Debris flow impact assessment caused by 14 April 2012 rainfall along the Al-Hada Highway, Kingdom of Saudi Arabia using high-resolution satellite imagery

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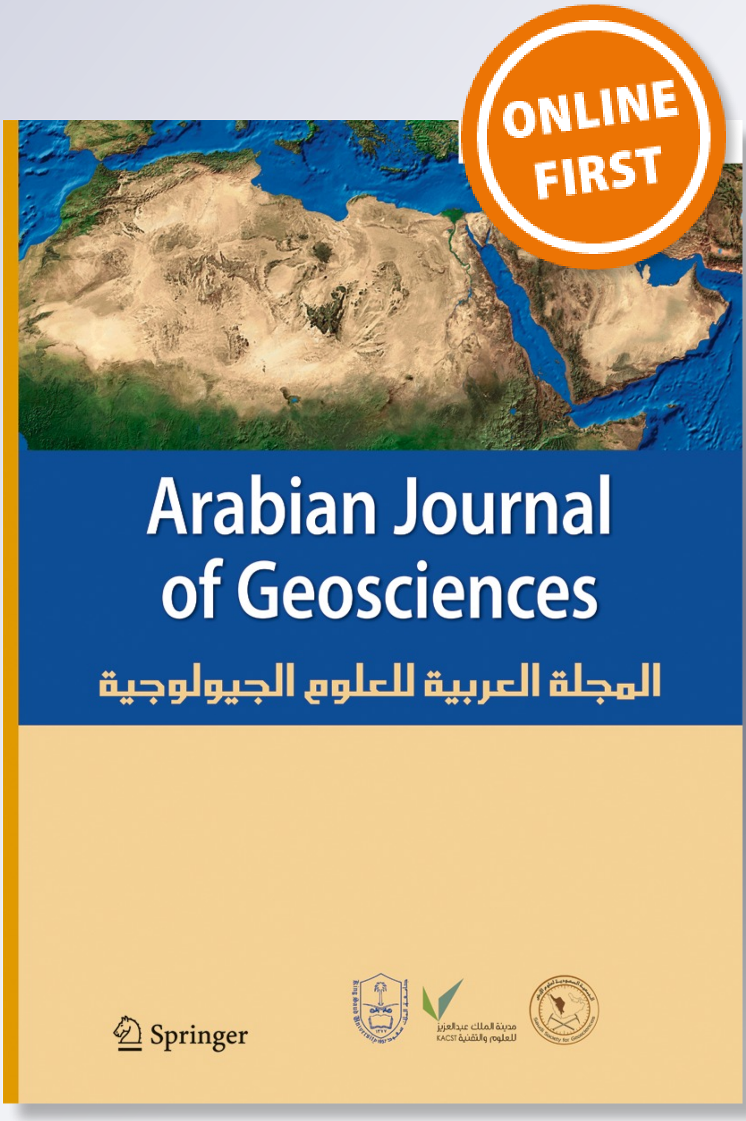

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ORIGINAL PAPER

Debris flow impact assessment caused by 14 April 2012 rainfall along the Al-Hada Highway, Kingdom of Saudi Arabia using high-resolution satellite imagery

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Abstract The Al-Hada highway that descends towards the west of the city of At-Taif is a major connecting highway in the western part of the Kingdom of Saudi Arabia. It is one of the series of descending roads connecting the holy city of Makkah and the city of Jeddah with the city of At-Taif and the cities farther south along the escarpment. The length of the Al-Hada highways is about 22 km. The Al-Hada highway has been historically exposed to landslides and other geohazards since the day it was opened to public some 60 years ago. The road has been reconstructed and many slope instabilities have been remediated and the road has been expanded to two lanes in each direction. Heavy rainfalls occurred on the 14th of April 2012 in the province of At-Taif, causing huge debris flows in two places along the Al-Hada highway. As a result of that, these debris flows closed all four lanes of the highway for 2 weeks in order to remove the debris. The current research deals with mapping of all debris flows along Al-Hada highway and determining their volumes and their impact on the road. Finally, suitable solutions have been suggested to address these critical sites to minimize and/or avoid the debris flow hazards in the future.

Keywords Debris flow · Landslide · Geographic information systems (GIS) · Remote sensing · Volume estimation · Mitigation methods · KSA

Introduction

The Al-Hada escarpment road, which descends from the top of the escarpment near the city of Al-Hada down to the police checkpoint near the village of Kara, was one of the first roads constructed through the extremely difficult mountainous terrain. It connects the Red Sea coastal plain and its low-lying hinterland with the towns and the cities east of the top of the escarpment. It is an important road, as it offers private vehicles and light-duty trucks convenient access between the Holy City of Makkah and the metropolis of Jeddah, both below the escarpment, and the city of At-Taif and large towns and villages southeastwards, above the escarpment. It is located in the mountainous area covered between the southern and eastern parts of the Kingdom of Saudi Arabia (KSA) (Fig. 1).

