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# Rainfall induced shallow landslides on sandy soil and impacts on sediment discharge: A flume based investigation

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Abstract: The impact of rainfall induced shallow landslides on hillslope sediment discharge is not well understood. The aim of the research was to investigate how varying soil profile depth affects the location and occurrence of shallow slope failures as well as how it impacts sediment yields. Four flume based experiments were conducted using a sandy soil and a 30 and 10 degree compound slope configuration under average rainfall intensity of 50 mm/hr for soil profile's depths set to 20, 30, 40 and 50 cm. Sediment discharge and runoff were collected from the flume outlet at 15 minute intervals. Changes in soil profiles after landslides and changes in soil properties like soil armouring were also recorded. Results showed that sediment yields at the outlet, before landslides occurred, were very low and limited to the finer soil particles as would be expected for a sandy soil. However subsequent variations in sediment discharge were strongly related to failure events and their proximity from the outlet. The sediment yield was also affected by the original soil thickness. The results provide a clear link of landslides and sediment discharge to hydrological processes occurring in the hillslope which are related to the soil thickness.

## 1. Introduction

Water induced shallow landslides are natural processes which can cause considerable hazards in hillslopes in rainy environments. Landslides are typically stochastic and non-continuous processes possessing high spatio-temporal variability of the sediment yield to the stream channel. Shallow landslides can affect the sediment yields to nearby streams immediately following the landslide and also in the long term due to changes in overall topography and soil physical properties.

A considerable amount of research has been conducted on small scale shallow landslides under controlled laboratory conditions. For example, liquefied landslide experiments conducted by Sassa (1984) showed that rapid increases in pore pressure, due to localized subsidence, occur suddenly before a landslide is triggered. Okura et al. (2002) performed laboratory flume experiments and noticed that the collapsing slope undergoes three stages: the volumetric compaction with shear, rise in pore pressure in saturated zone and rapid shearing around the slip surface. Wang and Sassa (2003) through a series of water induced shallow landslide investigations in small scale flume demonstrated that grain size and amount of fine particle content can both have significant impact on the mobility of water induced shallow landslides. Gabet and Mudd (2005) reported that particular site's potential for debris flow mobilization after shallow landslide is independent of porosity but sensitive to the sand content. Olivares and Damiano (2007) used a flume based experiment to observe that high shear strain and maximum pore pressure recorded at the base of flume are the basic reasons behind the landslide fluidizations.

Although a significant amount of literature exists to model top soil erosion and deposition at the catchment scale, only a limited number of studies have dealt with subjects related to the depositional patterns and sediment yield behaviour after shallow landslides. Benda and Cundy (1990), for example, developed an empirical model that uses channel slope to predict debris-flow deposition. Johnson et al. (2000) report the slope failure initiation, runout and deposition pattern of more than 300 landslides and debris flow and observe that major portions of those failures are deposited within the catchment instead of reaching the main channel. Sediment discharge monitoring in a channel conducted by Schuerch et al. (2006) conclude that the sediment yields in the channel are significantly high after slope failure events; however not all the sediment from the landslides reach the channel; a notable amount of sediment remains within the catchment. Several studies report that the contribution of shallow landslides to the total annual catchment sediment budget is relatively low (May and Gresswell, 2004; Chen et al., 2005; Bathurst et al., 2007); however no or few studies report on how landslides can change topography and soil properties which impact long term erosion within a hillslope or catchment.

Shallow landslides can also act as a trigger to processes such as soil armouring. Soil armouring is an important process in hillslope erosion that leads to surface coarsening because of the selective removal of the finer transportable materials from the soil surface by rainfall and overland flow. Stable armouring thus protects the underlying materials from being eroded. The physical properties of soil such as particle size distribution are affected by the armouring process. The thickness of the armour layer is at least one grain size if the runoff remains less than or equal to the armour forming flow (Proffitt, 1980). The rate of coarsening is high at the start of the run-off event reflecting the relatively high fine sediment yield (Willgoose and Sharmeen, 2006a). Willgoose and Sharmeen (2006b) studied long term erosion and armouring processes and noticed that there is a reduction of cumulative erosion rate by 81% in sandy soil. Cochrane et al. (2007) demonstrate that erosion is reduced by more than 75% in heavily armoured soils as compared to the fresh soils.

