



Experimental Investigation on Slope Runoff, Sediment, Hydraulic Parameters Under Different Underlying Surface



Zuliziana Suif^{1*}, Siti Norhafizah Hamisak¹, Jestin Jelani¹, Nordila Ahmad¹, Muhammad Izzul Akhtar²

¹Department of Civil Engineering, Faculty of Engineering, National Defence University of Malaysia, Malaysia

²Ministry of Defence, Malaysia

Abstract

This study utilizes a rainfall simulator to conduct an experimental investigation of slope and rainfall on various underlying surfaces. This study aimed to determine the relationship between various hydraulic factors and sediment concentration by estimating runoff, sediment concentration generation, and hydraulic parameters on various underlying surfaces. The flow velocity, flow depth, shear stress, and unit stream power are the hydraulic parameters in this experiment. The soil sample will be set up appropriately in the rainfall simulator with a slope of 20° and subjected to a rainfall event for two hours on four trays with various underlying surface types. The rainfall intensity of 10 Lmin⁻¹ was designated for the rainfall simulator. Throughout a two-hour period, the runoff flow was collected at intervals of 30, 60, 90, and 120 minutes. The measured sediment concentration using Total Suspended Solid (TSS). Then measurements were conducted of the sediment concentration, runoff discharge, and hydraulic parameters. According to the results, the stream power of the four covers is higher for the dried leaves (0.004606 ms⁻³), grass cover (0.003274 ms⁻³), gravel (0.00232 ms⁻³), and bare soil cover (0.00081 ms⁻³). But bare soil produces the maximum concentration of sediment and surface runoff, which is then followed by grass, gravel, and leaves. In general, the generation of sediment began with the bare surface, gravel, dry leaves, and grass in descending sequence. Research has shown that rain-induced plant cover can be used as a low-cost strategy to reduce soil erosion on construction slope sites.

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Corresponding Author:

Zuliziana Suif
Department of Civil Engineering,
Faculty of Engineering, National
Defence University of Malaysia,
Malaysia
Email: zuliziana@upnm.edu.my

INTRODUCTION

Research on erosion and sediment started long ago to improve the erosion that commonly happens or takes place on a development site [1]. This phenomenon typically occurs in the preliminary stage, which comes before the earthwork phase's structural work starts. Once the ground has been filled and excavated during an

earthwork phase, disturbing soil cover will be the main issue if the soil has no top cover [2]. Rainfall causes erosion to begin on the upper bank, where it begins to flow at a certain speed and carries the surface-eroding silt down with it. Generally, when excessive sediment flows through a drainage system, the silt settles and reduces the volume of the drainage [3]. In addition,

in other circumstances, a certain point will be reached when rain and silt flowing through the drainage channel at a high velocity get bundled together. Several forms of soil cover, such as bare, grass, leaf and gravel have been found to be effective in solving this problem.

The hydraulic factors that are normally employed in simulating detachment rates such as shear stress [4], stream power [5; 6] and unit stream power [7; 8]. Furthermore, the roles of shear stress and stream power have a greater association with rill detachment rates [4]. When it comes to soil detachment brought on by shallow flows, shear stress and flow energy show a less association [9]. Numerous studies found that stream power is a more accurate method for predicting sediment than shear stress [10; 11; 12].

The main aims of this study are to calculate runoff and sediment production, as well as to calculate hydraulic parameters and examine the relationship between these variables on various types of soil covers. Furthermore, other researchers will benefit from the experimental results by receiving the kind value of data of the sediment concentration and hydraulic parameters for modeling work.

MATERIALS AND METHODS

Several components will be included in this chapter such as the experimental setup and material used that had been determined in this study. The Universiti Pertahanan Nasional Malaysia (UPNM) is the location where the study has been done. An investigation using various types of underlying surface runoff, hydraulic parameters and sediment concentration. This investigation is being conducted in three laboratories. Initially, once the sieve examination is finished, the geotechnical laboratory allows a start of completely distinct aggregate sizes that surpass the sieve's metric linear unit by 1.18 mm and 0.6 mm. The hydrology laboratory is the second. A precipitation apparatus will be used in this laboratory experiment, and general data regarding the production of sediment was gathered and examined using the total suspended solids (TSS) test.

