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Overview of slope stability, earthquakes, flash floods and expansive soil hazards in the Republic of Yemen

Hussein Ahmed Hasan Zaid*, T.A. Jamaluddin, Mohd Hariri Arifin

Geology Programme, Faculty of Science and Technology, National University of Malaysia (UKM), 43600 Selangor, Malaysia
* Corresponding author email address: hussenhassan2012@gmail.com

Abstract: Yemen has harsh natural conditions that increase certain geological processes more than other regions, leading to a variety of geological hazards. Yemen's typical topography is distinguished by coastal plains of the Red Sea and cliff foothillls, followed by mountains of the Arabian Shield. These types of geological hazards can be classified into slope stability, earthquakes, flash floods and expansive soils. The current literature review presents a description backed with examples of the certain geological hazards in Yemen. The obtained results indicate that further consideration and thought are highly required for semi-arid regions. National and foreign organizations have to collaborate together with other individuals to maintain the adjusted environmental system and reduce the potential geological hazards. Therefore, mitigation measures should be implemented to avoid and minimize these geological hazards.

Keywords: Hazards, Yemen, flash floods, slope stability, expansive soils, earthquakes

INTRODUCTION

Geological hazards often occur where severe and extreme weather changes, climate events, earthquakes, volcanic eruptions and mountain-building movements occur naturally in many parts of the world and determine the topographic and geomorphological characteristics of the earth. These hazards are caused, controlled or associated with the geological factors that may cause loss of life or property damages (Dhakal, 2013).

Rockfall hazards are a frequent phenomenon in mountainous regions. The lack of awareness of the magnitude and frequency of the rockfall undoubtedly endangers people's lives and causes devastating damage to the infrastructure. There are several examples to prove the plausibility of infrastructures damaged or people killed by rockfalls (e.g., Mignelli *et al.,* 2012; Mackey & Quigley, 2014; Ferrari *et al.,* 2016). By definition, the rockfall is considered a moderately small landslide limited to the particular removal of rocks from a cliff face (Selby, 1982). When the rockfall exists in a large-scale mass movement, it is defined as rockslides or rock avalanches (Abele, 1994; Cruden & Varnes, 1996). Mitigation measures against rockfalls can be taken by constructing barrier fences, retaining walls and restraining nets (Hearn *et al*., 1992; Spang & Sonser, 1995; Peila *et al.,* 1998).

The tectonic movement and divergence of African plate and Arabian plate, comprising rifts of the Red Sea and Aden Gulf, are the main reason of earthquakes in Yemen, located in the south part of the Arabian Peninsula (Figure 1), which are common from historical sources over the last millennia (Mohindra *et al.,* 2012). Earthquakes that strike Yemen are primarily related to rifts of the Red Sea and the Aden Gulf (Adams & Barazangi, 1984). Flash flood is also one form of geological hazards, it killed many inhabitants in the south and north of Yemen and caused devastating infrastructure damages. Lastly, in this literature, expansive soil is addressed as a potential natural hazard, which can cause huge damage to infrastructures if it is not properly managed.

The present work focuses on evaluating the geological hazards in Yemen. The paper presents a review of the causes and impacts of these hazards, which are classified into slope stability, earthquakes, flash floods and expansive soils. However, a discussion of issues such as subsidence, fissures, karst and sand accumulations are beyond the scope of this paper.

GEOLOGICAL HAZARDS

Slope stability hazards

Transport structures, like roads and highways, are vulnerable to rockfalls and rockslides where they cross mountains, hills, edges and the similar topographic characteristics (Bunce *et al.,* 1997; Hungr *et al.,* 1999; Youssef & Maerz, 2013). Rockfall starts at the separation of rock from bedrock slopes. All bedrock slopes are affected by varying weathering degrees, which may trigger joints and fractures, thus they contribute to advancement of the rockfalls. The triggering degree is dependent on the environmental factors that lead to weathering, and on bedrock types (Day, 1997; Dorren, 2003; Pradhan & Fanos, 2017). Furthermore, earthquake activities and high groundwater pressure (after heavy rainstorms) will cause high slope failure risks (Youssef & Maerz, 2013; Islam *et al.,* 2019). In this literature, various mechanics that initiated rockfall in Yemen have already been demonstrated.

