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Research Article

Assessment of the Detached Soil Particles and Water Discharge from a Bare Soil Surface under the Simulated Rainfall Conditions

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Abstract: The study aimed to shelter the exposed soil surface once the embankments/road side slopes are constructed. To promote economical development, the need of roads is necessary. The embankments usually remain bare once the road is constructed which leads to the rills and gullies. This causes on-site and off-site affects in the form of road degradation, road accidents, siltation in the reservoir channel and worsening of the water quality. To observe the similar condition, a comprehensive field study on the bare soil surface was conducted in the Perak, Malaysia to understand the behavior of the detached soil particles and the water flow under different simulated rainfall intensities. The rainfall data for the Perak was collected and analyzed from Meteorological Department, Malaysia. The slope degree chosen to conduct the experimental study was 30° as the road side slopes are usually constructed with the gradients of 1 on 1.5 (≈30°). This study further includes the determination of kinetic energy of the rain drop for the given rainfall intensities and the determination of different soil physical and chemical properties. However, during the field study the maximum erosion rates observed for a period of 2 h under the rainfall intensity of 40 and 52 mm/h were observed to be 5.78×10^{-5} and 9.39×10^{-5} m^3/sec, respectively.

Keywords: Bare soil surface, raindrop-kinetic energy, soil detachment, water discharge

INTRODUCTION

Soil quality and its productivity is adversely affected by water and wind erosion as it reduces the soil depth which affects the infiltration rates, the water-holding capacity of the soil, the presence of nutrients in the soil and the organic matters. Asia, Africa and South America have remained the severe victims of soil erosion averaging the soil loss of 30 to 40 tons/ha/year whereas; United States and Europe remained lightly affected by this process averaging the soil loss of 17 tons/ha/year (Pimentel *et al*., 1995). Table 1 shows different regions affected by water and wind erosion (Ng, 2003).

Slow and steady erosion accumulates and leads to the drastic change by losing the large portion of soil. For example if 2/5" of soil is detached by the rainstorm over 2.5 acres of land then it will take about 20 years of natural process to recover those 13 tons of the top soil that were lost. The lost soil is usually the top soil which plays a vital role as it is rich in organic content having high concentration of microorganism which helps improving the biological activities that take place in that region (Quinn, 2011).

Rainfall characteristics can often be related to the potential susceptibility of a region to the erosion, which usually occurs in steep mountainous terrains (Sekitar,

Table 1: Different regions affected by water and wind erosion (Ng, 2003)

	Land area affected by erosion (10^6 ha)	
Region	Water erosion	Wind erosion
Africa	227	186
Asia	441	222
South America	123	42
Central America	46	5
North America	60	35
Europe	114	42
Oceana	83	16
World	1094	548

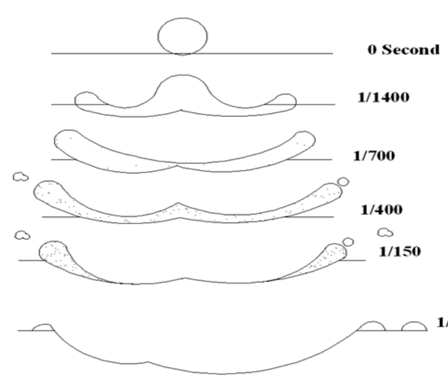

Fig. 1: The effect of rain drop on the bare surface (Schwab and Frevert, 1992)