Experimental Soil and Flume Layout

The soil sample that was utilized in this study was collected from a slope area close to a UPNM new development sites. As shown in Figure 1, four trays measuring 67 cm by 23 cm by 18 cm, each with a different underlying surface. In the centre of the tray shown in Figure 2, a pipe with a diameter of 2.5 cm that is cut in half and serves as drainage to collect the surface discharge. On the bottom of

the tray, there is another pipe that serves as drainage to collect the infiltration flow. In order to gather the water flow from the land stream, the outlet is connected to the pipeline [13]. The sample of soil was compacted to replicate field actual soil conditions. To make sure the sample is saturated before being exposed to rainfall using the rain simulator, it will be allowed to dry in the sun. The soil sample is first weighted for preliminary data and then put through a sieve to obtain the soil profile for further analysis.

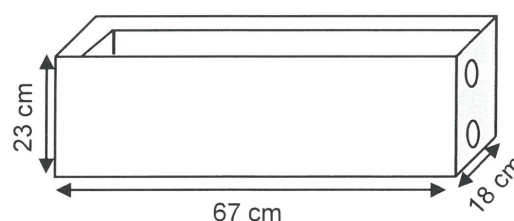


Figure 1. Dimension of tray



Figure 2. Arrangement of pipe as drainage

Experimental Framework

This study has multiple experiments. The sieve analysis is the first experiment for attaining the soil profile. In addition, the sample must be tested using a rainfall simulator to determine the surface runoff. Furthermore, the rainfall simulator was used to measure the hydraulic parameters. The soil sample was compacted and arranged correctly in the tray in the rainfall simulator. The rainfall event lasts for two hours, and every thirty minutes, surface runoff is collected in separate containers. The TSS involves collecting surface runoff and purifying it using a filtering apparatus. Next, the sample was dried in an oven at 105°C for an hour. The aim of this test is to remove the water and silt. Thus, the sediment content, Q_s (gm^3), and runoff discharge, Q (m^3s^{-1}) ascertain once the experiment is complete.

Rainfall Simulator

In order to analyze the various rainfall intensities, the Hydrology Laboratory is equipped with a rainfall simulator. This rainfall simulator's dimensions are approximately 2.4 m long by 1.0 m broad by 1.8 m high, and electric pump. The sieved soil is compacted inside the tray and placed below the rain simulator. In order to collect water that runs off the surface and through the soil, each rectangular tray in the test has a single hole at the top connected to a PVC pipe. This allows the channeled soil to flow into a bucket near the outlet of the tray. After allowing sediment to settle for half an hour following the highest rainfall event, the total runoff was calculated. The bucket was weighed after being removed off the tray. Subsequently, the sediments gathered at the bottom of every container will be dried until completely dry, at which point they will be weighed once more. For every aggregate size, the data were gathered three times following the highest rainfall event. Measurements and records were made of the sediment production's physical characteristics. During data collection, the slope angle will be changed from 0° to 20° , correspondingly. Figure 3 shows how the sample set up for flat surface. A brick is set beneath the tray as a basement to control the incline steepness like in Figure 4. When the incline steepness of $\theta = 20^\circ$, the height of the tray from brick must be 11.4 cm height.



Figure 3. Sample at $\theta = 0^\circ$

Sampling for Runoff and Sediment Concentration

For a duration of two hours, the infiltration and overland flows are recorded every thirty minutes. Water is collected in buckets and changed every 30 minutes. The TSS experiment will be conducted after the collection of samples since sediment contains unfilterable contaminants. The sediment that has been filtered will be dried in an

oven at 105°C for an hour. The sediment concentration, Q_s (gm^{-3}), and runoff flow discharge, Q (m^3s^{-1}), can be calculated from the weight of the dried sediment and the water that separates from the sediment.



