Rainfall induced erosion assessment on hill slope of GCE

Wan Zurina Wan Jaafar1, Md. Rabiul Islam1, Lai Sai Hin1, Normaniza Osman2

1Department of Civil Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia
2Institute of Biological Sciences, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia

Abstract: This study investigates the effect of northeast monsoon season rainfall to erosion on the hillslope of the Guthrie corridor expressway (GCE), Malaysia. The main focus of this study is to develop a relationship among the vegetation cover, slope steepness, and soil loss. A plot scale basis study area is established on hillslope along the GCE. To account for various vegetation densities, a number of five plots are proposed with various percentage of vegetation density. Experimental equipment is set up at those plots to allow collection of rainfall and soil loss for duration of five months, i.e. from November 2014 till March 2015, with twice collection per month. Based on the collected data, the effect of vegetation associated to soil loss is examined followed by propose of a new model. There are few points to summarize based on this study; 1) the observed rainfall pattern shows that mostly the recorded rainfall depth is about 5 mm with 20 minutes duration of rainfall; 2) plot without vegetation cover (i.e. NBNM) yields greater soil loss and with maximum runoff whereas the least is exhibited by the plot having natural dense microbe (NDM). Meanwhile, the planted vegetation is found affected the rate of soil loss; 3) a positive relationship is found between runoff and slope steepness regardless of the vegetation cover type; and 4) A newly proposed model reveals that higher Fv vs value implies a low density of vegetation; hence contributes to more soil loss.

Keywords: rainfall erosion; hillslope; vegetation cover; monsoon season

1Corresponding author: Email: wzurina@um.edu.my
1. Introduction

Soil erosion is one of the top-most environmental and ecological concerns in Peninsular Malaysia especially during the northeast monsoon. It causes loss of nutrient-rich topsoil and increases sedimentation, turbidity and level of pollutants in adjacent water bodies [1-6]. Construction activities and road systems account for the soil erosion and cause impact to the streams within highways [7, 8]. Construction of roads with concrete and bituminous materials changes the dynamics of plant and animal populations. It also alters the flow of materials in the landscape, due to the involvement of exotic materials and changes levels of available resources such as water, light and nutrients [9]. The disturbance of soil during construction activity is considered as a major non-point source (NPS) of water pollution by sedimentation [10-12]. Thus, construction activity is ultimately liable for the exclusion of topsoil, destruction of vegetation, surface runoff and soil erosion [13-17]. Based on the rate of sedimentation loading, surveyed throughout the US, the significance of erosion by construction sites was reported by the Azamathulla and Ghani [18]. It stated that the erosion caused by various construction sites may raise up to 500 fold, compared with erosion generated at undisturbed natural areas.

Another contributor to soil erosion is the road system. About 19% of the total land area is eroded due to the public road system [19]. Some researchers reported that most of the erosion occurred during the rainy season after a disturbance and half of the erosions were caused by roads from the logging operation. Even during low rainfall events, stream sedimentation is caused by a large volume of overland flow over linearly connected road systems through hydraulic erosion processes. Since erosion as a natural process cannot be eliminated completely, control and managing of sediment loading through best management practices (BMPs) might reduce its impact [18]. Numerous BMPs like porous pavement materials, vegetated buffers and
mulches, retention or detention basins and ponds, silt fences, hydro seeding and the placement of natural fiber mats have been proposed and implemented along highways [20-22]. Bare soil covering by grass or mulch was proposed by Zhang and Stanley [23] to control soil erosion. The intensity of surface erosion is related to the land use soil cover [24-27]. The soil coverage reduces the erosive power of rain drops and the volume of water infiltration to the soil surface [28].

An abundant use of BMPs has been proposed worldwide through different research locations, however the efficiency of some BMPs are still lacking detailed investigation [23, 29]. Considerable literature exists related to erosion control in a humid environment, but only a few studies evaluated the effect of planted and natural vegetation on sediment loss rate in active and established construction areas of hilly topography nearby highway. An evaluation of various vegetation densities that consist of planted and natural vegetation in relation to surface runoff and soil loss based on plot scale sites on hillslope adjacent to a highway is presented in this study. The significance of vegetation cover and the mutual interaction of vegetation cover and slope steepness on soil loss are also investigated.

