eocene and that subsequent materials from the overlying deposits filled the associated paleo-cave. The above material collapsed into the actively forming passage, where some of these cave passages even contain blocks of the surrounding materials. Filled caves are characterized by large blocks (up to 2 m in diameter) embedded in fine weakly matrix (sandy, clayey materials). The fine materials (matrix) are weak in strength (1.25–5 MPa) and easily eroded by seepage water and wind action. Along the study area, many filled caves were detected (Fig. 4a). When the road cuts through these carbonate rocks (anthropogenic excavation), these filled caves appear. In many sites, the filled caves are located at the bottom of the slope, and others are located above the road level by a few to tens of meters (Fig. 4a). These karstic phenomena can cause some particular typologies of landslides. They can damage the road network if rockfall occurs. The weak filling materials can be washed away because of wind and water actions leading to many slope instability features. The processes of landslides because of washing away the weak materials in the filled caves are described in four phases as follows: (1) the first phase (step) is distinguished by the presence of the filled caves inside the limestone rocks. In this phase, there is no collapse. (2) In the second phase, the road cut was constructed, and these filled caves with different materials appear along the rock-cut. These filled materials are composed of a large block of limestone cemented with weak materials. Above these filled materials, there is limestone as cap rocks that are affected

**Fig. 4** **a** Filled caves by boulders and weak materials located along carbonate rock slopes (along Assiut–Cairo highway (eastern limestone plateau)). **b** Sketch diagram showing step 4 in which rockfall occurred for the overhanging cap rocks



by many joints. Also, according to dissolution processes, many big blocks of limestone are detached from the main limestone bedrock. (3) The third step, because of the different weathering processes by water and wind, the weak materials washed away created small voids and increased with time. Overhang blocks are formed through the disappearance of weak material. The progressive collapse of filled weak materials, which is a result of the combination of the effect of karstic dissolution, water seepage, wind action, and gravity, slowly increases the size of the cave inside of the slope and an upward direction. The continuous development of caves leads to step (4), which is the cave formation that can be only a few meters wide. Eventually, this process leads to the collapse of the large boulders and cap rocks towards the highways (Fig. 4b). These types of landslides are directly affected by a slow washout action of the weak detrital materials.

#### Landslides due to the breakdown of caves along the carbonate slopes

Karstic phenomena and erosional action firmly on the progressive evolution of cave formation. Along the joints, there are many broken materials, representing the weakest points of the rock masses. The caves can evolve in response to slow karstic processes brought about by groundwater movement that runs along the contact boundaries between highly fractured rocks and less impacted areas (Santo et al. 2007). Maffei et al. (2005) mentioned that chemical dissolution leads to the formation of various small cavities in the bedrock (ranging in size from a few centimeters to some decimeters). If the frequency of these cavities becomes high, compared to the whole volume of the rock, tangential resistance can be overcome and cause the formation of a sinkhole on the surface. The karstic process results in the widening of discontinuities and the occurrence of breakdown processes. Esposito et al. (2003) indicated that many karstic caves formed by the combination of karstic phenomena and

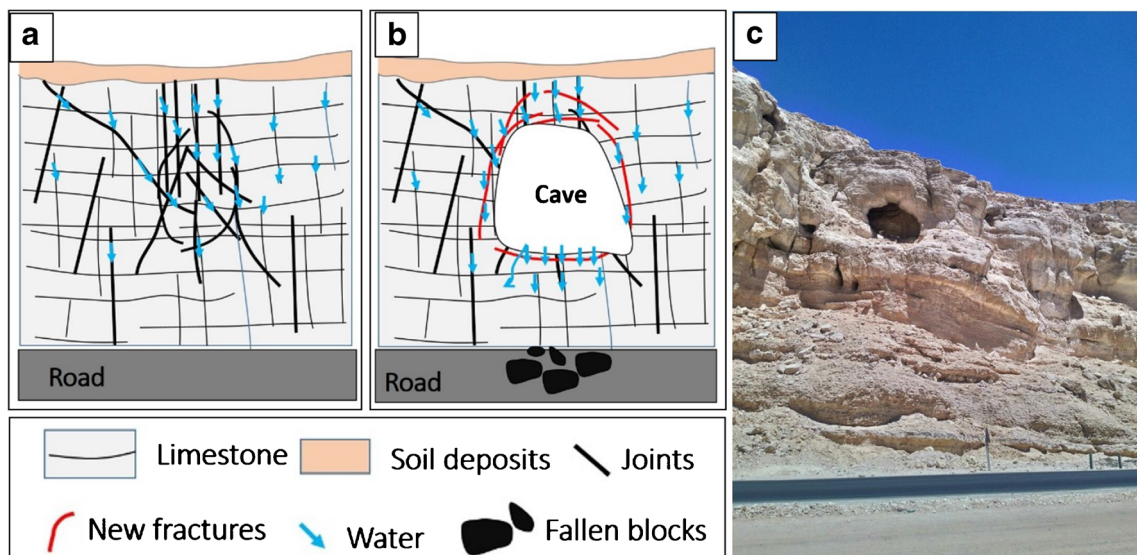
erosional wave action. They formed through the dissolution and erosion of deeply fractured areas that were worked by the sea. Figure 5a, b shows the different stages of caves development and landslides problems; the initial phase is distinguished by the presence of many discontinuities (stage 1) in the rocks (Fig. 5a) and with the slow action of dissolution where a small cave will be formed (stage 2). The progressive collapse of rocks, which is a result of the combined impact of karstic dissolution and gravity, gradually widens the cave towards the inside of the rock slope and upwards (stage 3) (Fig. 5b).