Figure 4. Sample at $\theta = 20^\circ$

Hydraulic Parameters

The flow velocity, v (ms^{-1}), depth flow, D (m), shear stress, τ (Pa), and unit stream power, U (ms^{-1}) are the hydraulic parameters that will be used in this study. The runoff discharge, Q (m^3s^{-1}), might be calculated using (1).

$$v = \frac{Q}{t} \quad (1)$$

Equation (2) is used to determine the sediment concentration, Q_s (gm^{-3}), as shown below. The sediment that passed through the TSS test and was dried in the oven is known as the mass of the sediment, m (g), whilst the amount of water collected, V (m^3) depends on the amount of water collected for each soil cover.

$$Q_s = \frac{m}{V} \quad (2)$$

The flow velocity, or v (ms^{-1}), is the most crucial parameter that is frequently used to determine other hydraulic parameters. It is dependent upon the flow discharge and slope gradient. The average flow depth, D (m), was calculated by (3) [14].

$$D = \frac{q}{v} \quad (3)$$

where q is average unit flow discharge per unit width (m^2s^{-1}) and v (ms^{-1}), measured the flow velocity. The shear stress was calculated using (4).

$$\tau = \rho g D S \tag{4}$$

where ρ is density of water is (kgm^{-3}) [4], gravitational acceleration, g is the constat of gravity (ms^{-2}) and S is tangent value of bed slope in degree. Then, the unit stream power (U , ms^{-1}) was calculated using (5) [15], where D is average flow depth (m), and S is the is tangent value of bed slope in degree.

$$U = D S \tag{5}$$

RESULTS AND DISCUSSIONS

Runoff

The result of runoff shows in Figure 5 and Figure 6 that collected for slope 0° and slope 20° respectively. The two slopes indicate disparities in result since steepness of slope influenced by runoff discharge [2; 16].

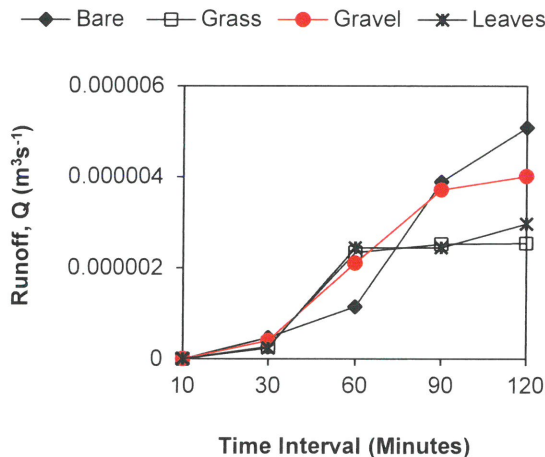


Figure 5. Runoff generation on different underlying surface for slope 0°

The most surface runoff is collected by bare soil since there is no cover on the top for both slopes presented. Soil without any vegetation does not consist of any flow resistant on the surface. After that followed by a gravel cover also for both slopes. The water flow of gravel surface from the top hill to the channel cannot be directly compared to bare soil because the gravel surface soil may disrupt rainfall that falls on the soil surface. Next, dry leaves are dispersed throughout the soil surface. Dry leaves could absorb rainwater until the leaves water storage was full. While compared to other surfaces, the root structure of the grass

cover may provide an additional channel for water to travel in addition to the overland flow. In comparison to other surface covers, grass has the highest amount of infiltration flow.

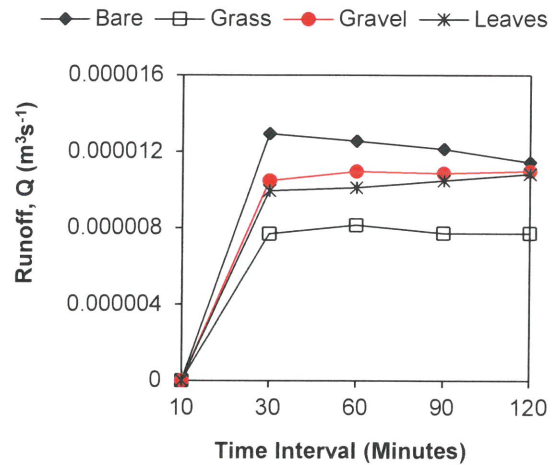


Figure 6. Runoff generation on different underlying surface for slope 20°

Sediment Concentration

Based on the sediment concentration results, it can be inferred that in both slope situations shown in Figures 7 and 8, respectively, bare soil generates a significant amount of sediment. This could occur because bare soil prevents overland flow, which makes rainfall water strike surface of soil and readily distort so that it flows directly to the drainage.

