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Soil Detachment Rate of a Rainfall-Induced Landslide Soil

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Abstract: In recent decades, the number of rainfall-induced landslides has increased significantly in many parts of Malaysia, especially in the urbanized and hilly areas. The disturbance of hilly morphology as a result of human activities has increased the potential for erosion on man-made slopes, especially during extreme rainfall during rain events. Most hilly areas in Malaysia are covered by a thick layer of soil, which is known to have a significant impact on soil erosion. However, little is known about how soil erosion and rainfall could be the driving force behind landslide initiation, especially on stabilized slopes. Therefore, this study focuses on the soil detachment rate of landslides triggered by rainfall at different rainfall intensities. A sandbox model is used to represent real slope conditions. The relationship between the soil detachment capacity, soil properties (water content, slope, clay layers and soil compaction), hydraulic parameters (flow shear stress and stream power) and rainfall intensities (low, medium and high) was investigated. The results showed that the hydraulic parameters and the rainfall intensity are directly proportional to the detachment rate of the soil. Water content and slope show a higher soil detachment rate and a lower critical flow shear stress than other soil properties. It can be concluded that high saturation and steep slope increase the risk of soil erosion because the cohesion and friction of the soil are significantly reduced, leading to a weakening of the soil structure at the surface. The results of this study can feed into the existing analysis of slope stability and formulate the onset of a landslide triggered by rainfall, especially in eroded soils.

Keywords: rainfall-induced landslide; soil detachment rate; rainfall intensities; sandbox; water flow shear stress; stream power

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1. Introduction

Rainfall-induced landslides are geological hazards that result from the interaction between rainfall and the geological environment. These events are prevalent worldwide and can cause severe damage to infrastructure, property and human lives [1]. They are often caused by a combination of factors such as soil properties, slope gradient and rainfall intensity [2]. Soil properties play a critical role in forming landslides, as cohesive soils such as clay and silt are more susceptible to landslides than granular soils such as sand and gravel [3]. The slope gradient also influences the occurrence of landslides, with steeper slopes having a higher likelihood of failure than gentler slopes [4]. Rainfall intensity is also critical as extreme rainfall events can cause soil saturation and instability, even in soils generally resistant to failure [5].

Rainfall-induced landslides are complex systems in which various processes interact and can significantly affect sediment transport [6]. In Malaysia, these landslides are widespread, especially during the monsoon season, due to the country's tropical climate and high levels of rainfall at up to 700 mm per month [7]. This high level of rainfall can saturate the soil and cause its mechanical properties to weaken, leading to a decrease in the stability of the slope. The intensity and duration of rainfall during the monsoon season are essential factors in triggering landslides, and careful monitoring is necessary to prevent or mitigate the risks associated with landslides.

In recent years, there have been numerous landslides in the Kuala Lumpur and Selangor regions [8]. In most cases, these landslides occur on slopes where large amounts of soil mass are moving rapidly. The problem is exacerbated by the rapid development of new infrastructure and housing, which has resulted in a rise in landslides on unstable slopes [9]. This is primarily due to the soil erosion, soil compaction and removal of vegetation caused by human activities [10]. The last major landslide in Kuala Lumpur occurred in Taman Bukit Permai, Ampang Jaya, in March 2022. The landslide occurred on the man-made slope of the residual granite soil and was triggered by the increase in rainfall intensity in March 2022. The landslide in Taman Bukit Permai affected fifteen houses, two of which were completely buried; ten vehicles were buried and four people were killed. Forty-eight houses along Jalan Teratai 1/2 K, Jalan Teratai 1/2 J and Jalan Mega 15 had to be evacuated after the area was later declared a disaster zone.

Although rainfall-triggered landslides have been occurring for a long time, there is little research in the literature on the behavior of soil detachment (Dr) in landslides. The Taman Bukit Permai incident highlights the need to better understand the factors contributing to landslides and the behavior of soil detachment in slopes. Soil detachment is the separation of soil particles from the soil mass at a specific location on the soil surface due to the action of raindrops, water or wind [11,12] and is a common parameter for evaluating rill flow. The widely used Water Erosion Prediction Project (WEPP) model considers soil erodibility (Kr) and critical shear stress (τc) as well as soil detachment rate to determine the intensity of rill-type erosion [13–18] with stream power being the most significant parameter for modelling the erosion process. These hydrodynamic parameters are positively related to the soil detachment rate [19,20], using both linear and non-linear regression methods.

Investigations on steep slopes in permanent gullies of weathered granite soil showed that the Dr rate increases with increasing profile depth [21]. This study shows that the bare bottom has a detachment rate 2–27 times higher than the three layers above. It is worth noting that any slope, regardless of its vegetation cover or erosion state, can have a differing soil detachment rate along its vertical slope profile, which can lead to slope stability problems, especially when rainfall infiltrates. The relationship between rainfall-induced water flow and soil detachment in a slope is therefore crucial and needs to be evaluated together with soil properties and relevant hydrodynamic parameters to understand the governing factors responsible for triggering landslides.

Soil properties such as slope gradient, texture, bulk density, initial water content and soil cohesion are among the relevant properties that influence soil detachment [17]. A study conducted on five different types of loess soils on the Loess Plateau in China found that the detachment rate of the soil depends significantly on the effective particle size, with the sandy loess having a larger Dr value than the clay loess soil.

