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RAINFALL-INDUCED DEBRIS FLOWS CASE HISTORY ALONG AL-HADA DESCENT HIGHWAY WEST OF SAUDI ARABIA

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ABSTRACT

Al-Hada descent lies at the western region of Saudi Arabia at elevation of about 2000m, characterized by sharp cliff. Al-Hada descent road was constructed with an elevation difference of 1500m between the highest and lowest heights along the road. The road alignment is intersected by 8 very steep gullies of almost 60 to 80 degrees. The gullies contain large quantity of mud, old levees and large rock blocks. Al-Hada descent road hit two weeks ago with heavy rainfall last about 2 hours. The rainstorm initiates 11 debris flows on steep gullies, and caused them to travel rapidly down along the gully channel. Once the flow reaches a less confined area at the retaining wall, it partially destroy the gabions above it, and edges of the retaining walls across the gullies and overflow them, as they received more rolling, sliding and bouncing rocks from higher steep elevations. The moving debris flows spread out, loose speed and deposited beyond the highway opposite side.

Temporary solution is made by removing almost 100.000m^3, of the debris flow in one gully and scaling the remaining debris body to an angle of more than 35°. A permanent solution for this case history is under intensive study.

INTRODUCTION

Debris flow is a flow of sediment and water mixture in a manner as if it was a flow of continuous fluid driven by gravity, and it attains large mobility from the enlarged void space saturated with water or slurry (Takahashi, 2007a; and Takahashi, 2009). Debris flow is one of the most destructive mass movements. Sometimes regional debris flow susceptibility or hazard assessments can be more difficult than the other mass movements (Tunusluoglo et al., 2007). Determination of debris accumulation zones and debris source areas, which is one of the most crucial stages in debris flow investigations, can be too difficult because of morphological restrictions (Tunusluoglo et al., 2007). The landslides initiated as small debris slides, and developed into debris avalanches and debris flows involving the shallow pyroclastic deposits that lie on the steep, vegetated slopes of this area (Guadango et al., 2005).
Three types of debris flow initiation predominate (Takahashi, 2007b). The first type is due to the erosion on channel bed. Following a severe rainfall, surface water flow appears on a steep channel bed on which plenty of debris is accumulating, and the water flow destabilizes the bed and entrains the debris rapidly to form debris flow. The second type is due to landslide. The slid earth mass is successively destroyed while in motion, and it transforms into debris flow by mixing of debris with water that has been contained originally in the earth mass or supplied from behind. The third type is the destruction of natural dam. A landslide sometimes dams up a river, and sooner or later, the dam is destroyed by the overtopping of river water or by the collapse of the dam body itself under the effects of seepage water and/or hydraulic pressure. From the mechanical point of view, the debris flow initiation process due to overtopping of a natural dam can be considered similar to the first type, and that due to collapse of the dam body is akin to the second type (Takahashi, 2007b).

Subaerial massive sediment motions, closely related to sediment hazards, are basically divided into fall, flow and slip. Figure 1show eight blocks represent these phenomena based on the specific aspects. The upper five blocks represent the phenomena in which particles are dispersed in the flowing body, and the lower three blocks represent the phenomena in which the moving bodies are mostly the agglomerates of soil and rocks (Takahashi, 2007a). If the slipping rigid body is liberated from the constraint of the ground surface on which it slips, it becomes a free falling body, and if the liquefaction at the lower part of the slipping body proceeds during motion, it requires high mobility and can be called a debris avalanche. If the entire body is liquefied, it is then called debris flow. Thus, the arrows starting from the landslide/landslip block towards the debris avalanche block or debris flow blocks represent the process from initiation to full development. High water content is necessary for the development of liquefaction, so that, for a large-scale debris flow, avalanche, the mountain body that starts moving should have been saturated with water at least at the lower part. But, in the case of debris flow, if the volume of the slid body is small, even if it is not saturated with water, the addition of water from outside may be enough to transform it into a debris flow. A supplement explanation for the mechanism of a debris avalanche may be necessary. Dry granular flow is not able to keep going on a slope flatter than the angle of repose of the material.