The Al-Hada escarpment road is about 22-km long, measured from the top of the escarpment (2,000 m above sea level (asl)) from the west to the police checkpoint at the base of the escarpment to the east (approximately 700 m asl)

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Fig. 1 Location of the study area in the KSA map. Al-Hada highway connects different areas and cities with each other

(Fig. 2). It features numerous switchbacks. It was constructed in the 1960s without the use of any controlled blasting techniques. In the recent years, the Ministry of Transportation reconstructed the Al-Hada highway to add two traffic lanes in each direction, to make it a suitable highway for the new developments along the area. This road was closed for construction from 2000 to 2004.

Unfortunately, many of the debris flow channels that were crossing the road were not remediated effectively. Typically concrete walls were emplaced to intercept these debris flows. Along these sections, from time to time, debris flows cascaded over these concrete walls and covered the road causing traffic accidents to the passing vehicles and inconvenience to those who get trapped along the highway during rainstorms. Consequently, the road was commonly closed by the police during rainstorms. The Al-Had area is characterized by the most extreme climatic conditions that can be found in this region.

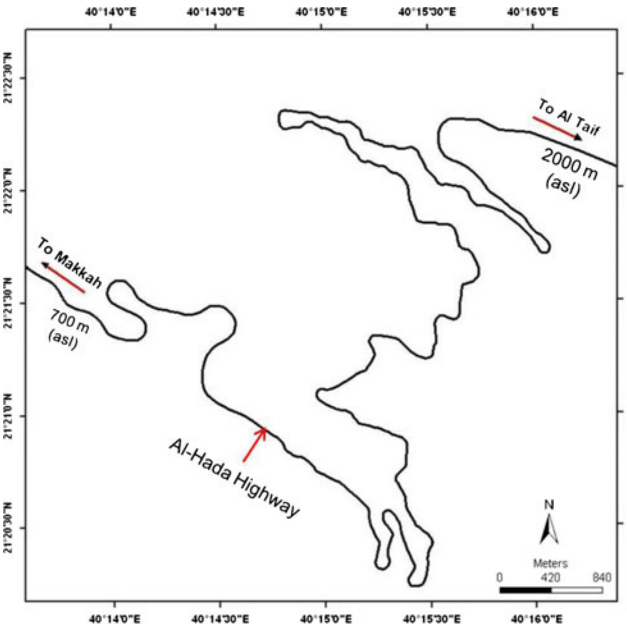

Fig. 2 Detailed alignment of Al-Hada highway

The main objective of the current study is to evaluate the debris flow problems that have occurred along the Al-Hada highway; to map all the debris flow channels; to quantify the debris volume and their impacts on the Al-Hada highway; and to find the most suitable solutions to minimize the impact of the debris flows along the mapped sites.

Debris flows

Debris flows occur when masses of poorly sorted sediments are agitated and saturated with water, moving down the slopes. Both solid and fluid forces strongly influence the motion, distinguishing debris flows from related phenomena such as rock avalanches, turbidity currents, and sediment-laden water floods. Whereas, solid–grain interactions dominate momentum transfer in avalanches, and fluid turbulence dominates momentum transfer in turbidity currents and floods; solids and fluids must transfer momentum synergistically to sustain the type of motion that characterizes debris flows (Iverson et al. 1997). By using this fundamental principles, many events were identified as debris slides, debris torrents, debris floods, mud flows, mudslides, mud spates, and lahars which can be regarded as debris flow (Varnes 1978; Johnson 1984; Pierson and Costa 1987; Regmi et al. 2013). Evans (1982) concluded that the generic term of debris flow can be mainly divided into open slope debris flow and channelized debris flow. Pierson and Costa (1987) addressed channelized debris flows and has a classification convention. Other terms for debris flows, such as debris torrents, have been used by many researchers (Swanston 1974; Miles et al. 1979; VanDine 1985; Chatwin et al. 1994) in British Columbia and the US Pacific Northwest. Also, the debris torrents have been used in the Queen Charlotte Islands by Wilford and Schwab (1982), Chatwin and Rollerson (1984), Krag et al. (1986), Tripp and Poulin (1986), Sauder et al. (1987), and Gimbarzevsky (1988). The diverse nomenclature reflects the diverse origins, compositions, and appearances of debris flows from quiescently streaming sand-rich slurries to tumultuous surges of boulders and mud.

Debris flows can originate through various means, as when pyroclastic flows entrain and melt snow and ice (Pierson et al. 1990) or when abrupt floods of water undermine and incorporate ample sediment (O'Connor et al. 1997), or when mobilization from landslides predominates (Johnson 1984). Hungr et al. (2001) mentioned that debris is a loose unsaturated material of low plasticity such as colluviums (mass wasting processes), residual soil (weathering materials), till (glacial transport sediments), granular pyroclastic deposits, and deposits related to human activities. Contrasting styles of deformation help to discriminate the mobilized debris flows from landslides that do not mobilize. Debris flows exhibit pervasive, fluid-like deformation that facilitates motion of even boulder-rich debris through tortuous channels, across gentle slopes, and around obstructions. A debris flow can be defined as a mass movement that involves water-charged, predominantly coarse-grained inorganic and organic material flowing rapidly down steep slopes, in a confined along the preexisting channels (VanDine 1985).

