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ORIGINAL ARTICLE

Overview of some geological hazards in the Saudi Arabia

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Abstract The Saudi Arabia has harsh environmental conditions which enhance some geomorphologic/geological processes more than in other areas. These processes create different geological hazards. The general physiography of the Saudi Arabia is characterized by the Red Sea coastal plains and the escarpment foothills called Tihama, followed by the Arabian Shield Mountains, the Arabian Shelf plateau and finally the Arabian Gulf coastal plains. These types of geological hazards can be categorized into sand accumulations, earth subsidence and fissures, flash floods, problematic soils, slope stability problems, and karst problems. The current study gives an overview of all these hazards with examples, as well as develops a geohazard map for the Saudi Arabia. Our findings indicate that the desert environment needs much concern and care. National and international agencies have to join together with other people to keep the system balanced and to reduce the resulting geological hazards. Also, remedial measures should be proposed to avoid and reduce these natural hazards.

Keywords Geological hazards · KSA · Mapping

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Introduction

Using conventional means of ground surveying is not sufficient to prepare a geological hazards map, land use guidelines, and sustainable development planning, but it is considered by several authors as having great potential and as an extremely valuable tool (Xiuwan et al. 1999; Turker and Derenyi 2000; Wyatt 2000). However, conventional methodologies have some limitations on the detection (monitoring), assessment (analysis), modeling (assimilation), and predicting (projection) the geological hazards on the land use change and sustainable development. On the other hand, new data sources and GIS technology provide some promises to improve studies on the impact of geological hazards on land use change and sustainable development in most areas all over the world. Techniques and methods of using satellite imageries, aerial photos, and topographic maps as data sources have been developed and successfully applied to geological hazard detection, land use classification, and change detection in various environments including rural, urban, and urban fringes (Robinnove et al. 1981; Jensen and Toll 1982; Fung 1990; Pathirana 1999; Wyatt 2000). Many other studies have been done to deal with different types of geological hazards all over the world such as; Marisol and Sergio (2010) who studied the Landslide susceptibility and hazard assessment in San Ramón Ravine, Santiago de Chile, from an engineering geological approach; George et al. (2012) which they study the potential suitability in urban planning and industrial development using natural hazard maps and geological–geomorphological parameters; Gomaa et al. (2012) used the GIS-based estimation of flood hazard impacts on road network in Makkah city, Saudi Arabia.

In general, deserts are known as barren areas which scientifically represent a water shortage or aridity, a soil type, or a topography and vegetation. UNESCO (1979) presented a map showing that most of the Middle Eastern countries are located within the semi-arid, arid, and hyper-arid desert zones. These zones are characterized by an aridity index (which represents the ratio between annual precipitation and mean annual potential evapotranspiration) ranging between >0.03 and <0.20. Most of the geological hazards associated with desert environments in the Saudi Arabian are principally related to different conditions such as aridity, climate, geology, and human factors. The Saudi Arabia has harsh environmental conditions which enhance some geomorphologic/geological processes more than other areas.

The present study focuses on the evaluation of the geological hazards in the Saudi Arabia. The study gives an overview of the geological hazards and gives examples, as well as develops a geological hazard map for the Saudi Arabia. These types of geological hazards can be categorized into sand accumulations, earth subsidence and fissures, flash floods, problematic soils, slope stability problems, and karst problems. However, other problems related to recent faults, volcanic activities, and earthquake hazards are out of the scope of this paper.

Geomorphology of the Saudi Arabia

The geomorphology of the Saudi Arabia, has been drawn using ArcGIS 9.3 which is provided by ESRI, is shown in Fig. 1, it is characterized from west to east by the following zones: Zone (1) is represented by the eastern coastal plains of the Red Sea and the foot hills known as Tihamah. Along this zone, sabkha areas exist in longitudinal stretches parallel to the shore line of the Red Sea. Zone (2) is the escarpment of the Arabian Shield Mountains which is located east of Zone (1). The mountains are locally raised over 3,000 m above sea level. Zone (3) is the central plateau of the Arabian Shelf located to the east of Zone (2) and is bounded westward by the Tuwaiq escarpment and is largely covered by sand seas. Zone (4) is the Arabian Gulf coastal region, along the west coast of the Arabian Gulf, partially covered either by extensive areas of sabkha or by the Jafurah sand sea. Several steep dry valleys flow from the Arabian Shield escarpment (Zone 2) westward toward the Red Sea, while other gentler slope valleys flow eastward.

Climatic conditions

Saudi Arabia is classified climatically as a Semi-Arid (BWh) region according to the "World Map of Kopper-Geiger Climate Classification" (Peel et al. 2007) (Fig. 2). These climates tend to have hot, sometimes extremely hot, summers and mild to warm winters. Semi-arid climates receive precipitation below potential evaporation, rainfalls are few and irregular, and precipitation exhibits strong spatial and temporal variability. The seldom-received rain makes Saudi Arabia one of the driest countries in the world. The Empty Quarter in KSA is the largest continuous expanse of sand desert in the world (Atlas 1984). It is located in the eastern and south-eastern parts of Saudi Arabia. However, because of the influence of regional subtropical high-pressure systems, and many fluctuations in elevation, there are considerable variations in temperature and humidity across the Saudi Arabia. The south-western region of Saudi Arabia is characterized by having the highest amount of precipitation compared to the other regions. From the Red Sea to the edge of the Sarawat mountain range, within a distance of less than 100 km, topographic relief may exceed 2,000 m and the mean annual rainfall increases with altitude enhanced by the local convective air circulation (Al-Mazroui 2010; Abdullah and Al-Mazroui 1998). The average annual precipitation can reach more than 600 mm in the mountains, and decreases to 120 mm on the coast side to the west and to 100 mm on the leeward side to the east (Fig. 3). The south-western region is the most important area in the country in terms of renewable water resources due to rainfall-runoff recharge events. This region is also the most highly cultivated and populated region in KSA. The analysis of the rainfall distribution in Saudi Arabia raises a great challenge essentially due to the undulating terrain surface. Besides the climatic factors, such as atmospheric conditions, winds and storm seasonal patterns, topographic factors, including elevation changes, steep slopes and mountain side, leeward and windward position, and distance from sources of moisture have different and significant effects. Among this second category, several investigations have confirmed that elevation is the most important factor, effecting both intensity and distribution of precipitation especially in the mountainous regions (Taher and Alshaikh 1998). Annual and monthly orographic rainfall has been found to increase with altitude in the south-western region of Saudi Arabia (Alehaideb 1985). Several relationships between rainfall and topography using isohyetal the method, harmonic analyses, and regression techniques have been proposed to assess the spatial variation of precipitation in south-western regions (Taher and Alshaikh 1998; Al-Mazroui 2010).

