Assessment of Landslides of the Hillslopes in Makkah Using Remote Sensing and GIS Techniques

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Abstract: The landslides of Makkah hillslopes have been assessed using remote sensing, GIS and fieldwork techniques. The geology and geomorphology of Makkah is controlled the urban development of the city on limited alluvial plains, footslopes and rock-cut parcels of the piedmonts. High resolution satellite images were utilized to determine rock-cut slopes, land use and land cover maps, which were created by geographic information system (GIS) and verified in the field. The development of regolith covers hillslopes is controlled by the dominant geological setting, structures, weathering mechanisms and palaeohydrological setting. The stability conditions of debris materials on hillslopes have been affected by the ongoing rock-cutting processes of the piedmont. The simple slopes covered by regolith of different shapes and dimensions are in stable conditions, as the surface roughness, which is high and could retain the limited landslides. On the other hand, compound slopes are mantled by abandoned terraces of various-sized sediments and assigned as the most susceptible for landslides. The relict palaeohydrological features and abandoned terraces are being gullied by occasional heavy storms and resulting overland flow and runoff. The extent of gulling, mud and debris flows and the buildup of debris at talus cones are characterized by high spatial variability. Furthermore the landslides also depend on the morphometrical parameters of abandoned terraces, profiles of hillslopes and upslope contributing areas of the overland flow and runoff. However these slow and occasional landslides may have very limited impact on urban areas, but further complication could arise as, for example, a key electricity distribution station in Makkah is constructed on the top of local piedmont being gullied by occasional storms. Moreover, the buildup of dumping sites for waste rock fills has also induced significant changes in the landforms of Makkah, which has blocked certain active alluvial channels used to covey flash floods.

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Introduction

The landslides are very complex process; the instability of slopes can be triggered by variety of mechanisms and causes including, but not limited to, earthquakes (Refice and Capolongo, 2002), dynamics of soil moisture (Talebi e al., 2007), weathering mechanisms (Chigira et al., 2002) and heavy precipitation processes (Tarolli et al., 2011). This control is likely to vary with the composing geological materials structures, and the landform (Clague, 1980). However, the currently active-processes are determined, to some extent, by the form evolution; the slopes may possess relict features formed under different climatic conditions. Moreover, denudation, transportation and accumulation of landslide materials are strictly applicable to certain points throughout the whole slope length and vary considerably over space and time. The scale of landslides may range from spontaneous creeping that only extent few meters in dimension, to rare gigantic slides or avalanches, which could cover up to several kilometers in size and thus affecting sizeable populations (Horn and Scott, 1975). The detritus of landslides is also various, and it can be entirely composed of rock fragments, others of soils only, and a few are of mixed materials. For considerations of effects on people and engineering works, the speed at which a landslide develops and moves is the single most important feature (Youssef et al., 2009). Few defenses are available against rapid and unexpected movements that frequently result in damage, injuries and fatalities. However, landslides which move very slowly or over longer period of times will seldom cause causalities, as mitigation measures can be taken. Although the impact of landslides can be considerable, but the processes itself is highly complex and therefore assessment can be also difficult (Carrara et al., 1991).

Therefore, different methodologies are being proposed to assess susceptibility of various landslide hazards (Saha et al., 2002). The simplest approach to analyze a landslide depends on direct field observation of mass movement occurred during past landslides, or mapping the interpreted recent landslides from available aerial photographs and high-resolution satellite images (Wieczorek, 1984). Monitoring of susceptible areas can be achieved using installed survey networks and control stations, where target prisms are placed on and around areas (i.e. on stable ground) of anticipated instability. Thus, angles and distances between them are regularly measured to detect any movement on slopes and to obtain quantitative estimates. Additionally, air born Synthetic Aperture Radar (SAR) can also be used to generate a high quality Digital Elevation Model (DEM), and to detect delicate surface disturbances (e.g. Furneu and Achachi, 1996; Massonet, 1997).

These different observations and measurements can be correlated with other morphologic and the driving force to obtain quantitative index for landslide analysis, and to propose a numerical scheme for landslide analysis (Montgomery, et al., 1991). Geographic Information System (GIS) proved very efficient to compute certain morphometrical parameters from DEM as well as compiling, manipulating and analyzing different co-registered parameters (Terlien et al., 1995) Of course the weighted parameters are very subjective and elaborated on certain experience, types of landslides and geological and geomorphologic setting, thus their regional application can be totally misleading. Therefore, it remains necessary to understand control and distribution of landslides in certain areas to determine the potential hazard. This paper will investigate the susceptible landslides of Makkah city, which is mainly built on sets of alluvial channels bounded by steep mountain ranges. The complex geological and geomorphologic setting for the study area has confined the urban growth of Makkah at the foot slopes of surrounding mountains. Notably, considerable areas of piedmonts and foot slopes are being cut and cleared for urban development. Therefore, it is necessary to assess the human impact on the stability and equilibrium conditions of Makkah hillslopes, and to determine the potential landslide hazards.