Although a considerable amount of research has been conducted to understand landslide initiation, motion, and deposition of the materials after landslides, knowledge on the occurrence and advancement of shallow landslides and their impact on sediment discharge are limited. Therefore, further research was required to better understand the impact of water induced shallow landslides on hillslope sediment discharge. This paper reports on the experimental results of a flume based shallow landslide and sediment discharge investigation carried out using sandy soil at different soil thickness. The objectives of the study were to determine:

- how the depth of the soil profile affects the shallow landslide initiation and how it affects the advancement of the slope failure with the continued rainfall
- how slope failure events affect the sediment discharge
- the change in soil profile shape and physical soil properties (such as soil armouring) as a function of continued rainfall and original soil depth.

## 2. Materials and Methods

### 2.1 Experimental Flumes

A large two section experimental flume was constructed using galvanized structural steel and 1.50 cm thick acrylic sheeting that measured 3.94 m long, 0.30 m wide and 0.8 m deep. The upper part of the flume is 2.44 m long and has a fixed slope of 20°; however, the overall inclination of the flume can be changed by using a chain pulley. The lower portion of the flume has a length of 1.50 meters (figure 1). To maintain a high level of friction between the material in the flume and the bed of the flume, silica-sand grain was glued to the surface of the flume base.

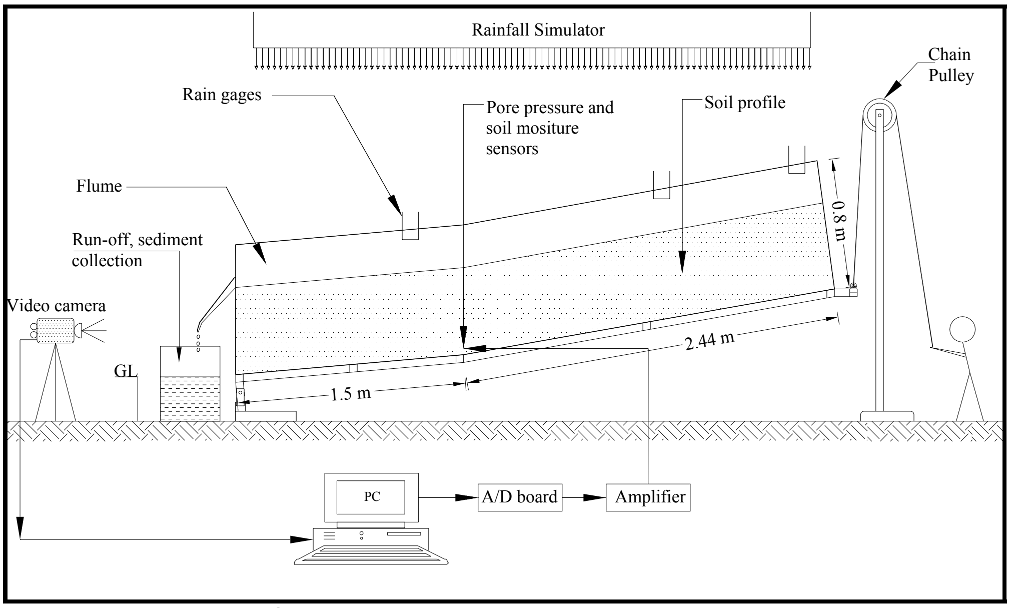


Figure 1. Schematic diagram illustrating the experimental set up.

Six cylindrical rain gages were installed distributed along each side of the upper section of the flume to verify rainfall intensity and distribution delivered by a rainfall simulator. All experiments were run at a fixed rainfall intensity of approximately 50 mm/hr. The experimental flume was coupled with a video camera set in front of it to monitor activities associated with water induced shallow landslides, such as, time and location of failure initiation, its advancement with respect to time and space, and motion of the failed mass. A soil moisture sensor was installed at the interface of two sloping section to measure the soil saturation with time during continued rainfall events. These devices were connected to a personal computer to capture and store the data. At the end of the flume, a funnel was used to collect the run-off and sediment discharge over time.