Jaeger and Nagel (1992) and Jaeger et al. (1996) mentioned that the distinction between landsliding and debris flow is gradational and analogous with respect to sand that slips incrementally along discrete failure surfaces, as what may happen under foot on a beach, and sand that flows rapidly, as what may happen on a steep dune face. However, Iverson et al. (1997) stated that the effects of pore water give debris flows mobility that surpasses even that of dry, flowing sand. The qualitative difference between sliding and flowing motion, and the key role played by water and agitation in facilitating flow, has long been apparent to astute observers.

Debris flows are extremely mobile and composed of highly concentrated mixtures of poorly sorted sediments in water (Pierson, 1986). The material incorporated is inherently complex, varying from clay-sized solids to boulders of several meters in diameter. Based on the texture, it was found that debris is a mixture of sand, gravel, cobbles, and boulders with different proportions of silt and clay and sometimes it contains a significant amount of organic materials such as logs and tree stumps (Swanston 1974). Due to their high density, which exceeds twice the water density, and their high mobility, debris flows represent a serious hazard representing a major impact for people, properties, vehicles, and infrastructure in mountainous regions. Costa (1984) and Rickenmann (1999) mentioned that the front of a debris flow can reach velocities up to 30 m/s. The peak discharges of debris flows reach tens of times greater than for floods occurring in the same catchment (Pierson 1986; Hungr et al. 1984; ONR 2007). Prochaska et al. (2008) mentioned that debris flows are hazardous due to their unpredictability, high-impact forces, and their ability to deposit large quantities of materials in inundated areas.

There are three forms of debris flow hazards from which roads, stream crossings, building and other structures require protection. Hungr et al. (1987a, b) described the debris flow hazards as follows: (1) hazards related to the direct impact of high-energy coarse-grained debris that can destroy structures, (2) hazards due to the indirect impact lower-energy of coarse and fine grained debris that can bury structures, and (3) hazards from flood waters that are forced from the normal channel by debris deposits and have the potential to erode unprotected surfaces and cause flood damage. Many factors affect the debris flow such as rainfall intensity, stream flow discharge, local weather cells, antecedent rainfall and snowfall, channel profile, the existence of debris in the stream, and a wide variety of triggering mechanisms (VanDine 1985; Church and Miles 1987).

Debris flow mitigation structures may be required to minimize the risk to developments on alluvial fans. Debris flow velocity is an important factor in the design of mitigation structures because it influences the impact forces, run up, and super elevation of the flow. Debris flow velocities are conventionally back-calculated from previous super elevation events (Johnson 1984) or predicted using flow equations (Lo 2000). Debris flow mitigation measures were applied in many research areas such as DeNatale et al. (1997), Frenez et al. (2004), Rickenmann (2001), Rimbock and Strobl (2002).

Geomorphology and geology of the study area

The Al-Hada area is located at the edge of the Hijaz plateau and is part of the range of Scarp Mountains referred as the Red Sea Escarpment in the literature. The escarpment itself is the result of erosional retreat of uplifted Precambrian rocks that were elevated concurrent with initiation of rifting in the Red Sea during the late Paleogene era. The escarpment runs in a northwest–southeast direction roughly parallel to and from 40 to 75 km inland from the Red Sea coast, extending over 2,000 km in length, from the Gulf of Aqaba to the Gulf of Aden at a point where the Al-Hada highway descends the escarpment. The landscape is extremely rugged and the relief is as great as 1,300 m, with variation in elevation from 700 m above sea level, at the base of the escarpment, to 2,000 m above sea level at the top of the escarpment. Natural slopes range between 55° and 88° in the vicinity of the Al-Hada escarpment, and man-made slopes on the road cuts are even steeper reaching as much as 90° in some sections.

Geologically, the escarpment and foothills are part of the exposed Neoproterozoic Arabian shield and are composed of faulted and jointed monzogranite, granodiorite, and granite that intrude greenschist- and amphibolite-grade Precambrian metamorphic rocks. The detail geological map was prepared by Marzouki (1977).

Abo Saa'da (1981, 1990) investigated the stability of the slopes along the Al-Hada descent using simple conventional techniques and without taking into consideration of the effect of rainwater. Similarly, made an investigation to account for the geological and geotechnical conditions prevailing along the road based on the conventional techniques.