The study area:

Makkah city is located in the southwestern part of Al Hijaz province of the Kingdom of Saudi Arabia, between the low-lying coastal plain (Tihamat Al Hijaz) and the escarpment of the rugged Sarawat mountains that has resulted from the uplift associated with the Red Sea rifting (Fig 1). The geomorphology has controlled the unique urban pattern of Makkah metropolitan city, which has sprawled in radial direction on the limited surface areas of the complex alluvial channels always being separated by the steep mountain ranges. It is estimated that approximately 9000 hectares of alluvial channels and footslopes of the mountain were converted into urban areas from 1978 to 2000 (Al Ghamdi and Al Naggar, 2002). The Wades of Makkah dissecting the mountain ranges are characterized by complex and interlocking patterns. This complex pattern of intersecting alluvial areas are very common in the dry land setting and reflect the morphotectonic evolution of these drainage basins, where the paleo-channels (i.e. palaeohydrology) were used to flow through different directions than the contemporaneous flow pathways (e.g. El Bastawesy et al., 2010). However, the restricted attachment of urban neighborhoods, were overcome through tens of tunnels and rock-cut corridors through these mountains ranges. Because of the disappearance of land parcels suitable for urban development, it is now common in Makkah to cut the piedmont and footslopes of the neighbouring mountains in order to create new suitable plots for buildings, especially in the areas near the Holy Mosque of Makkah. Similarly, the footslopes of the mountains bordering the Holly places (i.e Arafat, Muzdalepha and Mena) were also cut to provide more spaces and infrastructures for millions of pilgrims are annually gathered for few days to perform Hajj. Due to the importance attached to the holly places, multiple rock fall mitigation measures were adopted including, concrete barriers, berms and Gabion walls, grouted dowels and shotcrete lining (Fig 2). While mitigation measures in the other urban areas included terracing of the cut-slopes and supporting some cut-slopes with shot Crete lining and addition to considering a safety-zone between urban and the cut-slopes.

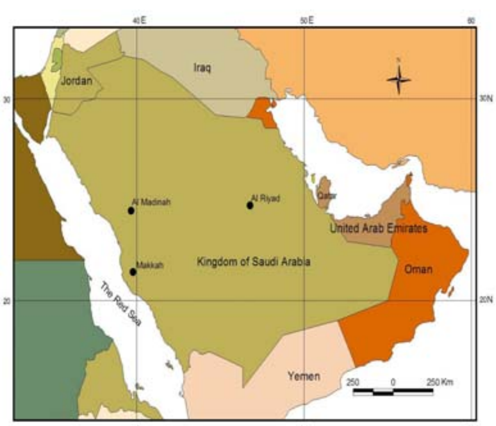

Fig 1: Location map of the study area.

Fig 2: A field photo shows the loose boulders and the constructed gabion wall on the eastern hillslope of Wadi Mena.

The mountain ranges of Makkah are structurally controlled; they are aligned in northwest-southeast (e.g. Mena Mountains) or east-west directions (e.g. El Tarqi Mountains). However, few mountains are isolated and conform semi-circular shape such as Thour Mountain (755 m) and El Nour Mountain (642 m). The chronology of underlying rocks units in Makkah area is complex; the isolated outcrops of amphibolites, gneiss and schist are of uncertain stratigraphic relationship to other layered rock units of the mountain ranges, and thus they are left unassigned on the geological map of Makkah Quadrangle (Moore and Al-Rahaili, 1989) (Fig 3). These outcrops are of moderate to steep relief, and also range from massive to well deformed and foliated plutons depending on the genesis and tectonic evolution of these rocks. However, most of the slopes in Makkah are genetically of simple type (i.e. composed of one rock type), and compound slopes (formed of more than two rock types, or more than one succession of two types) are less common. But the tectonic movements has played a significant role in the formation several discordant sets of joints, and fault plains that supported the splitting of various blocks and rock slabs.

