Landslides
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Remote sensing applications to geological problems in Egypt: case study, slope instability investigation, Sharm El-Sheikh/Ras-Nasrani Area, Southern Sinai

Abstract The Sharm El-Sheikh/Ras-Nasrani area is one of the most attractive tourist resorts in Egypt particularly and in the world in general. The area has been rapidly growing during the last few years. Many construction projects including villages, hotels, beaches, and roads have recently been undertaken. The following study demonstrates the use of high-resolution satellite images, QuickBird imagery, acquired on June 2nd, 2007 (0.61 m spatial resolution), for detailed mapping of the recent developments and the slope instability hazard zones. The results were confirmed by field reconnaissance. Our findings indicate that there are many development areas threatened by unstable zones. The hazard areas have been delineated and classified, and a final slope instability hazard map has been established. Different factors were found to have a crucial impact on the slope instability, some natural and others man-made. These unstable localities need to be remediated and/or monitored to avoid any loss in property and/or lives.

Keywords Slope instability · Hazard assessment · Satellite images · Egypt

Introduction

Much of the Egyptian economy relies on tourist income. Egypt's climate and location makes it very attractive for many people all over the year. To increase and manage these types of investments, the Egyptian government helps with new private investments in tourist activities. To cope with the increase of tourist activities, new urban areas, highways, roads, and other infrastructure have been established. Because of the nature of the terrain and population distribution along Egyptian territories, a significant number of projects were constructed in mountainous and/or hilly areas. These hilly areas are characterized by frequent slope instability including rockfalls and rockslides. These can result in traffic accidents, blocked lanes and roads, and increased maintenance costs, as well as other hazards to the public (Bateman 2003). Numerous factors can contribute to slope instability including climate, slope conditions, geological characteristics, and construction. A landslide is a rapid disaster which involves falling, sliding, or flowing of soil and rock. Every year, landslides cause the death or injury of thousands of people and significant property loss (Raju et al. 1999). Prediction of potential landslides has been always very difficult because of the complexity of the factors involved and their relationship to each other (Yuan et al. 1997). Normally, the potential for landsliding is determined by carrying out sampling of the soil or rock, measurement of slope inclination, land cover, underground water level, and examining the morphology and geology of the slopes at the site. It is difficult and time-consuming to do this for a large area containing many potentially unstable slopes. By using high-resolution satellite images, all the information can be combined, manipulated, and analyzed to determine potential landslide areas quickly and efficiently.

Mountainous areas are strongly affected by landslide hazards due to their steep topography. The situation is aggravated by the construction of rock cuts and construction on top of cliffs. Slopes and cliffs facing the sea are areas where ground-based collection of data and monitoring is particularly difficult, prohibitive, or impossible. Such reasons have prompted the application of airborne and space-borne remote sensing techniques for monitoring and assessing high-mountain hazards (Kääb 2000 and Huggel 2004). Many authors have used the analysis of aerial photographs for glacial hazard research (e.g., Röthlisberger 1987; Kääb 1996; and Margreth & Funk 1999). It however has been only in recent years that satellite imagery has increasingly been used in the analysis of hazardous slopes, owing to improved spatial resolution and a growing recognition of the potential of such studies. Most applications in the past have thereby focused on detection and assessment of ice avalanche potentials (Salzmann et. al. 2004) or identification of debris flow initiation zones (Huggel, et. al. 2004). These studies were mainly based on optical satellite sensors such as ASTER, Landsat, or SPOT. The lack of fine-resolution satellite data until last decade has limited most satellite-based landslide studies to regional scale assessments. For example, RÖessner et al. (2002) give an overview of monitoring large landslides in Central Asia using platforms and sensors. They emphasize the importance of using multi-temporal images for landslide detection. Yamaguchi et al. (2003) used multi-temporal SPOT data to detect slow movement in a large landslide. However, further studies have shown that classification methods based on multispectral imagery with a spatial resolution of about 15–30 m (e.g., Landsat-TM, ETM, and SPOT) did not yield satisfactory results in mapping slope instability. For example, Marcelino et al. (2003) were only able to identify small landslides a few tens of meters wide using SPOT and Landsat images. Petley et al. (2002), using Landsat ETM+ images in the Himalayas, were only able to identify 25% of the total number of landslides, i.e., those over 50 m wide, even when the multispectral bands with 30 m resolution were Pan-sharpened to a resolution of 15 m.