Geological hazards

Most of the geological hazards of Saudi Arabia, have been drawn using ArcGIS 9.3 which is provided by ESRI, are generalized in Fig. 4 and are interpreted from topographic and geological maps and remote sensing images of the

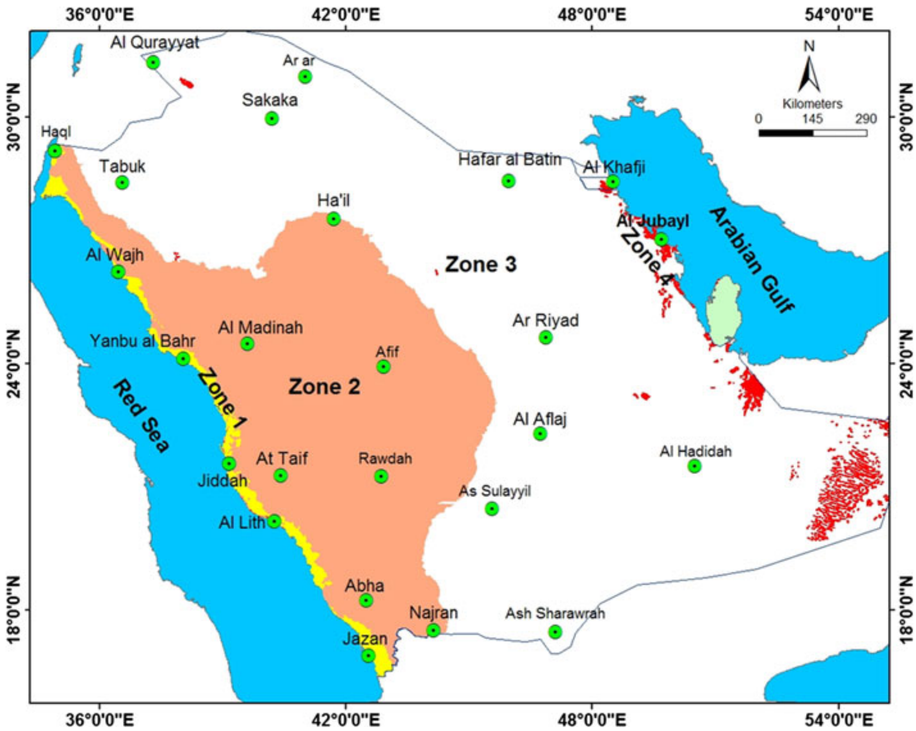

Fig. 1 General physiography of Saudi Arabia, (Zone 1 = the eastern coastal plains of the Red Sea; Zone 2 = Escarpment of the Arabian Shield; Zone 3 = the central plateau of the Arabian Shelf; Zone 4 = The Arabian Gulf coastal region; and *green dots* are the city locations)

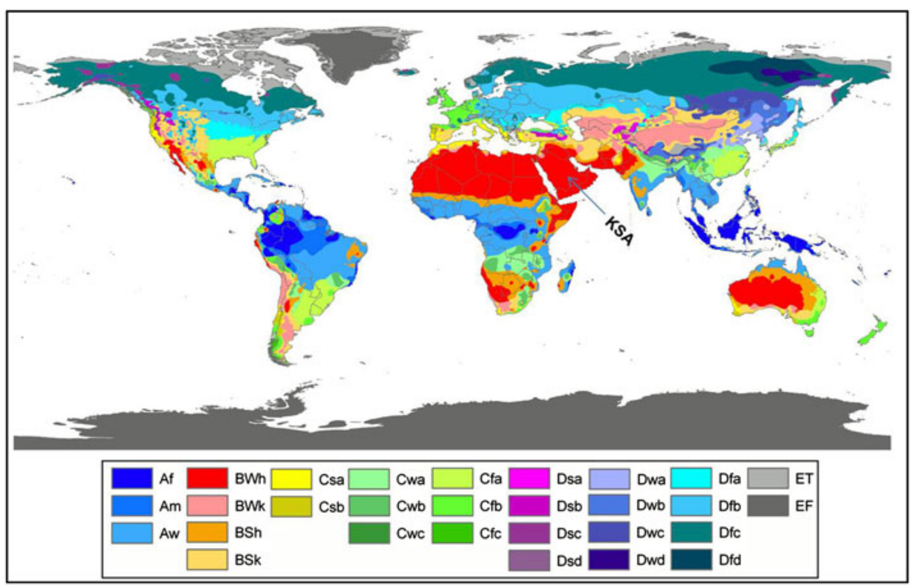

Fig. 2 Kopper Map of climate classification, Saudi Arabia is classified as BWh (Hot Semi-Arid) (Peel et al. 2007)

Saudi Arabian peninsula. These types of the geological hazards include sand accumulations, earth subsidence and fissures, flash floods, problematic soils, slope stability problems, and karst problems. Other problems related to recent faults, volcanic activities, and earthquake hazards are not highlighted in this paper.

Flash flood hazards

The rainfall distribution over the year usually consists of one or two intense thunderstorms of short duration in most of the KSA; however, some areas such as Taeif, Abha, Sarawat, and Jizan mountains have rainfall events during many days of the year. Flash floods and associated debris flows are quite common along the steeper slopes and canyons of the western escarpment (e.g. between Jeddah and the Yemen border). The Saudi Arabian soil, despite the arid environment, exhibits a low retention potential in response to short duration rainfall events. Wadis (ravines) which are usually dry can quickly turn into raging rivers during and after heavy rains. In the cities, low lying areas along the roads and highways can be quickly filled with