Landslides and rockfalls are the most common geological hazards in Yemen, and they are caused primarily by poorly managed water drainage systems, vegetation removal, slopes and climate. Al-Jabali *et al.* (2009) revealed that the rockfalls in Yemen are caused by different components, such as excessive rainfalls, pore water pressure at rock porosity, earth gravity, earthquakes, vegetation removal, shearing stress, constructions and development of quarry activities. Dorren (2003) illustrated another reason for rockfalls, after investigating the connection between seismic activity and rockfall, he concluded the seismic activity is a triggering factor to the rockfall. Al-Jabali *et al.* (2009) mentioned that the Red Sea and Gulf of Aden faults centre that expands to other zones and leads to rockfall hazards are considered to be one of Yemen's seismic tremors effects (Figure 1). The rockfalls in the mountain highlands in the seismic centre zone are triggered by earthquake waves that propagate horizontally and perpendicularly. These are evident with the occurrence of several rockfalls and landslides in Yemen during and prior to the devastating earthquake in Dhamar city on December 13, 1982 (Al-Jabali & Wang, 2005).

Human activities like road construction, the use of explosives during excavation and crest regions loading lead to the slope instability (e.g., Al-Massbah area, Jabal Amid). The unplanned development at the top of slopes increases loads on the body of slopes and raises the gravitational forces, and consequently causing slope instability and construction failure. Additionally, sewage chambers constructed in inclined bodies would increase water pressure among discontinuity surfaces and thereby decrease cohesion between them as a result of spilling water into lower frail volcanoclastic deposits zone through the joints in the rock masses of slopes in the upper zone. Furthermore, the saturated pore spaces restore the overlying material weight, hence reducing the contact effect. Lastly, using explosives in excavation on slopes toe increases failure and damages to buildings constructed (Al-Qadhi & Janardhana, 2017).

Ahmed Al-Qadhi (2018) grouped the factors that control the slope instability conditions in his study area in Taiz city into two classifications, namely I. Causal factors group including, 1) geological factors (e.g., rock type, intact rock strength and unfavourable orientation of discontinuities), 2) Morphological factors (types of slope and the processes that produce them) and 3) Hydrological factors (drainage system and filtration). II. Triggering factors group including rainfall, weathering, earthquakes, human activities and undercutting.

Earthquakes hazards

Seismically, the Arabian Shield and the Arabian Platform are principally known to be a fairly stable region. However, western regions of this shield are prone to seismic activities attributed to volcanism, rift system and sea-floor expansion in the Red Sea (Ambraseys *et al.,* 2005). The northwestern parts of the Arab peninsula experience higher rates of seismic activities, primarily due to the spreading of the northern Red Sea from Aqaba Gulf (El-Isa & Shanti, 1989). The Arabian Plate diverges at a rate of about 10-20 mm per year from the African plate. This divergence is due to the expansion of the transform fault zone along the Dead Sea and the spreading of the Red Sea from the Aden Gulf