## 2.2 Experimental Method

Four experiments were carried out using a sandy soil for soil depths of 20, 30, 40 and 50 cm (table 1). The sandy soil was used for the experiments with more than 90 percent of angular silica grains. In order to maintain uniform soil characteristics in the flume and between experiments, the soil was uniformly filled in layers of 4 to 5 cm thick and compacted uniformly with an air compressor under 4 $kgcm^{-2}$ of pressure. The inclination of the upper slope was set to 30 degree to trigger the shallow landslide and the slope of the lower section was set to 10 degree to enhance the deposition after the slope failure. The flume bed was impervious and thus not permitting infiltration and percolation below the underlying bed.

Table 1. Summary of experiments, rainfall and time.

| Exp. No. | Thickness (m) | Time to initial slope failure | Total experiment time (hr) | Cumulative rainfall (mm) |
|---|---|---|---|---|
| 1 | 0.20 | 1 hour 2 minutes | 4.00 | 210.00 |
| 2 | 0.30 | 1 hour 46 minutes | 5.00 | 260.00 |
| 3 | 0.40 | 2 hours 3 minutes | 6.00 | 300.00 |
| 4 | 0.50 | 2 hours 28 minutes | 6.50 | 360.00 |

The soil's engineering and geotechnical properties (table 2) were obtained through lab tests carried out prior to running the flume experiments. An average rainfall of 50 mm/hour was applied by the rainfall simulator and the rainfall intensity and distribution was verified by monitoring the rain gauges on the flume every half hour for all experiments. The time when a slope failure occurred was recorded as well as scarp depth and location of the failures. The runoff was collected immediately after runoff initiation and at 15 minute intervals thereafter from the end of the flume. Sediment discharge and runoff rates were obtained by weighing and drying the collected runoff samples. Particle size distribution of the top 2 cm of soil was measured immediately after each experiment to quantify armouring behaviour of the soil material. Soil armouring characteristics were further investigated after the end of the experiments by collecting a 1cm deep sample from topmost layer.

Table 2: Physical properties of the soil.

| SN | Properties | Unit | Lower & upper value |
|---|---|---|---|
| 1 | Angle of internal friction ($\varphi$) | ° | 41.60 |
| 2 | Organic matter content (OM) | % | 0.70 |
| 3 | Initial moisture content (w) | % | 7.00 |
| 4 | Uniformity coefficient (UC) | - | 3.82 |
| 5 | Coefficient of curvature (CC) | - | 0.76 |
| 6 | Mean grain size ($D_{50}$) | mm | 0.57 |
| 7 | Effective grain size ($D_{10}$) | mm | 0.20 |
| 8 | Specific gravity (G) | $gcm^{-3}$ | 2.63 |
| 9 | Bulk density ($\rho$) | $gcm^{-3}$ | 1.624 – 1.675 |
| 10 | Dry density ($\rho_s$) | $gcm^{-3}$ | 1.52 – 1.554 |
| 11 | Porosity (n) | % | 41.54 – 40.23 |

## 3. Results and discussions

### 3.1 Landslide initiation and its advancement

In all experiments, the water induced shallow landslides initiated as toe failures at the interface of the two sloping sections of the flume. Such toe failures start after the wetting fronts reach the base of the flume rising the saturation degree (Wang and Sassa, 2003). The infiltration from the rainfall accompanied by subsurface flow from the upslope contributing area (Beven and Kirkby, 1979; Montgomery and Dietrich, 1994; Acharya et al., 2006) saturates the soil around the toe of the flume and then triggers the landslides. Localized subsidence was noticed in all cases just prior to the slope failure. According to Sassa (1984), local subsidence is the result of soil saturation. Air pore spaces in the soil profiles are filled in with water during infiltration and this process makes the soil more compact causing the subsidence. Pore water pressure increases more rapidly in the saturated area compared to unsaturated through rapid compaction. Iverson et al. (1997), for example, report that pore pressure increases by more than 2 times during failure.
Water induced shallow landslides are the function of topography, upslope contributing area, soil properties, rainfall characteristics and others. The initiation of landslide is directly related with landforms (Johnson et al., 2000). Another equally important parameter in the slope failure initiation and advancement is the soil thickness. As the depth of the profile increases, the stabilizing force also increases; therefore greater destabilizing forces and factors are required to induce the landslides. Experiments revealed that 50 cm thick profile took approximately 2 and half hours to initiate landslides whereas that for 20 cm profile was only about 1 hour (figure 2). Therefore, a clear relationship between the time of failure initiations and depths of the soil profiles was noticed.