Results and discussion

Evaluation of the current problem

During the 14th of April 2012, heavy rainfalls that occurred for 2 h from 4 p.m. to 6 p.m. along the Al-Hada area caused huge amounts of debris flow along two debris flow channels over the Al-Hada highway. Site 1 is located at latitude 21°21′50″ N and longitude 40°8′35″ E, and site 2 is located at latitude 21°21′37″ N and longitude 40°15′44″ E (Fig. 3).

These debris flows covered the entire road (all four lanes) and led to the closure of the road in both directions for 2 weeks in order to remove the debris along site number 1. One vehicle was trapped by the debris in site 1 (Figs. 4, 5, 6). In site 2, the debris filled up the channel and the entire area behind the jersey barrier walls that were designed to contain the debris flow (Fig. 7).

Debris flow locations mapping using high-resolution satellite images

The principal drainage on the escarpment is through Wadi Al-Korr and Wadi Al-Alq which flow towards the east. The drainage pattern of the two wadis is dendritic with subparallel channels. The upper part of the Al-Hada escarpment has a denser network of drainage than the lower part (Fig. 8a). The major landforms in the area along the road include scarps and rock flows. The scarps are steep slope features parallel to the escarpment, whereas the rock flows are unconsolidated material mainly of boulder size that fills the wadi channels. Present day movement of rock flows is evidenced by rock flows banked up against and sometimes overtopping the retaining walls, which were constructed where the mountain wadis cross under the upper part of the road.

The debris flow channels were mapped using high-resolution satellite images (QuickBird® imagery with a ground resolution of ~61 cm/pixel acquired at the end of 2011) (Fig. 8b) and have been verified during field investigations. Debris flows from the basins may have entrained material along their travel paths; these events were generated from the discrete landslides. The mapped areas and the data collected from the field investigation showed that more than 15 debris flow channels are present (Fig. 9).

Estimation of debris flow parameters

A summary of the data parameters for the debris flow has been determined and is shown in Table 1. These parameters include the highest and lowest point for each debris flow area that will impact the Al-Hada highway, slope for each channel, length of the debris channel, and area of the debris flow zone.

Volume estimation was deemed to be absolutely essential in this paper. The area and thickness of the debris flow channels have been estimated during the field studies and by using topographic maps, a digital elevation model, and high-resolution images. Many authors have attempted to estimate the volume of the debris flows and related phenomena (Iverson et al. 1998; Siebert 1984; Gartner et al. 2008).

Fig. 3 Location of the two debris channels that intersect the Al-Hada highway, where the highway was completely closed

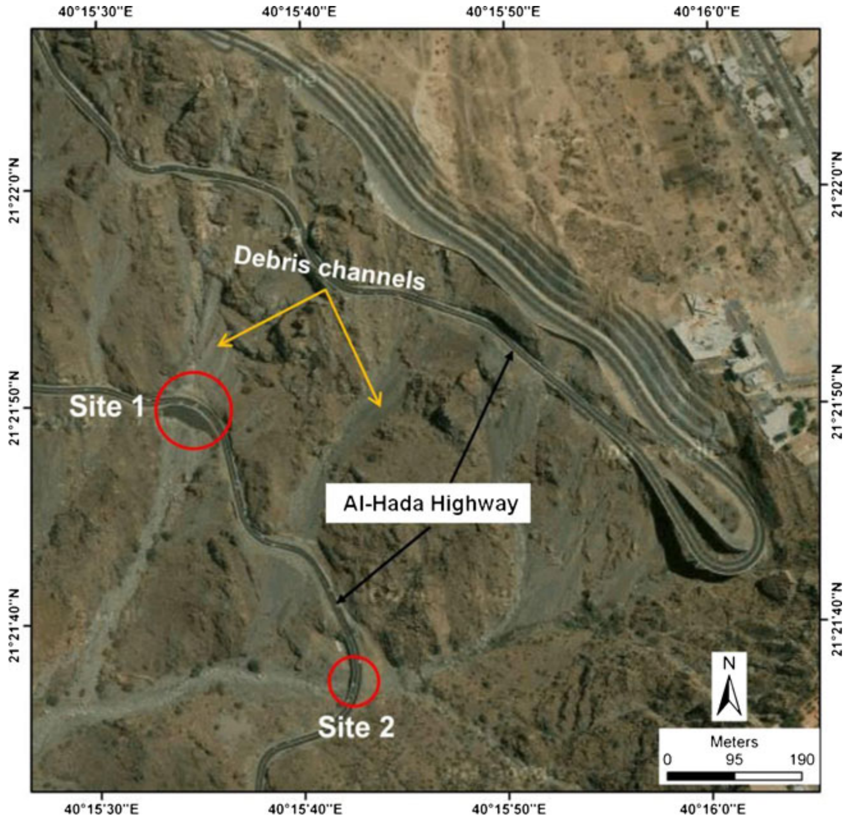

Fig. 4 Debris flow along site 1 in Al-Hada highway and the existing bulkhead type barriers

In the current paper, the maximum thickness of all debris flow channels were determined by surveying these channels in the area especially the part which discharges toward the Al-Hada highway. To determine the average thickness of each debris channels, a triangle cross section (V shape) of the debris channel is assumed where the thickness decreases towards the sides to become zero and decreases in longitudinal section toward the upstream section to be zero (Fig. 10). The maximum thickness of each debris channel was measured using a surveyor's bar, which has a length of 2 m and is marked at 10-cm intervals. The average thickness for each debris channel can be calculated by Eq. 1.