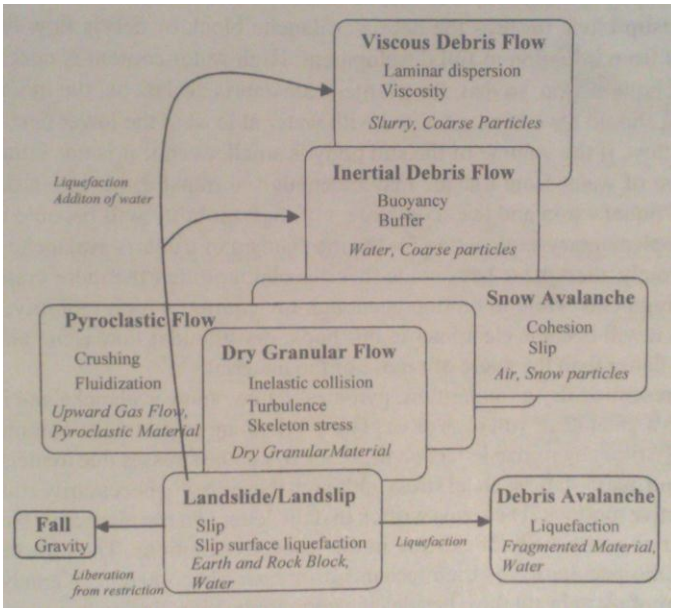

Fig. 1. Subaerial mass movements; their mechanical resemblances and differences (after Takahashi, 2007a).

Debris flows are one of the most hazardous types of landslides in mountainous areas because they are fast moving and can occur with little warning. Crosta, et al., (2004), Boultbee et al., (2006), Pirulli (2009), and Xu et al., (2009) recorded incidents of catastrophic rockslide events. Field observations and existing literature indicate that three primary types of non-volcanic debris flows affect mountainous areas: 1) debris flows that mobilize from landslides (Varnes, 1978) and travel over the surface of the hillslope, often flattening vegetation and leaving a thin veneer of deposits (Ellen et al., 1988), 2) debris flows that mobilize from slides that then erode and entrain hillslope and channel materials (Jakob et el., 2000), and 3) debris flows that initiate from surface water runoff that erodes and entrains hillslope and channel materials (Larsen et al., 2006). Most of published papers are concerned with the third type (Coe et al., 2008).

For a debris flow, besides the operating stresses, the buoyancy effect and possibly the buffer effect of interstitial fluid to particle collisions and the mass effect, in order to accelerate the surrounding fluid, would be important. If a debris flow body contains much of fine sediments (clay and silt) the viscosity in the interstitial fluid (slurry composed of the mixing of clay and silt with water) becomes very large and turbulence is necessarily suppressed. In turn, the particle collision effect becomes minimal, and instead, the laminar dispersion mechanism should operate (Phillips et al. 1992). Consequently, the common mechanism between viscous and inertial debris flows is the buoyancy. Viscous debris flow also has little shared with debris avalanche, pyroclastic flow and snow avalanche as shown by no overlap between the blocks representing these phenomena (Phillips et al. 1992).

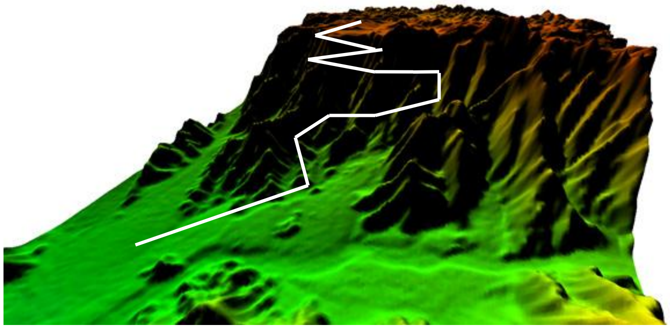

Fig. 2. A 3D model of the Al-Hada descent shows the elevation difference and the sharp angle of the slopes, in addition to the rough estimation of road alignment.