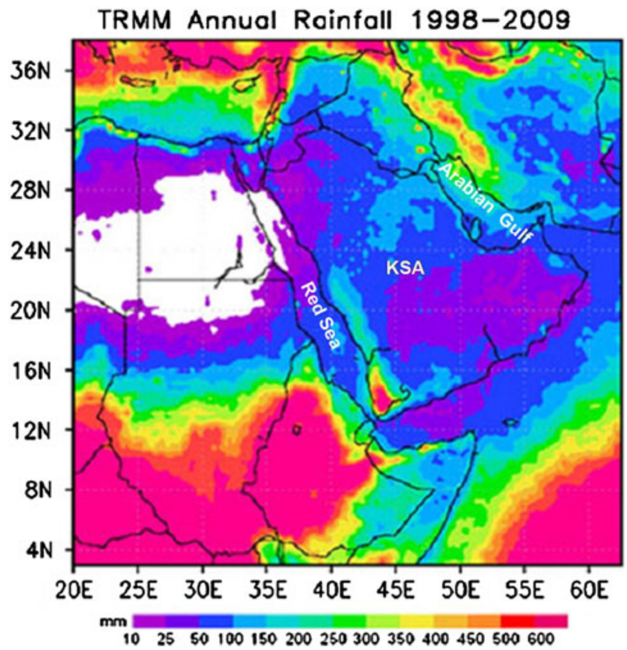

Fig. 3 TRMM rainfall annual distribution over Saudi Arabia during 1998–2009 (Al-Mazroui 2010)

floodwater, trapping unsuspecting motorists, and causing severe damages to the urban infrastructure. AMS (2001) defined four seasons in Saudi Arabia including winter from December to February, the spring from March to May, summer from June to August, and autumn from September to November. However, Al-Mazroui (2006) defined only two seasons based on the synoptic conditions in Saudi Arabia, namely the wet and dry seasons, from October to May, and from June to September, respectively. In the south-western region, rainfall mainly occurs during the wet season, whereas the dry season is almost entirely rainless. Due to the occasional rainfall events in October and May, these months are considered as transition months. The average precipitation along the coasts and in the desert areas of Saudi Arabia does not exceed 100 mm/year, where as the precipitation in the high elevation terrain of the Arabian Shield can reach more than 600 mm/year along the Sarawat and Jizan Mountains (Fayfa). Generally, the rain falls on the high lands and is collected by major wadis and drains in the east and the west directions toward the central plateau of the Arabian Shelf (Zone (3) and the Red Sea coast (Zone 1), respectively. The wadis located to the west of the Arabian Shield are steep and very active where flood waters can reach the Red Sea coastal areas causing damage to the urban infrastructure. Many examples of flash flood problems have been recognized along the wadis toward the Red Sea as shown in Fig. 5.

Slope stability hazards

Transportation systems such as roads and highways are vulnerable to rockfalls/rockslides wherever they cut across or skirt along mountains, plateaus, ridges and similar

Fig. 4 The main geological hazards in the Saudi Arabia (*green circle* is the city location)

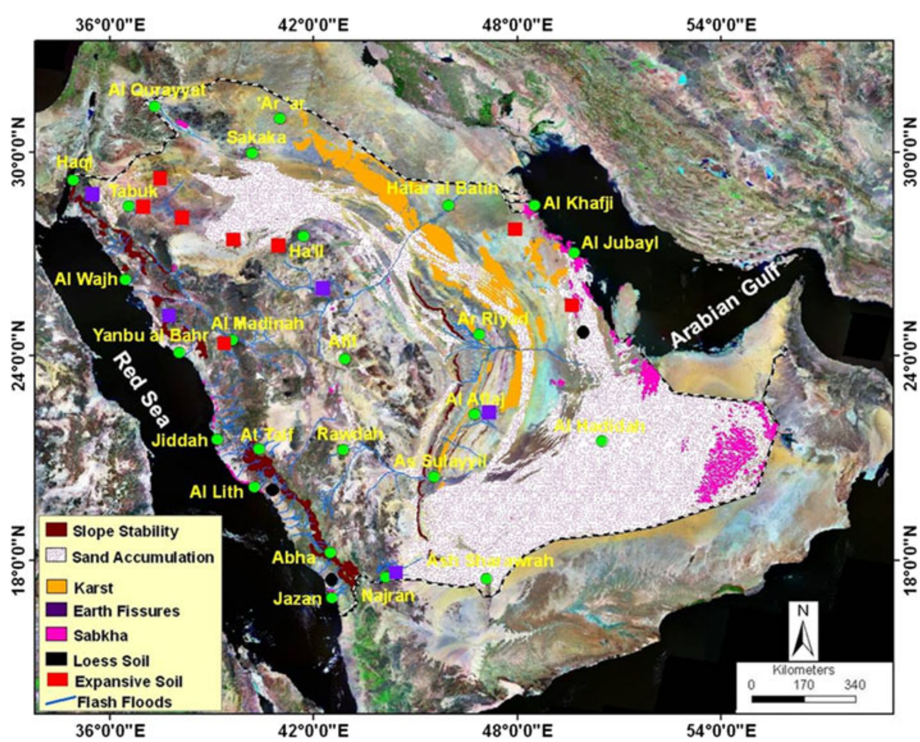

Fig. 5 Some examples of flash flood problems in Saudi such as, **a** Flash floods in Wadi Baish; **b** Flash floods in Jeddah 2009; **c** Flash flood Jeddah 2011; **d** Flash flood of Wadi Al-Laith 2010

topographic features (Bunce et al. 1997; Hungr et al. 1999). Potentially, unstable slopes present hazards and pose risks to the traveling public, to the transportation infrastructure, to local economies and to the environment. Road and highway cuts fail from time to time. Seismic (earthquake) activity or high groundwater pressures (after heavy downpours) can trigger large rock blocks or even larger assemblages of rock to crash down on the road surface below. Often, the failed material is contained in the ditch. Sometimes, the material spills out onto the road and causes damage to the road surface or to vehicles traveling along the road. Infrequently injury and death to occupants of vehicles occur. Highways in mountainous terrain often require investigations and analysis to control the incidence of the rock falls and rock slope failure. Kliche (1999) mentioned that there are two different types of accidents: accidents and events from minor falls that damage tires and body work and a large falls that caused fatality, injury and economic loss with the closing of the highways.

New requirements to establish civil infrastructure across difficult terrain as population centers expand in coming decades will increase the number of rock cuts along transportation systems (Dai et al. 2002). Highway systems may receive rockfalls/rockslides on a daily basis; but these may not be considered hazardous unless rocks enter the roadway (Chau et al. 2003, 2004; Maerz et al. 2005; Youssef et al. 2007; Youssef and Maerz 2012). Although, the public is not generally aware of rockfalls/rockslide except where a particular event results in significant loss of convenience, property, or life (Budetta 2004), rockfall/rockslide remains an irritant in the side of many transportation agencies, which are responsible for providing and maintaining safe and reliable highways and routes in an economical fashion.