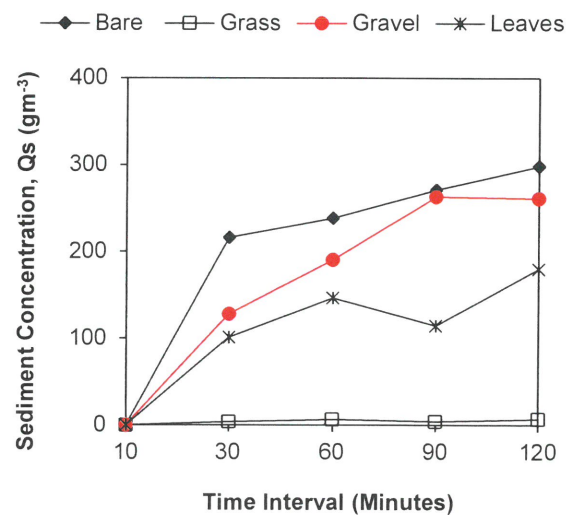


Figure 7. Sediment concentration generation on different underlying surface for slope 0°

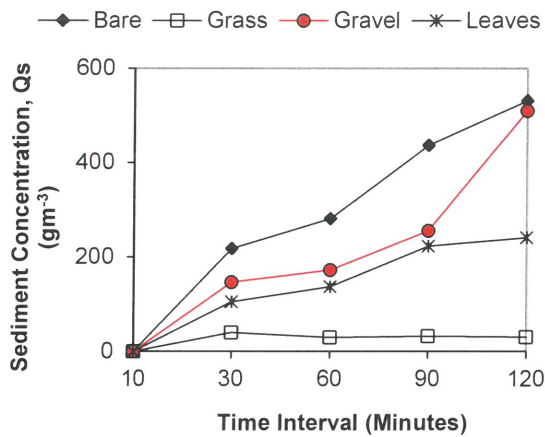


Figure 8. Sediment concentration generation on different underlying surface for slope 20°

The surface covered by gravel generates the highest amount of sediment after bare soil. The only thing that will cause overland flow is the presence of gravel on the surface, which acted as a barrier to allow sediment to flow and in addition to obstructing flow velocity. Cover mainly dry leaves produced the third most sediment. It makes sense that once the leaves absorb rainwater to fill their water storage and gain weight, the sediment beneath them may find it difficult to move beneath them. Finally, the cover that generates the least amount of sediment formation is grass. The production value is almost nothing. The most preferred cover to avoid sediment concentration and lower flow velocity is grass.

Relation between Sediment Concentration with Hydraulic Flow

The hydraulic parameters that were connected to sediment detachment were unit stream power, flow velocity, flow depth and shear stress. These characteristics have been utilized to replicate the soil detachment process in process-based erosion models [17]. After analyzing the relation between Qs, and these four hydraulic parameters, it was discovered as shown in Table 1. The measured Qs of all four tested overland surfaces increased with all four hydraulic parameters. The performance of flow velocity with $R^2 = 1$ as predictors for Qs were satisfactory. Moreover, the flow depth (R^2 varied from 0.0123 to 0.9199 with a mean of 0.5131), shear stress (R^2 varied from 0.3764 to 0.9444 with a mean of 0.641) and unit stream power (R^2 varied from 0.0717 to 0.9552 with a mean of 0.3679) were all satisfactory as predictors for Qs. Furthermore, no significant difference was discovered among all these

characteristics. This finding was in line with previous studies [18; 19; 20] that demonstrated that flow velocity, flow depth, and shear stress are useful hydraulics parameters for simulating soil detachment. Except for the grass surface, all underlying surfaces had low coefficients of determination (R^2), indicating rather weak predictor performance for unit stream power.