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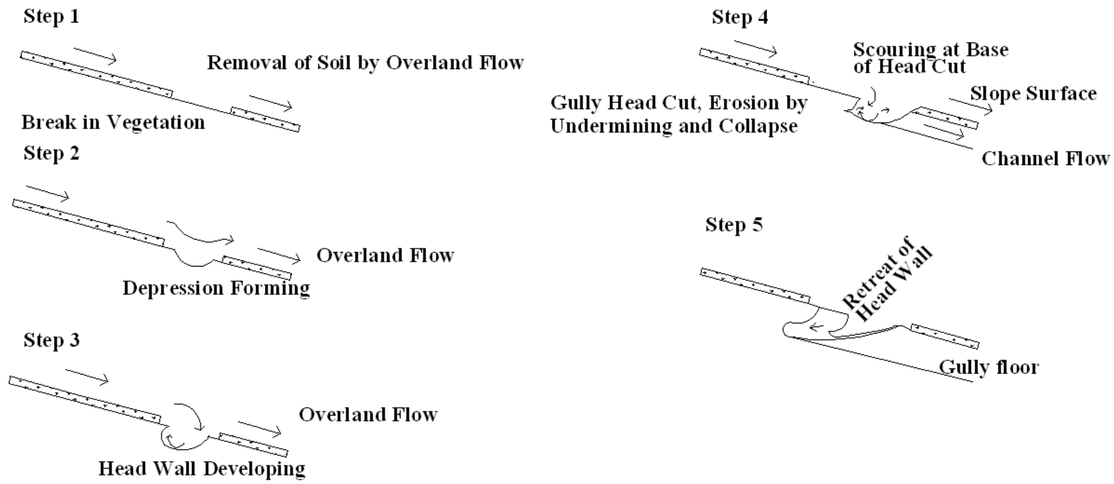

Fig. 2: Affects of the surface runoff (Morgan, 2005)

1996). When the soil surface is bare and comes in contact to the raindrop then it detaches the soil particles which are then available for surface runoff as shown in Fig. 1 (Schwab and Frevert, 1992). The surface runoff moving with the sufficient velocity contributes to the continuous scrubbing of the soil particles which forms the concavity and results in the formation of the gully floor as shown in Fig. 2 (Morgan, 2005). However, raindrop impact is considered more important which causes soil dislodging than the runoff water (Rose, 1960).

To promote economic development, road construction is among the major infrastructures. It influences the local environment (Dong *et al*., 2012) and is considered responsible to induce the higher rates of erosion (Cerdà, 2007). The loss of cover crop during the road construction makes the soil surface bare which leads to the risk of slope instability (De Oña *et al*., 2009). This causes both on-site and off-site effects by undermining the roads utilities, loss of fertile top soil, high cost for the maintenance, instability to the stream channels and siltation in the reservoirs resulting in the loss of water capacity of the water channel (Sekitar, 1996).

Problem statement:

- Several studies have proved that the bare surface gives the worst condition when the erosion process occurs.
- However, limited studies have been conducted on the steep slopes to observe the erosion process.
- Majority of the researches on water erosion and the soil conservation practices have been carried out on the slopes less than about 20% (≈12°) (Presbitero *et al*., 2005).
- This research intends to observe the erosion process for the slope angle of 30° (≈57%) which is the representative of the usually constructed road side slopes.

Objectives: Primarily the objective of this study is to observe soil behavior when subjected to the simulated rainfall intensities of 40 and 52 mm/h. The study will attempt to:

- Assess the soil loss using rainfall simulators on the bare soil surface.
- Compute the water discharge at different intervals of time.
- Determine the kinetic energy E_k of the raindrop based upon the exponential relationship as proposed by Van Dijk *et al*. (2002) and Marques *et al*. (2007).
- Determine different soil physical and chemical properties.

Scope: The study will be limited to the following:

- When rainfall occurs, water penetrates the soil and fills the water capacity of the soil causing surface runoff. However, for this experiment some initial soil wetting (infiltration) would be there to obtain the natural effects of the rainfall on the slope using rainfall simulator but the infiltration is not calculated.
- The concern of the research is with the detachment of soil particles and observation of the water discharge.
- This study is limited to the slopes of 30° which represents the common road side slopes constructed with the gradient of 1 on 1.5.

