Assessment of the risks of landslides in Thawr Mountain in Makkah by measuring slope stability factors and geographic information system

Fathy Shaaban, Turki Habeebullah, Safwat Gabr, Waleed El-Saud, Essam Morsi, Abd Allah Ghoram Allah
Institute of the Custodian of the Two Holy Mosques for Hajj and Umrah Research - Umm Al Qura University

تقييم مخاطر الإنهيارات الصخرية بجبل ثور بمكة المكرمة بقياس عوامل استقرار المنحدرات ونظم المعلومات الجغرافية

فتحي شعبان، تركي حبيب الله ، صفوت جبر، وليد أبو السعود، عصام مرسي، عبد الله غرم الله
معهد خادم الحرمين الشرفين لابحاث الحج والعمرة، جامعة ام القرى

ملخص البحث (Abstract):

عدم استقرار الميول هي المشكلة الأكثر خطورة في مناطق التلال والجبال بالمملكة العربية السعودية. مدينة مكة المكرمة هي واحدة من هذه المناطق حيث تحتوي العديد من المناطق الحضرية التي تحيط بها بالجبال. ويمكن رؤية أنواع مختلفة من عدم الاستقرار في المنحدرات في هذه المنطقة التي تشمل الانتشار الجانبي ، والإسقاط ، والزحف ، والانهيارات الأرضية ، والانزلاقات الأرضية.

جبل ثور هو من الأماكن التي يقصدها الحجاج في موسم الحج والعمرة ، يزوره تقريبا مايقارب من ٢٠٠٠ زائر يوميا، ويقع جنوب مكة المكرمة على بعد ٤ كم، بين سهل وادي المفجر شرقاً وبطحاء قريش غرباً، ويشرف الجبل على حي الهجرة، ويصعد إليه الحجاج لرؤية غار الثور الذي اختبأ فيه الرسول عليه الصلاة والسلام مع أبي بكر الصديق أثناء الهجرة إلى المدينة المنورة، وجبل ثور هو جبل له قاعدة مستديرة الشكل وله قمم جبلية مدبّبة ترتفع من قاعدته الدائرية وعددها عشرة. يرتفع جبل ثور عن مستوى سطح البحر نحو ٧٥٤ متراً. يعد جبل ثور أحد المناطق التي تهدد الانهيارات الصخرية به على الطرق والمناطق المحيطة به. يستخدم الآلاف من الزوار والجولات السياحية طريق الجرف لزيارة غار ثور الذي يقع في الجزء العلوي من جبل ثور، بالإضافة إلى المناطق الحضرية المحيطة بالجبل والتي يزداد انتشارها على مدى السنوات الأخيرة، والتي تعاني من سقوط الصخور المتكرر في الغالب في موسم الأمطار، وزيادة شدة الانحدار للمنحدرات على طول الوجوه المختلفة للجبل يجعل هذه المناطق عرضة للمخاطر بسبب عوامل مختلفة مثل التجوية والتآكل وتأثير الإنسان. وقد تمت هذه الدراسة لتحديد مدى استقرار جرف جبل الثور ، من خلال تحديد المناطق غير المستقرة ، و بتطبيق المحاكاة الصخرية وخاصية الاستشعار عن بعد ، دراسة ميدانية ومحاكاة بالكمبيوتر ثنائية الأبعاد باستخدام برامج قياس درجة استقرار الميول والكتل الصخرية .

تم تحديد المناطق غير المستقرة المختلفة على طول طريق جبل ثور والجسور باستخدام القياسات الحقلية والاستشعار عن بعد على أساس تحليل الصور. بالإضافة إلى تحليل محاكاة الصخور أشار إلى إمكانية حدوث انهيارات صخرية في عدة مناطق على جانبي الطريق الصاعد الى غار ثور والتي سيكون لها تأثير على السياح، أيضا بعض المناطق من الجبلة المطلة على المواقع الحضرية المأهولة بالسكان. تم اقتراح عدة تدابير وقائية مناسبة للحد من مخاطر الصخور المتساقطة قبل الوصول إلى المناطق الحضرية والطريق الصاعد ايضا.

الكلمات الدالة: الإنهيارات الصخرية، جبل ثور، مكة ، استقرار المنحدرات.

Slopes instability is the most serious problem in the mountain and hills of Saudi Arabia. The city of Makkah is one of these areas where many of the urban areas are surrounded by mountains. Various types of instability can be seen in the slopes of this area which include lateral landslide, rotational landslide, creep and rockfalls s.