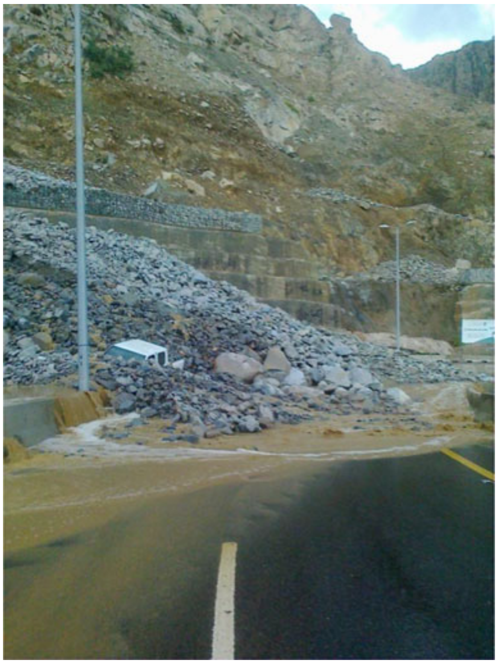

Fig. 5 Both sides of the Al-Hada highway were completely closed along site 1. Notice the vehicle that is trapped inside the debris and water flows

Fig. 6 Removing the debris from the road along site 1

$$\mathrm{Tdc} = \mathrm{MaxT}/2, \tag{1}$$

where Tdc is the average thickness for the whole debris flow channel, MaxT is the maximum thickness that was measured in the field.

Table 1 shows the maximum thickness and the average thickness of each debris channel in the study area. Consequently, the volume of the debris flow at each channel can be calculated simply by using Eq. 2. Table 1 shows the volume calculations for all debris flow deposits in the study area.

$$V = A \times \mathrm{Tdc}, \tag{2}$$

where V is the volume of the debris flow, A is the area of the debris flow channel, and Tdc is the average thickness of the deposit in each debris channel.

Proposed mitigation measures

From an engineering point of view, there are various types of measures that can be used to reduce the impact of debris flows. An outline of potential methods is given by Huebl and Fiebiger (2005). These include:

- Decreasing runoff by land management techniques or runoff diversion
- Decreasing erosion by land management techniques, runoff diversion, or channel bed alterations
- Controlling water discharge by water management or runoff diversion
- Controlling debris by engineering the movement of the flow

VanDine (1996) determined the design considerations for the debris flows which include the volume of the debris flow, the likely flow paths, potential run-out distance,

Fig. 7 Debris flow along site 2

impact forces, run-up, and probable storage angle. VanDine (1996) mentioned that the terminal walls, berms, or barrier terminal walls, could be constructed across the debris flow path to encourage deposition by presenting a physical obstruction to flow. These structures will increase the length of the flow path and could be built with a finite length so that fine-grained sediment and water from the debris flow can find their way around either end of the berm. He mentioned that as soon as the debris are deposited upstream of a terminal structure, the coarse-grained debris must be removed from the area.

Deflection walls or berms have been used to refer to deflection dams by Eisbacher and Clague (1984) and as debris flow direction controlling works in Japan (Government of Japan 1984). These deflection walls or berms are similar to lateral berms where both are built immediately down slope from the apex of the debris fan and parallel to the desired path of the debris flow whose lateral movement they are used to constrain. They are also different from the lateral walls or berms where they deflect the flow path and prevent it from going straight. These deflection walls or berms can be used to protect a structure by deflecting the flow to another area, or by increasing the length of the flow path, and decreasing the overall gradient and encouraging deposition. Hollingsworth and Kovacs (1981) mentioned that the deflection walls are used in California to decrease the angle of impact on a structure. These deflection walls are usually constructed of reinforced concrete; however, the berms are usually constructed from local materials or can be a composite. Eisbacher and Clague (1984) mentioned that many earth deflection berms have been constructed in British Columbia.