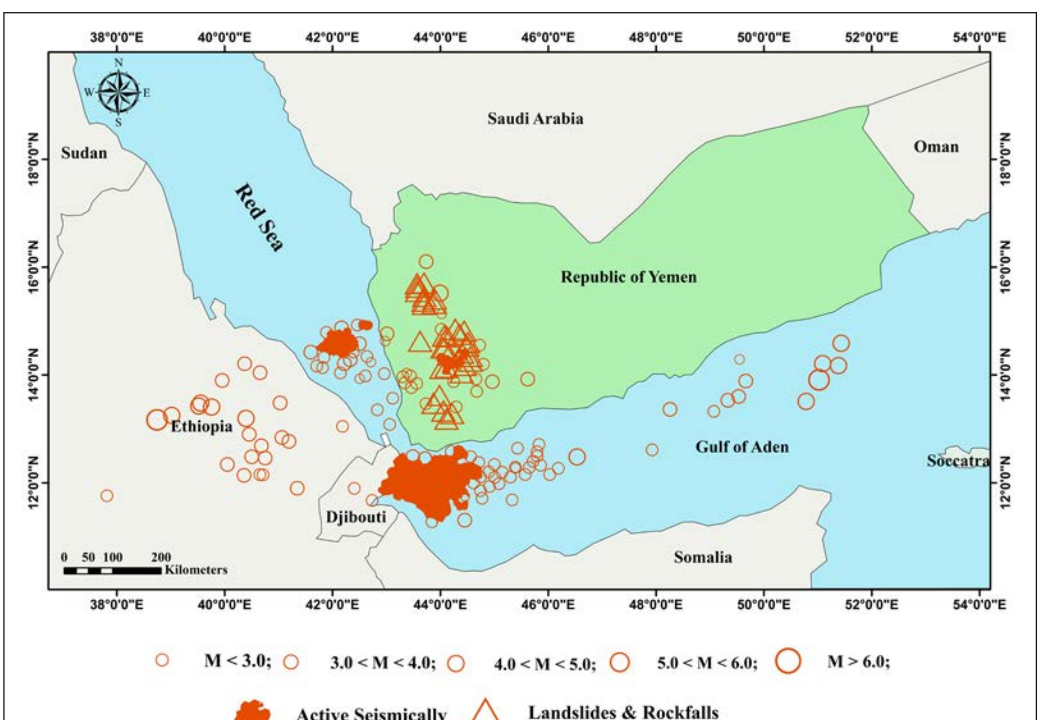

Figure 1: The map of landslides, rockfalls and centres of earthquakes distribution (Al-Jabali *et al*., 2009).

(Figure 2). In relation to Eurasian Plate, the African Plate is shifting north at a rate of about 15-20 mm per year. The collision between Arabia and Eurasia is almost absorbed in the deformation zone stretching from the Makran subduction zone through the Zagros Fold Belt and across Iran into Turkey. The Arabian Plate is spreading from the Indian Plate in the Owen Fracture Zone towards the southeast (Grainger, 2007; Pascucci *et al.*, 2008).

Yemen's seismic history reveals the occurrence of huge seismic tremors between a 20-year period (Al-Sinawi & Al-Aidarus, 1999), between 1941 and 1909, where two major earthquakes occurred. The most common occurrence (magnitude, M = 6.5) and two consequential convulsions (M = 5.8 and M = 5.2) caused almost 1,200 fatalities in 1941 and destroyed almost 1,400 homes. During the seismic tremor of 1909, nearly 300 people were killed and about 400 houses were destroyed (Al Aydrus, 1997; Mohindra *et al.*, 2012). The Dhamar city earthquake on 13 December in 1982 (M = 6.0, epicentre 14.7°N and 44.2°E) (Figure 3), proved to be the Yemeni's deadliest earthquake. This earthquake was felt across the Arabian Peninsula (Central Eastern bed) where over 1500 people were killed and wounded. This devastated and damaged about 1,500 properties (Arya *et al.*, 1985; Ambraseys, 2005).

Possible origins of future earthquake zones are reflected from their historical activities geographically situated. These are delineated on the basis of the seismo-tectonic characteristics of the region, and the past seismic activities are expected to be a strong indicator of the potential