It has been found that the spatial resolution played a crucial role in the distinction the areas that have high potential for instability problems. Most recent developments in optical satellite remote sensing have now led to a limited number of very-high-resolution sensors, presently represented by panchromatic band of IKONOS (0.81 m), QuickBird (0.61 m), OrbView-3 (1 m), and SPOT-5 (2.5 m) (Birk, et. al. 2003). Because of the recent emergence and the relatively high cost of these images, studies using these types of sensors for high-mountain hazards are yet rare.

In the last decade, construction projects such as roads, urban areas, hotels, and others have increased dramatically in the study area, These construction projects required a detailed assessment for the stability problems especially for the rock cuts for highways and for the slopes that overlook urban and beach areas. This study aimed to use high-resolution satellite (QuickBird) images, acquired on June 2nd, 2007 (0.61 cm spatial resolution for panchromatic band) with the help of field investigation to: (1) map the development in the area under consideration; (2) identify and categorize the slope instability regions and create a detailed slope instability map; (3) Analyze the factors that contribute to the slope instability and develop a model for the slope instability especially along the cliffs facing the beaches. These models could help the decision makers and planners for the suitable methods of remediation.

Characteristics of the study area

The study area is characterized by its unique location on the Red Sea between Sharm El-Sheikh and Ras-Nasrani. It extends as an elongated narrow coastal strip on the southwestern coast of the Gulf of Aqaba at the extreme southern tip of the Sinai Peninsula (Fig. 1a). It is considered one of the most popular tourist resorts in the world owing to its beauty, climate, and geographical position. Hundreds of thousands of tourists come every year from all over the world. The development in the area began in 1968 on a high coral spur that dominates two large and well-sheltered bays which are veritable natural harbors Sharm El-Maya and Sharm El-Sheikh (Fig. 1b). Subsequently hotels and other tourist facilities sprang up both around the beaches surrounding Sharm El-Maya and some kilometers to the north, around a beautiful bay located where a large Wadi joins the sea. This bay, which was named Marsa El-Art by the Bedouins and is known today as Naama Bay, soon become a very important seaside resort.

The morphology of Sharm El-Sheikh /Ras-Nasrani area is unique (Fig. 1b). It is surrounded from east by Gulf of Aqaba and from the northwest by a basement complex belt. There are some famous hills towards the west including Gabel Um Tartir, Gabel Qaida, Gabel Watr, and Gabel El-Safra. At Ras-Nasrani and Naama Bay, flat beaches are suddenly transformed into a belt of flat-topped cliffs. The cliff wall in the study area ranges from 0 to 30 m. There, some Wadis cut the reef cliff, making low-lying flat beaches; the most famous one is the Naama Bay area.

The study area is characterized by the presence of different rock types including Precambrian granitic rocks, Cretaceous Nubian sandstones, Pleistocene coral reefs, and Quaternary sediments (Fig. 2) (The Egyptian General Petroleum Corporation 1987). The Precambrian rocks are located to the west of the study area. However, most of the urban areas and other activities are constructed above the coastal raised reefal beaches and Quaternary deposits.

Methodology

Commercial high-resolution satellite, such as QuickBird, has been launched in 2001 with a meter to submeter spatial resolution (0.61 m for the panchromatic band). Table 1 shows the main technical characteristics and specification of the sensors used with QuickBird. Corrected imagery has been used in this research. QuickBird panchromatic and multi-spectral images in "Ortho Ready Standard" format from 2nd June 2007 were acquired. In addition, Enhanced Thematic Mapper Plus (ETM+) data of 2001 and published geological data were used to map the geological units. A visual interpretation was performed on the high-resolution QuickBird data to obtain a more detailed derivation of the