2. Methods

2.1. Description of the Study Area

Hillslope of the Guthrie Corridor Expressway (GCE), Malaysia (latitude 3°13'12.40"N to 3°13'27.30"N; longitude 101°30'29.30"E to 101°30'50.21"E) is chosen as a study area. The annual average precipitation is about 1570 mm with average minimum and maximum temperatures of 26°C and 36°C, respectively. A number of five plots (sizes of 8 × 8 m and 5 × 5 m are established at two different locations with vegetation density varies between 5 to 95%. The average elevation is about 45 to 75 m whereas the slope percentage ranging from 50 to 80%. On
the basis of the slope values, the study area can therefore be characterized as prone to soil erosion [30]. The location and details of those plots are shown (Figure 1 and Table 1). The soil group is classified under the group B implies water infiltration rate is ranging from 3.81 to 7.62 mm h\(^{-1}\), i.e. well-to-well-draining soils. As for the soil texture, it falls under the categories of 2 and 3, i.e. fine and coarse granular.

2.2. Plot Characterization and Plant Transplantation

In this study, some of the vegetation cover is seeded with microbes. The seeds of Melastoma malabathricum L and Lantana camara L are germinated with a surrounding temperature of 30°C. About three weeks later, they are placed in a PVC pipe filled with sandy loam soil and placed in a greenhouse at the Institute of Biological Sciences, Faculty of Science, University of Malaya. When the seedlings reached about 1.0 m height, they are then transplanted to the site and a 50 g of commercialized bio-fertilizer is applied a week after transplantation. Bio-fertilizer is buried at 10 cm of soil depth adjacent to the transplanted plants in the microbe treated planted plot (PDM). A plot that received the transplantation but did not use the bio-fertilizer is named as the non-microbe planted plot (PDNM). At some plots, although the transplantation of Melastoma malabathricum L is not applied, this species is still available naturally. By applying bio-fertilizer to the naturally grown plants, the plot is characterized as natural plants with microbes (NDM). A plot that has a few naturally grown plants of similar species but without bio-fertilizer is known as a natural bare non-microbe plot (NBNM). Similarly, a plot with few naturally grown plants and with bio-fertilizer is known as a natural bare microbe plot (NBM). It should be noted that there are three things taken into account associated with a plot’s name; source of plants, i.e. either natural or planted, density of the plants and the inclusion of bio-fertilizer which indicates the presence of microbes or not.
2.3. Field Settings

In order to improve the accuracy of ground precipitation measurement, it would be ideal if the chosen location for a tipping bucket rain gauge installation is set close to the experimental plots. Therefore, a site reconnaissance survey is the first thing to do to identify the most suitable location for the rain gauge installation so that the precipitation measurement would not be hindered by anything. As the experimental plots are located on hillslope, the crown of the small territory was considered as a suitable position for the rain gauge installation [31]. A HOBO data logger is attached to the rain gauge to facilitate collection of the precipitation data. The next task is to set up a boundary plot based on the chosen size. Minimal disturbance on the slope area is the first priority in setting up the equipment. In light of this, a reasonable size of wooden barrier for establishing the square plot areas is decided whereby those plots are enclosed along their periphery by 25 cm height wooden barriers. The surface runoff collected by the plot is channeled to the sediment tank through the PVC pipe. The sketch diagram of the barrier setup and the layout plan of experimental plot with sediment tanks, pipes, barrier etc., are depicted (Figure 2 and Figure 3). As the surface runoff is collected on the plot basis, a sediment collector or tank is therefore set up at all plots and the sketch diagram of this collector is shown (Figure 4).
2.4. Surface Runoff and Sediment

The observation data of surface runoff and sediment are collected on a semi-monthly basis since the duration of this study is relatively short. It should be noted that the tank size is designed to be similar for all plots. The design capacity of the tanks is made to be sufficient to hold the surface runoff and eroded soil for the semi-month retention period. In each observation, the accumulated runoff is measured by volume and the sediment yield is determined by weight. To ensure the collected data is of high accuracy, eroded soils together with the suspended particles are both observed in this study. Therefore, water sampling tests are also performed using the TSS analyzer, for measuring concentration of suspended soil particles. The wet eroded soil deposited at the bottom of the tank (after removing the water) is taken out and weighed in the laboratory after drying it at 105±5°C for 24 hours.

The precipitation observation data is collected from November 2014 until March 2015 as monsoon season occurs within these months. The intensities of observed rainfall events that exceed 2.75 mm h\(^{-1}\) is considered as erosive rainfall and therefore are used for runoff and erosion computation. In this study, the observed rainfall and soil loss are measured at plots whereas as for runoff, the SCS method is used to derive this parameter. The collected rainfall and sediment data at plot is carried out every 15\(^{th}\) day of the month. The SCS runoff curve number method had been used to predict the potential runoff in Alor Gajah and the Jasin basin [32].