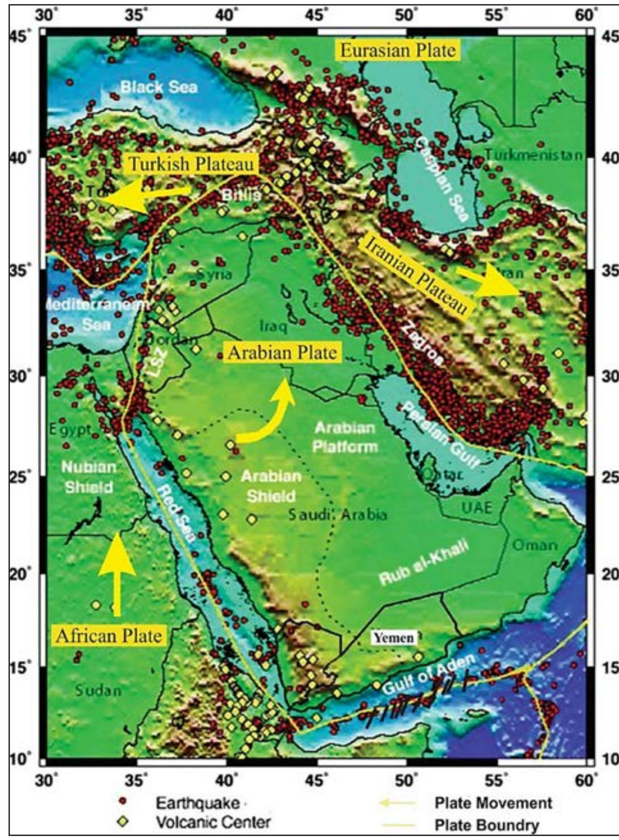

Figure 2: Plate-tectonic and geological features of the Arab Peninsula. Earthquakes and volcanic centres are marked with red circles and yellow diamonds respectively (Al-Amri *et al.*, 2008).

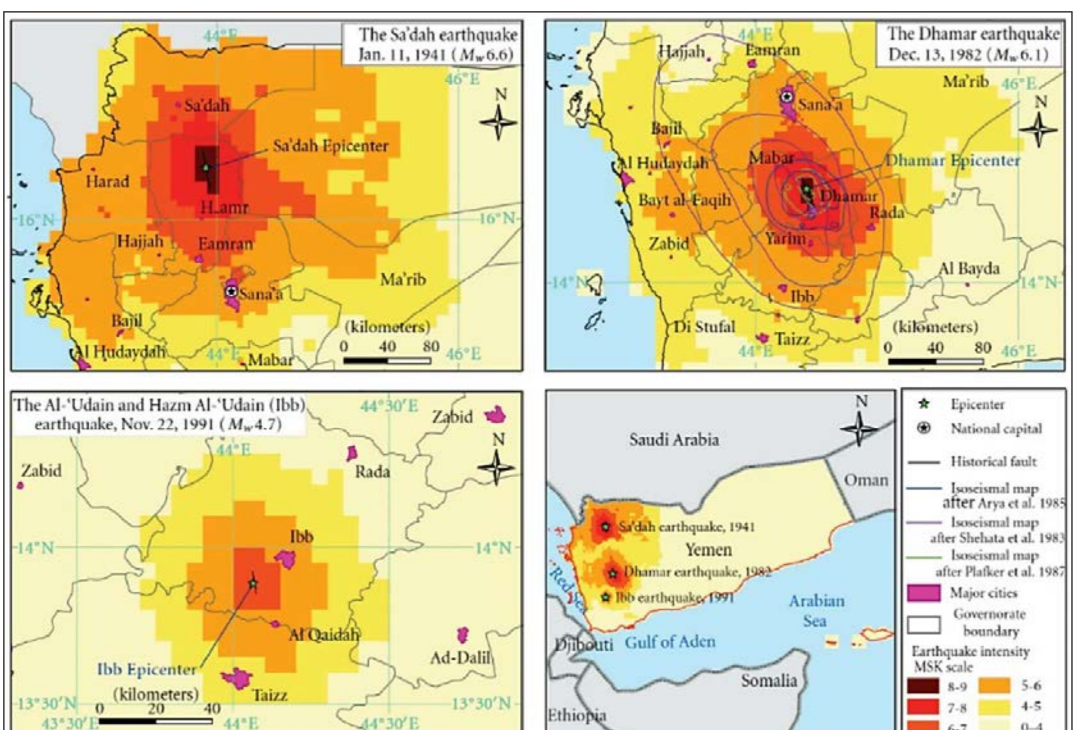

Figure 3: The modelled intensities of historical earthquakes occasions, which is compared by intensities surveys for Dhamar events (Shehata *et al.*, 1983; Arya *et al*., 1985; Plafker *et al*., 1987).