LITERATURE REVIEW

To determine the erosion rates it is necessary to key out the major factors which are responsible for the occurrence of the erosion process. This includes slope

Table 2: Soil loss obtained from grass covered (plot A), mulch covered (plot B) and bare surface (plot C) under different rainfall patterns (Li *et al*., 2011)

Rainfall pattern	Date	Rainfall intensity (mm/h)	Sediment yield A (Kg/mm/ha)	B (Kg/mm/ha)	C (Kg/mm/ha)
Middle rain	10th Dec, 03	0.8830	0.0137	0.0120	0.3299
Heavy rain	17th April,04	1.3826	0.0025	0.0038	0.0440
Rain storm	21st Feb, 04	2.5592	0.0038	0.0051	1.0998
Heavy storm	17th July,02	5.1455	0.0042	0.0057	6.2789

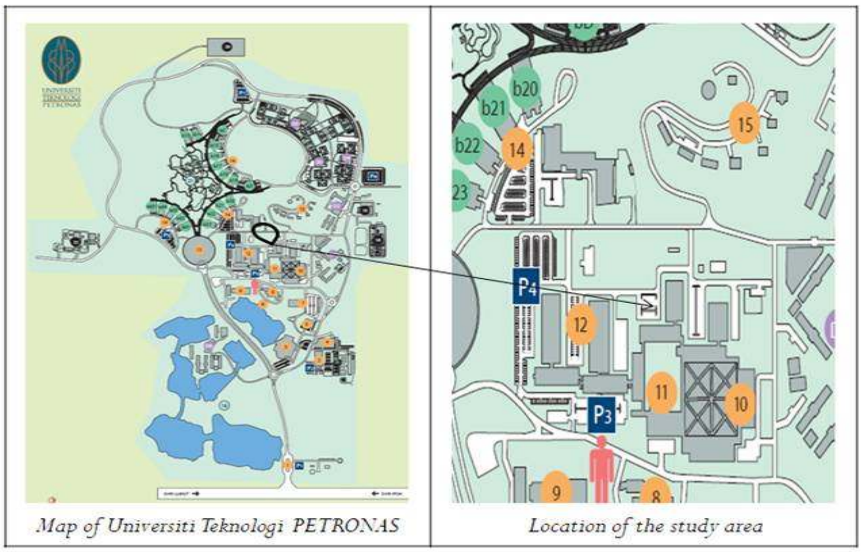

Fig. 3: Location of the study area

steepness, soil type and the rainfall intensity. Several studies have been conducted to observe the erosion rates from a bare surface (control) while comparing it with the agronomic, engineering and non-engineering soil conservation techniques to determine the efficiency of these practices in mitigating the erosion process.

From the findings of Wang *et al*. (2012), on the Exposed Soil Without Grass (ESWOG), Exposed Soil With Grass (ESWG), Natural Barren Land (NB) and Natural Vegetation (NV), it was observed that the bare soil (ESWOG) yield sediments four times more than that of grass planted plot (ESWG) which shows the erodible nature of the disturbed soil and its contribution to the higher rates of sediment loss and runoff.

Similarly, a study was conducted to determine the soil loss and runoff rates under the natural rainfall conditions from different shrub covers (*Colutea arborescens*, *Dorycnium pentaphyllum* and *Medicago strasseri*) and a bare surface. The results showed that the total soil loss and runoff from the bare plot were 37.45 Mg/ha and 128.8 mm, respectively. For *M. strasseri*, *D. penyaphyllum* and *C. arborescens* covers the soil loss and runoff rates were 0.34 Mg/ha and 7.1 mm, 1.21 Mg/ha and 16.0 mm, 1.92 Mg/ha and 21.2 mm, respectively (Garcia-Estringana *et al*., 2011).

Table 2 shows the soil loss obtained from grass covered surface (Plot A), mulch covered surface (Plot B) and the bare surface (Plot C) under different rainfall patterns. Reduced erosion rates were observed from Plot A during the heavy rain, rainstorm and the heavy storm. However, when the erosion rates from the bare surface compared with the mulch covered surface, it was observed that the soil loss from the mulch covered surface was only 3.63, 8.63, 0.46 and 0.09%, respectively of the soil loss observed from the bare soil surface under the middle rain, heavy rain, rainstorm, and heavy storm (Li *et al*., 2011).

MATERIALS AND METHODS

Site location: The study area is located in Universiti Teknologi PETRONAS, Perak as shown in Fig. 3. The site was selected as it met the requirements of the experiment, provided with the appropriate drainage and natural slope angle of 30° which is the, representative of the newly constructed road side slopes.

Determining the slope angle: Figure 4 shows the existing site location and the way how the angle of the slope was determined. The height obtained for the bare surface was 2.995 m which equals 9.82 ft. The Slope hypotenuse was already determined using measuring tape that equals 6 m or 19.68 ft which gives the slope angle of approximately 30°.