The fallen blocks may be easily transported outside the cave and reach the roads (Fig. 5b). These particular joints set patterns to form the pathways of the local superficial groundwater, which work on removing the fallen materials. In this case, a progressive widening of a tiny cave can be obtained, sometimes with the formation of significantly large caves that can reach a few meters of heights. In some cases, the continuous development of the caves upward causes thinning of the cave's roof, resulting in a sudden collapse of a part of or all the cave. Along the study area, there is clear evidence of old caves that have fallen because of the presence of wide hollows. These phenomena can cause highly risky situations (rockfalls when they collapse). Numerous caves were detected along the limestone rocks (Drunka Formation) that appear along road cuts/slopes of the study area. They are often of considerable sizes, from less than a meter to a few meters high (Fig. 5c).

#### Landslides due to the breakdown of rocks resulting from differential erosions

Through this study, it becomes evident that there are processes that can increase the slope instability because of active weathering processes (differential erosions). Studying these weathering processes and erosional features in detail are important for many engineers and engineering geologists as these processes lead to stability reduction of such slopes and





**Fig. 5** **a, b** Sketches modified after Santo et al. (2007), it shows the different stages of caves formation along highly fractured carbonate slopes. **a** Development of small opening due to the dissolution along

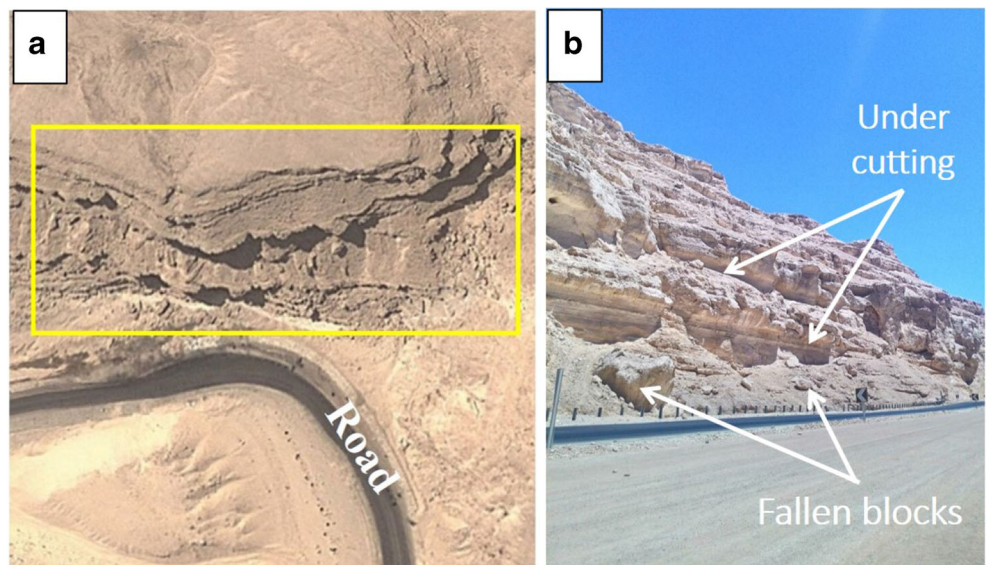
the discontinuities. **b** Increase the cave size where the fallen blocks could reach the highways causing severe problems and **c** cave system along the Sohag–Red Sea highway (eastern limestone plateau)