Jabal Thawr is one of the places frequented by pilgrims in the Hajj season, it is visited by almost 2,000 visitors a day. It is located 4 km south of Makkah, between Wadi Mufajar east and Qurish in the west. The mountain overlooks Al-Hijra, and pilgrims climb to see the cave where the Prophet Mohamed and Abu Bakr al-Siddiq were hidden inside, during the migration to Medina. Mount Thawr is a mountain with a round base shape and has ten raised mountain peaks, it rises from sea level to about 754 meters. Mount Thawr is one of the areas where rockfalls s threaten the roads and surrounding areas. Thousands of visitors and tours use the Cliff Road to visit Thawr cave, which is located at the top of Mount Thawr, in addition to the mountainous urban areas that have been increasing over recent years and which suffer frequent rockfalls s in the rainy season. Increasing the slope intensity of the different faces of the mountain makes these areas susceptible to hazards due to various factors such as weathering, erosion and human impact.

This study was carried out to determine the stability of the Thawr mountain, by identifying unstable areas, applying rock simulation and remote sensing, field study and computer simulations using two dimensional measurement programs slopes and rocks stability.

Using field measurements and remote sensing based on image analysis, in addition to the analysis of rock instability, various unstable areas were identified along the mountain specially the ascending track that will have an impact on tourists, also some areas of the mountain overlooking the urban sites inhabited. Several appropriate preventive procedures have been proposed to reduce the risk of falling rocks before reaching urban areas and the rising road as well.

Key words; Rockfalls, Makkah, Thawr mountain, slope stability.

1. Introduction:

The common phenomenon that can affect separated homes, long roads, entire villages, railways and other human facilities is the rockfalls. These structures are at risk of rocks in or near the base of steep rock slopes. Rockfalls is a fast block movement produced by rocks that separate from a slope and fall free and slope. Because of their high speeds and unpredictability, such events can cause injuries, even with small rock volumes less than 1 m3 (Gigli et al., 2014; Volkwein et al., 2011). Most often, the risk of rocks can not be eliminated because of their frequency and magnitude, which differ on the temporal and spatial level. The main difference in the fall of rocks from the phenomena of other unstable slopes is the high movement of falling rocks (Frattini et al., 2008). Reducing the risk of rock resonance by the absence of high-accuracy geological data on mileage, rock removal, soil engineering and rock path. (Dorren, 2003).

The rock risk assessments reliability depends on the quantity and quality of available data (Pradhan et al., 2014). Rock hazards are usually estimated by a two-dimensional or three-dimensional emulation (Fanos and Pradhan, 2016), which assesses the paths of rocks, velocities, kinetic energy and bounce height of the falling masses. Simulated models emulate the imitation of rock movements, and calculate motion displacement based on Newton's second law while ignoring air friction (Bradhan and Venus, 2017b). Some of these models explicitly include the rolling movements of rocks (Lan et al., 2007). However, the study of rock impact assessment (rock interaction with topography during serial communication) remains a major scientific challenge in rock modeling (Matas et al., 2017).

Slope instability is the most serious hazard in mountainous and mountainous areas in Saudi Arabia. The city of Makkah is one of these areas where there are many urban areas surrounded by mountains. Various types of slope instability can be observed in this area, which include lateral propagation, projection, crawling, rotational landslides, sequential landslides and rocks (Youssef et al., 2009, 2012). Among these different types of landslides, rocks are one of the most important geological hazards in this region. Fewer studies have been conducted to investigate them along the city of Makkah. Thawr Mountain is one of the most attractive mountains in the Makkah city. It comprises a Thawr cave at the top and is a tourist site for religious pilgrimage. Attracts thousands of tourists and visitors every year from all over the Islamic world. Thawr Mountain became an urban area and urban areas expanded to reach the toes and over the gentle slope of the mountain. Most rocks occur along the mountainside because of an ongoing process of weathering which ultimately deteriorates the strength of the rock mass and opens the joints and fractures.

Rockfalls are a kind of slippery (small slide), where unsupported rock blocks are separated from the surface of the cliff and located freely under the influence of gravity. These rock blocks can be separated by different mechanisms such as natural mechanisms such as freezing and melting cycles (McCarroll et al., 1998; Matsuoka and Sakai, 1999); seismic activities (Bull et al., 1994; Viderih et al., 2001; Abebe et al., 2010) or human activities along cliffs and mountain regions by blasting, the movement of a heavy drilling machine (Dorren, 2003; Vijayakumar et al., 2011) and more importantly by slow deformation depends on the slope material time.

This study was carried out to evaluate the impact of falling rocks on urban areas and to assess the risk for travelers traveling through the Thawr ascending route to the top of the mountain. This area has recently experienced different types of rocks that have caused many problems. In the present study, two main objectives were analyzed: (1) the stability of Mount Thawr; (2) the causes of the rocks, hazards, and simulations of Mount Thawr were investigated in relation to the surrounding urban areas and the Thor Path. Extensive field investigations have been used to determine the stability of the mountains and to determine the location of critical unstable zones. The risk of rock collapse was determined by field and rock simulation. Therefore, the development of a complex mountain topography model has become a major challenge because of the complex process that can increase the calculation time. In general, 2D rock simulation is preferred.