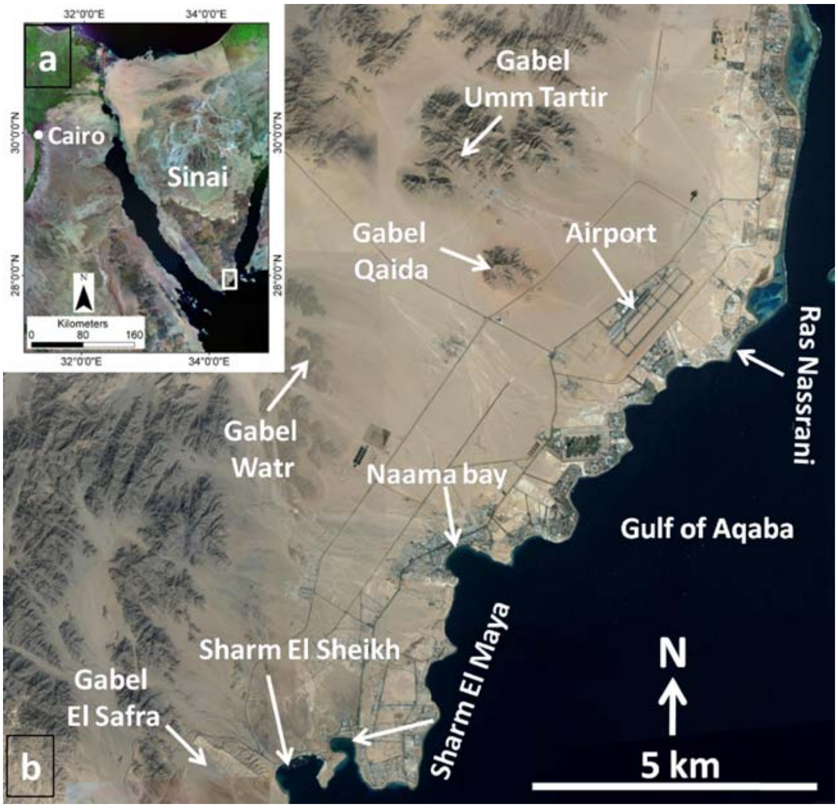

Fig. 1 **a** 7-4-2 Landsat Enhanced Thematic Mapper Plus image showing the location of the Sharm El-Sheikh–Ras-Nasrani area (*white box*) in relation to Sinai Peninsula and Eastern Desert of Egypt. **b** Physiographic features of the study area