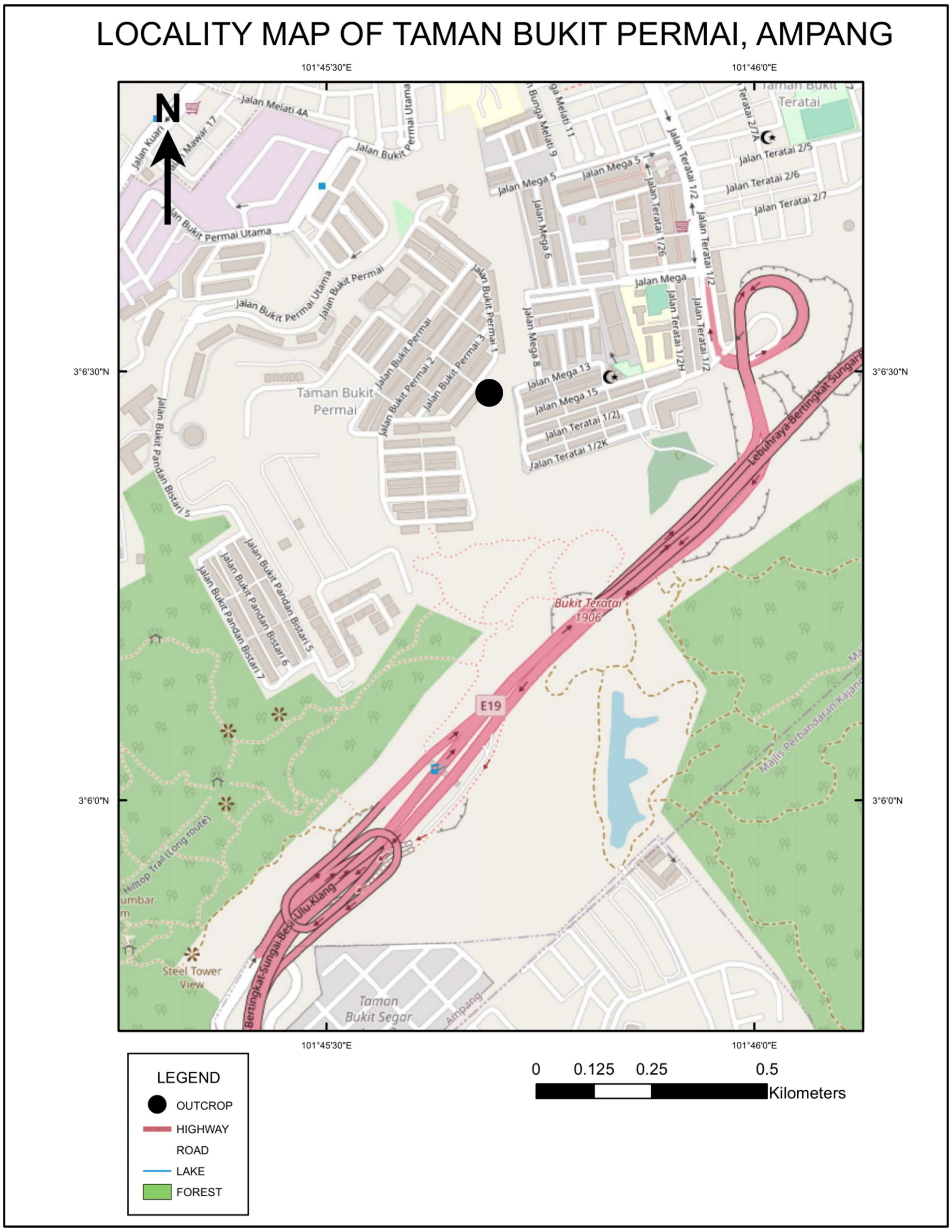
Therefore, this study aims to determine the relationship between the detachment rate, hydraulic parameters and soil properties of a rainfall-induced landslide soil using a sandbox model. The sandbox model is used as it replicates field-to-lab slope physical conditions and is better for studying 3D deformation [22]. The findings from this study will contribute to the knowledge behind erosion as a responsible driving force for the triggering of rainfall-induced landslides and provide insight into the influence of soil detachment as one of the controlling mechanisms, which is currently under-researched in the literature. Ultimately, this research can be used to formulate predictions for the onset of failure for eroded soil slope and adopted into Early Warning System applications.

2. Materials and Methods

2.1. Study Area

The study area is located in Taman Bukit Permai, Ampang, Selangor. The Kuala Lumpur granite surrounds the entire Bukit Permai. This granite is part of the western side of the Main Granite Range. Geochronological studies indicate that the age of this granite is about 215–199 million years, which places it in the Late Triassic period [23]. The Taman

Bukit Permai granite is generally medium- to coarse-grained, has porphyritic textures occurring on a rare to medium basis, and is grey to bluish grey. The slope in this area is the origin of the rest of the granite soil. The study area consists of a slope located at latitude 3°6.6433″ N and longitude 101°45.5069″ T. The topography of the studied slope is 150 m–180 m. Figure 1 shows the study area and the occurrence of landslides in Taman Bukit Permai, Ampang Jaya. Table 1 summarizes the features identified from the landslide map and field observation.



(**a**)

Figure 1. *Cont.*

(b)

Figure 1. (a) The location of the study area, (b) the extent of the landslide as shown in plan view.

Table 1. Features measured from the landslide map and field observation.

Features	Number
Landslide area	8671 m^2
Landslide length	178.96 m
Landslide width	74.98 m
Landslide depth	3 m
Landslide volume	≈26,013 m^3
Houses affected	16
Type of landslide	Complex (Rotational, translational, flow)

2.2. Soil Sampling and Preparation

Disturbed soil samples were collected from the accumulation zone (toe) of the landslide site. It is common to take soil samples from the accumulation zone as this is the area where the landslide debris has come to rest and it can provide insight into the properties and behavior of the soil that contributed to the landslide.

To prepare the soil for laboratory simulations, 5–6 kg of dry soil finer than 2 mm was required for each soil detachment simulation. The soil samples were air-dried to remove any excess moisture and then pulverized to segregate the grains. This process is important because the size of the soil particles can significantly affect the soil's behavior and properties, and segregating the grains ensures that the soil used in the laboratory simulations is consistent.

Before the soil detachment simulation, distilled water was added to the soil to achieve the field water content. The water content of the soil is a critical factor that affects its behavior and properties, and achieving the field water content ensures that the behavior of the soil in the laboratory is consistent with its behavior in the field. The soil was then placed in a sandbox model using layering techniques and lightly compacted to achieve a density similar to that found in the field. This is important because the density of the soil can affect its behavior and properties, and achieving a density similar to that found in the field ensures that the behavior of the soil in the laboratory is consistent with its behavior in the field.

2.3. Experimental Setup

The physical sandbox model used in this study was designed to simulate a scaled soil detachment under controlled artificial rain. The model had the dimensions of Height: 50 cm × Width: 15 cm × Length: 150 cm. The setup of the sandbox model is shown in Figure 2A,B. The model was constructed with transparent glass on both sides to allow for easy observation of the water level and soil detachment mechanism. This transparency also facilitated the capture of photographs from different angles. To allow for efficient drainage of water from the soil, a 1 cm layer of gravel was placed at the bottom of the sandbox. The model was placed on a balancer throughout the simulation to measure the sediment loss continuously.