2.5. Vegetation Cover and Topography

A ground-digital camera is used to capture the actual density of vegetation. Using a portable camera, a ground image of the plot is captured vertically from 2.0 m above the ground to examine the distribution of vegetation cover based on the plot basis. Once the image is captured,
it is then processed using the maximum likelihood algorithm in the ArcGIS10.1. In each image, a few representative pixels of the two classes namely bare soil and vegetation cover are selected as a reference for the algorithm classification. However, as the different images contain different pixel counts, a weightage area for the two classes is applied in the computation. The percentage of vegetation ground cover is computed by taking a ratio between the area of vegetation cover to the total area (i.e., vegetation cover and bare surface). Despite the fact that photograph images might not have been captured with a particular scale, the results obtained are normalized as all images are acquired in the same manner. Slope steepness is measured based on the digital elevation model (DEM) of the study plot.

2.6. Vegetation and Slope Integration Factor

The vegetation cover appears to be more effective in reducing soil loss especially on hillslope. For this reason, the mutual interaction of vegetation cover and slope steepness on soil degradation is explored. Here, a new determinant of the soil erosion process is proposed, i.e. vegetation and slope integration factor ($F_{vs}$) that focusing mainly on the topography and vegetation cover. The relationship between $F_{vs}$ with the slope steepness and vegetation cover is as follows

$$F_{vs} = \left(\frac{100 - V_c}{100 + V_c}\right) \times \frac{S_s}{100}$$

(1)

where $F_{vs}$= vegetation and slope integration factor, $V_c$= vegetation cover (%), $S_s$= slope steepness (%). The magnitude of the $F_{vs}$ factor is not constant over a period of time as the vegetation cover undergoes rapid changing and the slope steepness alteration was found to be very slow. The value of $F_{vs}$ factor for all plots and their corresponding soil loss are calculated
based on direct observation followed by application of the nonlinear regression analysis to derive a relationship between the $F_{vs}$ and soil loss. The proposed equation is then validated by using data from similar studies prior to applying it to our plots.

3. Results

3.1. Rainfall and Runoff Patterns

The recorded mean monthly rainfall observation was 310, 273, 220, 77, and 240 mm respectively. A number of 121 rainfall events counted throughout the observation period with the magnitude, duration and intensity ranging from 3.6 to 52.6 mm, 15 to 396 min and 1.03 to 49.37 mm h$^{-1}$, respectively. In terms of runoff, about 21, 23, 23, 7, and 16 runoff events were obtained in November, December, January, February, and March in that order. The rainfall frequency, duration and intensity are depicted (Figure 5). There is some rainfall patterns observed throughout the period of which in most rainfall events; the highest recorded rainfall depth was about 5 mm with 20 minutes duration of rainfall that mostly occurred and with the intensity of 5 mm h$^{-1}$. The most important part of this study is to investigate the effect of vegetation on the surface runoff on hillslope area as we know the vegetation cover and slope steepness have contributed to the amount of runoff yields. The quantity of surface runoff is influenced by the vegetation types and density and simultaneously depends on slope steepness [33]. The runoff yielded in relation to the number of rainfall events for all plots is depicted (Figure 6). Out of five plots, the NBNM plot has yielded the largest amount of runoff followed by the NBM, PDM, and PDNM. The amount of surface runoff in plots NBM, PDM, and PDNM are almost similar. For the surface runoff at the NBNM plot, the amount is about equal to the event rainfall. This might be due to minimal vegetal cover and therefore less opportunity for infiltration into the subsurface to occur. Conversely, only a few events of runoff are observed at the NDM plot. Correlation
between rainfall and surface runoff is also shown (Figure 7) where most of the $R^2$ values are well correlated with their values are nearly 0.99.

3.2. Factors Affecting Surface Runoff and Soil Loss

This section investigates mainly on how the slope steepness and vegetation cover affect the surface runoff and soil loss. As the location of plot is close to each other therefore not too much variation found in terms of slope value, i.e. 77%, 78%, 68%, 56%, and 76% for NBNM, PDM, PDNM, NBM, and NDM plots, respectively. The amount of surface runoff obtained for the respective plots were 1058.77, 502.42, 438.92, 580.19, and 16.02 mm. A probable reason of surface runoff variation is due to slope steepness and the infiltration rate of which associated to the vegetation cover. In NBNM plot, the maximum runoff was obtained and it was measured 9 times higher than that of the NDM plot. In spite of high slope steepness at the NDM plot, the computed mean runoff per unit area is relatively low owing to dense vegetation throughout the plot area (Gimeno-Garcia et al. 2007). On the other hand, the rest of the plots have demonstrated a positive relationship between runoff and slope steepness regardless of the vegetation cover type. The relationship between runoff and slope steepness with the presence of a vegetation fraction is almost consistent amongst all plots [34],