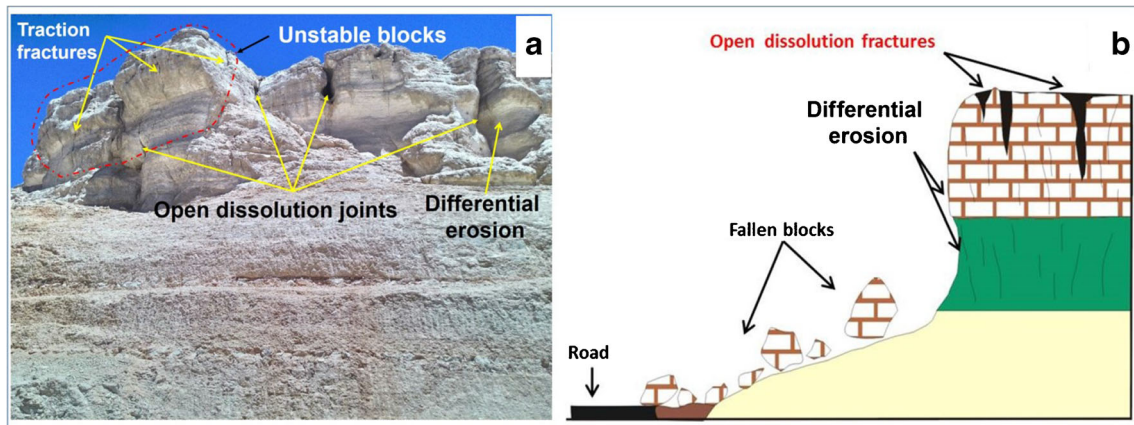
hence increase the maintenance costs. Admassu et al. (2012) and Neiman (2009) proved that the Marl layer is affected more extensively by weathering processes than other unweathered rocks surrounding it due to the process of differential weathering. This weak layer is crumbled quickly and gradually washed away because of wind action, gravity, and rainfall. Hampton et al. (2004) showed that differential erosion because of the presence of weak materials has a significant contribution to produce rockfalls. Different types of examples of surface deterioration, differential erosion induced by weathering/erosion processes (wind and water actions) along the road cuts and natural slope of the study area were detected using high-resolution 3D images (Fig. 6a). Also, the

weak material precipitated at the bottom of the slope could be detected from the high-resolution 3D images.

The impact of weathering and differential erosion processes on the stability of carbonate slopes can be found in many sites along the study area (Fig. 6b). The weathering and erosion rates vary from highly weathered in marly limestone, chalky limestone, and shale layers within these cliffs and slopes. Low weathered massive limestone is almost unchanged in the engineering characteristics. After sufficient time of weathering, the blocks detach due to their weight. The resulting rockfall causes a danger to the area at the base of the slope. Erosion of the weak materials (marly limestone, chalky limestone, and shale) in the study area along the rock

**Fig. 6** **a** 3D high-resolution professional Google Earth image showing differential erosion zones (yellow box) along Sohag–Cairo highway (western limestone plateau). **b** Differential erosion and fallen blocks due to the intercalation of marly limestone layers between the massive limestone (overhanging layers) along Sohag–Red Sea highway (eastern limestone plateau)





**Fig. 7** a An example of an open fracture that could cause a massive rockfall (along Sohag-Red Sea highway). b Sketch of a diagram showing the mechanism of rockfall

cuts/slopes produce overhanging of the massive rocks and eventually collapse. The ability of a rock type against erosion can be defined as a durability parameter (Khalily et al. 2013). As mentioned before in the laboratory tests, it was found that weak materials are more susceptible to weathering and causing overhanging of hard rocks.

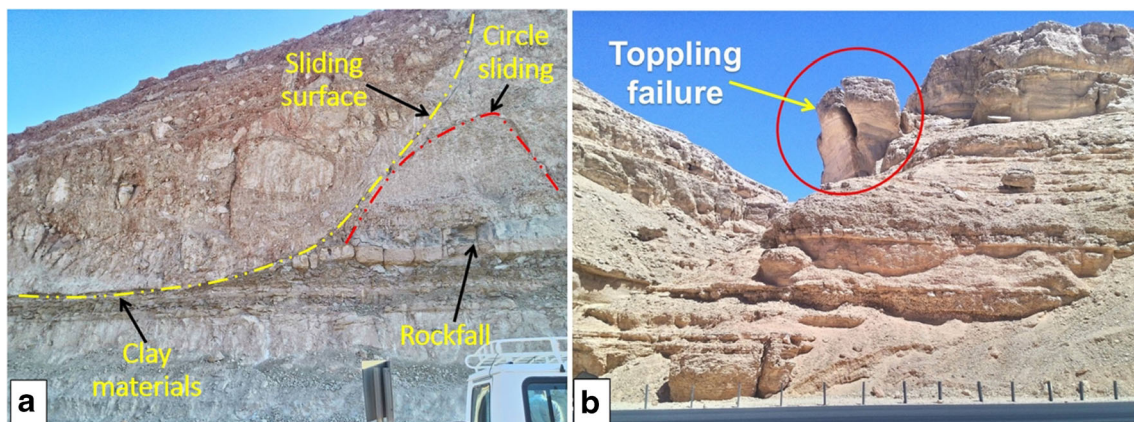
#### Landslides due to dissolution along large fractures