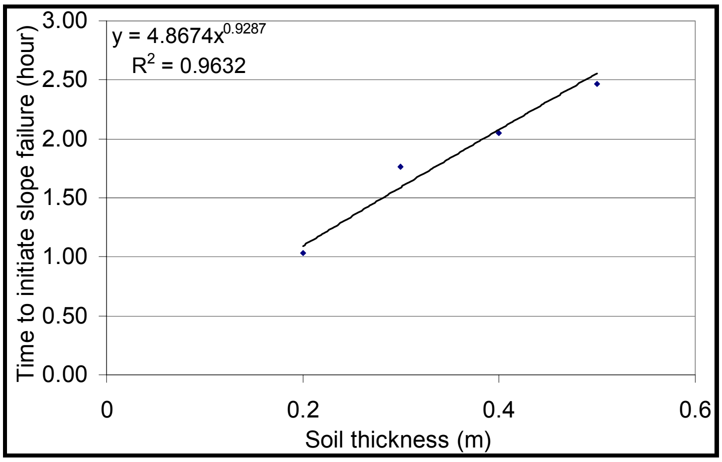


Figure 2. Time of failure initiation for different soil profile depths. Observations are represented by dots and best fit trend line by the solid line.

The Coulomb slope failure model dictates that the failure must occur at only the depth where the shear stress equals the Coulomb yield strength. The scarp depth of the initiated landslide is again dependent on the thickness of the overlying soil. The thinner soil possesses low soil weight reducing its shear strength. A shallower profile is more prone to failure compared to the thicker one because of the decrease in the stabilizing force. Therefore, the greater the thickness of the soil profile, the smaller is the depth of the initiated landslides and vice versa. This was readily observed in the experiments as face depths of the initial slope failures were 3 and 9 cm for the 50 and 20 cm thick soil profiles respectively (figure 3).
Hillslope gradient and slope morphology coupled with climatic characteristics such as rainfall intensity and duration, influence the landslide processes, density and frequency (Dymond et al., 2006). In all experiments, slope failures advanced upward from the interface of the two sloping sections in the flume with the continued rainfall. However, the frequencies of the landslides decreased as the distance of their advancements from the interface increased. This means landslides were triggered more frequently in the lower reach compared to the upper reach of the upper sloping section of the flume; for instance the time interval between first two major failures was only about 12 minutes whereas that between the last two was nearly 46 minutes for the 20 cm thick soil profile. Dai and Lee (2002) also report that as distance from stream line (i.e. most outward line in a hillslope) increases, the frequency of landslides generally

decreases. The decrease in upslope contributing area with the upward propagation of soil collapse reduced the frequency of subsequent failures.