Another method used to protect from the debris flow are debris racks, grizzlies, or other forms of debris-straining structures. They are used to separate the coarse-grained from the fine-grained debris, thus encouraging the coarse-grained portion of the debris flow to be deposited. These types of structures are used commonly in British Columbia (Thurber

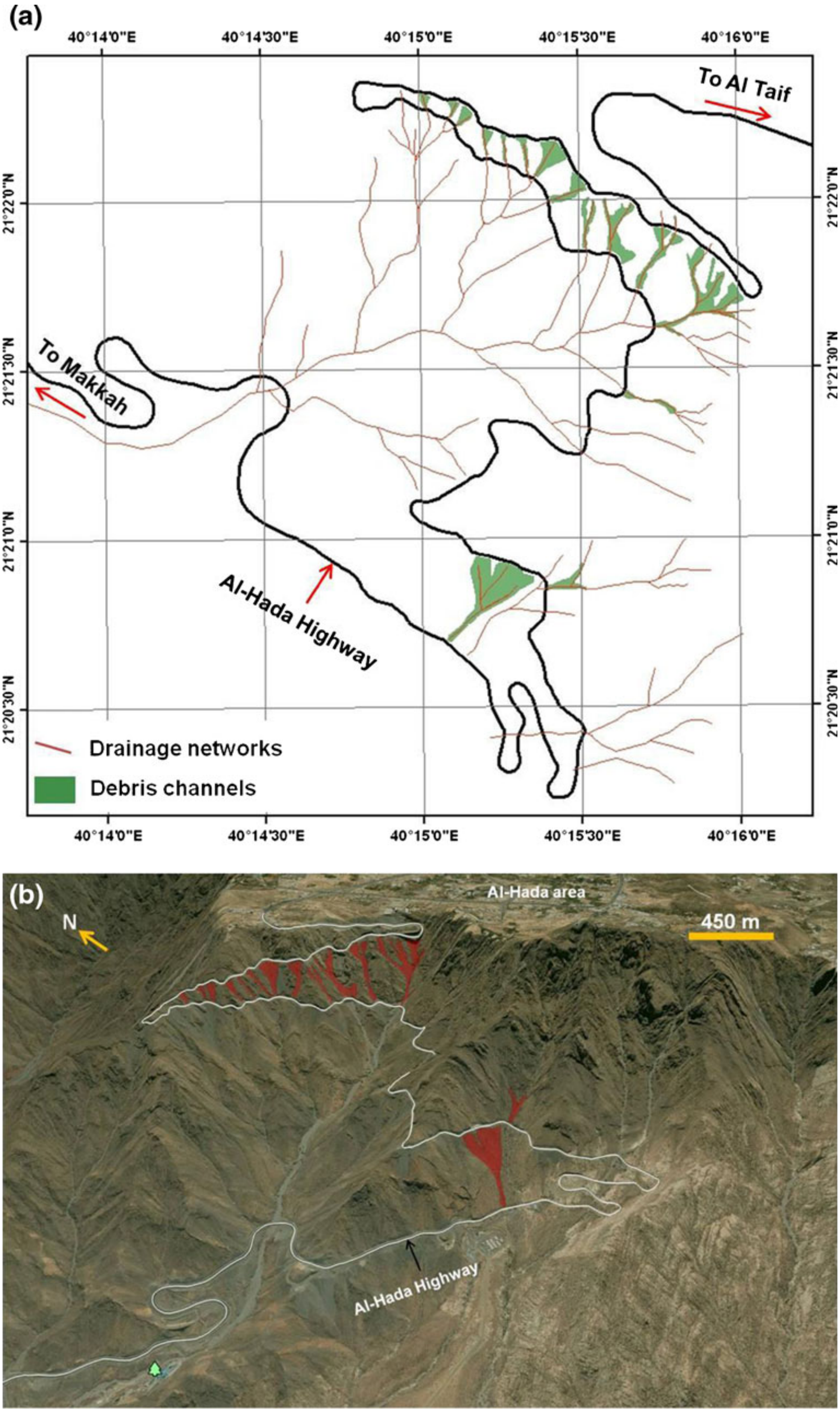

Fig. 8 **a** Plan view of debris flow locations that intersect the Al-Hada highway. *Green zones* show the debris flow channels. (**b**) 3D view of debris flows that intersect the Al-Hada highway using QuickBird imagery with a ground resolution of ~61 cm/pixel. *Red zones* show the debris flow channels mapped in this project

Consultants 1984; VanDine 1985; Hungr et al. 1987a, b). They also used to prevent culvert openings and bridge clearances from becoming blocked with debris. Debris racks are used as an integral component of debris barriers. In

