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Assessment of rockfall hazard at Al-Noor Mountain, Makkah city (Saudi Arabia) using spatio-temporal remote sensing data and field investigation

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ABSTRACT

Rockfall is one of the major concerns along different urban areas and highways all over the world. Al-Noor Mountain is one of the areas that threaten rockfalls to the Al-Noor escarpment track road and the surrounding urban areas. Thousands of visitors and tourisms use the escarpment track road to visit Hira cave which is located at the top of Al-Noor Mountain. In addition, the surrounding urban areas of Al-Noor Mountain are continuously spreading over the recent years. The escarpment track road and the surrounding urban areas are highly vulnerable and suffers from recurrent rockfall mostly in the rainy season. The steep and highly jointed slope along the different faces of the mountain makes these zones prone to failure due to different actions such as weathering, erosion and anthropogenic effect. Therefore, an attempt has been made in this study to determine the Al-Noor cliff stability, by identifying the unstable areas, and to apply the rockfall simulations. A combination of remote sensing, field study and 2D computer simulation rockfall program were performed to assess surface characteristics of the cliff faces. Bounce height, total and translational kinetic energy, translational velocity, and number of blocks have been estimated. Different unstable zones along the Al-Noor Mountain and escarpment track road were determined using filed investigation and remote sensing based image analysis. In addition the rockfall simulation analysis indicated that rockfall in zone 1 and zone 2 of the Al-Noor Mountain may reach the urban areas, whereas rockfall in zone 3 will not reach the urban areas, and rockfalls along the Al-Noor escarpment track road will have highly impact on the tourists. Proper preventive measures are also suggested to arrest the movement of falling rocks before reaching the urban areas and the Al-Noor escarpment track road. If proper care is taken, then further uncertain rockfall hazards can be prevented.

1. Introduction

Slope instability is the most critical hazard in hilly and mountainous areas of Kingdom of Saudi Arabia. Makkah city is one of these areas where many urban areas are located and surrounded by mountains. Different types of slope instability can be seen in this area which includes lateral spread, topple, creep, rotational landslides, translational landslides and rockfall (Youssef et al., 2009, 2012). Among these different types of landslides, rockfall is one of the most significant geological hazards in this region. Fewer studies have been carried out to investigate them along Makkah city. Al-Noor Mountain is one of the most attractive mountain in Makkah city. It includes Hera cave at the upper portion which is a religious pilgrimage tourist site. It attracts thousands of tourists and visitors every year from all over the Islamic world. The areas surrounding the Al Noor Mountain has become urbanized and the urban areas expand to reach the toe and above the gentle slope of the mountain. Most of the rockfall takes place along the mountain cliff faces due to continuous process of weathering which ultimately deteriorates the rock mass strength and further opens the joints and fractures.

Rockfall is a type of landslides (small slide), where unsupported rock masses get detached from the cliff face and fall freely under the influence of gravity. These rock blocks can be detached by

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different mechanisms such as natural mechanisms such as freeze–thaw cycles (McCarroll et al., 1998; Matsuoka and Sakai, 1999), seismic activities (Bull et al., 1994; Vidrih et al., 2001; Abebe et al., 2010) or by anthropogenic activities along the slope cuts and mountain areas by blasting, movement of heavy earthmoving machine (Dorren, 2003; Vijayakumar et al., 2011) and most importantly by slow time-dependent deformation of the slope materials. Sassa et al. (2009) indicted that rockfall assessment research in relation to other types of landslides is relatively small. However, the rockfall studies increased according to the increase of the urban areas in mountain and hilly areas (Davies, 1996; Erismann and Abele, 2001; Zhang and Yang, 2004; Ulusay et al., 2006; Zorlu and Tunusluoglu, 2009). In the literature, rockfall studies have been carried out in various fields such as protection and preservation of historic sites and monuments (Topal et al., 2007; Park et al., 2009; Wang et al., 2012), effects on forests (Dorren et al., 2006; Perret et al., 2004) along the road cut slopes (Budetta, 2004; Youssef and Maerz, 2009; Ansari et al., 2012; Palma et al., 2012; Youssef et al., 2009, 2012), and mines and quarries (Stockhausen and Alejano, 2003; Alejano et al., 2007).