The current research proposes a methodology aimed at determining the precise terrain of the slopes and the three-dimensional positions of the important features (eg, current protection measures, risk elements, etc.). In addition, it aims to identify the dimensions and shapes of rocks and major rock source areas. Several studies have already addressed some of these topics, using either light detection and range (LiDAR) or pictorial data (Abellán et al., 2010; Ferrero and Umili, 2011; Ferrero et al., 2011; Gigli et al., 2014). Although many studies have been conducted on rock risk assessment, information on impact sites in the literature has not been discussed. However, the impact site is the most important factor in assessing the risk of rock collapse and the design of mitigation processes. Moreover, the time component of existing studies has not been considered, although it is an essential component of early warning processes. Some researchers used a two-dimensional modeling approach to modeling rock movement (Keskin, 2013; Papathanassiou et al., 2013).

2. Study area and geological setting:

2.1. Location:

The study area is located in Makkah province (Fig. 1) in Makkah city. Thawr Mountain is located to the northeast of Al-Haram mosque, it has altitude of 757 m above the sea level, many urban areas are located near Thawr Mountain from all directions. Rainfall usually take place during the wet season from November through January, according to the metrological station located about 7 km southeast of the study area, and operated by the custodian of the two holy mosques research institute of hajj and omrah. Most of the rainfall is relatively short duration for few hours. The average annual precipitation is reported as about 75 mm/year. The peak monsoon seasons fall between July and October.

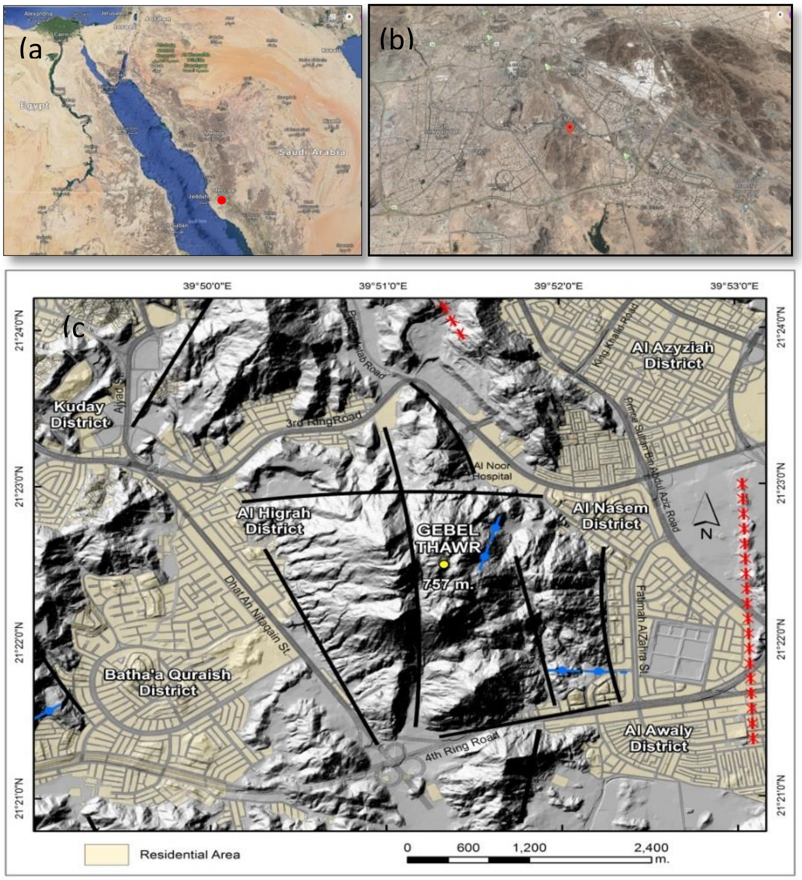

Fig.(1): (a) Location of Thawr Mountain in Saudi Arabia, (b) Thawr Mountain location in relation to Al-Haram Mosque, (c) Hillshade map prepared from the DEM showing the topography and main structural elements affecting Gabal Thawr area.