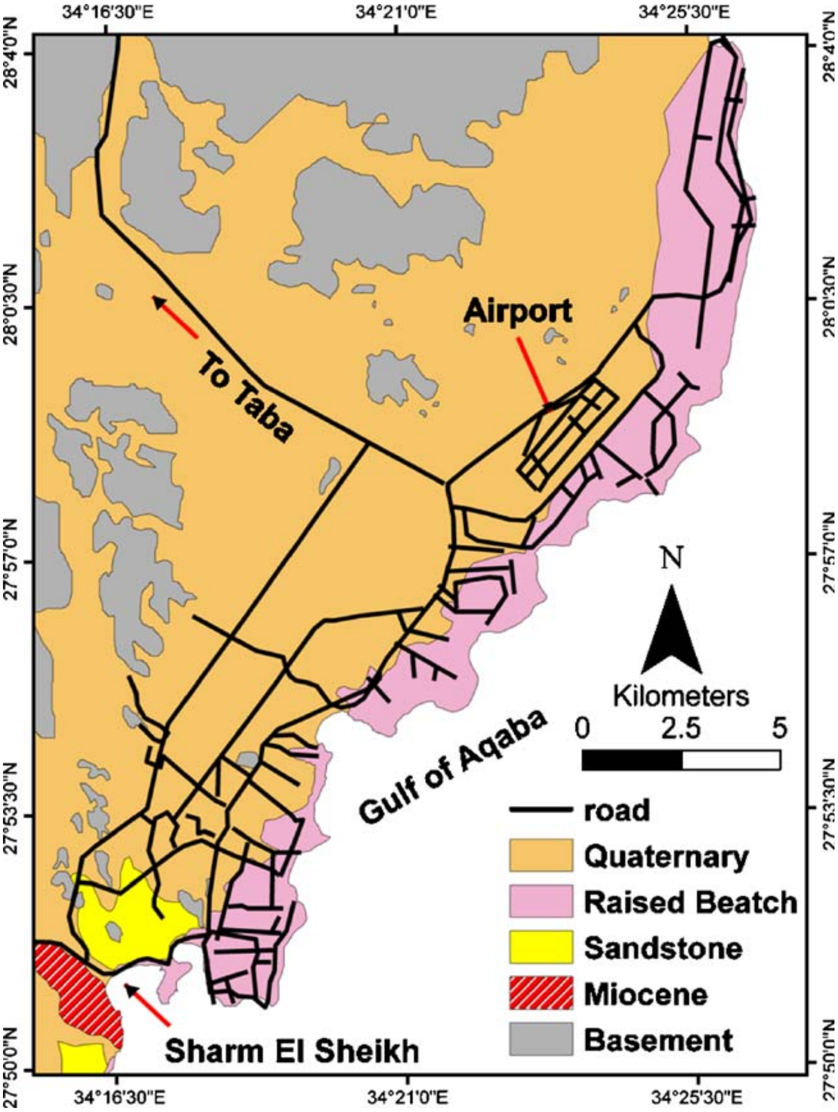

Fig. 2 Geological map of the area showing spatial distribution of various lithological units of the region. The map is developed from the interpretation of ETM+ 15 m and previous geological information (Egyptian General Petroleum Corporation and Conoco Coral 1987)

development in the area on a larger scale. For this purpose, a fused image, from the panchromatic and the multi-spectral channels, has been generated. The results were integrated into the geographic information system (GIS) environment for identifying the development distribution and the slope instability hazard zones on large scale. On the other hand, field trips have been conducted to investigate most of the rock cuts and cliffs in the study area. The study included identifying and measurement of the different features along the unstable cliffs and slopes, as well as identifying the factors affecting the slope instability.

Results and discussions

Visualization of high-resolution image

Optical high-resolution sensors can be used to identify unstable slopes on a regional scale. However, in practice, the detection of

Table 1 Technical specifications of very-high-resolution satellite sensors (Kramer 2002)

Satellite sensor, provider	Spectral bands	Spatial resolution/swath width (at nadir)	Average revisiting time, off-track viewing angle	Price per km^2 (USD)
QuickBird, DigitalGlobe	Panchromatic	0.61 m/16.5 km	1–3.5 days, ±30°	~24
	450–520 nm	2.44 m		
	520–600 nm	2.44 m		
	630–690 nm	2.44 m		
	760–900 nm	2.44 m		

steep slopes and rockfalls from remote sensing imagery is a major challenge. In this study, the high-resolution images were used. This allowed us to detect where buildings, beaches, and traffic routes could be affected by rock falls and/or slides. Endangered areas were thus identified. For mapping the endangered zones, the high-resolution satellite images (QuikBird) were an excellent means and visualization tool. They can replace topographic maps at the scale of 1:2,000 (Fig. 3).

Visual inspection of these images in the GIS environment helped us to detect the fallen blocks and the irregular cliffs that indicate instability (Fig. 3). Generation of a hazard map for the study area was based on two main factors: (1) the presence of irregular cliffs and (2) the presence of fallen blocks that could be recognized from the high-resolution satellite images (as shown in Fig. 3). These considerations result in a hazard rating (red zone) for the instability areas.

Development and hazard zonation map of the study area

The area under investigation has been subjected to dramatic changes in urban and infrastructure activities in the last decade. Many new development and recreation activities have been recognized. Several tourist villages, hotels, clubs, and resorts are built above and below the escarpment. The urban development map, generated from high-resolution images (QuickBird mosaic 61 cm special resolution), shows the distribution of the urban areas, touristic villages, hotels, and other infrastructures (Fig. 4a). It is obvious that most activities are concentrated along the coast line. Others are distributed away from the coast line towards the desert section in a northwest direction (Fig. 4a).

In addition, the final slope instability hazard map is shown in Fig. 4a. It was found that these zones are usually immediately adjacent to the beaches, urban areas, buildings, and highways (red zones in Fig. 4a, b). Also, many of the constructed resorts, decks, villas, hotels, and other structures are adjacent to these areas which are prone to these slope instability hazards. These are also the areas that are most frequented by visiting tourists.