In the Saudi Arabia many escarpments roads and highways have been established all over the western regions where the Arabian shield is located (Fig. 4). These highways and roads connect many cities located at high elevation of the mountains with other cities located along the Red Sea coast. Some of these roads include the road from Taeif city to Makkah; from Makkah to Jeddah; from Abha to the Red Sea coast and local roads in the Jazan region. Along these areas many rock falls have occurred that not only block the roads, but also damage infrastructure and cause injuries and fatalities, some of which remain unreported (Fig. 6).

In general, stability assessment of slopes requires comprehensive information about the geology and engineering geology of the area such as geological structures, the properties of the rock mass discontinuities for the structural controlled failures, as well as the characteristics of the rock cut faces for the raveling type failures (Maerz et al. 2005; Youssef et al. 2012a). Other factors related to the traffic density and road designs are also required, because these affect the risk to moving vehicles. Recently, a rockfall hazard rating system will be established for the KSA to deal with rock and slope cuts also to deal with the best method for remediate and mitigate these areas.

Fig. 6 **a** Rock falls along the Al-Hada highway; **b** debris flow along Al-Hada Highway; and **c** slope failure in Jazan; **d** slope failure in Taeif

Land subsidence and earth fissures

Introduction

Ground cracks or fissures in soil and rocks, and the associated subsidence represent a major problem in many countries. Most of these fissures, cracks, and subsidence are related to the downward ground movement of the earth's surface compared with surrounding areas (Whittaker and Reddish 1989). Davis (1978) concluded that most of the ground fissures are associated with the subsidence of the ground surface, ranging from a strain cracks to large faults, starting from the ground surface in non-cemented sediments. The cracks begin as small traces that expand because of a number of external factors such as living organisms, erosion due to the movement of surface water, and rain. Sometimes these earth fissures are caused by the change in the nature of the soil especially along the sides of the basins due to the presence of hard rock topography underneath these soil layers. Some authors such as Lofgren (1978) and Helm (1994) indicate that the ground cracks start from great depths below the surface, as a result of horizontal movement in the aquifers because of excessive withdrawal (pumping) of the ground water from the uncemented reservoir layers, due to loess soil, and earthquake activities. These earth fissures and subsidence could cause many problems in different urban and agricultural areas, and damage infrastructure. Holzer (1984) put some scenarios of these earth fissures are as follows: (1) Earth collapse in the form of long stress cracks accompanied with faults. These collapses are a sign of a ground subsidence due to uncemented subsurface sediments that have been subjected to the process of hydro-consolidation during the withdrawal of ground water. (2) Earth fissures can extend for a distance of tens of meters to kilometers due to tensile stresses, but they are typically dilated to only several centimeters. (3) Erosion processes contribute to the widening of the cracks, up to 1–2 m wide, and ranges in depth from 2 to 3 m. And they appear on the surface in some cases as faults, with vertical offset of up to 0.5 m, and lengths up to 1 km, in extreme cases the vertical offset can be one meter and the length exceeding 16 km. (4) The vertical displacement increased by rate of 4–60 mm/year and that most movements occur when the soil is in the plastic case.

Earth fissures related to groundwater withdrawal

Under arid desert conditions, the shortage of groundwater resources and excessive pumping may cause continuous decline in the groundwater levels. When the aquifer is formed of unconsolidated sediments of high porosity and is inter-bedded with clay aquitards of low permeability and high compressibility, the rapid lowering of the groundwater level may also cause subsidence and possible ground failure in the form of earth fissures. Many areas in Saudi Arabia which are suffering from excessive ground water withdrawal are subjected to land subsidence and ground fissures (Fig. 7). The land subsidence and earth fissures are reported in several places and lead to damage of agricultural areas due to loss of water and sometimes injuries from the hidden fissures. Also, these earth fissures could damage building and infrastructure. Amin (1988) investigated the problem of Tabahin area where he proved that the land subsidence, ground fissures and surface faults are due to excessive pumping within the old crater. Amin and Bankher (1995) indicated that there are potential hazards due to excessive groundwater withdrawal. Bankher (1996) mentioned that the land subsidence in western Saudi Arabia is related to excessive groundwater withdrawal and hydro-consolidation of sediments. Groundwater management and the pumping of water within a safe yield become very essential, especially in the areas that may undergo subsidence due to ground water withdrawal.

Earth fissures related to earthquakes

Earthquakes can cause sudden ground movement which can leave cracks that show over long distances on the surface of the earth. Delta sediments that are saturated with water and sabkha areas are the most important areas that could be subjected by subsidence and fissures or faulting as a result of earthquakes (Whittaker and Reddish 1989). Areas near active faults are also subjected to subsidence when exposed to earthquakes. One of the most important examples of faulting, fissuring, and subsidence due to earthquake and volcanic activities occurred in Harrat Lunayyir Saudi Arabia (east of Younba City), where the movement of magma led to seismic activity, resulting from the rise and subsidence in the Earth's surface, resulting in numerous cracks and faults (Fig. 8).

Earth fissures related to compressibility of Loess soil

Grains of silt carried by the wind and deposited in arid and semi-arid zones form deposits called loess. These sediments are characterized as loose and of low-density due to the high proportion of voids inside its structures. Generally, they are strong and bear the loads and stresses in dry conditions. However, loess soils when exposed to water suddenly collapse and cracks appear on the ground (Lofgren 1969). Water may be the cause of this problem in the form of rain or storms or floods, or leakage from agricultural irrigation channels, or from neighboring houses. In loess the subsidence occurs under load and due to water (Feda 1988). Rogers et al. (1994) mentioned that many water channels have been established on a land characterized by the presence of loess deposits in the Tashkent region, and the channel subsided by 1.5–2 m along the center line after the flow of water and many fissures formed. Similar subsidence and cracks occurred in Arizona due to leakage after the establishment of water, sewage, and gas lines (Gelt 1992). There are many examples of loess-related failures in the Saudi Arabia such as the areas north of Jizan city, El-Darb Area and North of Al-Nai village of Hail region (Fig. 9).

Hazards related to problematic soils

Different types of problematic soils have been detected in the Saudi Arabia environment including sand dune, sabkha, loess, and expansive soils.