activities. Seismicity in Yemen is primarily due to seismic tremors arising from the area of transform fault and the area of the stable continent, Mohindra *et al.* (2012). In the southwest portion of the Arabian plateau (Arabian shield), a number of earthquakes took place near a complex triple junction of active spreading ridges along the Red Sea, Aden Gulf and Afar depression. The seismic activities along the spreading ridge across Yemen are generally noticeable. Some small to moderate occurrences took place in the Arabian Plate at distances of 200 to 300 km from the Red Sea axis (Ambraseys, 1983). The western and southern areas of Yemen have a high risk of seismic hazards in comparison with eastern and central regions. It can be observed, occasionally, from the western region of the Arabian Plate, which are the most contributors to seismic hazards in Yemen, Mohindra *et al.* (2012).

A seismic zoning model for Yemen was proposed, based on values of the hazards estimated for the return duration of 475 years, as the first attempt to zonate seismic hazards in Yemen. The country is composed of three seismic zones (Figure 4). Particularly, each zone is characterized by a consistent hazard, measured by distinctive esteem of the reference peak horizontal ground acceleration (PGA) as illustrated in Table 1. Sana'a (capital of Yemen) and the Dhamar city are situated within zone II, which represents the largest level of seismic hazards (Mohindra *et al.*, 2012).

The Arabian Peninsula volcanoes are observed mainly in the western regions and on the Yemeni coast at the southern end of the Red Sea (Figure 2). In Saudi Arabia, there are extensive basaltic lava flows, popularly known as "harrat". From southern Yemen to North Turkey these harrats occupy an area of about 180,000 km^2. Well-defined Arabian Peninsula volcanic eruptions are as follows: near Dhamar in the north of Yemen (1937) and Red Sea Island

Table 1: Parameters of seismic zonation in Yemen (Mohindra *et al.*, 2012).

Seismic zone	Maximum horizontal ground acceleration with 10% exceedance probability in 50 years	Median value of PGA
I	0.20-0.30 g	0.25 g
II	0.10-0.20	0.15 g
III	<0.10 g	0.05 g