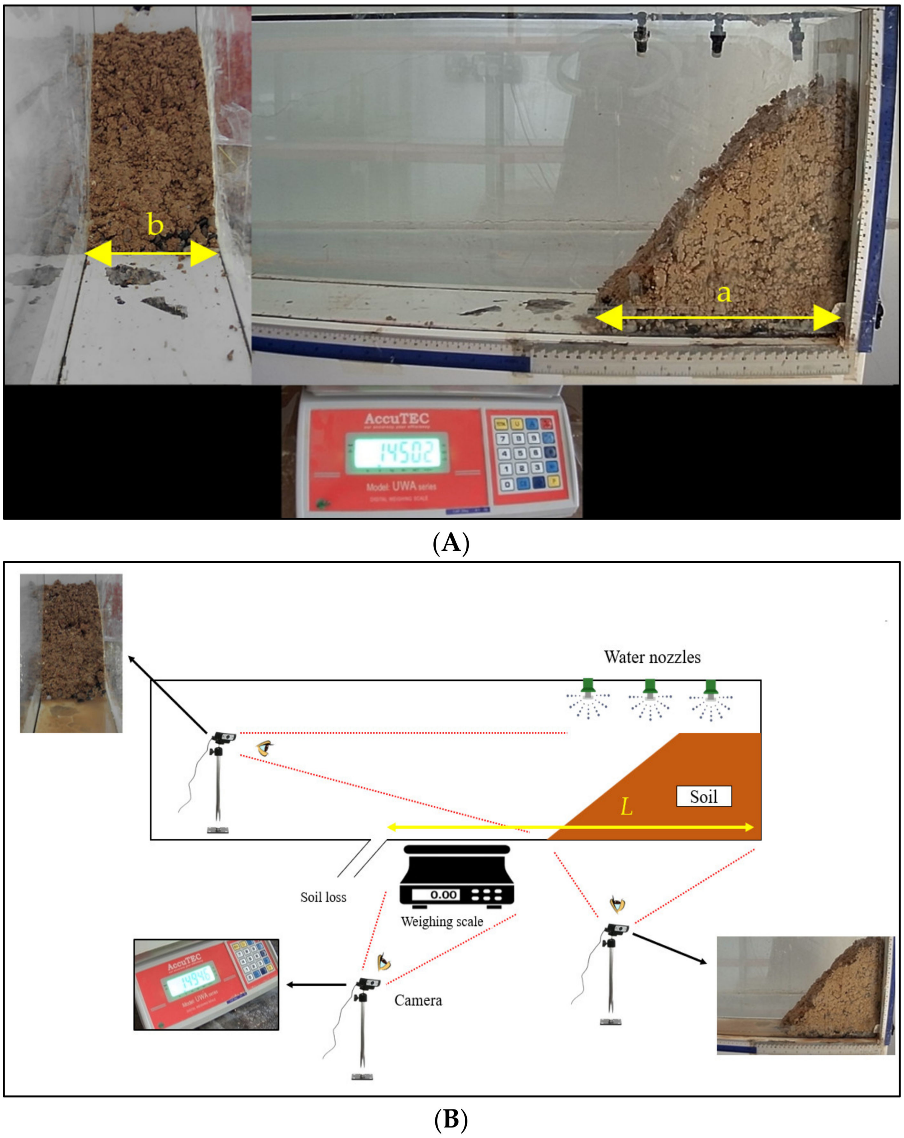


Figure 2. Sandbox model setup: (**A**) front view, (**B**) schematic diagram.

The simulation was recorded using three cameras that were set up to capture the simulation from top and side angles. All three cameras were connected to a laptop, and simulations were recorded using the OBS Studio software. This software allowed for the synchronization of all three capturing, which was essential in creating a comprehensive understanding of the detachment process.

2.4. Rainfall Simulator

The rain simulator used in this study was a single-arm sprinkler system that was equipped with three nozzles. The nozzles were controlled by a water pressure valve to allow for the adjustment of the water flow rate and the rain intensity. To ensure that the rainfall was evenly distributed across the sandbox model, the system was set up on a leveled platform. This allowed the simulator to deliver rainfall evenly to the model and ensure that the results were accurate and representative of actual rainfall events. The water pressure valve was adjusted to produce low, medium and high rainfall intensities of 16 mm/h, 42 mm/h and 105 mm/h, respectively. These intensities were chosen based on their representation of different levels of rainfall in Malaysia, allowing the study to simulate a range of rainfall scenarios.

2.5. Simulation Conditions

Detachment rate for the landslide soil was simulated for four different conditions: moisture content, different slope angle inclination, clay layer and soil compaction (Figure 3) and under each condition, three different sets of tests were configured. For the moisture content condition, the soil was placed in a sandbox at three different initial moisture contents: below the plastic limit (20%), at the plastic limit (35%) and at the liquid limit (60%). For the slope angle condition, the soil was placed in a sandbox at three different slope inclinations: 30°, 45° and 80°. Under the soil compaction condition, the soil was placed in a sandbox at two different compaction values: compacted soil (1.7 g/cm^3) and non-compacted soil (1.2 g/cm^3). For the clay layer condition, a 1 cm thick clay soil was layered horizontally with varying numbers of clay layers. After the setup, all slopes were subjected to one hour of rainfall and left for observation for 24 h in a temperature-controlled room. The detachment rate was then recorded and analyzed under each condition.