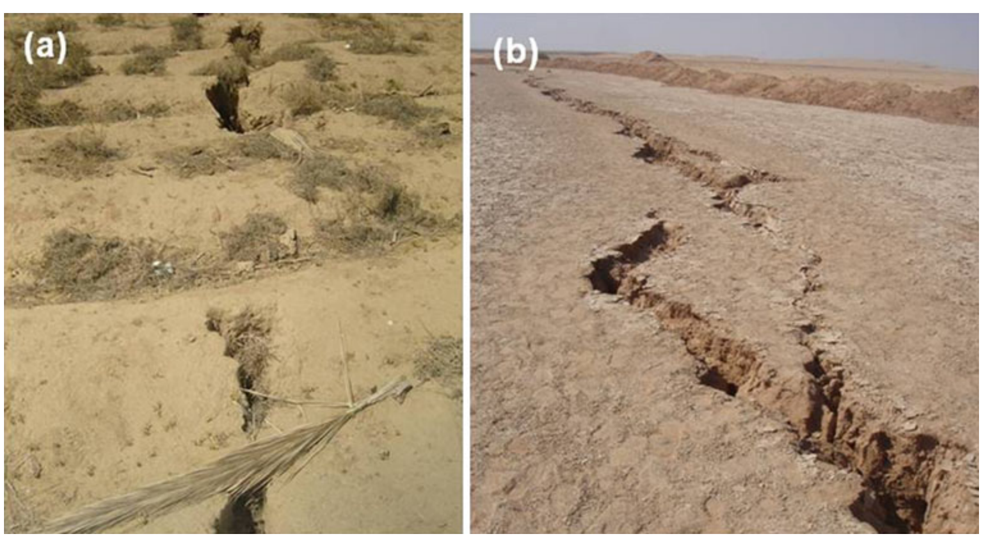

Fig. 7 Surface fissuring associated with subsidence due to groundwater withdrawal; **a** in Najran and **b** in Al-Aflaj area

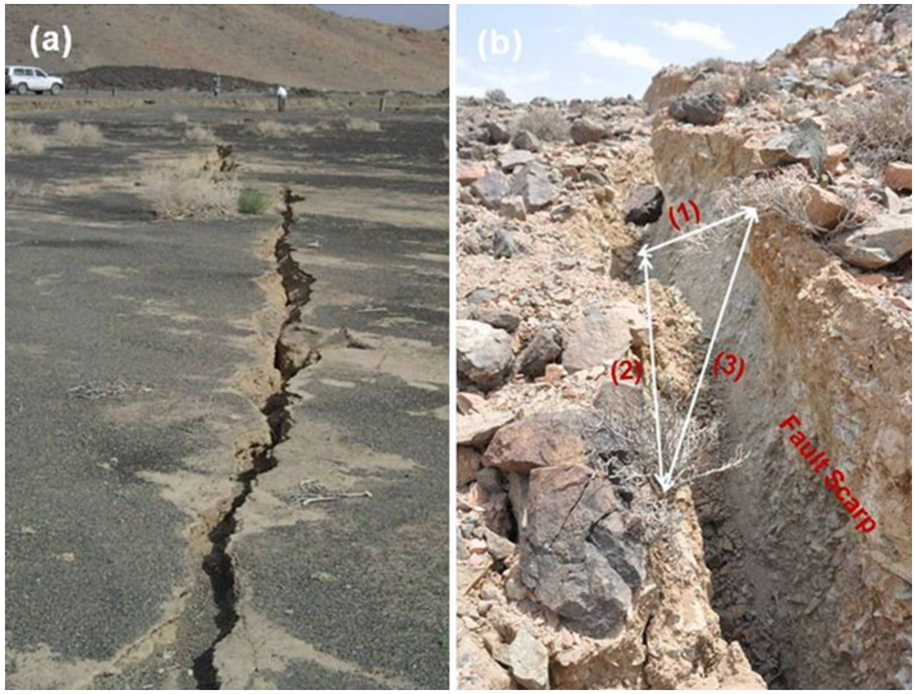

Fig. 8 **a** Subsidence and fissures in Harret Lunyyir, and **b** fault with a length of 8 km occurred in Harrat Lunayyir, Saudi Arabia due to earthquake activity in relation to magma movements. Note: *1* fault (use *white lettering o* opening 45 cm, *2* fault down drop 78 cm, and *3* fault total motion 91 cm

Fig. 9 Earth fissure cracks in Al-Nai area due to loess soil

Sand accumulations

In most arid environments throughout the world, the geologic processes of sediment weathering, transport, and deposition are constantly ongoing within active sand transport pathways. The analysis of sand accumulation, composition and movement is critical for the interpretation of past climatic conditions, local geology, environmental hazards, and future desertification potential. This type of comprehensive study typically involves many years of data collection, mapping, and sample classification (Muhs and Holliday 1995). Recently, the use of remote sensing over the past several decades as a tool to study dynamic features such as dunes and sand accumulations has given the geologist a synoptic view of entire eolian systems as well as their sediment sources (Breed et al. 1979; Blount et al. 1990; Edgett and Christensen 1995). In addition, the ability to examine changes over time allows for the extrapolation of past climatic regimes and the monitoring of marginal areas susceptible to future desertification (Otterman 1981; Tucker et al. 1994).

In the Saudi Arabia, sand accumulations cover a large areas all over the kingdom including western regions especially along the Red Sea coast and the area between the Arabian shield and the east border of Saudi (Fig. 4). A visual interpretation of satellite images was performed on high resolution QuickBird data (0.61 m resolution) to obtain more detailed information about the distribution of