Table 1. Regression results between sediment concentrations and flow velocity, flow depth, shear stress and unit stream power

Flow velocity, v (ms ⁻¹)		
Soil Cover	Eqn.	R^2
Bare	$Q_s = 235.24e^{35.093v}$	1
Grass	$Q_s = 5E-09e^{10193v}$	1
Gravel	$Q_s = 193.01e^{37.779v}$	1
Leaves	$Q_s = 119.43e^{61.572v}$	1
Flow depth, D (m)		
Soil Cover	Eqn.	R^2
Bare	$Q_s = 368.93e^{-37.04D}$	0.8995
Grass	$Q_s = 1.6214e^{158.84D}$	0.9199
Gravel	$Q_s = 498.46e^{-130.4D}$	0.0123
Leaves	$Q_s = 69.044e^{98.275D}$	0.2206
Shear stress, τ (Pa)		
Soil Cover	Eqn.	R^2
Bare	$Q_s = 1849.9e^{-0.078\tau}$	0.9444
Grass	$Q_s = 737.45e^{-0.046\tau}$	0.4013
Gravel	$Q_s = 3E-05e^{0.6746\tau}$	0.3764
Leaves	$Q_s = 0.0044e^{0.3278\tau}$	0.8419
Unit stream power, U (ms ⁻¹)		
Soil Cover	Eqn.	R^2
Bare	$Q_s = 253.93e^{66.735U}$	0.2738
Grass	$Q_s = 5.0409e^{2331.7U}$	0.9552
Gravel	$Q_s = 202.24e^{51.788U}$	0.0717
Leaves	$Q_s = 132e^{101.65U}$	0.1710

There is a good correlation between flow velocity and Qs generation, as indicated by the relationship for all covers in the two types of slopes (Figure 9). In comparison to a flat slope, the bare surface with the steepest slope produces a significant amount of sediment. The same remains to grass, gravel, and leaves. According to [21], grass has a small value of velocity flow and produces lowest amount of Qs. Steep slopes naturally result in high flow velocities and significant concentrations of sediment. In addition, soil cover is crucial for overland flow.

There is a positive correlation between the two variables, as demonstrated in Figure 10 by the relationship between sediment concentration and flow depth. The greater the depth of flow, the less Qs is produced [22]. Grass on a flat slope only exhibits an adverse relationship as causes about the same amount of Qs as grass cover on a 20° slope with a depth range between the bare, gravel, and leaf surfaces. The highest generation of sediment is produced on bare surfaces on flat slopes, followed by gravel. Conversely, the bare soil on slope 20° demonstrated that a large

concentration of sediment will be produced at the lowest flow depth.

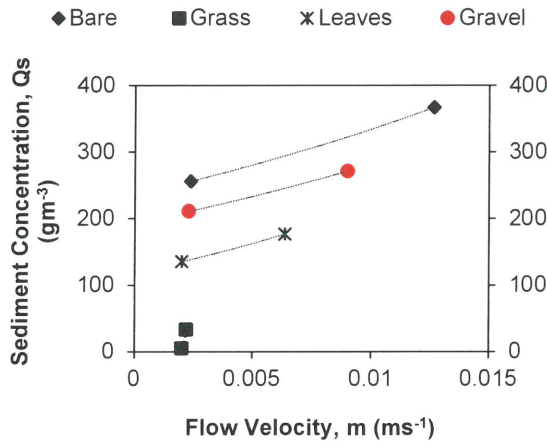


Figure 9. Sediment concentration generation as exponential functions of flow velocity

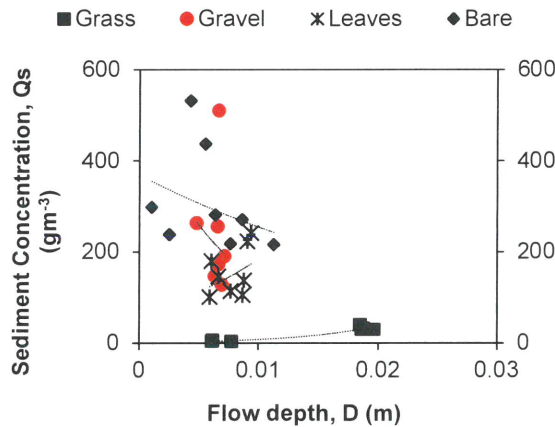


Figure 10. Sediment concentration generation as exponential functions of flow depth

Figure 11 displays the relationship between sediment concentration and shear stress. Based on the tangent of the slope being zero, the results demonstrate that there is no shear stress for any underlying surfaces on a flat slope. Though there is a slope, shear stress occurs [23; 21]. Nonetheless, the graph indicates that those two factors have a positive relationship. There is significant stress on the grass surface at 20 degrees slope, preventing soil deformation from rainfall. The soil cannot prevent soil deformation due to the impact of rainfall on surfaces with low shear stress. It is difficult for rainfall to erode the soil close to the grass cover because the vegetation's root system has firmly grasped the soil. Since the bare surface in this study

experiences the least shear stress, overflow and the effects of rainfall might readily distort the sediment to flow with it.