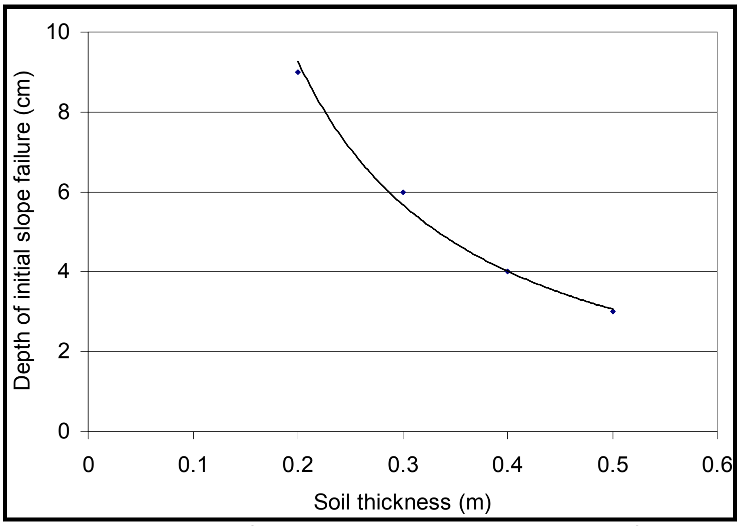


Figure 3. Relationship between the depth of the initial landslides and the depth of the soil profile. Experimental observations are represented by dots. The best fit trend line has an R squared value equal to 0.99.

### 3.2 Pre and post failure soil erosion and sediment discharge

Rainfall induced soil erosion is a dynamic and complex process that varies with topography, land-use, soil and climate. Soil erosion involves two major processes: detachment of the soil material and transport of the resulting sediment. Upland erosion can be divided into two major types, viz. rill and interrill. Interrill erosion is a function of the detachment and transport by raindrop impact and overland flow. Rill erosion will not occur until the rills are initiated by the interril erosion. Interill soil erosion in these experiments was negligible because of very low quantity (less than 1% by weight) of finer (than 0.075 mm) soil material leading to low erodibility. However, the sediment discharge increased significantly after rills were fully developed during post failure events.

The sediment yields increased considerably in the post failure events and once the rills were developed. Figure 4 shows how the sediment yield and runoff vary with time for the 20 cm thick soil profile. The sediment discharges were very low and limited to the finer materials in the initial phase of the experiment. After two subsequent major failures at around 1 hour 15 minutes of rainfall, however, when the rill was developed and a portion of failed materials gradually moved towards the outlet transported by the concentrated flows in the rill, the sediment discharge started rising. When this happened, the sediment yields suddenly increased and reached about 16 gram per litre of the runoff. This value decreased and was restricted to about 10 grams per litre of the run off despite another subsequent failure. Again, when the subsequent fractions of failed mass reached the rill, the sediment discharge increased to a maximum value of about 25 gram per litre of the collected run off. Contributions of the coarser materials were significantly high during these peaks, but for the most part, sediments were limited to finer soils. Considerable time is required to transport the coarse material after slope failure to attain the peaks in sediment yields.

The low sediment discharges are shown in figure 4 by the points A, B, C, D, E, F and G and these values are predominantly represented by fine textured sediments. The sediment discharges at those points are gradually decreasing and the reason for such a decrease is believed to be due to soil armouring. Soil armouring can be qualitatively observed and quantified in laboratory experiments by sampling of runoff and determining particle size distribution of the top soil layer after the experiments. The rate of armouring is entirely dependent on the intensity of rainfall with higher rainfall intensity leading to quicker armouring due to increased runoff production (Cochrane et al., 2007). When the surface runoff initiated, the transportable finer materials contributed much in the sediment yields (‘A’ in figure 4) but later in the experiment with continued rainfall such underlying finer materials were protected from being transported by armouring and therefore the values of sediment concentration decreased gradually in points B to G as compared to the value at A (figure 4). Furthermore as the shallow landslides propagated in the upstream section, their impact on the sediment discharge at the outlet decreased.