The geomorphologic characteristics of different regolith, rock fragments and detritus sediments on the hillslopes of Makkah mountains have been developed from the interplay of geological setting, structures and weathering processes. The granodiorite and gabbro plutons were the least affected by tectonic movements, and these rocks have kept the primary texture and structures. Therefore, weathering processes are quite limited; the surface grains and crystals are disintegrated and etched, thus resulting in massive and clean slopes (Al Solami et al., 2006). On the other hand, the structurally-distorted and deformed rock units, the prolonged weathering processes resulted in the decay of rock-forming minerals along weakness plains into clay minerals and thus dispatched the regolith on top of these hillslopes. Additionally boulders of different dimensions are developed on the outcrops of some grantic hillslopes and inselbergs, and these boulders are quite rounded and may have developed by exfoliation mechanism. The piedmont of hillslopes are usually mantled by mixture of rock boulders ad fragments embedded into matrix of coarse and fine sediments, which may owe their development to the paleohydrology and morphotectonic evolution of the study areas.

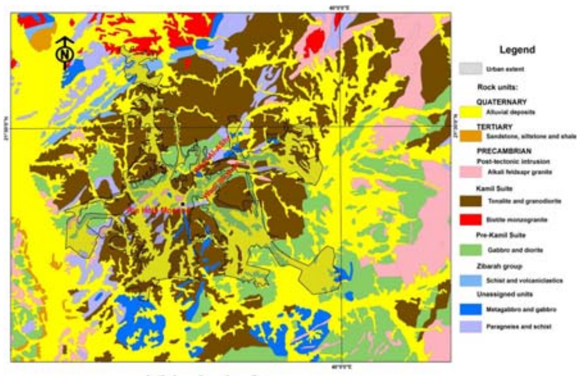

Fig 3: The geological map of the study area (after the Saudi Geological Survey, 1989).

Data and methods:

The assessment of landslide hazard in the city of Makkah required the integration of multiple datasets including recent SPOT 5 satellite image, DEM, geological data and detailed fieldwork. The SPOT 5 satellite image was acquired in February 2011, and it was co-registered into Universal Transverse Mercator (UTM) projection, the other datasets were also co-registered in same coordinate system. The rock-cut slopes were easily distinguished on the satellite image, as the spectral reflectance of excavated rocks is markedly higher than non-excavated outcrops, and also from the shadow of these artificial cliffs (Fig 4). However, the orientation of some high topography to the angle and direction of image acquisition areas has had little impact the expression of rock-cut slopes, and therefore the delineation of rock-cut slopes and landfill sites were accomplished with a high degree of accuracy. The geological setting of these hillslopes was determined from the available geological map (1: 250,000) (The Saudi Geological Survey, 1989). However, the scale of this geological map is very coarse and may be inadequate data source for a detailed study, but most of the mountains are composed of single rock unit and thus genetically compound slopes are not common particularly within the metropolitan city of Makkah. The geological structures, spacing and orientation of joints sets were measured in the field of study to determine the impact of the structural control on the development of rock fragments on the hillslopes. The geomorphology of hillslopes, regolith and detritus materials was also elaborated from the field investigation. This is to highlight the extent of weathering processes on the distribution of different materials susceptible to landslides, and to clearly identify the dominant types of these landslides.

Fig 4: A recent SPOT-5 image for an inset of the study area shows the development of urban features on

The recent large-scale cutting of the pediment has affected the stability of up slopes, 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. Therefore, the DEM of the Shuttle Radar Topography Mission (SRTM) was processed to estimate the slope degrees and aspects for different hillslopes and to derive the hydrological parameters of upslope length and flow contributing areas for the incised channels (Fig 5). The morphometrical parameters were delineated from the SRTM DEM following the Arc Info multi-steps procedure of the D-8 method. The processing of a DEM to produce hydrologically correct and connected drainage networks requires that sinks be first removed (Wise, 2000). Once a hydrologically connected DEM is produced by sink removal, flow direction is calculated for each cell in the DEM into the most down slope of the neighbouring cells. The 'flow direction' grid is then used to calculate a grid of 'flow accumulation', and finally thresholding is applied to extract up-slope contributing areas for all the drainage channels in the DEM (Jenson and Dominque, 1988). The resulting drainage networks were overlaid on the satellite image to identify their relation to cut-slopes and the urban features. Moreover the fluvial sags (i.e. abandoned terraces on hillslopes) were implied from the visual interpretation of satellite image, and their distribution relative to urban areas was mapped. Thus the gullying extent of the detritus mantle and the accompanied formation of cones at toe of cut-slopes can be determined in the field, in order to assess the magnitude of landslide hazards.