Field investigation, verification, and factors affecting slope instability

Various field trips have been done to investigate these sites, to verify the interpretation of satellite images (Figs. 4b and 5), and to identify failures and classify the mode(s) of failure. Figure 4b shows some selected areas that have been chosen to understand the using of satellite images in identifying the unstable irregular cliffs and the fallen blocks. Figure 5 shows a comparison between the high-resolution satellite images (Fig. 5a, c, e) with the field photographs that have been taken for a part of these zones (the numbers in Fig. 5a, c, e). These field photographs show the rock slopes toward the road, faults, and irregular cliffs (Fig. 5b, d, and f). The results indicate that the instability characteristics need remedial action to minimize and avoid any loss of property as well as casualties.

Factures causing slope instability in the study area

Previous studies have amply demonstrated that landslides are predictable if terrain characteristics are available. The factors generally attributed to causing landslides are lithology, slope angle, geomorphology, structures, and land use. However, the triggering factors include pore water pressure; wind and water erosion; seismic activities; and man-made factors such as over-steepening of slopes. In the current studies, it was found that three main factors have the main impact on the slope instability including: (1) Lithology; geological units have the main impact on the slope instability in the study area. As the general geological structure here is one of horizontal bedding, it is important to consider not only the exposed surface material but the underlying material as well. The area under investigation along the cliff (raised beach) is characterized by a top layer of Pleistocene coral reef rock with a thickness ranging from 10 m toward the coast (east side), thinning out toward the west (away from the beach). The analysis of the area indicates that the strong coral reef layer is underlined by a weak to very weak clastic layer (Fig. 5f). This clastic layer is composed of sand inter-bedded with conglomerate that has a weak matrix. This clastic material can be easily eroded. The erosion phenomena can be enhanced due to the effect of water and wind (Fig. 5f). (2) The faults and shear zones in some localities in the study area have impact on the slope instability problems. Along these zones, the cliffs and rock cuts are facing raveling and sliding. Figure 5d shows raveling and rock falls occurred along these zones. (3) Water is very effective in deteriorating the weak unit and increases the incidence of overhanging and rock falls. The seepage problems have been

Fig. 3 High-resolution image (QuickBird acquired on June 2nd, 2007 with 61 cm spatial resolution) showing a portion of cliff in the study area. **a** The presence of large boulders under the irregular cliff. **b** The distribution of resort areas under an unstable irregular cliff. Note the distribution of the urban areas and the *green* (irrigated) fields that may increase the potential for slope instability due to problems of water seepage and increased pore pressures