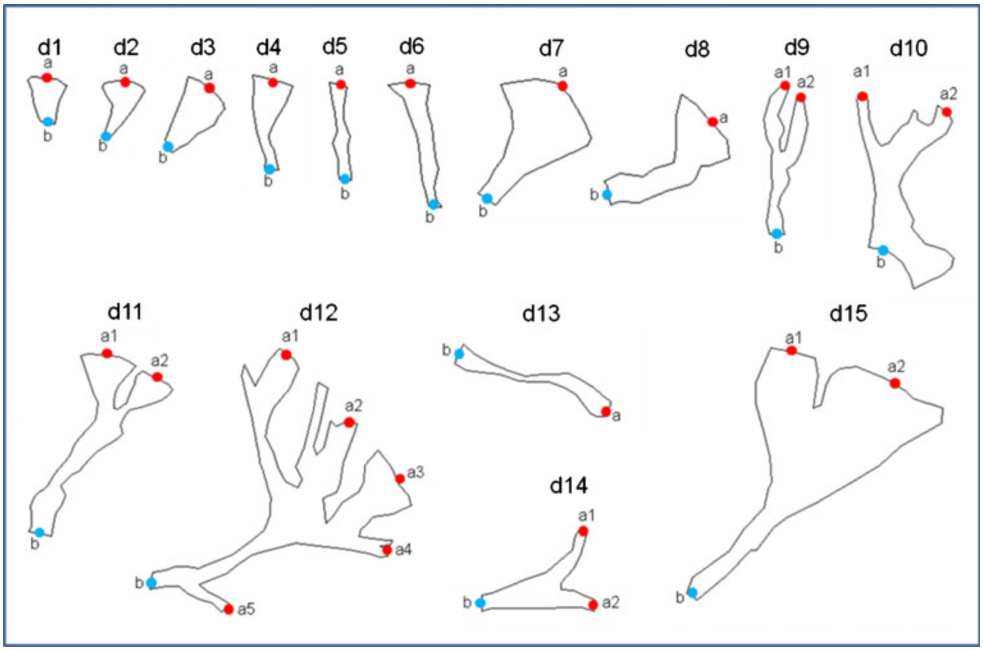

Fig. 9 Outline of the debris flow channels that intersect the Al-Hada highway. Note that the *red points* indicate the highest elevation on the flow while the blue points indicate the lowest elevation

addition to remain effective, the coarse-grained debris must be removed from behind these structures regularly.

Many of these proposed solutions will simply not work for these very steep, high-volume debris flows, in arid desert

Table 1 Debris flow parameters along Al-Hada highway

Number	Segment	Highest point (m)	Lowest point (m)	Height difference (m)	Length (m)	Slope (m/m)	Surface area (m^2)	Maximum depth (m)	Average depth (m)	Volume (m^3)
d1	Ab	1,753	1,713	40	91	0.439	3,024	1.5	0.75	2,268
d2	Ab	1,757	1,700	57	103	0.553	3,310	1	0.5	1,655
d3	Ab	1,767	1,694	73	134	0.545	6,048	3	1.5	9,072
d4	Ab	1,773	1,684	89	156	0.571	5,116	2.5	1.25	6,395
d5	Ab	1,783	1,681	102	157	0.649	3,108	2	1	3,108
d6	Ab	1,794	1,667	127	211	0.602	5,789	2.2	1.1	6,368
d7	Ab	1,804	1,664	140	222	0.631	17,837	3.5	1.75	31,215
d8	Ab	1,809	1,654	155	217	0.714	12,721	2.5	1.25	15,901
d9	a1b	1,793	1,634	159	286	0.556	10,527	2	1	10,527
	a2b	1,797	1,634	163	270	0.604				
d10	a1b	1,821	1,618	203	290	0.700	26,211	8	4	10,4844
	a2b	1,841	1,618	223	291	0.766				
d11	a1b	1,853	1,589	264	370	0.714	21,276	3	1.5	31,914
	a2b	1,863	1,589	274	370	0.741				
d12	a1b	1,859	1,584	275	600	0.458	56,609	3	1.5	84,914
	a2b	1,857	1,584	273	507	0.538				
	a3b	1,841	1,584	257	501	0.513				
	a4b	1,835	1,584	251	456	0.550				
	a5b	1,662	1,584	78	156	0.500				
d13	Ab	1,753	1,579	174	303	0.574	7,426	1	0.5	3,713
d14	a1b	1,509	1,397	112	254	0.441	11,274	0.6	0.3	3,382
	a2b	1,493	1,397	96	216	0.444				
d15	a1b	1,437	1,199	238	523	0.455	71,418	0.8	0.4	28,567
	a2b	1,414	1,199	215	548	0.392				

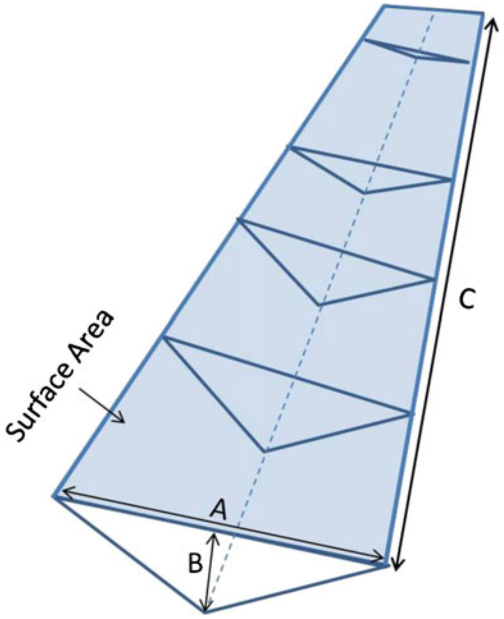

Fig. 10 Diagram showing the simplified method to calculate the depth and volume of each debris flow channel (*A* = width of cross section at the outlet of the debris channel, *B* = Maximum thickness, and *C* = longitudinal length)