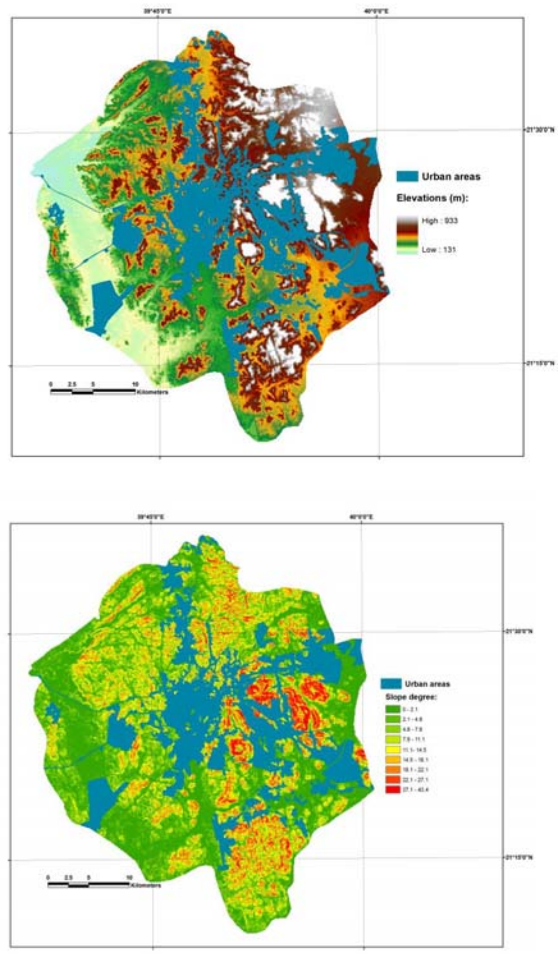

Fig 5: the distribution of urban areas and surrounding hillslopes, note the differences of elevation ranges (top) and slope degrees (bottom).

Results:

The landslides of Makkah hillslopes is a complex process; it has strictly been controlled by variety of factors including Geology, geomorphology, hydrology and the recent changes on land cover and land use, those factors have major influences at different sub-sites in the study area. A detailed land cover map was created from the satellite image; the different units were visually interpreted, digitized and verified in the field (Fig 6). The landslides of Makkah were assessed to address their negative impact on urban, which is growing rapidly on the excavated land parcels at footslopes and piedmont of hillslopes embracing Makkah. The geological and geomorphological data obtained from relevant maps, interpretation of satellite image and field work suggested a high variability of regolith types, genesis and distribution in the study area. However, the hillslopes are originally composed of massive basement plutons to foliated metamorphic rocks, but secondary structures have resulted in the development of blocks and fragments of different dimensions. The detachment of these materials from the hillslopes, degree of weathering and roundness of boulders is not uniform even on a single hillslope. The exfoliation from granitic hillslopes was a responsible factor 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 footslopes. Therefore, loose boulders upslope of now steep and smooth surfaces could result in some hazard if no longer stable on these critical slopes.

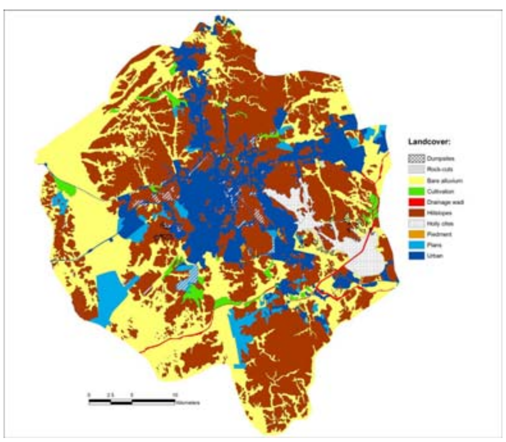

Fig 6: The produced landcover map which shows the spatial distribution of rock-cuts, urban features and hillslopes.