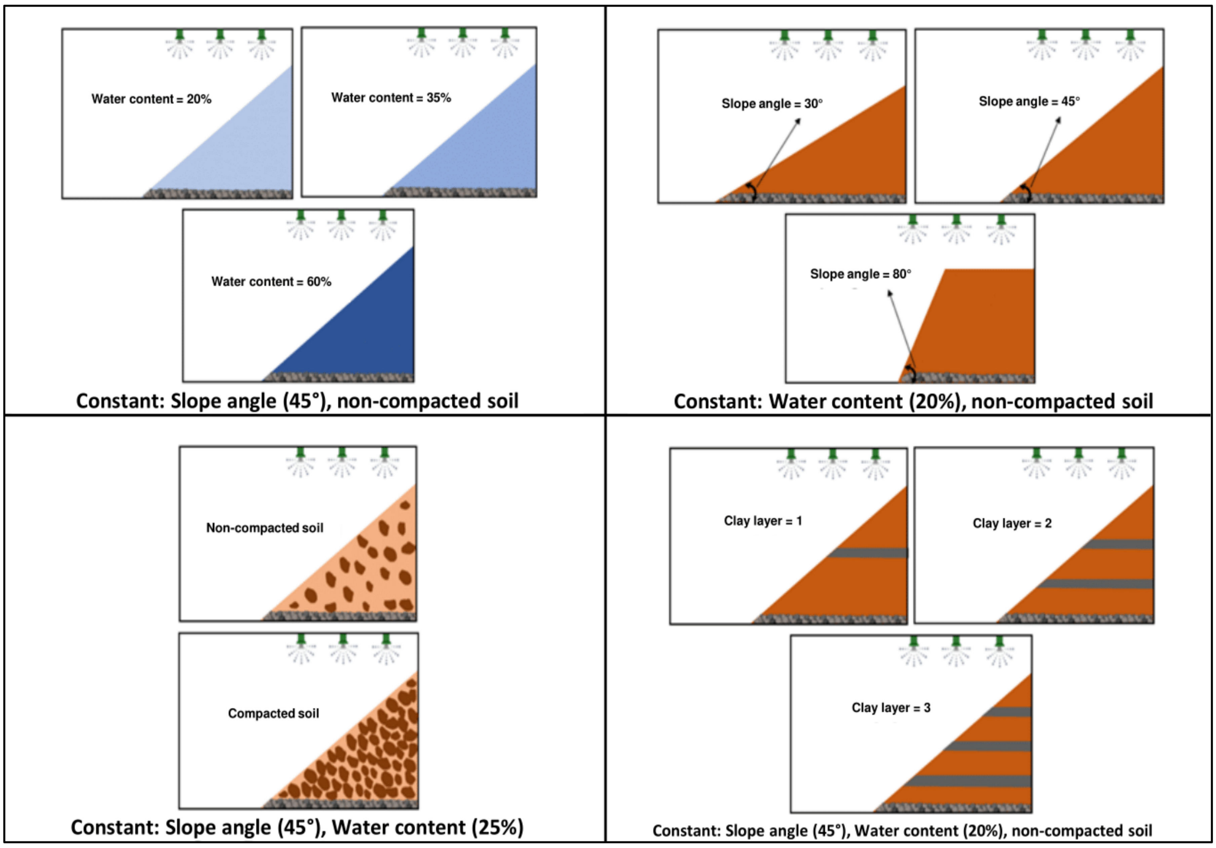


Figure 3. Four different simulated conditions.

2.6. Soil Detachment Rate, Hydraulic Parameters, and Data Calculation

All equations used in this study were adopted from the rill detachment modelling [13,24]. To calculate the detachment rate in the current study, the reverse water content method was used. The total amount of soil loss from the sandbox model was quantified by measuring the initial and final weights of the soil sample. The difference between the two weights was then used to determine the weight of the soil lost during the experiment. The detachment rate of the soil, Dr (kg s^{-1} m^{-2}), was calculated using the following equation:

$$Dr = \frac{M}{tbL} \quad (1)$$

where:

M (kg) is the dry weight of the soil loss;
t (s) is the duration of rainfall;
b (m) is the mean water flow width during the rainfall time;
L (m) is the total flow distance of water that can transport sediment.

Flow shear stress and stream power are two common hydraulic parameters used to describe flow hydraulics from the perspective of force and energy. Determining these hydraulic parameters can accurately predict soil detachment rate and help to understand soil detachment mechanisms and develop process-based erosion models. The flow shear stress (τ) and stream power (w) were calculated using Equations (2) and (4).

$$\tau = \rho g R J \quad (2)$$

where:

ρ (kgm^{-3}) is the density of water;
g (ms^{-2}) is the gravity acceleration;
R (m) is the hydraulic radius of the slope;
J (mm^{-1}) is the slope gradient.

The hydraulic radius (R) was calculated using Equation (3), by considering a rectangular wetted perimeter for a laminar flow type in the Reynolds number method [25].

$$R = \frac{2ab}{a+b} \quad (3)$$

where:

a (m) is the mean water flow length of the slope during the rainfall time;
b (m) is the mean water flow width of the slope during the rainfall time.

$$w = \tau V \quad (4)$$

where:

τ (Pa) is water flow shear stress;
V (ms^{-1}) is the average flow velocity.

2.7. Statistical Analysis

All analyses were carried out using Microsoft Excel 2304 and Origin 6.0. The regression analysis examined the relationship between water flow shear stress, stream power and soil detachment rate, as well as slope physical properties including water content, slope angle, soil compaction and clay layers in soil.

3. Results and Discussion

3.1. Physicochemical Properties of Soil

Laboratory analyses were carried out to determine the physical and chemical properties of the soil sample taken from the accumulation zone in the landslide area using ASTM standards. Table 2 gives an overview of the properties of the soil. The soil is categorized as a residual soil derived from the complete weathering of granitic soil. The soil's light-orangey colour indicates dominance of felsic minerals, primarily quartz, feldspar and plagioclase, with the presence of biotite as an accessory mineral.

Table 2. Physicochemical properties of the landslide soil.

Soil Characteristics	Standard	Results
Bulk Density (g/cm^3)	ASTM D698-12 [26]	1.71
Moisture Content (%)	ASTM D2216-19 [27]	34.54
Specific Gravity	ASTM D854-00 [28]	2.57
Gravel (%)	ASTM D6913-04(2009)e1 [29]	7.4
Sand (%)	ASTM D6913-04(2009)e1 [29]	42.6
Silt (%)	ASTM D7928-21e1 [30]	36.8
Clay (%)	ASTM D7928-21e1 [30]	13.2
Liquid Limit (%)	ASTM D4318-17 [31]	61.2
Plastic limit (%)	ASTM D4318-17 [31]	36.4
Plasticity index (%)	ASTM D4318-17 [31]	24.8
Mineral content		Quartz, muscovite, halloysite
Optimum moisture content (%)	ASTM D698-12 [26]	25.8
Maximum dry density (g/cm^3)	ASTM D698-12 [26]	1.49
Dispersion	ASTM D4221-18 [32]	Non-dispersive

3.2. The Effect of Various Soil Conditions on Soil Detachment Rate

Figure 4 shows that the rate of soil detachment increases with the soil water content. A soil water content of 60% has a higher detachment rate (0.0052–0.0062 kg s^{-1} m^{-2}) than a soil water content of 35% (0.0043–0.0057 kg s^{-1} m^{-2}) and 20% (0.0031–0.0053 kg s^{-1} m^{-2}). Water content is one of the most important factors influencing erosion during rainfall, as it affects the structure and hydraulic behavior of the soil [33,34]. Even when a low-intensity rain falls on a soil with high moisture content, it can trigger soil erosion.