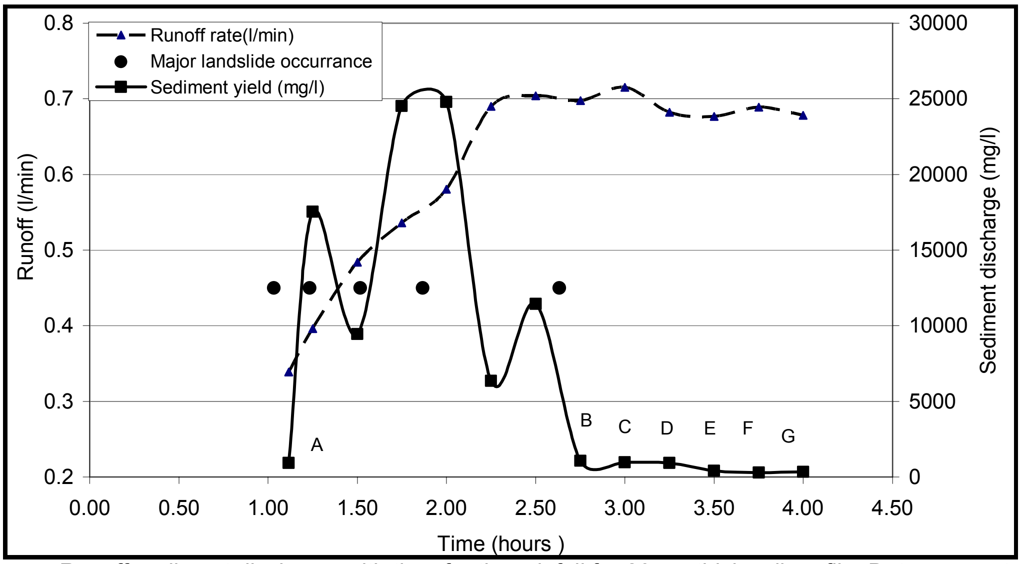

Figure 4. Runoff-sediment discharge with time for the rainfall for 20 cm thick soil profile. Dot represents the occurrence of the slope failure in time series.

The soil armouring phenomena was further investigated by conducting a particle size analysis of the armoured materials collected from the top 1 cm layer of the deposited material in the flume and comparing with that of the fresh soil before the experiments. Figure 5 shows how particle size distribution of the soil layer is affected by the armouring behaviour. Mean size ($D_{50}$) of the armoured soil material was observed as 0.98 mm compared to the original value of 0.57 mm. Similar results were obtained for all experiments and the variability of the results among them is calculated to be less than 5%. In general, the particle size distribution curves shift towards coarse grained material after armouring (figure 5).

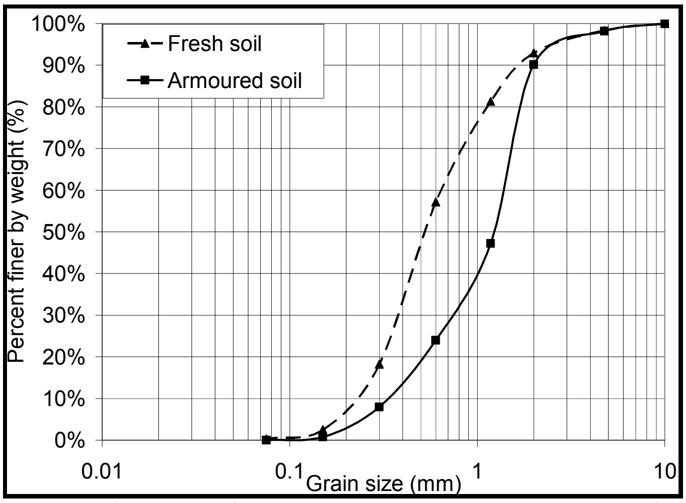

Figure 5. Particle size distribution of the soil before an experiment run and soil sample after the experiment showing armouring phenomenon.

The slopes along the sliding sections stabilized at around 23 degree slopes whereas those in the deposition sections were nearly 13 degree (table 3). The slopes of the deposition sections increased gradually in the upslope part of the flume and such increments were more pronounced in the thicker profiles. The distances between two major subsequent failures were larger in shallow profiles than thicker ones and failure blocks were redistributed in longer stretches making the slopes milder. The slope of the deposition material decreases with the increase of runout distance (Malet et al., 2005) thus reducing the slope with increase in the distance.

Table 3: Minimum and maximum slope angles after experiment runs.

| Depth (m) | Range of slope (deg) | |
|---|---|---|
| | Minimum | Maximum |
| 0.20 | 12.25 | 22.76 |
| 0.30 | 12.79 | 22.88 |
| 0.40 | 13.08 | 23.01 |
| 0.50 | 13.71 | 23.27 |

Sediment discharge rate is higher in thicker soil profiles. The steeper slopes developed after slope failure events in the thicker soil profiles encourage higher sediment yields. Figure 6 shows the average and maximum sediment discharge according to the thickness of the soil profiles. Peak sediment concentrations increased from about 24 to 45 gram per litre of runoff with an increase in soil thickness from 20 to 50 cm. Likewise the average sediment yields increased from about 7 to 10 gram per litre of the runoff.