On the other hand, slopes covered by regolith of different shapes and dimensions are in stable conditions on the hillslopes, it seems that the high surface roughness would obstacle rapid landslides to the footslopes. Field observation of the regolith-covered hillslopes at different localities of cut-slopes showed no evidence for talus accumulation at their footslopes. It is understood that human intervention may have obscured some aspects of the physical processes of landslides, as previous landslides may have not been documented or their evidences have been obliterated. The most susceptible hillslopes for landslides are those mantled by ill-sorted sediments embedded with different-sized boulders. These abandoned terraces on the wadi slopes (i.e. spur-end slopes) most probably developed by tectonic activities, rather than being controlled by base level changes of the palaeohydrology. The supporting field evidences includes the local distribution of these terraces along few wadi slopes (particularly those trending NW-SE), and the marked difference of base heights. Indeed, the palaeohydrology within the time-scale necessary have developed appreciable form changes of the wadi slopes (i.e. relict features and abandoned terraces), which are now being gullied since the toe-slopes have been cut for urban development (Fig 7). The extent of gullying and the buildup of debris at talus cones is characterized by high spatial variability and it depends on the morphometrical parameters of abandoned terraces slope and upslope areas of the overland flow and runoff. Few slopes are of single sequence (i.e. the aspect is continuous along one segment) such as that of Al Aziziyah Mountain which border the southern suburb of Al Aziziyah in Makkah. But other slopes in Makkah are of multiple sequences which are composed of several segments of different profile and aspects. The single sequence slopes are steep (over 25^{o}) and locally incised by shallow first-order channels, which collects considerable amount of overland flow during heavy storms, thus washing the fine sediments on the piedmonts and hence the debris materials are slumped at talus cones. On the other hand, the larger mountain areas of different segments of hillslopes are interconnected into incised minor channels, which are integrated into a main channel filled with sediments and different rock fragments. The upslope contributing areas of beheaded channels at cut-slopes can reach up to 3.5 sq km such as in the tributary hillslopes gullies of Wadi Mena . The occurrence of heavy storms separated by long period of aridity is quite common in Makkah, and the analysis of recorded rainfall data suggested that the total precipitation depth for a designed storm with 50 years return period is 68 mm (Yousef, 1992). Thus the resulting runoff of this designed storm for the hillslope small sub-catchments can be enormous. Therefore, the artificial base level change for these small tributary channels to the main wades can result in washing and gullying of sediment material upslope by the developed surface runoff, and this gullying be recognized on high resolution satellite images spanned only by few years (Fig 7). It is so clear that the human modification of hillslopes for creating new plans suitable for urban development has affected the stability of regolith cover 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.

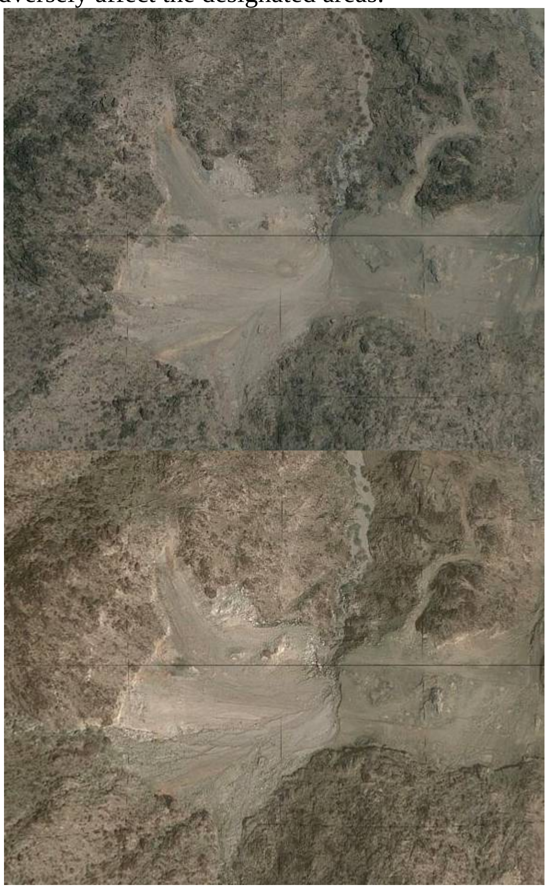

Fig 7: The gullying of abandoned terraces between 2007 and 2010 (source of images, google earth).