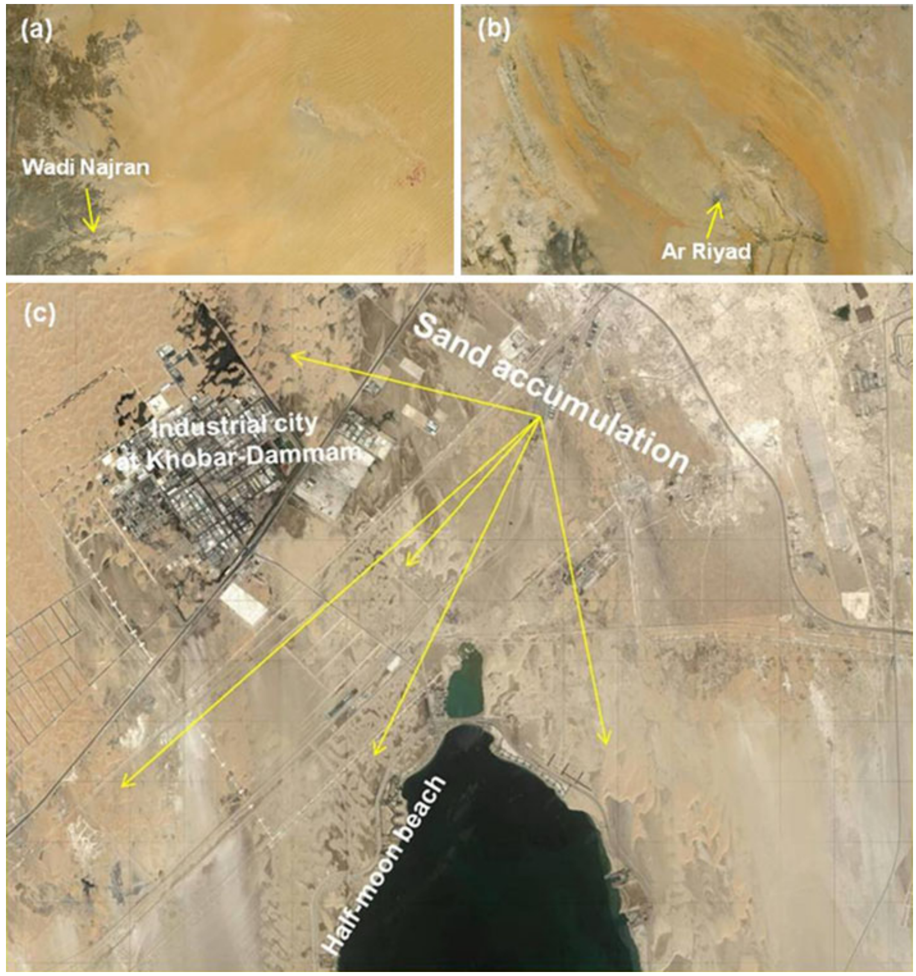

Fig. 10 **a** Sand accumulation to the east of Wadi Najran; **b** Sand accumulation to the east and north of the city of Ar Riyad; and **c** Sand accumulation in the east side of Saudi Arabia

sand accumulations (Fig. 10). Some areas where development reaches are characterized by sand accumulations remedial measures need to be assigned. Sand accumulation areas (sand dunes) could be stabilized by vegetation, by fences, by chemical spraying or by other mechanical means. Watson (1985) reviewed the different methods of sand control with special reference to Saudi Arabia. The use of vegetation and/or naturally occurring stabilizers usually shows better performance than man-made chemicals or fences. The design of a remedial measure is usually based on quantitative estimates of the magnitude of the affected area, the amount of drifting sand or dune movement rate, the prevailing wind direction, and the types and rate of growth of the selected vegetation.

Sabkha soil

Sabkha soil is formed due to the excess evaporation rate of salt water from the soil. Engineers classify sabkha into four common types such as (1) sabkha, (2) playa, (3) salt playa, and (4) saline. After the evaporation of saline water from a lake a crust of salt will be formed. The mineral composition of sabkha is characterized by the presence of aragonite, calcite, gypsum, and dolomite. There are two types of sabkha soils; coastal sabkha and continental sabkha. These two types exist under arid conditions where evaporation rate exceeds precipitation rate. The coastal sabkha is formed as broad coastal tidal flats that get cutoff from the sea by offshore islands (Evans et al. 1969 and Bush 1973) or by coral reef barrier. These tend to form a lagoon with a very small tidal range and consist of sandy, silty or clayey soil depending on the pre-existing geologic setting. The continental sabkha, on the other hand, is formed in a closed depression in which fine soils are accumulated by eroding off the surrounding formations. In the Saudi Arabia, extensive coastal sabkhas exist along the Arabian Gulf and the Red Sea coasts. Continental sabkhas are also present in different locations in the Eastern province, Hail area, Riyadh area and in the Northern Province.

The arid conditions with evaporation exceeding precipitation in both sabkha environments increase the salinization of the soil with a possible formation of salt crust. Both types of sabkha are also characterized by highly saline shallow ground water conditions. The geotechnical properties of the coastal sabkha soils in Saudi Arabia and their potential geological hazards were investigated by Rein-Ruhr (1973), Ali et al. (1985), Ali and Hossain (1987), Dhowian et al. (1987), Hossain and Ali (1988), Abou Al-Heija and Shehata (1986, 1989) and Shehata et al. (1990a, b) and Youssef et al. (2012b). Also, continental sabkha has been studied by Stipho (1985). Youssef et al. (2012b) indicated that the sandy sabkha is characterized by a dry density of about 1.97 gm/cm^3 for sandy sabkha and from 1.88 to 1.94 gm/cm^3 for clayey silt sabkha. Its water content ranges from 12 to 29.8 %. The liquid limit for silty clay sabkha ranges from 27 to 40 %. On the other hand, the grain size distribution shows that (1) For sandy sabkha, it was found that sand % ranges from 55 to 95 %, silt ranges from 6 to 26 %, clay ranges from 0 to 7 %, its friction angle is about 35°, however, cohesion is 20 kNn/m^2; (2) For clay silt sabkha it was found that sand ranges from 10 to 80 %, silt ranges from 17 to 80 %, clay ranges from 3 to 25 %, its friction angle ranges from 25° to 33° while cohesion ranges from 25 to 35 kN/m^2. On other hand, the sabkha soil is not homogeneous but generally loose or soft with Standard Penetration Test (SPT) values ranging from zero close to the groundwater level to >30 at depth. The low SPT values and the presence of water soluble salts such as halite may cause collapse conditions to the soil upon wetting. Figure 11a shows Jizan sabkha and Fig. 11b shows a dynamic penetration test in Jizan sabkha. Also, cross-sections shown in Fig. 12 (left figure has been drawn using ArcGIS 9.3 which is provided by ESRI and right figure has been drawn using Rockwork 15, developed by RockWare, Inc.,) indicate that sabkha soil is characterized by three layers and was verified by Youssef et al. (2012b). These three layers include:

1. The upper surface layer consists of dry sand that contains silt and ranges from 1–2 m in depth. This layer is under the effect of evaporation and deposition of salts that lead to the hardness of this layer. Water table generally exists in this layer and is 1–2 m below the ground surface. The top layers of sabkha may exhibit firm and stiff characteristics in its dry state. However, when dampened with water, the strength is highly reduced, as the cementing salts are susceptible to leaching and dissolution or softening thereby leading to strength loss in wet conditions. Moreover, sabkhas are characterized by volumetric changes increase/decrease in volume due to alternate hydration and dehydration of unstable gypsum under hot and humid conditions (Al-Amoudi 1992; Al-Amoudi et al. 1992; Al-Amoudi and Abduljauwad 1994).
2. The second layer is characterized by fine materials including plastic silty sand and clayey sand, which contains organic matter. It varies from non-plastic silty, clayey fine sand to highly plastic organic clays and silts. The thickness of this layer ranges from 5 to 9 m with an average of 8 m. This layer is compressible and it has a low bearing capacity. This layer is the main problematic layer and it is responsible for long-term subsidence due to secondary compression. Also, the secondary compression of the second layer is related to the high percentage of the organic matter which ranges from 2 to 8 % and this value decreases with depth. The organic matter in sand sabkha is less than that in clayey sabkha.
3. The third layer is the base of sabkha is a hard and firm layer and it is formed by a dense to medium dense sand with a high bearing capacity and low compressibility.