In this paper, field investigation coupling with other geotechnical, geophysical, and numerical methods were used in rockfall analysis (Guzzetti et al., 2002; Zhang et al., 2004; Lacroix and Helmstetter, 2011). Rockfall movement and trajectory is mostly dependent on different types of parameters such as slope geometry, slope height, slope inclination, surface irregularities, and blocks shape. It is known that, the rounded shape massive blocks travel the maximum distance down the slope, followed by the square shaped blocks (Basson, 2012). Four types of rockfall motion have been determined which includes free fall, bouncing, rolling, and sliding. Rockfall trajectory simulation represents a complex phenomenon. It plays an important role in the understanding of the trajectory of natural and manmade rockfall hazards. The mechanism of free-falling bodies is well understood, and certain parameters including coefficient of friction, restitution, size and shape of falling blocks pose real problem during modeling of rockfall hazards (Vijayakumar et al., 2011). Therefore, modeling a complex mountainous topography has become a big challenge due to complex process which can increase computation time. Generally speaking, 2D rockfall simulation is preferred.

The study has been conducted to replicate the effect of falling rocks on the urban areas and assess the risk to the commuters taking the Al-Noor escarpment track road to the upper part of the mountain. This area recently experienced different types of rockfalls which caused many problems. In the current study two main objectives were analyzed that includes; (1) the stability of Al-Noor Mountain, (2) The rockfall causes, hazards, and simulation of the Al-Noor Mountain were investigated in relation to the surrounding urban areas and Al-Noor escarpment track road. A digital elevation model of 2 m resolution was used to extract a 5 m contour interval which was used to obtain the 2D slope profiles for rockfall run-out modeling. Extensive field investigations were used to determine the mountain stability and to identify the location of critical unstable blocks. A rockfall danger zonation was identified according to the field and rockfall simulation.

2. Study area

The study area is located in Makkah province (Fig. 1a) in Makkah city. Al-Noor Mountain is located to the northeast of Al-Haram mosque (Fig. 1b). Altitude of the Al-Noor Mountain reaches 625 m above the mean sea level. Many urban areas are located near the Al-Noor Mountain from all directions (Fig. 1c). According to the rainfall station (J114) which is located about 6.7 km southwest of the study area, and operated by the Ministry of Water and Electricity (MOWE). Rainfall typically occurs during the wet season that spans November through January. Most of the rainfall is relatively short duration for few hours. The average annual precipitation is

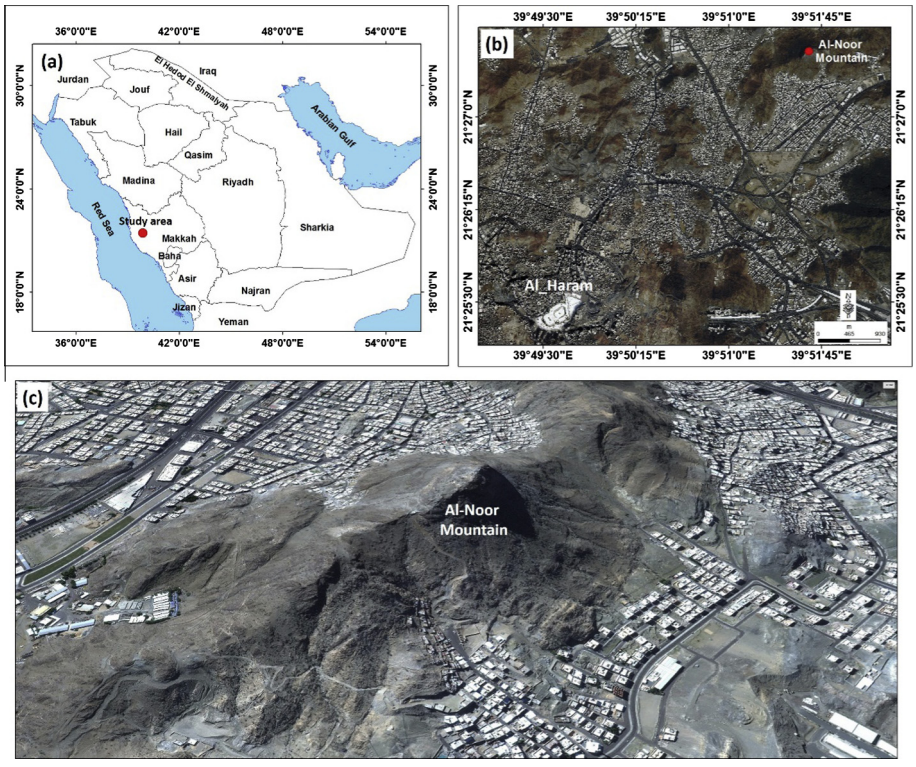

Fig. 1. (a) Location of Al-Noor Mountain location in Saudi Arabia, (b) Al-Noor Mountain location in relation to Al-Haram Mosque, (c) View of the 350 m height of Al-Noor Mountain surrounded by urban areas. Note that spreading of occupation towards the hill slopes around Al-Noor Mountain.