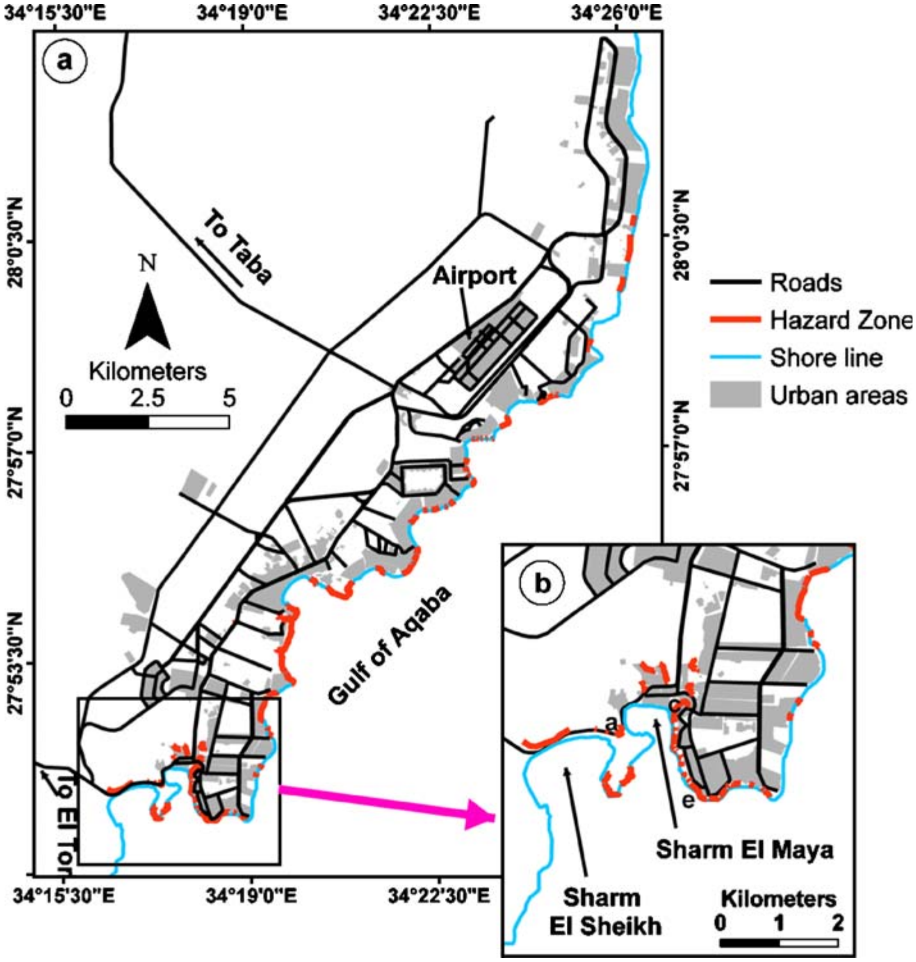

Fig. 4 Development activity map for the urban and road distribution in the study area. A hazard zone (*red line*) of the study area showing the high-danger zone in relation to urban and road distributions, based on interpretation of the high-resolution satellite imagery and field verification. Note: The *cutout box* highlights the areas shown in greater detail in **b**. Note that *a*, *c*, and *e* in **b** are the locations of the satellite images shown in Fig. 5a, c, e

noticed in many areas in the study area. Water introduced into the subsurface by drain fields, septic tanks, and improper handling of runoff might also initiate slides.

Slope instability model

Two different models have been used to explain most of the instability problems. One of them is based on erosion and undercutting. The other is due to sliding along the bedding planes (and release along faults, joints, and shear zones?). These instability problems could be activated due to many factors, e.g., geomorphological, geological, meteorological, and man-made factors.

Slope instability model I

For this model, the study reveals that erosion is caused by different mechanisms such as wave action, wind, water seeps, and human activities. Headlands and terraces are undercut, causing continual retreat of the cliff. Many areas along the coast cliff exhibit active instability problems (see red zone in Fig. 4). Also, an example is shown in Fig. 5e, f, where the undercutting is present at the lower part of the cliff and rockfalls occur on the cliffs. The underlying clastic beds are eroded easily by wind and/or water action. This erosion processes will leave a large volume of rock overhanging. Tension cracks will appear at the top of the slope, predicting failure (Fig. 6a, b). In some cases, catastrophic rock falls occur, while in others, the blocks deteriorate slowly. The slope failure mechanism is shown in Fig. 7.

Slope instability model II

This type of slope instability was found in the Sharm El-Sheikh sandstone formation. This formation has bedding planes with dips ranging from 20° to 33°, and most of the rock cuts in the southern part of the area are established in this formation as shown in Fig. (5a, b). This formation is characterized also by the presence of faults, joints, and shear zones. Figure 5b shows a planar sliding failure in the Sharm El-Sheikh sandstone formation which is predicted to fail catastrophically. The sandstone formation (Fig. 5b) is characterized by light brown sandstone, medium bedded, very widely jointed, slightly weathered, and moderate to weak in strength. The bedding (dip-direction/dip=170/33°) strikes parallel to the slope face and dips 32–33° towards the road excavation.

Recommendations

Many urban areas and beaches were built and developed along and beneath the raised beach cliffs. Evidence of past failures and over-steepened slopes raise questions as to the ability of these cliffs to withstand sustained human activity. Some form of beach and roadway protection may be required, coupled with some guidelines