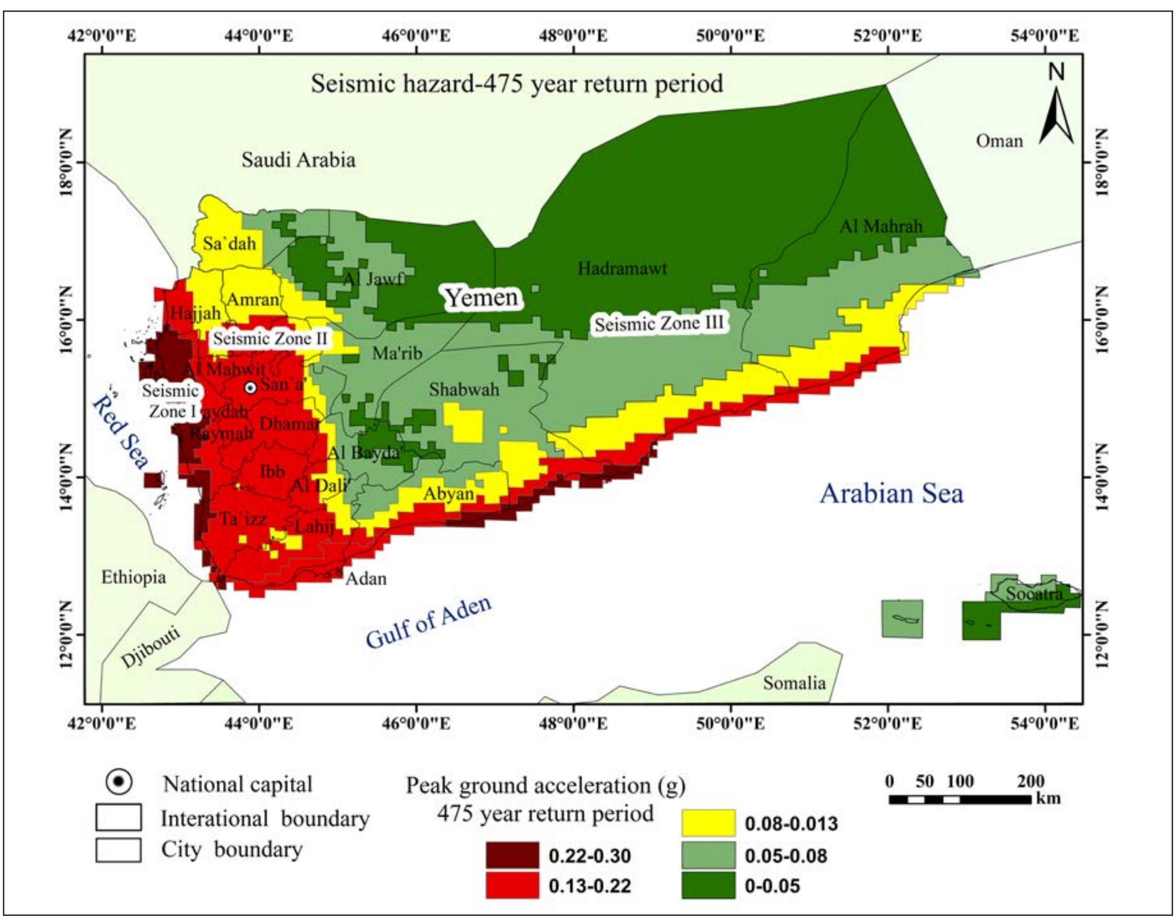

Figure 4: Three seismic zones in Yemen (Mohindra *et al.*, 2012).

Saddle northwest of the Yemeni port city of Hodaida (1846) (Kumar, 2013).

Kumar (2013) presented the most detailed and knowledge on volcanoes of the Red Sea. On 30 September 2007, the most recent volcanic eruption occurred on Jebel al-Tair, a volcanic island 150 km away from Hodeida. Lava flowed into the sea and remained for more than three days. There were many earthquakes previously recorded, and one measured 7.3 on the Richter scale was reported a day before the blast. According to Kumar (2013) "ash and pumice rafts drifted 10 km from the island. Fire fountains were observable on the northwest part of the island near the summit on 3rd November 2007. Satellite images revealed the volcano's hotspots until June 2008." This eruption created 1 km long of lava flow and blackened the water in an island area of 9.7 km. In this volcanic eruption, eight people including three Yemeni army staff were killed.

Flash flood hazards

Flood is a circumstance when an overflow of water submerges an area or land. After overwhelming rain occasions, flash floods can occur in any region. Most of the floodplains are vulnerable, and triggering factors like rains, heavy storms, ice melting and dam breaks may cause flooding in any part of the world. Furthermore, they may occur during a dry season when excessive rain falls on an exceptionally dry ground surface that cannot be penetrated by the water. Other factors like tornadoes, thunderstorms, monsoons, and extra-tropical cyclones, might trigger flash floods (Khan, 2013).

Most of Yemen's areas are situated in an arid climate with convective storms resulting in flash floods and causing significant damage. Tropical storms struck within the eastern portion of Yemen, from October 23 to 25 of 2008, causing extreme devastation and left thousands of people homeless (Khan, 2013). They caused torrential and prolonged rainfalls continuously over a period of days, resulted in a huge volume of water about 91 mm on Wadi Hadramawt (Figure 5) catchment region of two million hectares. The catchment zone gathered about two billion cubic meters of water and inflicted critical floods to the various areas, that rose up to 10 m in height (World Bank & GFDRR, 2010). Given the fact that the area was subjected to flash floods back in 1989 and 1996, this particular flood is one of the worst natural disasters that hit Yemen, Soliman *et al.* (2015).