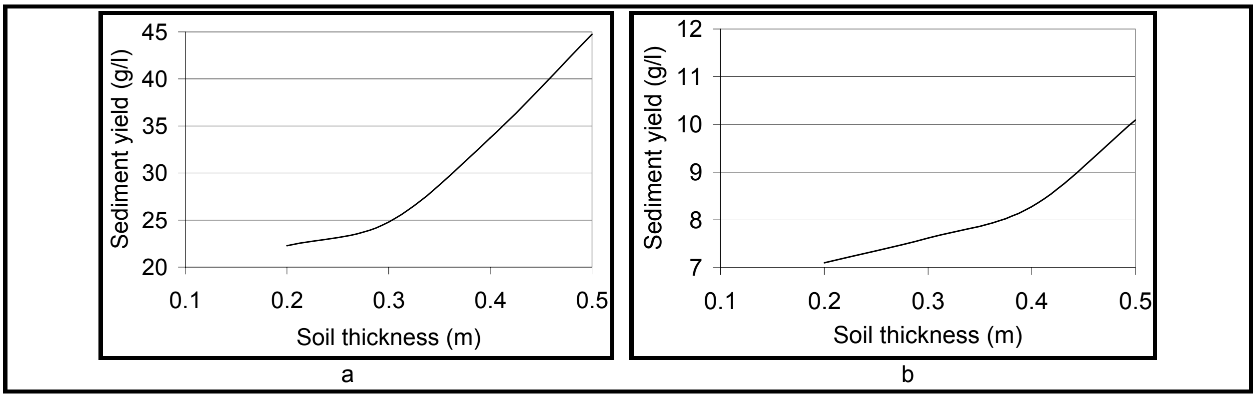


Figure 6. Plot of maximum (a) and average (b) sediment discharge in different depth of the soil profile.

## 4. Conclusions

Based on the results of the experiments conducted in sandy soil with fixed slope under rainfall intensity of 50 mm per hour but with varying soil depths, the following conclusions are drawn:

- Landslides initiation and their propagation are related to the soil profile thickness. Shallow soils are more prone to failures and the occurrences of water induced shallow landslides are more frequent. The upslope contributing area plays an important role in initiating slope failures. The frequency of the advancement of the slope failures decreases as they extend upward because of the gradual decrease in the upslope contributing area.
- Thicker soil is inherent to higher shear strength and therefore depth of the initial slope failure decreases with the increase in soil thickness. However, the depth of the failures gradually increases as the failure events advance in the upslope direction.
- Before landslides are triggered, sediment discharges at the outlet are quite low and mostly consist of fine grains of soil. Later, as the slope failures occur, sediment yields increase due to an increase in coarse grain yields. The peak sediment discharges in the post failure events are about 100 times higher than normal erosion rates. However, when the landslides propagate far away from the outlet, the effects of landslides on sediment discharge decreases.
- Mass redistribution after landslides makes the deposition profile steeper in thicker soil and therefore higher sediment discharge are observed from the thicker soil profiles as compared to the shallower soil. The slope of the deposit decreases with the increase in run out distance. The stabilizing slope in the sliding section was about 23 degrees and that in the deposition area was approximately 13 degree.

- Soil armouring was responsible for reducing erosion of fine grained material by approximately 6 times from the initial un-armoured condition.

Post-failure reductions in sediment discharge were observed and were attributed to post-failure events under continuing rainfall and extensive soil armouring near the outlet. The results provide a clear link to hydrological processes occurring in the hillslope which are related to the depth of the soils profile. Further research is underway to investigate the impact of slope variations and soil type on sediment discharge post-landslides. This knowledge is being used to develop a model to predict sediment discharges from hillslopes following shallow landslide events.

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