SITE CONDITIONS

Al-Hada descent lies west of Taif city, at the western region of the Kingdom of Saudi Arabia, at elevation of about 2000 m a.s.l. It is characterized by a sharp cliff edges at the highest elevations. The descent road was first constructed as 1-carriage road about 60 years ago. The elevation difference between the highest and lowest elevations at the descent is almost 1500m (Fig. 2).

THE GULLIES INTERSECT THE ROAD ALIGNMENT

The road alignment intersects with 11 gullies originated from higher elevations and a slope angle increase as the elevation increase close to the escarpment edge, ranging between 60°-80° (Fig. 3). All these gullies lies between road twists # 2 and 3, 9 of the 11 gullies had debris flows ranging between violent and weak intensity. Gully # 10 (Fig. 4) was not full of quantity of debris enough to trigger a debris flow.

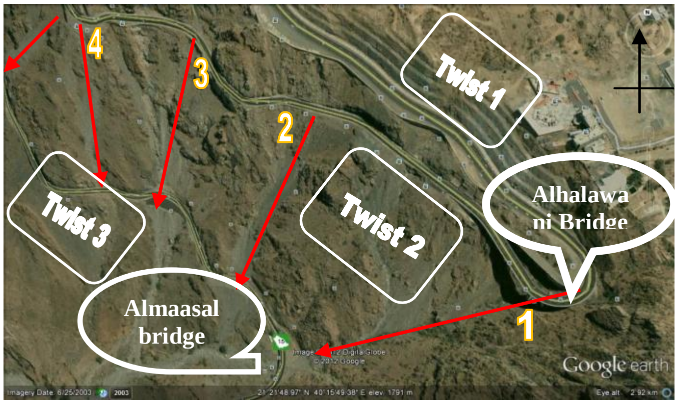

Fig. 3. Image of Al-Hada descent show debris flows number 1 to 4 and the road 3 twists.

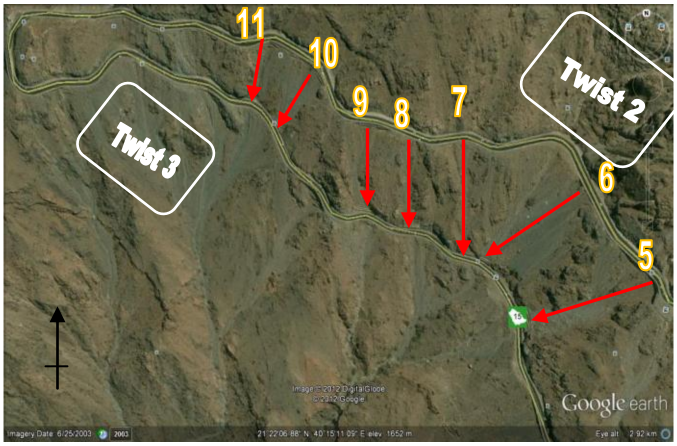

Fig. 4. Image of Al-Hada descent show debris flows number 5 to 11 and the road twists.

These gullies start from the right hand side (Fig. 3), and formed of a gully 30-90m wide and about 530m length, lies under Alhalawani Bridge, numbered as # 1. The length and width of gullies are decreasing towards west, where gully # 11 located (Fig. 4), which is 10m wide and 105m length. The debris composition of these gullies is changing from east (#1) to west (#11). Where the field observation of gully # 1 (Fig. 3) located at the east, indicate that it contains very large blocks of 1-3m in diameter and soil consists of sand, silt and clays. These contents decrease as going to gully # 11 (Fig. 4) located at the west, which is formed of large blocks of 0.5 – 1.5m in diameter, and less amounts of fine grained materials.