In the west of Yemen, many residents of the old historical Sana'a city (capital of Yemen) were killed by flash floods over several decades. The reason of flash flood is torrential rains brought by tropical storms, which is uncommon in arid regions. These precipitations are in a short period, but

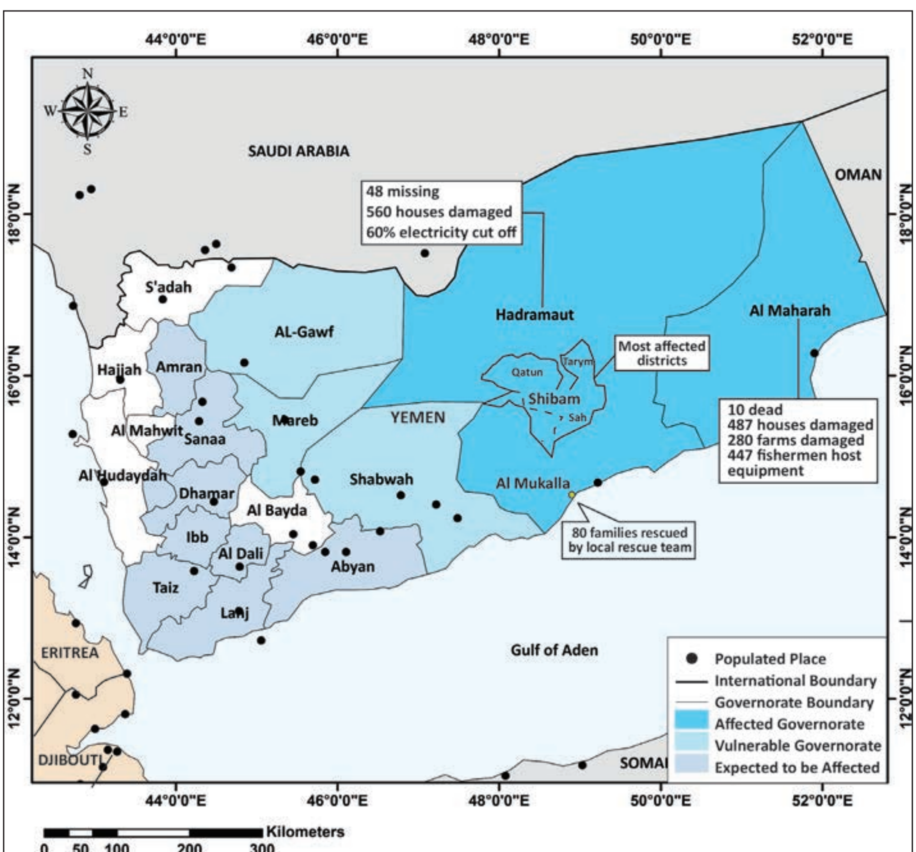

Figure 5: The regions that were affected by the flood in 2008 (United Nations Office for the Coordination of Humanitarian Affairs, 2008).

very intense. Climate change and rapid urbanization have resulted in the escalation of floods. Three main reasons caused by the human coefficient are land-use alteration, rising populations and constructions in flood-prone areas. The main drainage channel in Sana'a, which runs alongside the old historic city, is also used for transport routes (Figure 6). If a flash flood occurs, the channel is flooded, causing vehicles to be swept and endanger people's lives, and there are no mechanisms or alternatives to prevent vehicles from using the channel as a road (Papakos & Root, 2010).

Expansive soils

Expansive soils have a negative effect and cause damage to different civil engineering structures, particularly to pavements, buildings and canal linings. They should be solved technically to reduce or prevent these damages. Such issues with foundations are, slab-on-grade members, cracking and breaking of pavements, reservoir linings and channels (Viswanadham *et al.,* 2009; Chen, 2012; Verma & Marus, 2013; Al Fouzan & Dafalla, 2014). Active clay minerals are typically extracted through the weathering process from various types of rocks. Such minerals containing a large amount of silicate are produced from basic and ultrabasic igneous rocks and volcanic ash, schist, phyllite, shale, sandstone, and other rocks, which transform into clay minerals by hydration and dehydration, oxidation and reduction, ion exchange and leaching structures processes (Shi *et al.,* 2002; Mitchell & Soga, 2005; Keller & Devecchio, 2015; Aqeel, 2016).