In the highly fractured carbonate rocks, the karstic effect can slowly widen the width of these discontinuities to create open fractures (up to tens of meters long and more than 1 m wide). Maffei et al. (2005) indicated that failure phenomena can happen in highly fractured and karstic carbonate rocks. Some areas are influenced by karstic phenomena and erosional wave action, and they often are very fractured and can result in slope instability (Budetta and Santo 2000). The different karst processes can occur through water riling along fracture walls, through a condensation process, and most of all, over hummus filling, which makes the effect of the running waters more aggressive. In many sites of the current study, field investigation indicated that numerous open dissolution joints are

occurring at the upper bed of the carbonate slopes of the study area. These open dissolution joints and the presence of differential erosion of the marly limestone layer can isolate many rock blocks from the surrounding mass causing rockfall and toppling (Fig. 7a). Figure 7b shows a sketch diagram showing the mechanism of rockfall as a result of open dissolution joints and under-cutting (differential erosions).

#### Landslides due to sliding along discontinuities

The presence of adverse geologic structures (such as joints, faults, and shear zones) in the limestone slopes should cause different types of slope failures. Various studies indicated that the potential mode of failures depends on the discontinuity distributions (dip direction and dip angle magnitude) and the friction angle along the sliding planes (Andriani and Parise 2015; Gueguen et al. 2012; Harrison et al. 2002; Palma et al. 2012a, b; Parise 2008; Parise and Lollino 2011; Waltham 2002). The opportunities for slope instability increase because of the presence of shale layers and the weak weathering materials along the joint surface (clay). Four types of failures were detected, including circular, toppling, wedge, planar,



**Fig. 8** Different failure types along the carbonate slopes. a Potential circular failure. b Potential toppling failure along Sohag-Red Sea highway

and toppling failures. Figure 8 shows examples of circular and toppling failures along Sohag–Red Sea highway: (1) circular failure along the contact between filled caves and massive rocks (Fig. 8a). The occurrence of shale and weak beds under the filled sinkhole will trigger the circular failure to take place. Among the essential properties of the shale layers is the rapid decomposition due to water influence. Results of the Jar slake test showed that the shale sample degrades from a pile of flakes or mud (for yellow shale) to form many chips (for greenish-gray shale). (2) Toppling failure occurred due to the effect of undercutting of the weak materials (Fig. 8b). (3) Wedge failure occurs along the intersection of different joint sets. It was found that wedge sliding will be increased because of the effect of weathering action where the joint surfaces are stained by reddish materials (clay, silt, and sand). (4) Planar failure which located in some areas where part of the slope slides down on the highway along a joint surface.

## Conclusion

The eastern and western carbonate plateaus of Egypt show many cases of slope instability phenomena that can be linked to karstic processes. It is evident that various factors have different contribution, but the effect of karstic dissolution is crucial in the processes of joint and fracture widening, material movement, increase of the voids, and the reduction of rock strength. Egyptian government tends to expand in the development by establishing new urban areas and different lifelines (highways, roads, railroads, electricity lines, and water lines) along carbonate plateaus. Studying karst related problems (slope instability and sinkholes) in these plateaus are not considered seriously enough by the local management agencies or decision-makings. In the current work, five different landslide mechanisms in carbonate rock cliffs and slopes were identified and addressed using high-resolution remote sensing images, field investigation, and laboratory analysis. Our findings indicated that the main factors causing slope and cliff failures in carbonate rocks are the weathering process, differential erosion, and karst features (empty caves and filled caves). Different landslide mechanisms were categorized in carbonate cliffs and slopes, including landslide related to removing the filling detrital materials from filled caves, landslide due to breakdown of caves along carbonate slope, landslide associated with the breakdown of rocks as a result of differential erosions, landslide associated with dissolution along large fractures, and landslide due to slumping along a curved surface (along weak interlayers or discontinuities). It is worth mentioning that in order to face the high pressure acting on karst prone areas and to reach sustainable management in this peculiarities of karst terrains, careful understanding should take into account the specific features such as karst processes and landslide mechanisms. Evaluating the variety of processes

and geological settings of these areas could help in the identification of subsurface karst processes, makes the identification of the possible causes of the slope instability and sinkhole very easy. This will help the decision-makings, planners, department of transportation personnel, and engineers to maintain the sustainability of these developments by understanding different types of hazards related to karst prone areas to avoid future problems and to have firm actions toward their prevention and/or mitigation measures of the related risks.

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