Usually, plots with steeper slope had greater soil loss than those with the lower values of slope steepness [33]. The mean soil loss obtained was about 1833.4, 1173.32, 367.08, 192.42, and 11.92 g m$^{-2}$ for the NBNM, PDM, PDNM, NBM, and NDM, respectively as depicted (Figure 8). Erosion occurred at the NBNM was about 1.5, 5, and 9 times more than that of the PDM, PDNM, and NBM, respectively. On the contrary, the erosion rate was found to be lowest for the NDM plot owing to high dense developed shrubs [35, 36]. The shrubs make the top soil stable enough for protection against heavy rainfall and any detachment hazards [37, 38]. The rate
of soil loss increases with slope steepness and vice versa with the existence of vegetal coverage [39]. Hence, the erosion rate has individually demonstrated a negative and positive relationship with vegetation cover and slope steepness, respectively [40, 41]. In the steepest slope topography, the availability of vegetation cover serves as the best criterion in controlling soil erosion.

3.3. Validation of the $F_{vs}$ Equation

The next step is to validate the proposed equation as shown by Equation (1), i.e. vegetation and slope integration factor ($F_{vs}$). A number of seven similar studies have been referred here to validate the proposed equation of $F_{vs}$. Firstly, the $F_{vs}$ value is computed based on the data from the seven selected studies and finally their relationship with the soil loss is derived. The relationship between $F_{vs}$ and soil loss (SL) is illustrated (Figure 9) that reveals the proposed equation of $F_{vs}$ is somehow has a strong relationship with the soil loss and this improves our confidentiality of applying the proposed equation to study plots. It is presented the detail information about the selected studies together with their result (Table 2). Finally, the $F_{vs}$ equation is tested to study plots and result is shown (Table 3). It is noticed that a higher $F_{vs}$ value indicates a low density of vegetation and vice versa. As for the relation of $F_{vs}$ with soil loss, theoretically we would assume that lower vegetation density would contribute to more soil loss. Conversely in this case, another factor on our plot, known as microbe and planted vegetation plots, affects the interpretation of the proposed equation. Generally, comparison between NBNM and PDNM shows that a higher $F_{vs}$ value results in high soil loss and vice versa.
4. Conclusions

In this study, rainfall induced soil erosion is assessed based on the observation of soil loss and rainfall data from study plots located on hillslope of GCE with the main focus is to examine the effect of various vegetation density on the five experimental plots with either natural or planted vegetation and either with or without microbes. As the experiment incorporate natural and planted vegetation and microbes at those plots, the effect is somehow complicated. However, as for this study, the main focus is to investigate various density of vegetation at those plots in relation to soil loss that occurs during the monsoon season. In terms of vegetation, we can conclude that the naturally developed vegetation types especially fern and sod grass that grows on hillslope can contribute well in reducing the potential erosion. Based on the counted rainfall events data, the general pattern observed about the depth and duration is in most events, the frequent rainfall depth occurs is about 5 mm with 20 minutes rainfall duration. As for plots, plot without vegetation cover (i.e. NBNM) yields greater soil loss and with maximum runoff whereas the least is exhibited by the plot having natural dense microbe (NDM). Meanwhile, the planted vegetation is found affected the rate of soil loss. A positive relationship is found between runoff and slope steepness regardless of the vegetation cover type. Finally, this study has come out with a model that integrates vegetation and slope, known as $F_{vs}$. The model reveals that higher $F_{vs}$ value implies a low density of vegetation; hence contributes to more soil loss. The benefit of using the proposed model is somehow user can predict the extent of erosion to occur based on the vegetation and slope steepness data. This model, however, requires some further investigation in order to come out with the some threshold value or erosion zone classification based on the $F_{vs}$ value.
Acknowledgements:

The authors would like to acknowledge the University of Malaya for overall financial support and the PROLINTAS Expressway Sdn. Bhd., Malaysia for using their Guthrie Corridor Expressway (GCE) slopes as experimental sites. This research was carried out by University of Malaya Research Grant (UMRG) under the project “Investigate Soil Hydrological Aspects and Vegetation Cover for Slope Erosion” Project no. PR005B-13SUS.

References


Figure 1. Aerial view of the study area.

Figure 2. Sketch diagram of the barrier.
Figure 3. Layout plan of the experimental plot (a) Location 1 (b) Location 2.