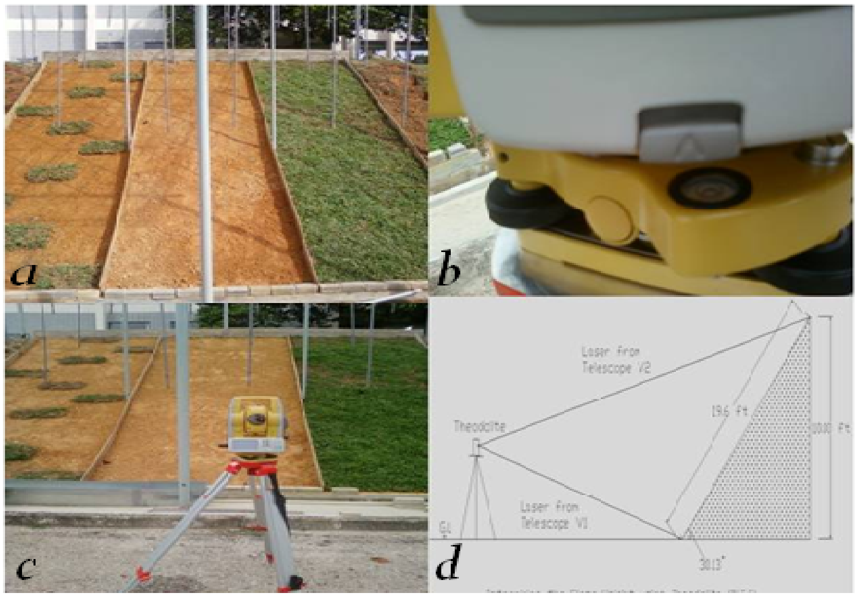

Fig. 4: The existing site location and slope determination, (a) front view, (b) theodolite, (c) determining the slope angle and (d) side elevation (autocad drawing)

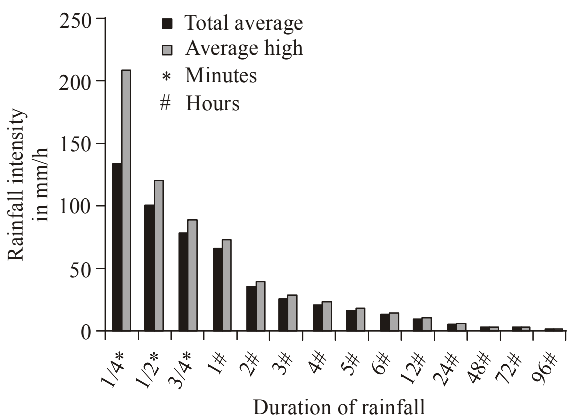

Fig. 5: The rainfall intensity in millimeters per hour for Lubok Merbau Perak, Malaysia

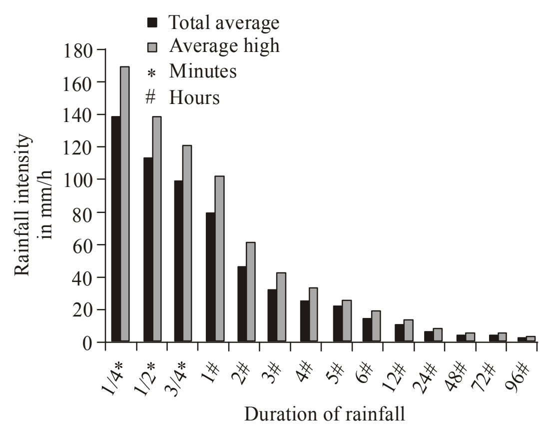

Fig. 6: The rainfall intensity in millimeters per hour for Ipoh Perak, Malaysia

Rainfall data collection: The rainfall data was collected from the Meteorological Department Malaysia. The department has three rainfall stations located in the Perak named as Lubok Merbau Station, Ipoh Station and Sitiawan Station as shown in Fig. 5 to 7. After sorting out the data it was observed that the total average rainfall and the highest average rainfall from the year 2005 to 2011 were ≈ 40 and 52 mm/h, respectively. Thus the study was aimed to observe the behavior of the bare soil under these simulated rainfall conditions.