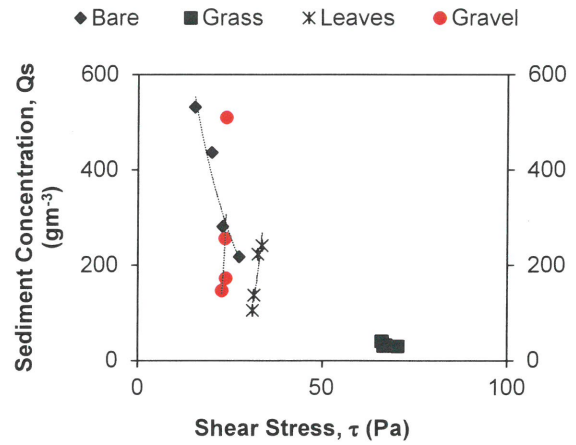


Figure 11. Sediment concentration generation as exponential functions of shear stress

Since a bare surface lacks a power stream, the relations between Q_s and unit stream of power must similarly disregard the flat slope as shown in Figure 12. Figure 12 illustrates the positive relations within two variables, showing that the soil surface with the lowest stream power produces less sediment. According to [24], the stream power of the grass is the lowest where the rainfall water stream is interrupted by vegetation on the cover.

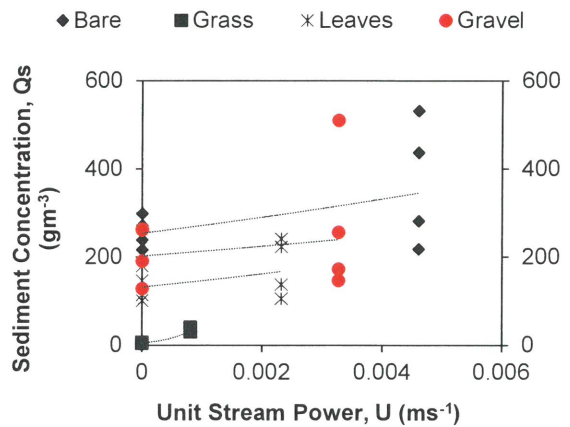


Figure 12. Sediment concentration generation as exponential functions of unit stream power

The condition of the vegetation determines the distinction between the surface of leaves and grass. For grass, humid leaves indicate dead vegetation, yet the live vegetation is present. High stream power and significant sediment

concentration are present in bare surfaces [25]. High stream power affects the strength of the overland flow, which might eventually distort the sediment it flows over [26].

CONCLUSIONS

This study aims to investigate the relationships within sediment content and the hydraulic characteristics of precipitation-induced overland flow on various underlying surfaces. Overall, the data indicates that sediment content and hydraulic parameters such as flow velocity, shear stress, flow depth, and unit stream power were positively correlated. The steepness of the slope has an impact on sediment generation as well. The most significant component that may potentially affect the creation of sediment is the resulting overland flow, in addition to the many underlying surfaces displaying it. Nevertheless, on the steepest slope and bare surface, the value of sediment concentration increases with low flow velocity and stream power, with no effect on overland flow.

Flow velocity, flow depth, and stream power are hydraulic parameters that exhibit an acceptable coefficient relation with sediment concentration. While the unit stream power parameter shows a low satisfactory coefficient as predictors of sediment generations. Ultimately, the recommended criteria that may be used to forecast the concentration of sediment are flow velocity, flow depth, and stream power.

The mini scale of the rainfall region replicated in the simulator is believed to have led to the soil surface to be entrain by overland stream forces. However, the stream force was insufficient to move sediment that had been pre-deformed by the raindrop contact due to the poor erosivity. These findings show that rainfall may be accurately represented in terms of flow velocity and stream power even when it is simulated on a small scale—as the simulation is carried out on a sloping surface. It is essential to keep measuring the stream power and flow velocity throughout the experiment.

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