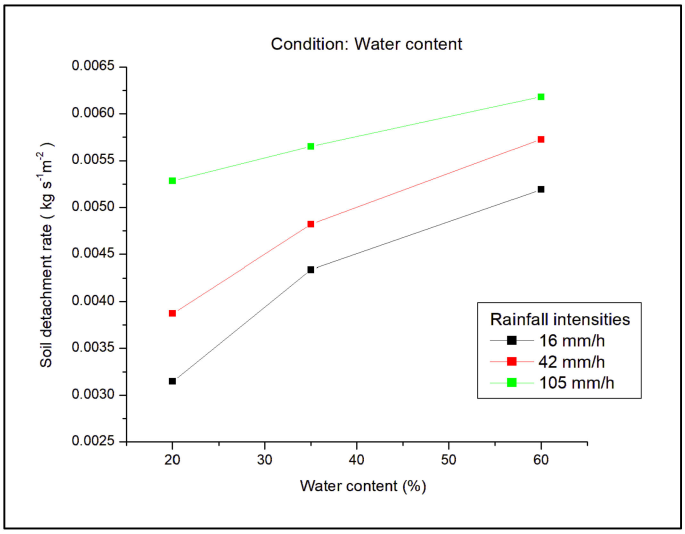


Figure 4. Water content against soil detachment rate.

In this study, it was found that the water content of the soil has a significant influence on soil detachment. When soil is saturated with water, the cohesive forces that hold soil particles together are weakened, making the soil more susceptible to detachment [35]. The soil particles become more mobile and are easily detached from the soil surface due to the reduced interparticle forces. This is because when the soil is saturated with water, the pore space between soil particles is filled with water, and there is little air to provide support for the soil structure. This makes the soil more susceptible to erosion and transport by the flowing water.

In addition, the water content of the soil can affect the hydraulic conductivity of the soil, which is the rate at which water can flow through the soil. When the soil is too wet, the hydraulic conductivity can be high, and this increases the potential for soil detachment and erosion. The flowing water can carry away soil particles more easily when the hydraulic conductivity is high, resulting in higher rates of soil detachment. For this reason, the soils with a water content of 60% in this study have the highest detachment rate. Soil moisture content thus plays an important role in soil detachment on this slope.

Figure 5 shows that the soil detachment rate increases with the slope angle. The detachment rate increases significantly when the slope angle increases from 30° to 80°. In general, steep slopes are stable during dry periods [36]. However, rainwater infiltration decreases slope stability when contact between particles increases due to the higher weight of the slope and gravity. As water flows over the slope's surface, it gains kinetic energy due to the elevation difference, causing the soil detachment rate to increase with increasing slope angle.

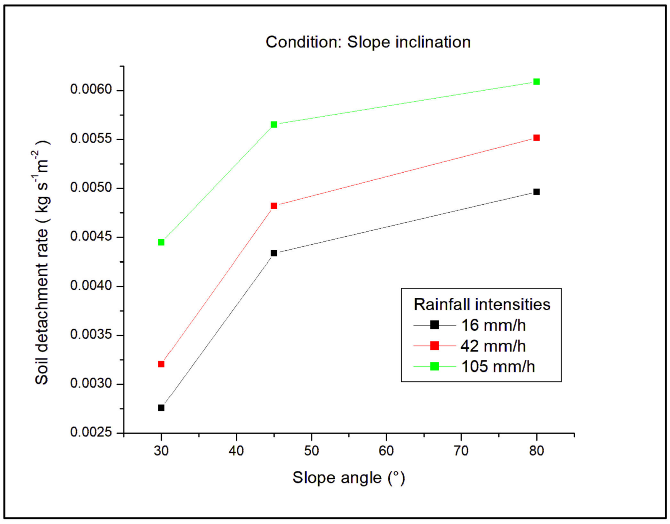


Figure 5. Slope inclination against soil detachment rate.

A steeper slope causes the water to move faster and with greater force [37]. It can exert a higher shear stress on the soil surface, which can detach soil particles and transport them downstream. In addition, the greater velocity of water on steeper slopes increases the likelihood of surface runoff, which can further erode and detach soil particles. Figure 5 shows that when the slope angle increases from 30° (0.0028–0.0044 kg s^{-1} m^{-2}) to 80° (0.0050–0.0061 kg s^{-1} m^{-2}), less rainwater remains on the slope because more rainwater flows as runoff. Therefore, only a small part of the rainwater penetrates the soil, resulting in a higher erosion rate on steeper slopes. The finding is consistent with another study conducted using digital close-range photogrammetry, which found that the erosion rate for 40° slopes was significantly higher than that for 20° and 30° slopes [38]. The study confirms that slope angle is an important factor that affects soil erosion rates, and steeper slopes are more vulnerable to erosion and soil detachment than shallower slopes.

Figure 6 shows that the soil detachment rate decreases with the number of clay layers. Soils with three clay layers have a lower detachment rate (0.0025–0.0038 kg s^{-1} m^{-2}) than soils with two clay layers (0.0027–0.0039 kg s^{-1} m^{-2}) or one clay layer (0.0033–0.0041 kg s^{-1} m^{-2}). The results of this study are consistent with those of another study in the Beijing region, where the detachment rate is negatively correlated with clay content [39]. Particles smaller than 2 μm (clay) contribute to high cohesion and low erodibility, whereas particles larger than 2 μm are easily eroded and associated with higher erodibility [40].

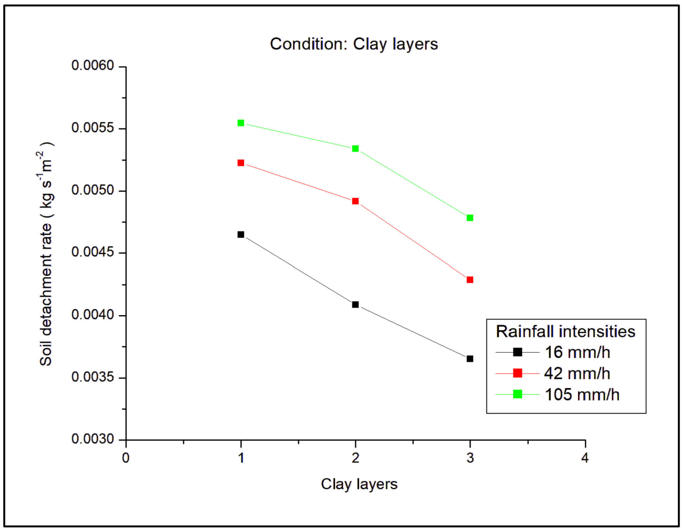


Figure 6. Clay layers against soil detachment rate.