Determining the kinetic energy E_k of the raindrop using the exponential relationship: Marques *et al.* (2007) stated that due to the differences in size of drop and terminal velocity the kinetic energy of natural and simulated rain cannot be same at equal intensities.

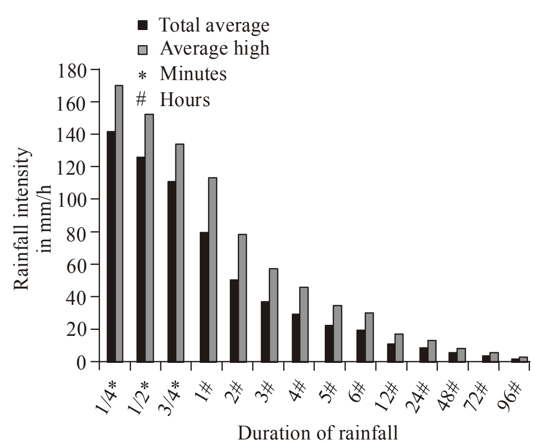

Fig. 7: The rainfall intensity in millimeters per hour for Sitiawan Perak, Malaysia

Table 3 shows the exponential relationship between the rainfall intensity and the kinetic energy as proposed by Van Dijk *et al*. (2002) for Perak. The relationship is given by:

$$E_k = 28.3\ (1 - (0.52e^{-0.042.I}))$$

where,
E_k = Kinetic energy (J/m^2/mm)
I = Rain intensity (mm/h)

Description of the experimental site: The comeplete description of the experimental site in Fig. 8 shows how the experiments were conducted. Initially, the area was cleared and excavated, the top soil was then placed and the soil physical and chemical properties were determined. Concrete slab at the top and bottom were placed to restrict the rainfall water from entering the bare surface. Roof for the soil protection against natural rainfall was then provided and the purpose of the rainfall simulators was to provide the artificial rainfall with the required intensity for which a flow meter was used.

Design of the bottom container: The bottom container was designed as shown in Fig. 9 to collect the surface runoff volume from the bare soil surface at different intervals of time i.e., 15, 30, 45, 60, 75, 90, 105 and 120 min, respectively. A plastic scale was affixed in the container for observing the water head. The formula used for determining the water discharge from a v-notch gives:

$$Q = C_d\ 8/15\ (2g)^{1/2} \tan \Theta/2\ h^{5/2}$$

where,
Q = Flow rate
C_d = Discharge constant = 0.581
h = Head on the weir
Θ = Angle of v-notch = 90°

Determination of soil physical and chemical properties: Table 4 shows the physical and chemical properties of the top soil used in the study. The soil tests which were conducted includes particle size distribution test, water content, bulk density, porosity, plastic limit, liquid limit, plasticity index, particle density and soil pH.

RESULTS AND DISCUSSION

Determination of the erosion rates: Figure 10 shows the graph which was obtained for the soil particles detachment, observed under the rainfall intensity of 40 mm/h.

Table 3: The rainfall intensity, duration, cumulated rainfall and the kinetic energy of the recommended rainfall intensities for the Perak state

Sub run	Rainfall intensity (mm/h)	Duration (min)	Cumulated rainfall (mm)	Kinetic energy (J/m^2/mm)
1	40	15	10	25.55
2	40	30	20	25.55
3	40	45	30	25.55
4	40	60	40	25.55
5	40	75	50	25.55
6	40	90	60	25.55
7	40	105	70	25.55
8	40	120	80	25.55
9	52	15	13	26.64
10	52	30	26	26.64
11	52	45	39	26.64
12	52	60	52	26.64
13	52	75	65	26.64
14	52	90	78	26.64
15	52	105	91	26.64
16	52	120	104	26.64