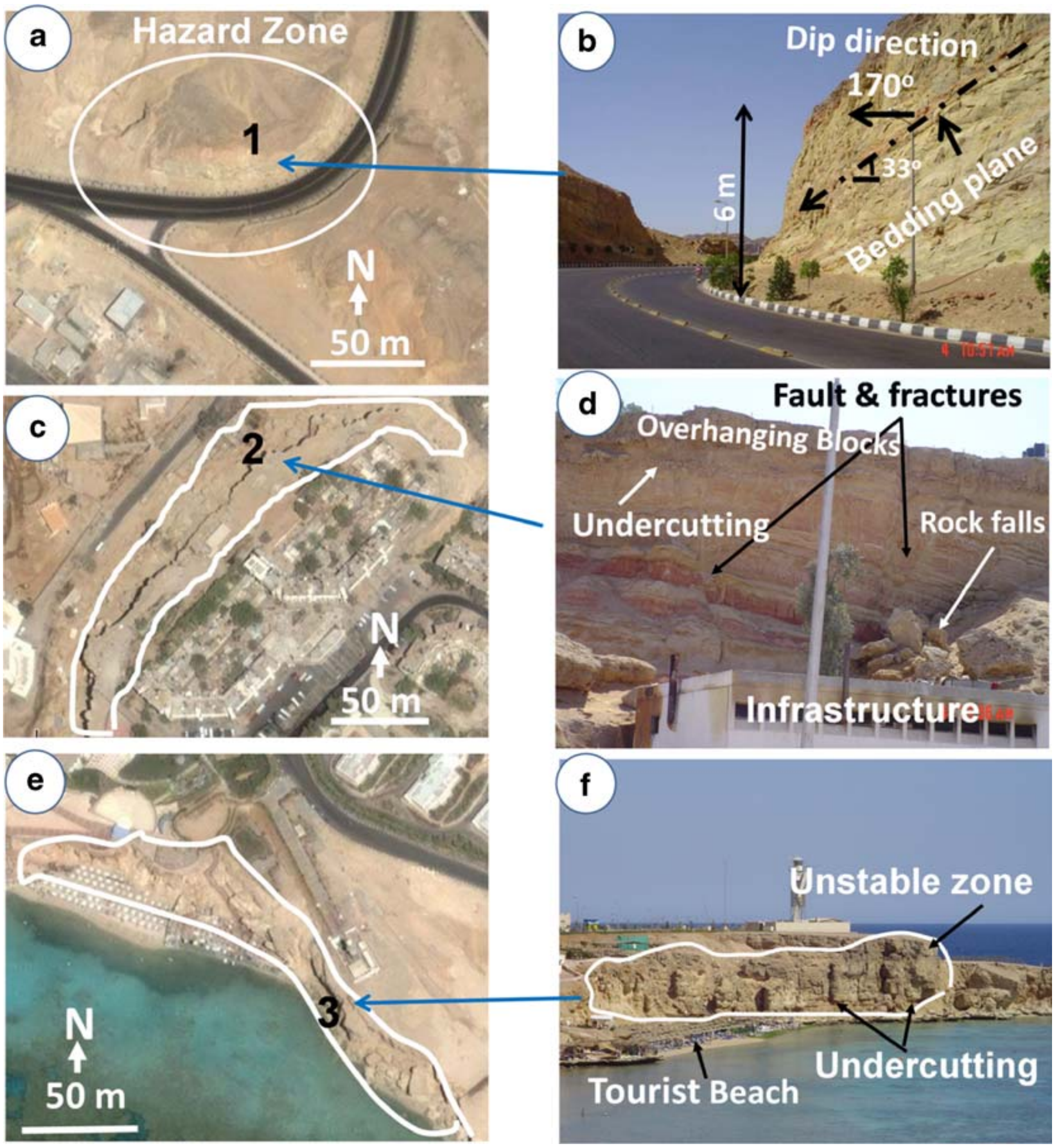

Fig. 5 The satellite and photo views of a rock cut (**a**). The terrestrial view showing tilting beds towards the road (**b**, site *1* on **a** as shown by the *blue arrow*). **c** The satellite view of a cliff overlooking road and infrastructure. **d** Photo showing the morphology of a crumbling rock cut (site *2* on **c** as shown by the *blue arrow*). **e** An unstable sea cliff overlooking a tourist beach; and **f** morphology of the crumbling sea cliff (site *3* on **e** as shown by the *blue arrow*)

and regulations for new urban development. Remediation and mitigation methods should include field assessment of risk, scaling of loose rock, and monitoring of tension cracks where failures could affect development or human activity. As a last resort, in critical areas, slope support could be considered.

Field assessment of risk

A risk/consequence assessment such as the system established for Missouri State Highways (Maerz, et. al. 2005) should be conducted on all cliff and rock slopes where failure could threaten both current and future human activities and infrastructure. Where the risk/consequence level is high, mitigation or remediation efforts should be proposed. The system was designed to evaluate the risk of failure as well as the consequence of these failures.