The presence of clay particles in soil can help to reduce soil detachment and erosion by providing a barrier against the impact of raindrops on the soil surface [40]. This is because clay particles have a strong cohesive force that holds them together, forming a dense and stable layer within the soil profile. This layer acts as a shield that protects the soil surface from the erosive forces of rainwater, reducing the potential for infiltration and water flow through the soil. However, the effectiveness of the clay layer in reducing soil detachment depends on its thickness and location within the soil profile. If the clay layer is too thin, it may not be able to provide sufficient protection against soil detachment. Similarly, if the clay layer is located too close to the soil surface, it may not be able to shield the soil from the erosive forces of rainwater. In such cases, the soil may still be vulnerable to detachment and erosion.

Additionally, the presence of clay in soil can also affect the soil's water-holding capacity, which can impact soil erosion. Clay soils can hold more water than sandy soils due to their smaller pore size and greater surface area. This means that water can infiltrate more slowly into clay soils and may be held in the soil for longer periods, reducing the amount of surface runoff and erosion. However, if the soil becomes saturated with water, the cohesive forces that hold clay particles together can be weakened, making the soil more susceptible to detachment and erosion. Thus, the presence of clay in soil can both aid and hinder the soil's resistance to detachment and erosion, depending on various factors such as its thickness, location and moisture content.

Table 3 shows that the soil detachment rate decreases with increasing bulk density (compaction). Compacted soil has a lower detachment rate (0.0024–0.0037 kg s^{-1} m^{-2}) than non-compacted soil (0.0043–0.0057 kg s^{-1} m^{-2}). Soil compaction can affect the soil's ability to resist erosion and stay in place. Soil compaction can have varying effects on soil detachment and erosion, depending on the degree of compaction and soil characteristics. Compaction can increase soil stability by creating a denser, more cohesive soil structure that is less susceptible to detachment and erosion [12]. This is because compacted soil has less pore space and can retain water better, making it more resistant to the erosive forces of water and wind. However, excessive soil compaction can have the opposite effect on soil stability. When soil is overly compacted, its ability to absorb water decreases, leading to increased surface runoff. This can result in erosion as runoff water gains significant energy and erodes the soil surface, leading to soil detachment and erosion.

Table 3. Detachment rate for soil compaction.

Bulk Density [g/cm^3]	Rainfall Intensity [mm/h]	Soil Detachment Rate [kg s^{-1} m^{-2}]
1.7 [Compacted soil]	16 42 105	0.002426069 0.002908041 0.003734985
1.3 [Non-compacted soil]	16 42 105	0.004337559 0.004821022 0.005652258

The effect of compaction on soil detachment and erosion was studied in this research, and the results showed that when the bulk density of the soil increases due to compaction, the overall soil mass becomes denser, and the cohesion of the soil improves. This has a significant negative impact on soil erosion since it increases the shear strength of the soil [41]. Therefore, the erosion rate of compacted soil is lower than that of uncompacted soils. This result was further supported by another study on different land uses on the Loess Plateau in China. The study found that the soil detachability decreases as a power or exponential function with increasing bulk density [18].

3.3. The Relationship between Rainfall Intensities, Hydraulic Parameters, Soil Conditions and Soil Detachment Rate

For all soil conditions investigated, the detachment rate is directly related to the shear stress of the flow and stream power (Table 4). The shear stress of water flow and the stream power for the slope surface increase with rainfall intensity [42]. The shear stress of water flow is closely related to stream power, as it can affect the amount of water flowing over the soil surface and the shear stress it exerts on soil particles. As a result, more soil particles may be separated and carried away by the flowing water, resulting in soil detachment.

Table 4. Measured detachment rate for all simulated conditions.

Conditions	Sub-Conditions	Rainfall Intensity [mm/h]	Water Flow Shear Stress [Pa]	Critical Flow Shear Stress [Pa]	Stream Power [kg s^{-3}]	Soil Detachment Rate [kg s^{-1} m^{-2}]
Water content	Water content = 20%	Low Medium High	576.785 711.699 1025.536	96.67	0.0501 0.0554 0.0651	0.003146806 0.003871489 0.005283061
	Water content = 35%	Low Medium High	761.988 870.213 1129.539		0.0567 0.0605 0.0654	0.004337559 0.004821022 0.005652258
	Water content = 60%	Low Medium High	1005.441 1147.563 1303.907		0.0630 0.0664 0.0699	0.005192218 0.005726852 0.006181125
Slope inclination	Slope angle = 30°	Low Medium High	579.774 721.696 868.224	86	0.0504 0.0557 0.0601	0.002759622 0.003204103 0.004445713
	Slope angle = 45°	Low Medium High	753.654 1023.572 1217.241		0.0553 0.0619 0.0657	0.004337559 0.004821022 0.005652258
	Slope angle = 80°	Low Medium High	1091.432 1128.566 1425.330		0.0630 0.0652 0.0706	0.004963666 0.005402778 0.006089983

Table 4. *Cont.*

Conditions	Sub-Conditions	Rainfall Intensity [mm/h]	Water Flow Shear Stress [Pa]	Critical Flow Shear Stress [Pa]	Stream Power [kg s^{-3}]	Soil Detachment Rate [kg s^{-1} m^{-2}]
Clay layers	1	Low	746.789	112	0.0560	0.003250472
		Medium	1042.024		0.0630	0.003825571
		High	1110.072		0.0647	0.004146902
	2	Low	708.905		0.0543	0.002687259
		Medium	825.976		0.0581	0.003516104
		High	1048.768		0.0630	0.003939352
	3	Low	627.490		0.0522	0.002454321
		Medium	766.651		0.0563	0.003388499
		High	853.062		0.0598	0.003783151
Soil compaction	Compacted soil	Low	1134.657	865.56	0.0564	0.002426069
		Medium	1191.610		0.0605	0.002908041
		High	1258.497		0.0654	0.003734985
	Non-compacted soil	Low	1367.358		0.0685	0.004337559
		Medium	1429.251		0.0727	0.004821022
		High	1478.153		0.0741	0.005652258

In this study, three different rainfall intensities (low, medium and high) were used, and the results showed that the shear stress of water flow and stream power were highest at high rainfall intensity and lowest at low rainfall intensity for all soil conditions. The shear stress of water flow and stream power were found to be almost 1.1–1.7 and 1.1–1.2 times greater, respectively, at high rainfall intensities than at low rainfall intensities. Thus, increasing these hydraulic parameters with rainfall intensity leads to an increase in soil detachment rate. However, in some cases, heavy rainfall may be short-lived, and therefore not produce as much flowing water or shear stress as a longer duration of rainfall. Therefore, the impact of rainfall intensity on shear stress and detachment rate may depend on various factors, including the duration and intensity of rainfall, the soil characteristics, and the topography of the slope. It is important to consider all of these factors in order to better understand the relationship between rainfall intensity, shear stress and soil detachment rate.