Table 4: Determination of soil properties

[1]Particle size distribution test		[2]Soil water content g/g (%)	[3]Bulk density (g/cm^3)	[4]Soil porosity	[5]Plastic limit of soil (%)	[6]Liquid limit of soil (%)	[7]Particle density (mg/m^3)	[8]Soil pH
Test sizes	Retain (%)							
2 mm	100	21.6	1.46	0.4	21	46	2.61	7
1.1 mm	96.20							
600 μm	86.70							
425 μm	77.50							
300 μm	61.70							
212 μm	44.80							
150 μm	31.00							
63 μm	10.20							
Passing 63 μm	2.19							

[1]: The mechanical sieve shaker; [2]: Oven-dry method; [3, 4]: Core method; [5]: References BS 1337: Part 2: 4.3/4.4; [6]: Cone penetrometer method; [7]: References BS 1337: Part 2: 1990: 8.2; [8]: pH meter

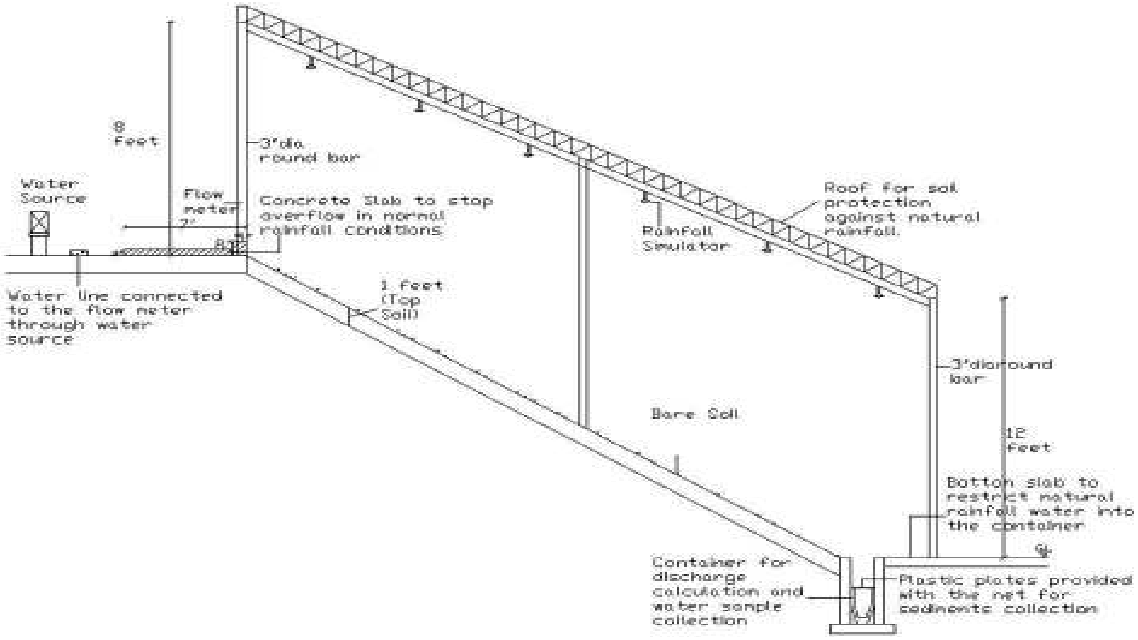

Fig. 8: The detailed drawing of the study area

Fig. 9: Details of the bottom container (a, b) bottom container view and (c) detailed drawing

Figure 11 shows the graph which was obtained for the soil particles detachment, observed under the rainfall intensity of 52 mm/h.

Estimation of water discharge: Figure 12 shows the graph which was obtained for the estimation of water discharge, observed under the rainfall intensity of 40 mm/h.

Figure 13 shows the graph which was obtained for the estimation of water discharge, observed under the rainfall intensity of 52 mm/h.