The debris allocated at these gullies formed of 2 parts:

1) Loose and unconsolidated debris, accumulated as a result of rockfalls and natural slopes failures of the unstable rock slopes at the higher elevations along the gully route. These blocks vary in size at both sides of the gully, as the rock mass geotechnical properties varies. In addition, it also includes the thrown rock blocks from the higher elevations, due to the road widening operation and frequent cleaning processes of the upper road sections.

2) Consolidated debris are tens of years in age, has a large thickness. This type is located below the loose debris on top and consists of a mix of sand, silt and clay matrix include large rock blocks. This type of debris located at the center of the gully route, where the angle of inclination is high due to its compaction along the steeply inclined gullies.

RAINFALL AND DEBRIS FLOWS AT THE GULLIES

It happened on the 14th of April, 2012 an intense rainfall happened on Al-Hada area associated with hail, and after 2 days another rainfall took place and lasted for almost 2 hours. The negative effect of the rainfalls highlighted especially on the upper part of the descent gullies, where it triggered a debris flows along these gullies, some of them were massive and destructive and others where weak (Fig. 5).

Fig. 5. Debris flows at a gully.

The characteristics of the rainfall on the gullies that it percolates through the soil by two methods:

1) It falls in an even distribution manner over a certain area/m^2. This cause percolation of the water throughout all soil particles and in between the soils and the rocks.
2) Such percolation decreases the cohesion (c) and angle of friction (ϕ) between the particles, which may cause an ease in the movement of the debris body causing debris flows.

3) A large amount of rain water accumulates from higher elevations flow downwards incise through soils layers and through soils and rocks along the gullies, which causes vertical grooves of depth range between 0.5 – 7 m (Fig. 6) according to the site topography of the unconsolidated debris flow, destroying all infrastructures and debris of various sizes (Fig. 6) on its way downwards.

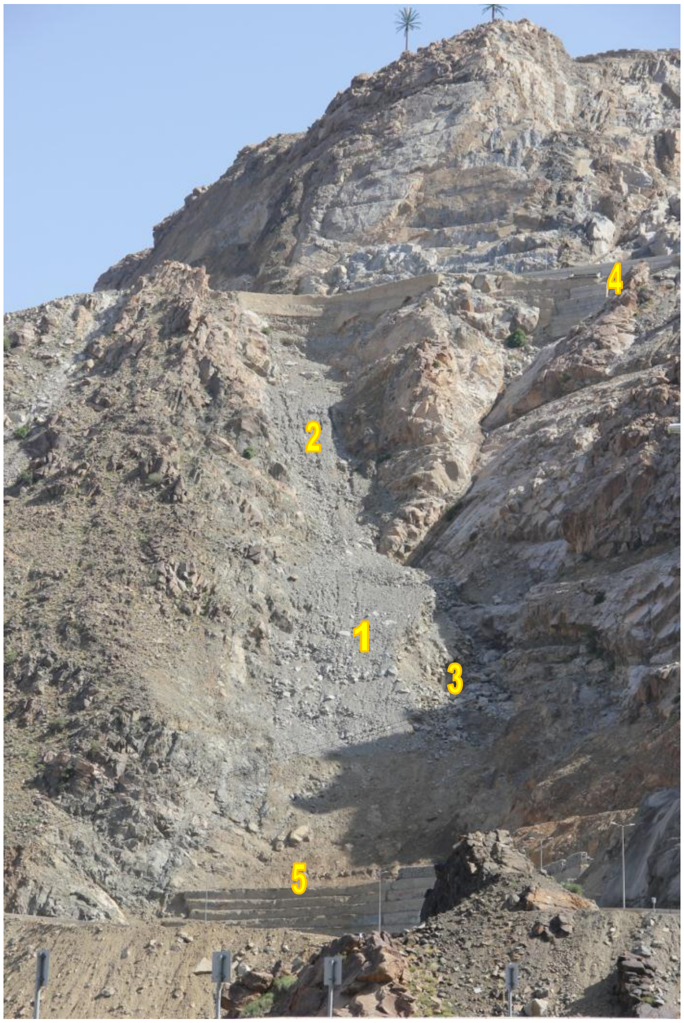

Fig. 6. The vertical grooves due to flowing water from upper elevations through an incised path (16/5/2012). 1. Consolidated debris, 2. Unconsolidated debris, 3. Vertical grooves, 4. Drainage hole below the upper road pouring water on the gully, 5. Brocken 1.5m-height debris barrier due to pouring water.