Loess soil

Loess is unconsolidated silt of eolian origin, buff in color and characterized by lack of stratification. It is porous and has low bulk density. The main loess mineralogical constituents are quartz, clay minerals, feldspars, micas, hornblende and pyroxene (Smalley and Vita-Finzi 1968). The

Fig. 11 **a** Sabkha soil in Jizan and **b** the dynamic cone penetration used in the sabkha soil in Jizan city

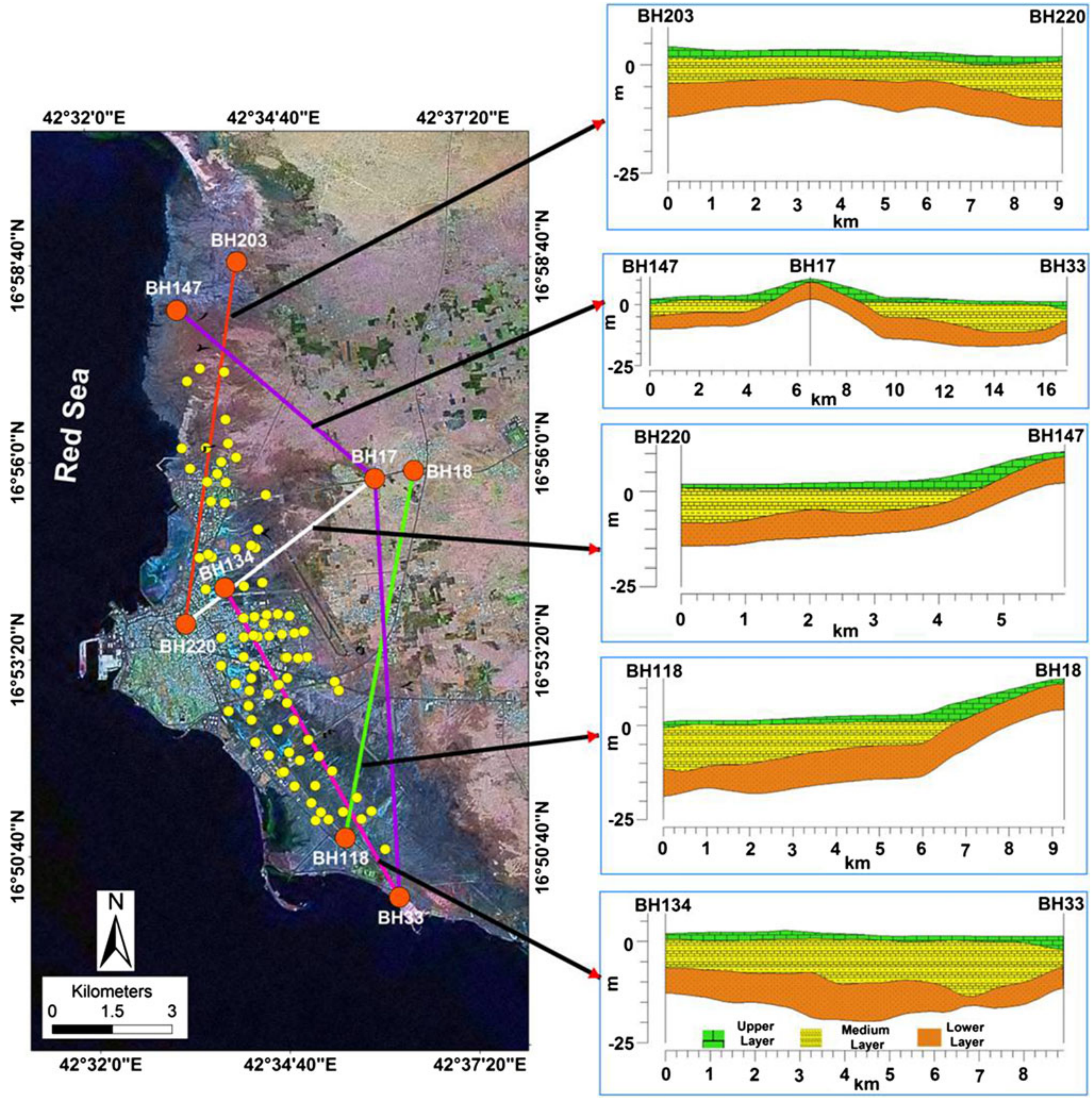

Fig. 12 Sabkha soil in Jizan city is shown in remote sensing image and the cross sections show the three layers

literature of loess recognizes two major sources of loess material formed under conditions of dry climate: glacial or periglacial areas and hot desert. In desert areas the wind-blown silt is trapped in these areas either adjacent to steppe lands or on wet soil or rock surfaces. Smalley and Krinsley (1978) showed that some desert loess is formed near mountain areas due to weathering of igneous rocks, while typical deserts such as Sahara lack loess deposits.

Loess structure undergoes dynamic changes upon changing its moisture content. Handy (1973) has shown that when the loess moisture content exceeds its liquid limit, its structure instantaneously collapses under the load and the soil subsides. This process was described as hydrocompaction by Lofgren (1969) and was termed hydro-consolidation and thoroughly investigated by Bally (1988), Feda (1988), Sajgalik (1991) and Rogers et al. (1994).

Therefore, when an area covered with loess is subject to flooding it will appreciably subside and the soil will become closely packed with increasing density. The magnitude of subsidence is dependent on the degree of saturation and the thickness of the loess layer. Any variations in these will cause differential settlement and failure of any overlying man-made structure. In addition to hydroconsolidation, loess may fail by liquefaction, fluidization or by progressive failure (Derbyshire et al. 1994) depending on the geomorphological setting of the material.

In the Saudi Arabia, very little geologic literature mentions the presence of loess (Smalley and Krinsley 1978). The soil atlas of Saudi Arabia (Anon 1984) does not include the term loess in its classification and only includes loam as one of the soil units present around the desert areas. Several loess occurrences are, however, recognized in the areas to the east and southeast of the Mediterranean Sea (Smalley and Krinsley 1978; Dan 1990; Goring-Morris and Goldberg 1990; Yair 1992; Pye 1994). Foder and Kleb (1994) mapped loess as a soil unit mixed with loamy soil in Hungary. It is therefore suggested that loess could be mistakenly mapped, in some locations, as fine loam as presented in the soil atlas. There are many areas in Saudi that include loess or loess-like soils especially in the downstream sections of the main valleys in Tihama, Jizan area (Fig. 13), and in the southwestern part of Saudi Arabia.