environments as studied in this paper. Land management techniques typically revolve around revegetation and reforestation which is practically impossible in arid climates. Channel bed alterations including cascading or other debris barriers and re-routing flows are just not very practical on very steep slopes. Using an accumulating pile of debris flow solids to reduce gradients over time or to otherwise hinder the flow is only effective if the system is not overwhelmed by massive amounts of material flowing down steep grades. For this particular environment, design options were considered to stop the debris flows and stabilize the slopes that include starving the potential flow of the water and/or starving the flow of the solid elements. This causes intercepting the flow using barriers, or alternatively allowing the flow to proceed under the highways.

The most effective and permanent solution is to raise the highway above the debris flow channels. This would involve either bridges or extremely large culverts with structural protection between these culverts. This would ideally allow flows to pass harmlessly below the road. The problem with this kind of solution, especially the construction of bridges, is that it is very costly. Furthermore, in a mountainous terrain where the road switches back below, the debris flow problems are merely passed down the side of the mountain to the next road below. While the installation of culverts is definitely less costly, it still leaves the highway at risk for overtopping or damage from high-volume debris flow events. For that reason, these solutions were rejected from a cost viewpoint.

Starving the potential debris flow of water is normally an obvious solution. This would require interception and diversion of surface flow. Starved of water, the debris flow would never be mobilized. In very steep slopes with significant rainfall, this is very difficult because the water has many sources, has to go somewhere, and ultimately may find its way back to the debris flow channel or into another channel where it can be equally as destructive. Attempting to channel water down the side of mountains as steep and unstable as these in designed open channel flow, could result in destructively high velocities with great erosion potential. The channel may overtop under the high flows. The channel could fail mechanically because of unstable steep slopes. Trying to channel water down in pipe flow will result in high velocities and/or high pressures, with an equal possibility of mechanical failure. In either case, these waterworks may fail quickly on the steep unstable slopes. This solution was rejected due to uncertainty, engineering difficulties, and cost associated.

Starving the potential debris flow of solids is very difficult because the rubble from the new highway construction upslope was simply dumped on the slope below. Removal of the construction rubble then becomes very difficult because of the steep slopes and the sheer volume of materials. As indicated before, cascading barriers to immobilize the solids is also not practical on the steep slopes. These solutions were rejected based on the engineering difficulties and high costs.

Intercepting the debris flows using structural barriers as the flow approaches the highway is a solution that was originally implemented here during highway construction. Freestanding retaining walls and gabions extending the height of the structure have been used to protect the highway from debris flows. This is probably the most cost-effective solution, but the design fell short on these steep slopes with high volumes of debris flow resulting in overflow of the physical barriers.

For this project, the recommended solution involves increasing the volume capacity of the bulkhead type barriers (as shown in Fig. 4) by raising the height of the barriers. We recommend that the structural concrete barriers be designed with appropriate factors of safety against sliding and toppling (based on dynamic loading of the debris flow) with horizontal drain holes along both the length and height of the barrier to reduce pore water pressures and decrease the mobility of the debris flow as it approaches the barrier. The use of techniques to block debris emanating above the highway will also serve to starve the debris flow channels below the highway from mobilizing and affecting the switch back below. It also can be recommended to implement a method for periodically removing the debris from behind the barriers so that debris can be removed following flow events, creating more catchment space for future flow events. This will require a proactive maintenance program and incur an indefinite maintenance liability.

Concluding remarks

Heavy rainfalls along the Al-Hada highway caused large debris flows leading to the closure of the highway for 2 weeks. The problem was related to different factors such as natural debris, man-made debris dumped on the slope, rainfall, steepness of the channels, and ineffective concrete walls. The authors found that channel erosion, scour, and design and construction errors are the dominant sources of debris in the channels that intersect the Al-Hada highway.

During the renewal of the highway from two lanes to four lanes, many rock cuts were established and all the excavated materials dumped into or near old debris channels. No method was used to stabilize these deposits and/or to make a suitable drainage system to drain the rainfall water away from these channels. It was found that the debris in the study area has two origins, one is from the old deposits which is related to soil blankets, talus, and colluvium along the steep slopes which fill the lower portion of these channels in the study area and the other one is related to the man made fills which are the dumped materials from the new rock cuts along the upper Al-Hada highway.

This paper deals with mapping of all the debris flow channels using high-resolution satellite images. Fifteen debris flow channels have been mapped which have a direct impact on the Al-Hada highway. Different debris channel parameters have been measured and calculated including, surface area, elevation of the highest point, elevation of the lowest point, longitudinal slope, length, height difference, maximum thickness, average thickness, and deposits volume. Finally, suitable mitigation methods have been prescribed to prevent and avoid the impact of these debris channels on the Al-Hada highway.

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