Figure 4. A sketch of sediment collector.
Figure 5. Frequency distribution of rainfall duration, depth and intensity.
Figure 6. Surface runoff and rainfall events of all plots.
Figure 7. Relationships between rainfall and surface runoff.
Figure 8. Mean soil loss.

\[ F_{v5} = 0.004(SL)^{0.63} \]
\[ R^2 = 0.77 \]

\[ F_{v5} = 0.000247(SL)^{0.81} \]
\[ R^2 = 0.99 \]

\[ F_{v5} = 0.014(SL)^{0.39} \]
\[ R^2 = 0.71 \]

\[ F_{v5} = 0.00007(SL)^{0.92} \]
\[ R^2 = 0.97 \]
Figure 9. The mutual relation between slope steepness and vegetation cover with soil erosion derived based on data from literatures.
<table>
<thead>
<tr>
<th>Plots</th>
<th>Description</th>
<th>NBM</th>
<th>NBNM</th>
<th>PDM</th>
<th>PDNM</th>
<th>NDM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural Bare Microbes</td>
<td>Natural Bare Non Microbes</td>
<td>Planted Dense Microbes</td>
<td>Planted Dense Non Microbes</td>
<td>Natural Dense Microbes</td>
<td></td>
</tr>
<tr>
<td>Plot size (m × m)</td>
<td>8 × 8</td>
<td>5 × 5</td>
<td>8 × 8</td>
<td>8 × 8</td>
<td>8 × 8</td>
<td></td>
</tr>
<tr>
<td>Hydrologic soil group</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Avg. elevation (m)</td>
<td>74.39</td>
<td>75</td>
<td>76</td>
<td>76</td>
<td>44.96</td>
<td></td>
</tr>
<tr>
<td>Slope (%)</td>
<td>56</td>
<td>77</td>
<td>78</td>
<td>68</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Permeability (category)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Vegetation cover (%)</td>
<td>25</td>
<td>5</td>
<td>60</td>
<td>70</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>No. of obs.</td>
<td>No. of Plots</td>
<td>Plot Length (m)</td>
<td>Slope Steepness (%)</td>
<td>Vegetation Types / (%)</td>
<td>Equations</td>
<td>$R^2$</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>----------------</td>
<td>----------------------</td>
<td>------------------------</td>
<td>-----------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>5 to 8</td>
<td>58-80</td>
<td>Perennial grasses and leguminous herbs (5 to 96)</td>
<td>$F_{vs} = 0.004(SL)^{0.63}$</td>
<td>0.77</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>50 to 75</td>
<td>36</td>
<td>Perennial grasses and leguminous herbs (3 to 80)</td>
<td>$F_{vs} = 0.00024(SL)^{0.81}$</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>10</td>
<td>50</td>
<td>NA/(2 to 51)</td>
<td>$F_{vs} = 0.014(SL)^{0.39}$</td>
<td>0.71</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>10</td>
<td>30-50</td>
<td>Seasonal crop and forest/(0 to 95)</td>
<td>$F_{vs} = 0.000014(SL)^{0.82}$</td>
<td>0.97</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>30.5</td>
<td>25-50</td>
<td>*</td>
<td>$F_{vs} = 0.047(SL)^{0.14}$</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>30.5</td>
<td>25-50</td>
<td>*</td>
<td>$F_{vs} = 0.029(SL)^{0.20}$</td>
<td>0.71</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>30.5</td>
<td>25-50</td>
<td>*</td>
<td>$F_{vs} = 0.033(SL)^{0.18}$</td>
<td>0.87</td>
</tr>
</tbody>
</table>

* Planted cover crops (*Triticum aestivum* L and *Hordeum vulgare* L) Perennial vegetation/(30 to 47.3) NA- Not available
Table 3  Vegetation and Slope Integration Factor (Fvs) and Soil Loss (SL) of all Plots.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Vegetation cover, $V_c$ (%)</th>
<th>Slope steepness, $S_s$ (%)</th>
<th>Soil loss, SL (g m$^{-2}$)</th>
<th>$F_{vs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBNM</td>
<td>5</td>
<td>77</td>
<td>1833.45</td>
<td>0.70</td>
</tr>
<tr>
<td>PDM</td>
<td>60</td>
<td>78</td>
<td>1173.32</td>
<td>0.20</td>
</tr>
<tr>
<td>PDNM</td>
<td>70</td>
<td>68</td>
<td>367.08</td>
<td>0.12</td>
</tr>
<tr>
<td>NBM</td>
<td>25</td>
<td>56</td>
<td>192.42</td>
<td>0.34</td>
</tr>
<tr>
<td>NDM</td>
<td>96</td>
<td>76</td>
<td>11.92</td>
<td>0.02</td>
</tr>
</tbody>
</table>