2.2. Geology:

Geology of Gabal Thawr is related to the Ju'ranah complex (kutg) (Moore and Al-Rehaili, 1989). It is composed of tonalite and subordinate granodiorite. It has a sharp steep intrusive rocks and composed mainly of medium to coarse-grained hornblende tonalite. The mineral composition showed that the hornblende tonalite is composed of plagioclase, quartz, and hornblende, and minor amounts of k-feldspar, biotite, epidote, chloride, sphene, apatite, and iron oxide (Makkah Quadrangle sheet 21 D)-GM-107c) (Moore and Al-Rehaili,1989). Other geologic units are present surrounding Thawr mountain which includes alluvial fan deposits (Qat), eolian sand (Qe), alluvial, elluvial, eolian deposits (Qu), gabbro (gb), gabbro–diorite (gd), microgranite (gmb), granite (gr), complex diorite–gabbro (mdg), diorite to quartz diorite (mdq), intrusive rocks (xam), metagabbro–gabbro (xgb) and zibarah group (zm). Different types of structures are encountered in the study area. These structures include some normal faults that run perpendicular to the Red Sea. The area follows these structures in an elongation shape. Other types of structures such as linear trend lines are dissected in the study area. The trends of these linear lines are ENE–WSW (Fig. 2). Most of the exfoliation and main joint trends were measured in the field and they have same linear trends. In the Makkah quadrangle which include the study area is characterized by two main trends of structures including north–northeast, to northeast and north–northwest. The first trend is related to Precambrian phases of deformation, whereas the second main trend reflect faulting, fracturing, and shearing that associated with the Red Sea rifting. The northwesterly faults are older and they are mostly normal faults that dip steeply to the southwest.The northeasterly trending faults displace the northwesterly faults. Other fault trend which is north facing is characterized by sheared faults that displace the northeasterly faults. In addition, the youngest plutons have an elongated form, mainly foliated, sheared, and faulting (Moore and Al-Rehaili, 1989). In addition, the contact between Ju'ranah complex and other surrounding rocks are sheared.

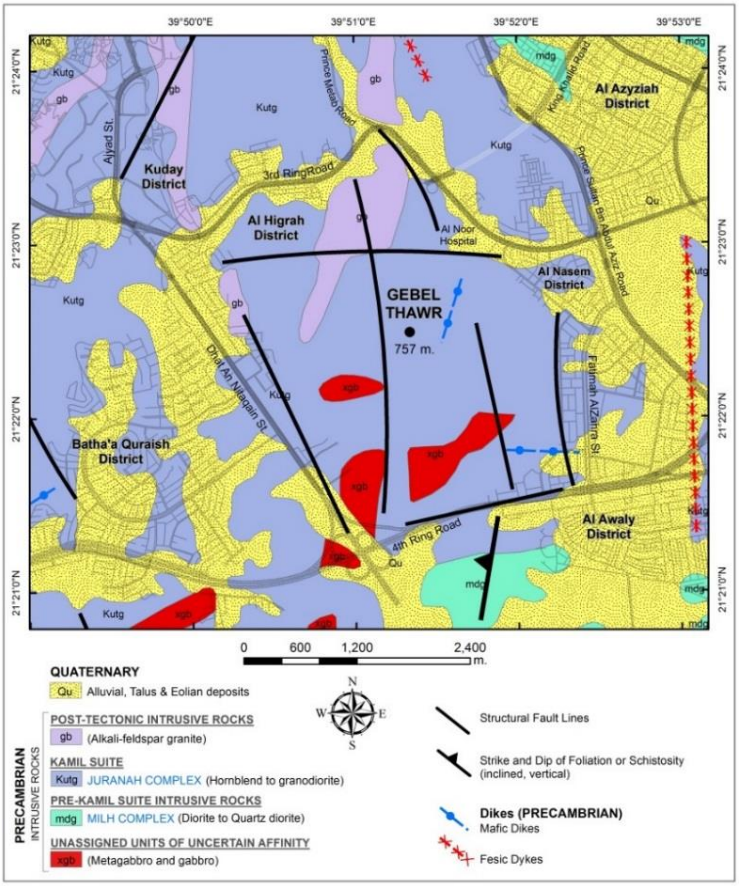

Fig.(2): Geology and structural map of Thawr Mountain and its surrounding areas.

2.3. Engineering geology of the Thawr Mountain;

The engineering geology characteristics of the study area were studied corresponding to field and laboratory investigations. Detailed field investigation have been done to determine the rock mass characteristics and determine the main areas that are lying down to the rockfalls. Whereas the laboratory investigation was done in order to determine the mechanical properties of the rocks (ISRM et al., 2007) (Table 1).

Table (1): Geotechnical properties of different rocks at Thawr mountain.

Property	Massive Tonalite	Grey Granite Weathered	Exfoliation Grey Granite	Cap Rocks
Deformation	No	Moderate	Moderate	High
Joints	3 joints + random	3 joints	Main one joints	Highly jointed
Average joint spacing	0.62 m	0.4 m	0.1 m	0.25 m
Weathering degree	Fresh – Slightly	Highly – Completely	Slightly – Moderately	Moderately
Persistence	10–25 m	8 m	20–30 m	10–20 m
Aperture	2–40 mm	-	20–100 mm	40–200 mm
Density (Mg/m3)	2.4	1.8	2.1	2.3
UCS MPa	200	3–10	10–35	50–100

Rock mass characteristics of Thawr Mountain is composed of tonalite and subordinate granodiorite. It has a sharp, steep, intrusive rocks, composed mainly of medium to coarse-grained hornblende tonalite. The mineral composition showed that the hornblende tonalite is composed of plagioclase, quartz, and hornblende, and minor amounts of k-feldspar, biotite, epidote, chloride, sphene, apatite, and iron oxide. The grey granite older ones are moderately to completely weathered, exfoliation characteristics appear in the grey granite weathered rocks (Fig.7). Three types of rocks were investigated in the study area including massive granite, weathered granite, exfoliated granite, and upper deformed rocks (Fig.8).