Expansive soils

Swelling clays derived from residual soils can exert uplift pressures, which can do considerable damage to houses and other infrastructure. Expansive soils owe their characteristics to the presence of swelling clay minerals. As they get wet, the clay minerals absorb water molecules and expand; conversely, as they dry they shrink, leaving large voids in the soil. Swelling clays can control the behavior of virtually any type of soil if the percentage of clay is more than about 5 % by weight. Soils with smectite clay minerals, such as montmorillonite, exhibit the most profound swelling properties. Potentially expansive soils can typically be recognized in the laboratory by their plastic properties. Inorganic clays of high plasticity, generally those with liquid limits exceeding 50 % and plasticity index over 30, usually have high inherent swelling capacity. Expansion of soils can also be measured in the laboratory directly, by immersing a remolded soil sample and measuring its volume change. However, there are many methods that could be used to determine the swelling pressure as on Odometer. In addition, in the field, expansive clay soils can be easily recognized in the dry season by the deep cracks, in roughly polygonal patterns, in the ground surface and this is only if the clay soil appeared on the surface. However, in the Saudi Arabia most of the clay materials are located under the ground surface. The zone of seasonal moisture content fluctuation can extend from 1 to 12 m deep. This creates cyclic shrink/swell behavior in the upper portion of the soil column, and cracks can extend to greater depths than imagined by most engineers.

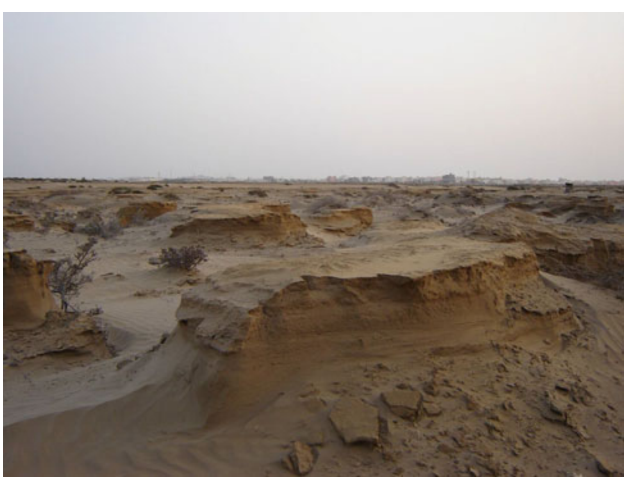

Fig. 13 Example of loess soil in Jizan area

Expansive soils in many parts of the Saudi Arabia pose a significant hazard to foundations for buildings and infrastructures. Government and private sectors pay out millions of dollars yearly to repair homes distressed by expansive soils. Many areas all over the Saudi Arabia are characterized by the presence of expansive soils (e.g. Al-Ghatt, Tabuk, Tayma, Jouf, Sharorah, Madinah, Qaseim, and Eastern regions) (Fig. 14). Infrastructures such as buildings, roads, and other facilities located above the expansive soil are very much prone to damage. Major damage and losses were reported in many areas of the Saudi Arabia which cost millions of Saudi riyals every year. The expansive soil in Saudi Arabia is derived from different types of sediments such as shale, clay stones, and calcareous clays. Example of swelling clay problems is shown in Fig. 14.

Karst problems

The central and eastern parts of Saudi Arabia are covered by sedimentary rocks and unconsolidated sediments. They are dominated by carbonate composition (limestone and dolomite) and evaporites. This part of the Kingdom belongs to the stable shelf (Powers et al. 1966). The rocks in this area were subjected to solution action and karstification phenomena as reflected by the creation of sinkholes. Occasionally, the sinkholes pose critical hazards to human and property in urban areas. In addition, they may cause geological hazards to the future development.

Fig. 14 Wall slipping/subsidence/fissures due to expansive soil

Limited studies have been conducted on the mode of formation, and their potential hazards in Saudi Arabia, and some authors reported that cavities and mechanically eroded features are common in the Dammam and Hadrukh formations (Grosch et al. 1987). The impact of the limestone cavities on urban areas was investigated by many authors, among them Davies and Lord (1981) in Dammam and Rus formations in the city of Al Khobar; El-Ruwaih and Khandker (1981) and Dhowian and Youssef (1981); Touma and Bellerjeau (1981) in Riyadh area; Vaslet et al. (1988) in the crevasse of Al Kharj area. Jado and Johnson (1983) documented two large solution cavities in the Dammam dome, one of these cavities was exposed during the construction of the Central Library in the University of Petroleum and Minerals. Al Saafin et al. (1989) dealt with the geomorphology and groundwater recharge in the karstic terrain of the As Summan Plateau in the Umm er Radhuma Formation (central Saudi Arabia). Finally, Al-Refeai and Al-Ghamdy (1994) included the karst in their evaluation of geotechnical hazards in Saudi Arabia, whereas Shehata et al. (1990b), and Amin and Bankher (1997) evaluated the general karst hazards in eastern Saudi Arabia. Several areas in the Saudi Arabia are affected by karst such as Um Lujj, Turabah, Tabarjal, As Sulayyil, Ar Riyad, Jazan, Rafha, Al-Khafji, Essawiya, and An Nu'ayriyah. Figure 15 shows different types of sinkholes and karst in the Saudi Arabia.

Conclusions

The Saudi Arabia represents a desert environment which is very fragile and is highly affected by human activities. Disturbance of many areas by urban development and infrastructures leads to geological hazards that cause serious problems to human life and properties. Many factors contribute to the appearance of these problems including climatic conditions, geology, geomorphic, and human activities. The geologic setting is usually the controlling factor influencing the type of hazards that will be found. The potential geological hazards that may occur under desert conditions may include sand accumulations and dune movement, earth fissures and subsidence, slope stability hazards, flash floods, karstification, and problematic soils. Engineering solutions for these problems require a detailed site investigation for each new development area

Fig. 15 **a** Circular sinkhole at Al-Nayreyah. **b** Karst in Rayad; **c** Karst in Al Khafji

to determine the geological hazards that will affect the project and to assign the best remediation method to avoid the presence of these types of hazards.

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