Scaling of loose rock

The first and most cost-effective level of remediation is to scale cliffs and rock faces where loose blocks threaten areas below. Scaling is a way to remove loose, overhanging, and unstable materials from the rock face. Scaling is usually the most cost-effective solution to reduce the risk of falling blocks, unless the blocks in question are very large. There are different methods for scaling, either manual or mechanized. Scaling is a short-term solution, as block loosens up over the years.

Tension crack monitoring

Where scaling is impractical, for example where the loose blocks are very large, and the appearance of tension cracks signals the beginning of instability, tension crack monitoring should be instituted. Tension crack monitoring is a cost-effective way to

Fig. 6 Showing tension cracks appearing. **a** On high-resolution images and **b** in the field at the top of the cliff

determine whether movement is accelerating to imminent catastrophic failure and can be used to predict the timing of the failure and where remedial or mitigation actions become urgently needed.

Measuring and monitoring the changes in crack width and direction of crack propagation is required to establish the extent of the unstable area. Existing cracks should be painted or flagged so that new cracks can be easily identified on subsequent inspections. Measurements of tension cracks may be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separations. Another common method for monitoring movement across tension cracks is with a portable wire-line extensometer. The most common setup comprises a wire anchored in the unstable portion of the ground, with the monitor and pulley station located on a stable portion of the ground behind the last tension crack. The wire runs over the top of a pulley and is tensioned by a weight suspended from the other end. As the unstable portion of the ground moves away from the pulley stand, the weight will move, and the displacements can be recorded either electronically or manually.

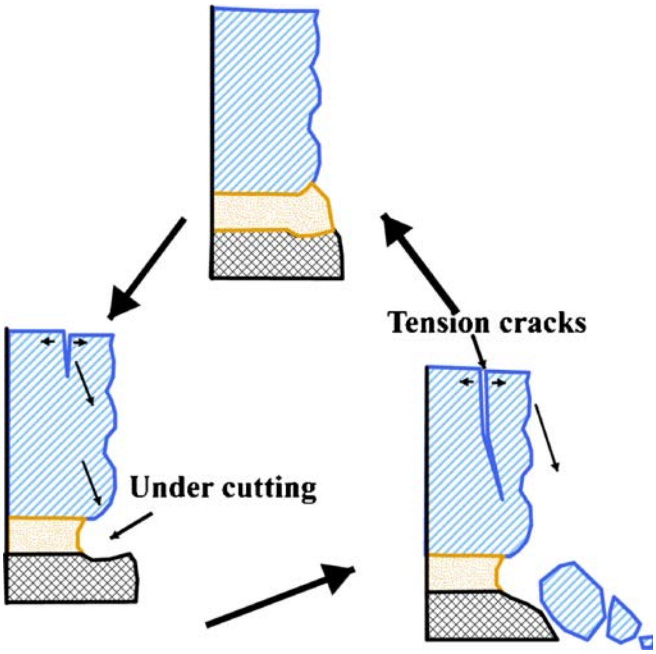

Fig. 7 Slope failure mechanism, model I, along the beach cliffs

Slope support

Only where none of the other measures are appropriate and the risk is high should there be other methods. Slopes can be supported in a number of ways (in order of cost) from rock/anchor bolts to sprayed concrete, tied back walls, and gravity walls and buttresses, All of these solutions are typically expensive and are cost effective only when threatening a high-value structure or activity area that covers a relatively small area. In some cases, moving the structure or activity area may prove to be more cost effective.

Conclusions

The emergence of very-high-resolution sensors such as QuickBird, along with cost-effective image data have significantly pushed forward their application to slope hazard assessment. The potential for using this new type of imagery has been demonstrated in this study in Egypt, where slope hazards threaten new and existing infrastructure critical to the tourist industry. Coupled with field assessments, the imagery was used to identify and differentiate areas of instability, and create hazard maps. Two models of slope instability were found: (1) undercutting of slopes by wave or wind action on weak layers or by ill-conceived construction and (2) planar sliding along 20°- to 30°-dipping bedding planes. Recommendations were made to mitigate and remediate such areas where infrastructure is threatened, preceded by a detailed systematic field assessment of risk and consequence of potential slope failures.

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