3. Materials and methodology:

Landslides in Makkah is a complex process since they are strictly controlled by variety of factors such as, geology, geomorphology, hydrology, the weathering processes, the recent changes in land cover and land use, etc., which have great influences at different sites in the study area. The hillslopes in the study area are originally composed of massive basement plutons to foliated metamorphic rocks. The formation of secondary structures (faults, joints, etc.) have resulted in the development of blocks and fragments of different dimensions. The detachment of these materials from the hillslopes depends on the degree of weathering, the slope angle, roundness of boulders, which is not uniform even on a single hillslope, etc. The exfoliation from granitic hillslopes is one of the main factors responsible for the development of massive rounded boulder, which may measure up to several meters in diameter. These exfoliation-boulders are the most susceptible for rockfall. Several hillslopes have very clean and smooth curved surfaces as being stripped off these boulders, which are now packed at the foot slopes. Therefore, loose boulders upslope of now steep and smooth surfaces could result in some hazard if no longer stable on these critical slopes.

The identification of potential zone for landslide hazards at Gabal Thawr requires the integration of multiple datasets including recent satellite images, DEM, geological data and detailed fieldwork. The rock-cut slopes can easily be observed using satellite images, as the spectral reflectance of the excavated rocks is markedly higher than non-excavated outcrops. Another mean of its identification is the shadow formed from the resulted artificial cliffs and the change detection using a time series of satellite images (Figure 3).

Fig.(3): Satellite images acquired in 2011 and 2018 showing the locations of rock cutting and land filling activities to the northeast of Gabal Thawr.

Using satellite images alone is not a reliable process since we cannot measure both the slope direction and amount. For this purpose, the use of Digital Elevation Models (DEMs) is a must (Figure 4) to produce both the aspect and slope maps of the area. The ArcGIS 10.6 software has been used to process the DEM of Gabal Thawr area, which has been acquired from the SRTM satellite mission (1 arc.sec).

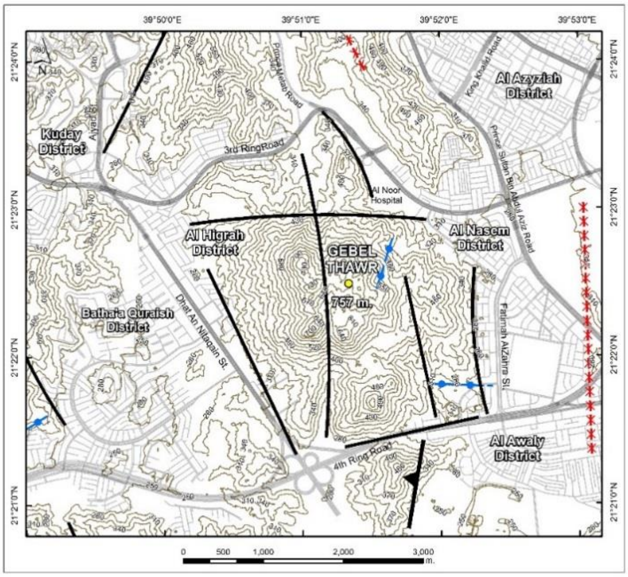

Fig.(4): Elevation contour map prepared from the DEM showing the topography and main structural elements affecting Gabal Thawr area.

The Aspect map is simply a map with 10 slope direction classes (Figure 5) ranging from flat surface to N-, NE-, E-, SE-, S-, SW-, W-, NW-, dipping surfaces. From Figure 5, we can easily see that the dominant slope trends in Gabal Thawr are N, S, E, and W. These main slope trends can easily be attributed to the N-S and E-W trending faults in the area, with the sloping surfaces represent the inclined fault blocks. It is worthy to notice that the increase of slope degrees (250- 340) towards the north and west banks of the mountain, this increases the likelihood of instability of the slopes and increase the chance of falling rocks, especially in the rainy seasons with the lack of friction between unstable rocks and the slope surface.