It should be noticed that making terraces at a consolidated debris body without any support (Fig. 7), did not, and will not prevent violent water flowing downward from incising the debris body (Fig. 7), removing it, hitting the New Jersey, cover them and the road to a height of about 5m. Water flows violently due to a presence of a drainage hole below the upper road (Fig. 8).

Fig. 7. Terraces at the debris engraved due to rainfalls, was not stabilized against the rainfall flow incision effects.

Landslides that enter gullied low-order drainages can either initiate debris flow or stop, depositing sediment in the channel (Brayshaw and Hassan, 2009). This process is one of the most common ways that debris flows initiate, but little attention to date has been paid to evaluating the factors that affect whether or not the initial landslide will become a debris flow or deposit sediment in the channel (Brayshaw and Hassan, 2009).

MECHANISM OF DEBRIS FLOWS MOVEMENT

The rainfall trigger the flow of the debris accumulations located at the gullies (high slope angles) and form a debris flow transported at a high speed downwards through an incised channel confined in the consolidated debris body. When the flow reaches a less confined area along the gully slope and being close to the concrete retaining wall topped by the gabion wall it show pressure on it (has low viscosity) due to movement of the pushing falling blocks from higher to lower elevations (high viscosity). When the flow pressure (water, soil and rocks) exceeds the strength of the gabion wall, it will break it. Then all the debris allocated at the gully will fall from elevation difference up to 100m, and overtop the concrete retaining wall, and fall over the ascending road. This will be successively overtopped by the falling debris, which will reach the descending road and continue flowing to drop finally in the valley, breaking all the constructed New Jersey barriers along the road. Then the water speed decreases and the carried rock blocks and soils will settle on the ascending and descending road. The measured debris flow speed was 16m/sec.

Fig. 8. The presence of the drainage structure directed the drained water to make a path from higher to lower elevations, and ease causing damage in the debris accumulation body below it.

MORE SITES ARE SUBJECTED TO DEBRIS FLOWS

One of the gullies contains consolidated debris overtopped by loose debris accumulations, where the debris incised by gullies resulted from water flow on the gully slope surface (Fig. 9). The angle of inclination is more than 45° which is greater than the soil angle of repose and shear angle, which consequently prone to a debris flow along this part of the road. Specially, where the road is not protected by any remedial measures means to stop the debris flows hazards. The longitudes and latitudes are N 21° 22’3.8”, E 40° 15’20.6”.

SIGHTED SOLUTIONS TO DEBRIS FLOWS

According to the site conditions topography and geotechnical properties of the debris allocated at the gullies, quick and permanent solutions could be assigned.

1) The quick solution

Due to the geotechnical properties of the loose and consolidated debris allocated along the gullies slopes and the sliding dates triggered by rainfalls, it should be scaled immediately. The scaling of all types of debris could be done by pouring water over it to simulate the rainfall effect, where the slide took place for all the materials. A fire truck could be used to pour water from the higher road alignment on each loose and consolidated debris accumulation along the gully path. The road could be closed temporary at this operation for safety purposes.

In addition, the whole body of the debris allocated behind the concrete retaining walls should be removed entirely, down to the bottom behind the retaining wall.

Fig. 9. A debris body include many incised grooves, may fail at the next rainfall incident, where no protection measures are taken.

2) The permanent solutions

This study will give solution on the debris flows, depending upon the study of the geotechnical properties of the debris located at the area. The next few permanent solutions are recommended:

1. Stabilizing the rock blocks on the gullies sides, by stabilizing the rock faces,
2. Constructing numerous dams or meshes across the flow route of the debris, along the path of each gully.

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