Many previous studies have shown that rainfall intensity significantly affects soil detachment positively, which means that higher rainfall intensity increases the risk of soil detachment and erosion [43–45]. These findings highlight the importance of understanding the relationship between rainfall intensity and hydraulic parameters such as shear stress and stream power to help predict and mitigate the effects of soil detachment and erosion caused by rainfall-induced landslides.

The critical flow shear stress (τc) is the minimum shear stress required to initiate soil detachment from the ground surface. The critical flow shear stress is calculated by interpolating soil detachment rate and flow shear stress by using linear regression where the X-intercept is critical flow shear stress [24] corresponding to a soil detachment rate equal to zero. If the shear stress exerted by the flowing water exceeds the critical flow shear stress of the soil, soil particles can detach and be transported downstream. In this study, correlation with the average detachment rate of soil was found to be highest for water content and slope inclination and lowest for soil compaction and clay layers at all three rainfall intensities. This is because the critical flow shear stress required for soil detachment was the lowest for water content (96.67 Pa) and slope inclination (86 Pa). The water flow shear stress was almost 5.8 and 6.7 times higher than the critical flow shear stress for water content and slope inclination, respectively. However, the water flow shear stress was only 1.3 times higher for soil compaction than the critical flow shear stress. Additionally, the soil detachment rate was observed to be the highest at a water content of 80% and a slope angle of 80°. These findings suggest that high water content and steep slope inclination significantly increase the risk of soil detachment and erosion.

Figures 7 and 8 show that the water flow shear stress and stream power are directly proportional to the soil detachment rate for all simulated conditions by using the power regression method. The coefficient of determination, R^2, ranged from 0.837 to 0.988 ($p < 0.05$). The R-squared value is considered to be a good fit, and thus the relationship between the shear stress of the water flow, stream power and the detachment rate of the soil is considered to be statistically significant and highly correlated.

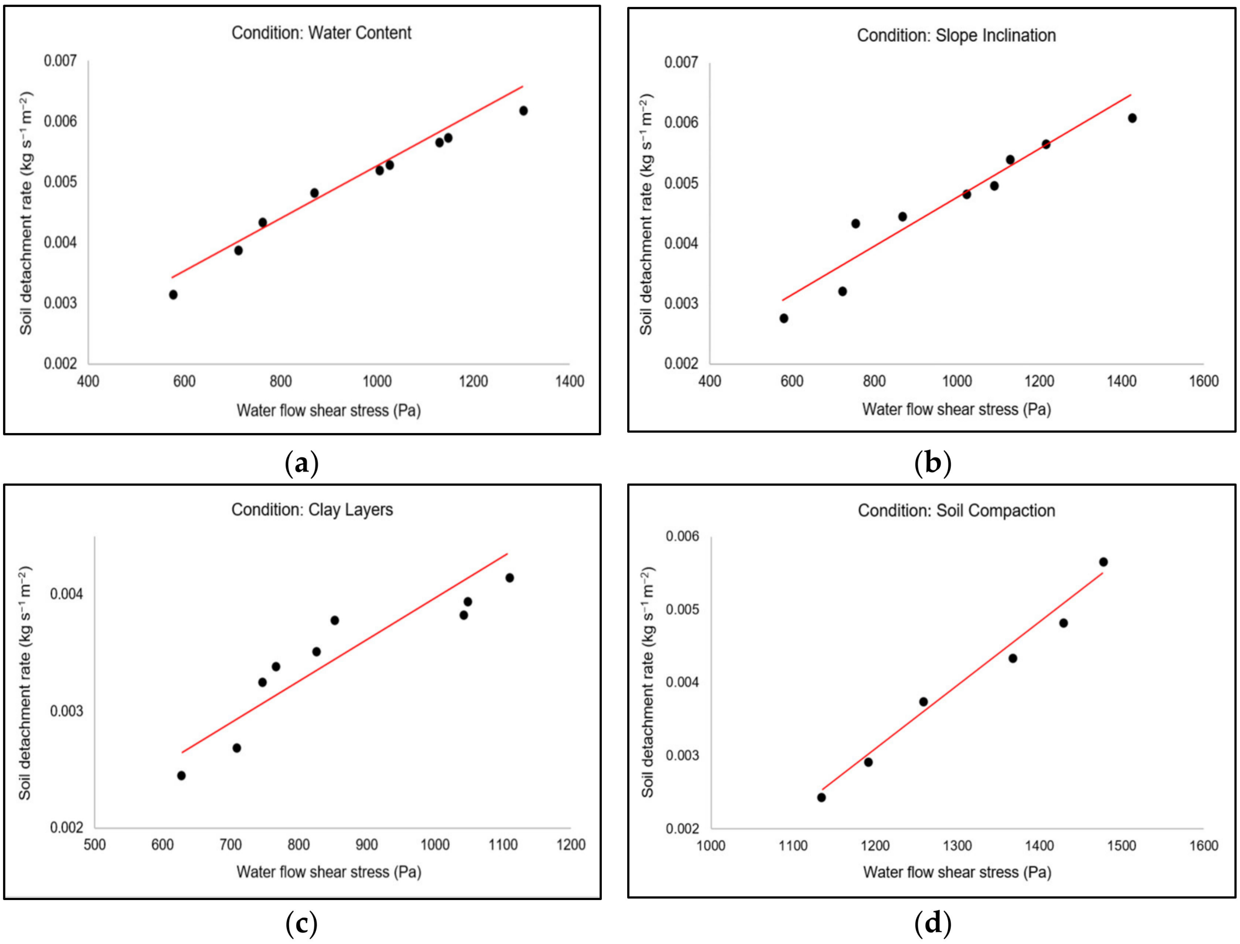


Figure 7. Relationship between soil detachment rate and water flow shear stress for four conditions: (**a**) water content, (**b**) slope inclination, (**c**) clay layers and (**d**) soil compaction.

The obtained fitting results with normal and power regression can be described in equations (Tables 5 and 6) by using the flow shear stress and stream power as independent variables and the corresponding soil detachment rates as dependent variables. Based on the Pearson correlation matrix (Table 7), the soil detachment rate is positively correlated with water content, slope angle, water flow shear stress and flow power. However, it is negatively correlated with clay layers and soil compaction.