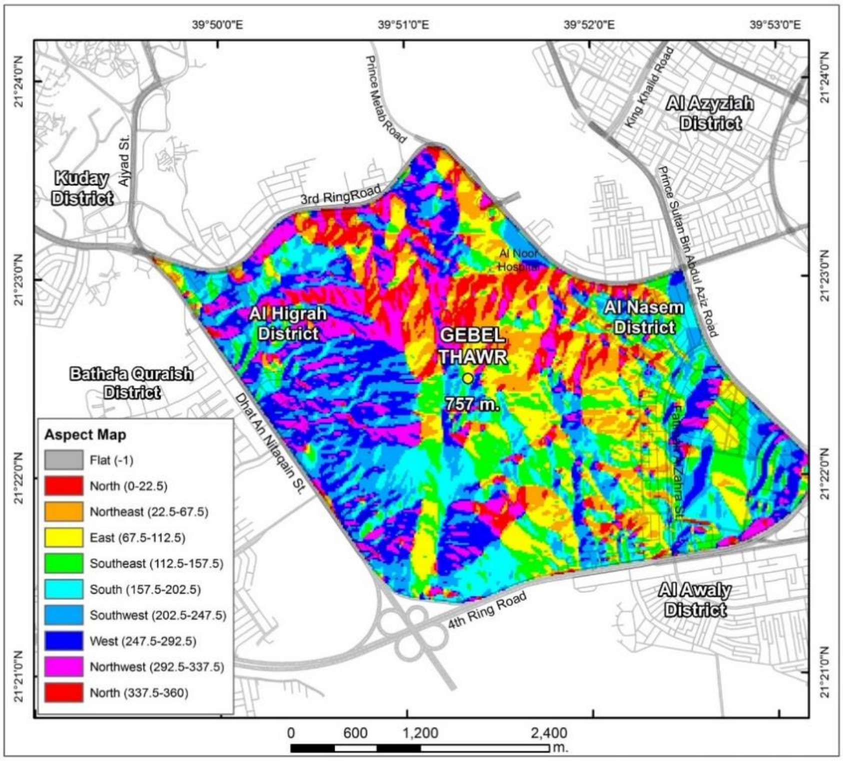

Fig.(5): Aspect map of Gabal Thawr area.

The slope map (Figure 6), on the other hand, showing the angle of which, the surface is dipping from the horizontal, where the value of 0 represents a perfectly flat horizontal surface and 90 represent a vertical surface.

It is important to say that the recent large-scale rock cutting in the area has affected the stability of the up slopes of Gabal Thawr, especially at areas dissected by incised channels and fluvial terraces now hanging on top of the artificial cuts. Therefore, it is necessary to estimate the potential runoff of given rainfall events for these particular hillslopes, in order to determine the potential landslides of detritus sediments and the embedded rock boulders.

It is so clear that the human modification of hillslopes for creating new plans suitable for urban development has affected the rock stability in certain areas. Furthermore, the dumping sites for waste rock fills are now widespread and their build in low-laying areas have also induced significant changes in the landforms of Makkah. These morphological changes may complicate the geo-environmental problems such as, blocking of drainage channels and altering runoff flows of occasional flash floods and hence adversely affect the designated areas. Duping of loose martials on top of the mountains for ground leveling may result in the washout of the rock fragments during heavy rain events.

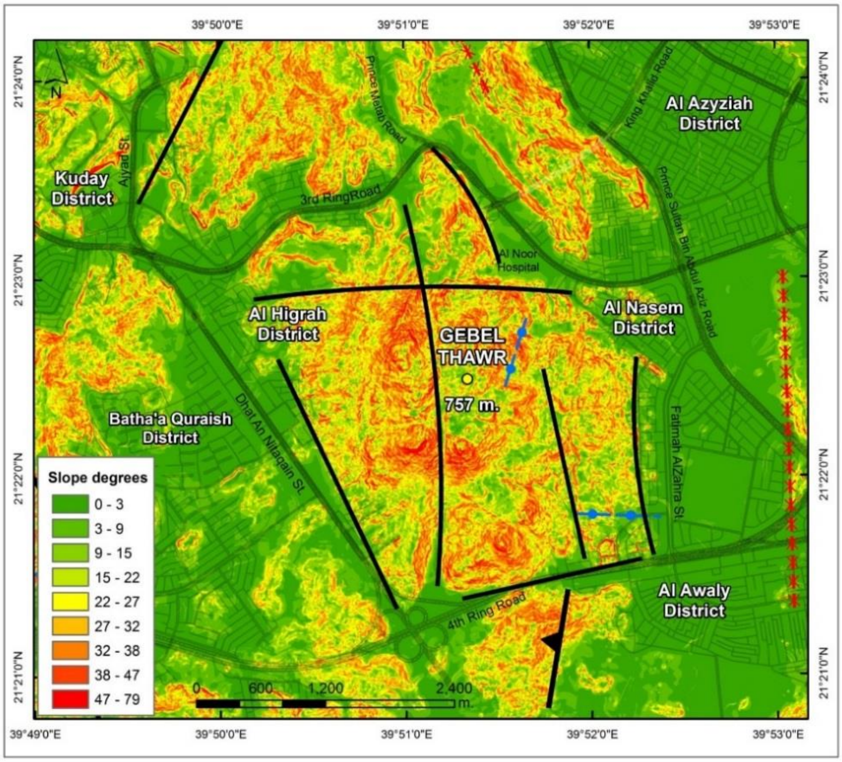

Fig.(6): A slope map of Gabal Thawr area.