The rainfall intensities analyzed for the Perak were very close which gave close results for both the erosion and water discharge. The results obtained are in compliance with the theory. The soil loss and water discharge observed to be increasing with the increasing

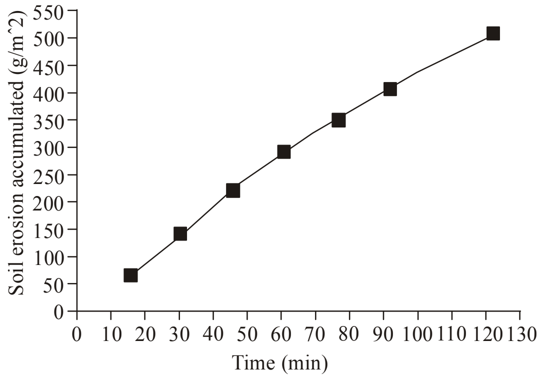

Fig. 10: The erosion rates observed under the rainfall intensity of 40 mm/h

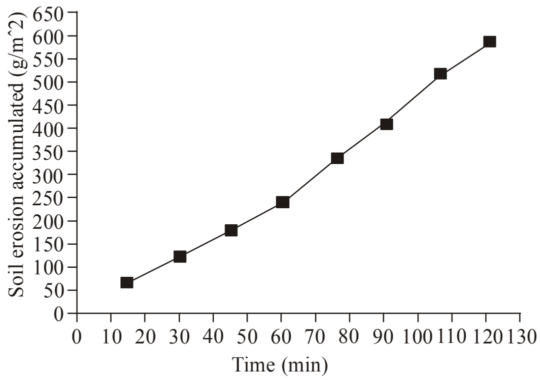

Fig. 11: The erosion rates observed under the rainfall intensity of 52 mm/h

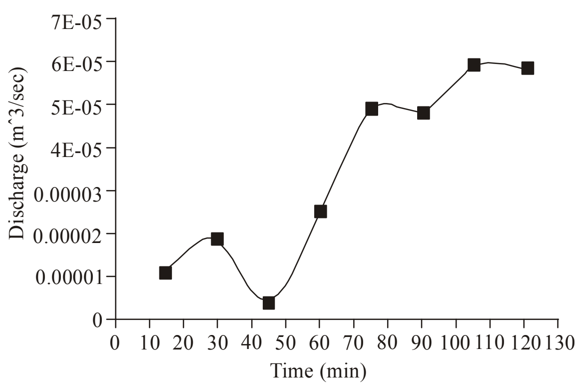

Fig. 12: The water discharge collected under the rainfall intensity of 40 mm/h

intensity i.e., 52 mm/h. The soil eroded at different rates at different intervals of time. The graphs obtained for soil erosion shows the accumulated soil loss at each interval of time. However, the volume rate of flow was found inconsistent throughout the experimental run but at one point it was found constant, the reason for which is suggested to be the water carrying capacity of the soil which got filled and did not allow the water to penetrate the soil pores aiding to the surface runoff.

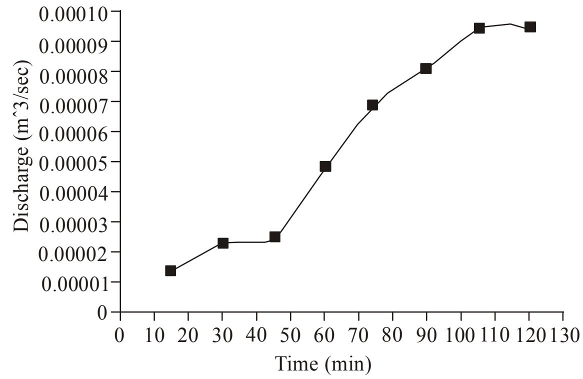

Fig. 13: The water discharge collected under the rainfall intensity of 52 mm/h

CONCLUSION

The study was observed for the rainfall data of the Perak, Malaysia. For the rainfall event of 40 mm/h the erosion rate observed at the time interval of 120 min was 500.9 g/m^2 whereas, for the rainfall event of 52 mm/h it was observed to be 578.7 g/m^2. Similarly, the discharge observed for the rainfall intensity of 40 mm/h was 5.78×10^{-5} m^3/sec whereas, for the rainfall event of 52 mm/h it was found to be 9.39×10^{-5} m^3/sec at the time interval of 120 min.

The research indicates that the construction of the newly built roads/embankments infrastructure contributes to the process of soil detachment and surface runoff which is reported as a drastic problem by several studies. However, based on the results obtained from the experiments it is recommended that once the embankments are constructed, the exposed soil surface must be protected with an appropriate cover in order to mitigate the on-site and off-site erosion impacts.

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