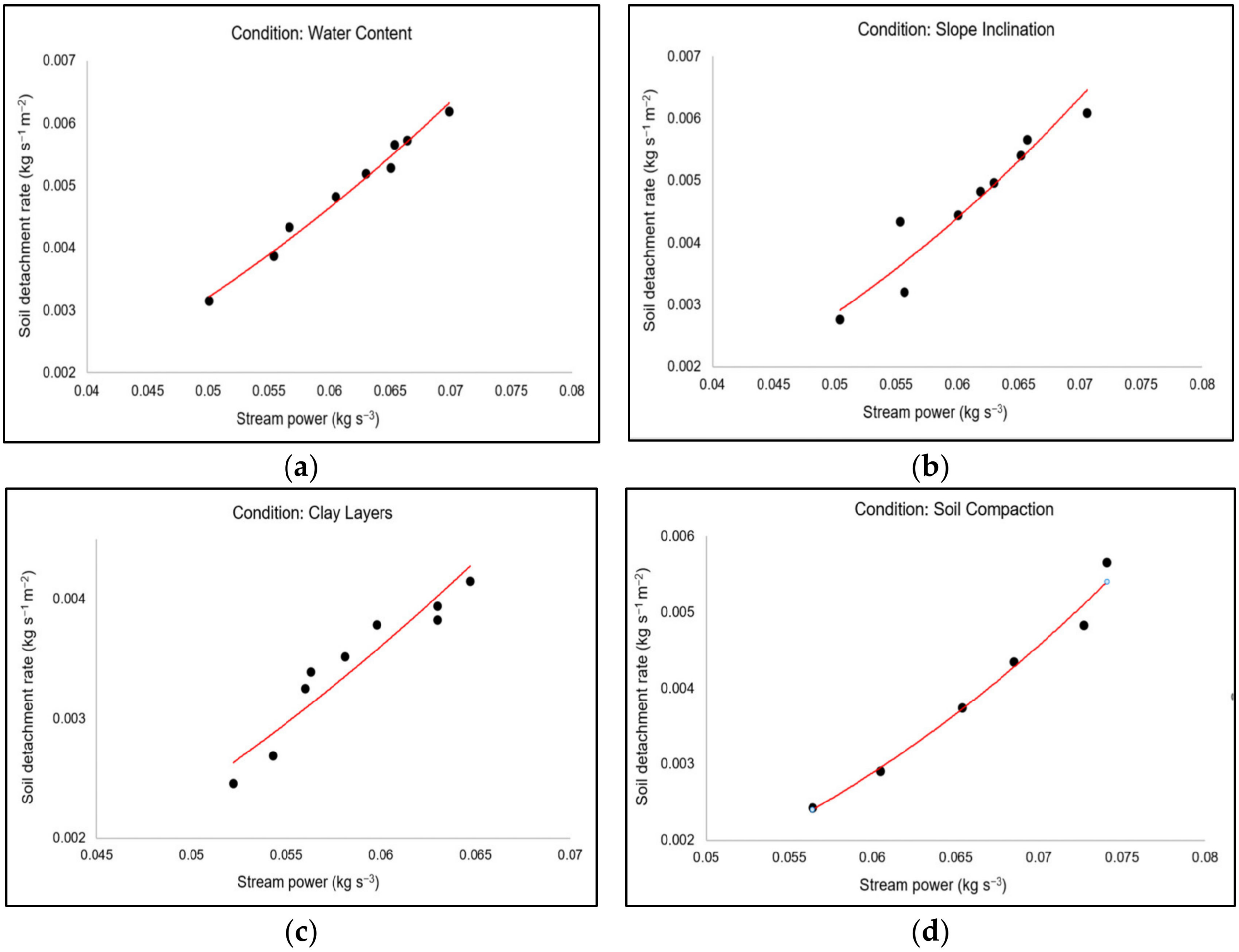


Figure 8. Relationship between soil detachment rate and stream power for four conditions: (**a**) water content, (**b**) slope inclination, (**c**) clay layers and (**d**) soil compaction.

Table 5. Power regression results between soil detachment rate and flow shear stress.

Condition	Regression Equation	Correlation Coefficient, r	Coefficient of Determination, R^2	Significance Level, *p*
Water content	$Dr = 0.013\tau^{0.810}$	0.989	0.976	0.0000001
Slope inclination	$Dr = 0.008\tau^{0.868}$	0.921	0.984	0.00004
Clay layers	$Dr = 0.009\tau^{0.8236}$	0.915	0.837	0.00055
Soil compaction	$Dr = 0.000001\tau^{2.965}$	0.990	0.981	0.00014

Table 6. Regression results between soil detachment rate and stream power.

Condition	Regression Equation	Correlation Coefficient, r	Coefficient of Determination, R^2	Significance Level, *p*
Water content	$Dr = 1.363\omega^{2.020}$	0.992	0.984	0.0000001
Slope inclination	$Dr = 4.036\omega^{2.427}$	0.967	0.934	0.00002
Clay layers	$Dr = 1.981\omega^{2.243}$	0.939	0.881	0.00018
Soil compaction	$Dr = 13.921\omega^{3.018}$	0.994	0.988	0.00005

Table 7. The Pearson correlation matrix between the studied parameters.

	Soil Detachment Rate	Water Content	Slope Inclination	Clay Layers	Soil Compaction	Water Flow Shear Stress	Stream Power
Soil detachment rate	1.000	0.487	0.429	−0.452	−0.357	0.634	0.821
Water content	0.487	1.000	−0.083	−0.289	−0.027	0.311	0.389
Slope inclination	0.429	−0.083	1.000	−0.099	−0.056	0.470	0.444
Clay layers	−0.452	−0.289	−0.099	1.000	−0.196	−0.346	−0.285
Soil compaction	−0.357	−0.027	−0.056	−0.196	1.000	0.354	0.027
Water flow shear stress	0.634	0.311	0.470	−0.346	0.354	1.000	0.919
Stream power	0.821	0.389	0.444	−0.285	0.027	0.919	1.000

4. Conclusions

Rainfall-induced landslides are common in Malaysia due to the tropical climate and frequent heavy rainfall events. The Taman Bukit Permai landslide is one of the recent examples of a rainfall-induced landslide on a man-made slope. The detachment of the soil causes the soil structure to weaken during rainfall and materials to detach from the surface, making it more exposed to erosion. The simulations with the sandbox model showed that soil water content and slope angle are positively correlated with soil detachment, whereas clay layers and soil compaction are negatively correlated. Water flow shear stress and stream power are positively correlated with detachment rate for all soil conditions, indicating the strong influence of rainfall on the landslide mechanism. These results can be used to understand the basic mechanism of a rainfall-induced landslide on an eroded slope, as soil erosion no longer occurs only on the surface but penetrates to a greater depth.

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