4. Results and discussion:

A detailed field investigation was carried out along Gabal Thawr. For this purpose, multiple field trips were performed in the study area and most unstable areas were determined along the extension of the ascending road to the Thawr cave at the topmost. It was observed that the major rockfalls problems occurred in different sides of the mountain and different unstable areas were determined along the Thawr escarpment road (track road) (Figs. 7&8). This escarpment track was used by tourists and visitors to reach the upper portion of the Thawr Mountain. However, based on the field investigation, four unsettled locations were identified and were used to apply the rockfall simulation. On the other hand, Satellite images acquired in 2011 and 2018 showing the locations of rock cutting and land filling activities to the northeast of Gabal Thawr, these human activates having a negative impact on the stability of the slopes of Mount Thawr because they generate small seismic waves during the work of machines in the rock cutting, which in turn works to increase and widen the cracks or lead to direct rock fall.

The GEO5 2018 slope stability software was used to examine the stability of some regions on the ascending road escarpment as represented in figures 9&10, the slope stability values resulting from the two cases was 0.6 and 1.12 respectively theses values are less than 1.5 which represent the safe slope stability factor.

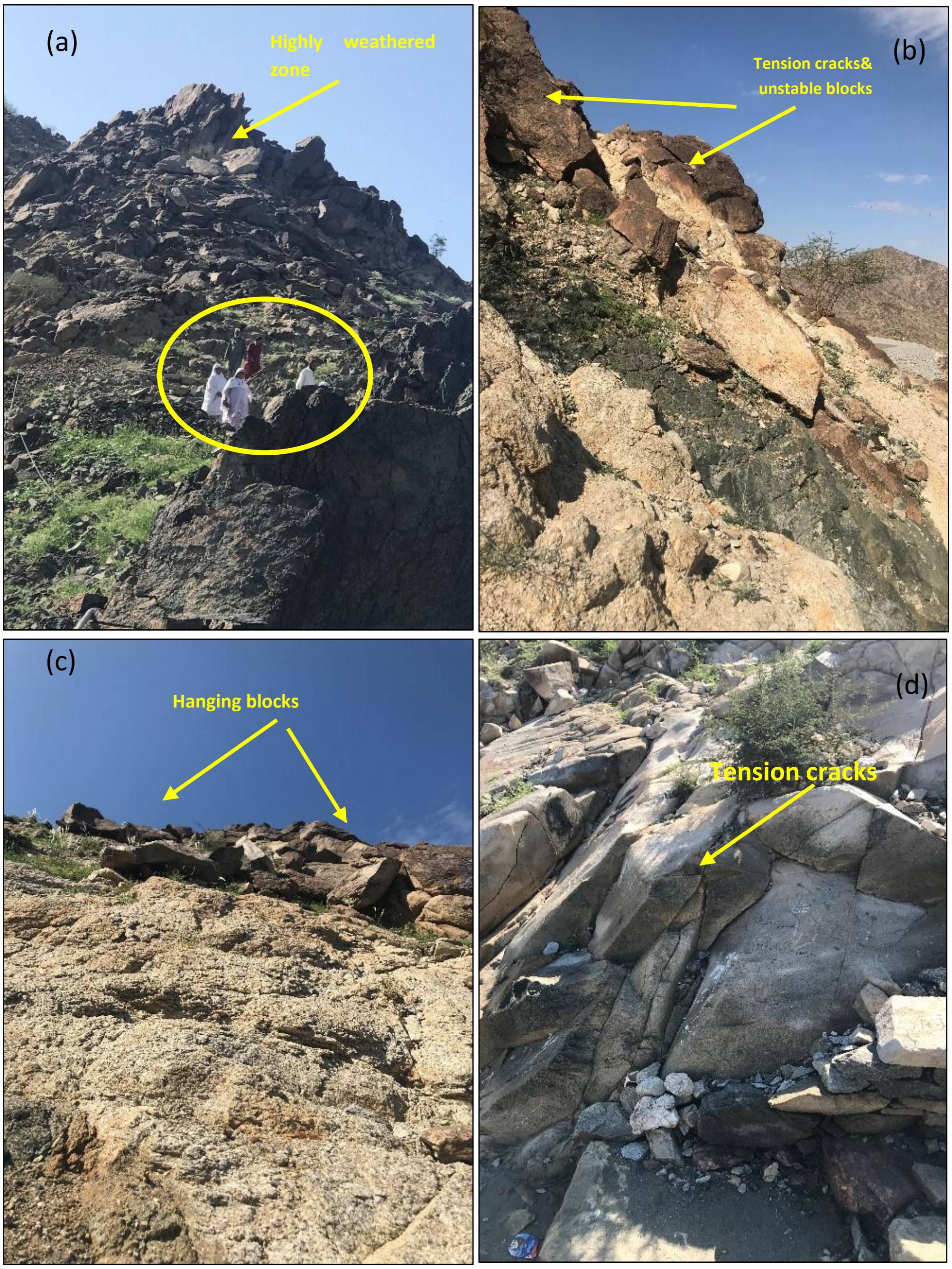

Fig.(7): Field photographs show (a) highly weathered granodiorite (b) unstable blocks and tension cracks structure at the road side (c) steep fracture planes at the road side, (d) small hanging blocks.