Discussion:

The dynamics of landslides in the city of Makkah is controlled by variety of interrelated natural parameters, and the impact of human activities to develop urban areas on the expense of surrounding hillslopes. Under the stress of population growth and the increasing numbers of pilgrims yearly coming to Makkah and the holy places, the urban has sprawled on most of the alluvial plains and adjacent flootslopes. Most of the new urban areas can only be constructed on cut-slopes areas of the adjacent hillslopes. However, different mitigation measures and techniques are being implemented in dealing with susceptible landslides, but the incomplete understanding of the physical processes of encountered problems has affected the efficiency of the adopted measures (Guzzetti et al ., 2009). The holy places of Makkah, where the Hajj is performed, are well protected from landslides thorough a set of different mitigation measures. The multiple defense system to protect the pilgrims' camps and network facilities in the holy places from landslides are stretching for more than 16 km along with the entire surrounding slopes**.** These different protection systems were designed and adjusted to the conditions of each site, the mutual interaction between both observations and computational analysis and the skillful communication between the different partners involved.

Despite of the spatial variability of landslides parameters and physical processes in Makkah, the terracing of cut-slopes is most widely adopted technique to control landslides. The facets of cut-slopes are segregated into segments; each is topped by a relatively wide bench so landslides from every upslope level can be intercepted (Ray and De Smedt, 2009). This technique is very effective in hillslopes composed entirely of massive rock units, but the stability of slopes was undermined in areas mantled by alluvial terraces or incised by hillslope channels draining a considerable upslope areas. The landslides in these are dominated by mud and debris flows which usually are developed following heavy storms (i.e. rain drop impacts) and resulting over land flow (i.e. sheet flow erosion of fine sediments). However, these slow and occasional landslides may have a limited impact on urban areas, but the resulting hazards can be further complicated by other factors. For example, a key electricity distribution station is constructed on the top of a small piedmont, which has artificially cut-facets and its upper part is composed of sediment materials (Fig 8). These sediments and boulders were not removed prior the construction, and this very small outcrop of abandoned terrace has developed notable gullying by the direct raindrop impact. As a result, the stability of this station is now in critical conditions and remedial action is required. Additionally, the towers of power lines grid are stretching across different hillslopes and the stability for some of these towers could also be affected by the landslides. It is obvious that the construction of urban areas and roads networks on the top of some hillslopes have also created artificial debris available for landslides. This scree covers several hillslopes of Makkah, and its response to heavy storms and landslides is quite slow and can be used as a marker to monitor the characteristics and development of landslides. On the other hand, the dump sites allocated for fill materials, which are excavated from the cut-slopes area, have altered the geomorphology of Makkah. Several fill sites are located in a low lying alluvial plain near the holy areas. Originally, this plain was undulated by several inselbergs, which are being covered by the build up of fill sites. It is anticipated that more footslopes will be cut to create suitable land parcels for urban, concurrently the fill sites will continue expanding. The problems of landslides of the fill areas are of negligible impact as long as these sites are not planed for development. However, the wider implications of the landfill sites are very critical; some of the active channels conveying flash floods have been blocked, hence the flash flood hazards is being complicated. Ultimately, the considerate assessment of the physical processes and their response to the interferences within the human habitats remains very essential to minimize the impact of potential natural hazards.

Fig 8: The landslide hazard at the installed electricity station of Al Aziziyah area, Makkah.

Conclusion:

The landslides of hillslopes in the city of Makkah is controlled by different physical parameters (i.e. rock types, weathering, slopes morphometry, etc) and the impact of human modifications and activities on natural setting of these hillslopes. High resolution satellite images has efficiently been used to identify rock-cut slopes and related features as well as producing land use and cover maps into GIS to determine the selection of field work activities. The limited availability of suitable land parcels for the necessary urban expansion of Makkah was compensated by cutting the footslopes and piedmont of the neighbouring hillslopes to exiting urban areas as well as developing some areas ontop of some hillslopes. Thus the stability of regolith cover materials and abandoned terraces is being variously affected by these changes. The cutting of single hillslopes composed of single rock units has not affected the stability of regolith upslope, but the rounded boulders developed by exfoliation constitute the main rock fall hazard particularly on steep and clean slopes. Furthermore, the most susceptible landslides are associated with hillslopes mantled by relict palaeohydrological features and abandoned terraces, which are being gullied by occasional heavy storms and resulting runoff. The extent of gullying, debris and mud flows and the accumulation of talus cones at the toe of hillslopes may not be of direct significant hazard to urban areas. But the landslides processes themselves can complicate other environmental hazards; particular facilities that can develop hazards (e.g. power and electricity stations, etc) may have been constructed on critical areas without enough mitigation measures. The accumulation of excavated materials in dump sites distributed in surrounding of the holy places are also being gullied by heavy storms, but the building up of these landfills have far more critical impact as they block some active channels conveying occasional flash floods outside the holy places occupied by millions during Hajj.

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