Soil dominated by a significant presence of certain clay minerals, like montmorillonite, which has a swelling lattice structure is generally attributed to expansive soil nature. Water can be absorbed promptly in the grid of montmorillonite causing it to swell (Sridharan & Prakash, 1998; Fityus & Buzzi, 2009; Bachouche & Boutaleb, 2013; Aref *et al.,* 2014; Keller & Devecchio, 2015). Soil expansion usually occurs in semi-arid regions. In general, soils are stiff to very stiff in these regions and the cracking due to settlement is quite improbable, particularly in lightly loaded buildings (Farook & Virk, 2009; Elkady, 2014).

Clay swelling in the soil changes enormously the volume of soil when a pressure-driven and chemical environment is modified. Thus, when clay soil is saturated, it tends to swell and if it dries, it tends to shrink and crack due to changing in volume. The swelling is more prevailed than shrinking. It is not essentially due to those soils heaving more than the shrinkage, but since brittle structures are more vulnerable to doming associated with swell as it places tensile stresses into the upper parts of the walls. However, shrinkage leads to dishing, tossing tensile stresses into the foundations, which can resist these stresses of structures constructed on expansive soils (Laredj et *al.,* 2012).

In Yemen, structures that have been built in some regions such as Taiz city collapsed and were damaged due to failures of structures and these foundations have been built on Tertiary volcanic flows and volcanic soils. In most explored areas, the samples of volcanic soil appear to have medium, high and very high degrees of potential swelling (Figure 7), as they contain montmorillonite minerals which can be swelled causing volume change when it becomes saturated. The flows of volcanic lava rocks have high densities and joints, particularly vertical discontinuities which can initiate penetration of water into the deeper layer. Landslides with buildings built over volcanic soil in Taiz city can be attributed to their low strength as identified from their ability to absorb water particularly during rainfall, erosion of the underlaying weak volcanoclastic, high porosity values and the existence of swelled volcanic soils (Janardhana & Al-qadhi, 2016).

Once the target location exhibits soil with an expansive tendency, several solution methodologies may be used

Figure 6: Saylah Channel through the Old Sana'a Historic City, Papakos & Root (2010).

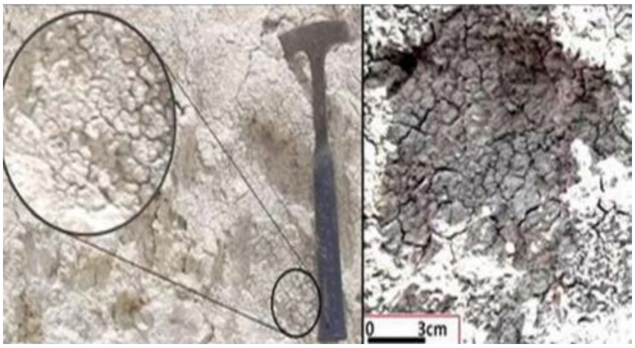

Figure 7: Field photograph showing volcanic expansive soil with ground shrinkage cracks under dry conditions (Janardhana & Al-qadhi, 2016).

before establishing any form of the foundations, including 1) Elimination of problem soils before construction, 2) Elimination of the water sources, 3) Maintenance of moisture equilibrium, 4) Chemical treatment with quicklime and 5) Utilize of Piling. However, it is recommended that the severely weakened soil zone areas should be discarded and if the geologic condition permits, a deep foundation into the hard bedrock is recommended (Janardhana & Al-qadhi, 2016).

CONCLUSIONS

Human activities such as infrastructure and urban development lead to geological hazards that threaten human lives and properties. There are other factors contributing to the presence of these hazards including climatic conditions, geology, earthquakes and geomorphics. The controlling factors which usually affect the type of the geological hazards are their geological settings. The potential geological hazards occur under semi-arid conditions may include slope instability, flash floods and expansive soils. The solution to these issues requires an in-depth site analysis to identify a caused factor in geological and hydrogeological triggering factors. The next step would then be selecting appropriate approaches for mitigation and remediation to reduce these types of hazards.

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