Fig.(8): Field photographs show (a) highly weathered granodiorite (b) unstable blocks and tension cracks structure at the road side (c) steep fracture planes at the road side, (d) small hanging blocks.

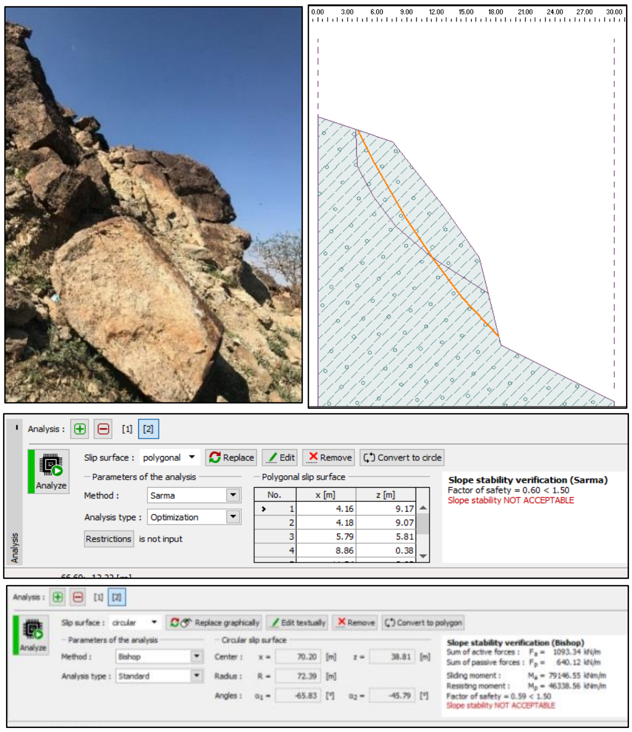

Fig.(9): An illustrative example for the study of slope stability at a part of the ascending road of Mount Thawr.

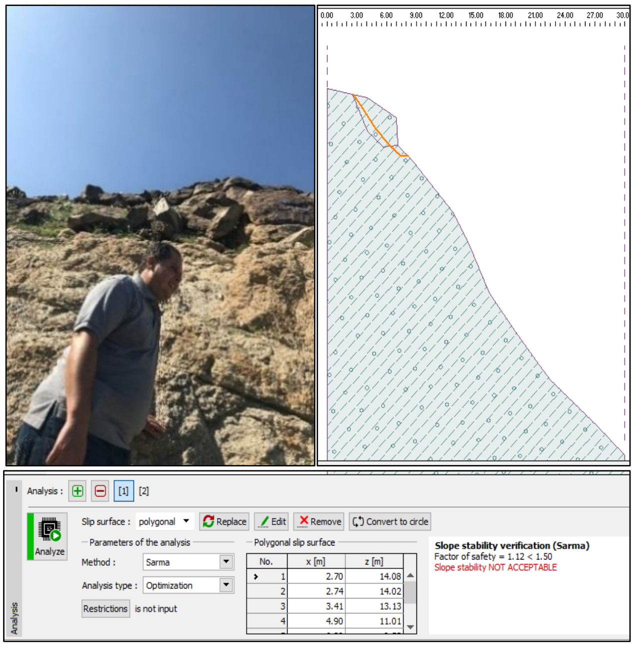

Fig.(10): An illustrative example for the study of slope stability at a part of the ascending road of Mount Thawr.

5. Conclusion and recommendation:

The identification of potential zone for landslide hazards at Gabal Thawr requires the integration of multiple datasets including recent satellite images, DEM, geological data and detailed fieldwork. It obtained that the increase of slope degrees (250- 340) towards the north and west banks of the mountain, this increases the likelihood of instability of the slopes and increase the chance of falling rocks, especially in the rainy seasons with the lack of friction between unstable rocks and the slope surface.

In addition to, the recent large-scale rock cutting in the area has affected the stability of the up slopes of Gabal Thawr, especially at areas dissected by incised channels and fluvial terraces now hanging on top of the artificial cuts. examine the stability of some regions on the ascending road escarpment as represented in figures 9&10, the slope stability values resulting from the two cases was 0.6 and 1.12 respectively theses values are less than 1.5 which represent the safe slope stability factor.

The researchers recommend that:

- Removal of the unstable rock masses on both sides of the ascending road at Mount Thawr which visitors use to climb up to visit the Thawr Cave,
- Fixing the sides that suffer from the accumulation of large rocks fragments on both sides of the ascending road.
- To stop the activities of rock cutting at the foot of the mountain.
- Detailed study required for the whole mountain specially the areas overlooking residential neighborhoods.
- This study should also be applied to the mountain areas surrounding the holy places.

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