Soil Erosion and Sediment Yield of a Sanitary Landfill Site – A Case Study

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Abstract - This research presents the results of a study on soil erosion rates and sediment yields of a proposed Level 4 Sanitary Landfill construction site located in Sibu, Sarawak. Assessments on potential soil erosion rates and sediment yields during pre-construction, construction and operation stages were carried out using the Revised Universal Soil Loss Equation (RUSLE) and Modified Universal Soil Loss Equation (MUSLE), respectively. It was found that soil erosion rates during construction and operation stages fell under "Moderately High" category, whereby highest sediment yield occurred during construction and operation stages. Comparative analysis on with and without Best Management Practices (BMPs) during construction stage demonstrated that BMPs could significantly reduce the rate of soil erosion, and thus sediment yields.

Keywords: Soil erosion rate, sediment yield, construction, RUSLE, MUSLE, BMPs

1. INTRODUCTION

In Malaysia, there has been an increasing concern over soil erosion due to deforestation, land conversion for highway, logging activities, industrial or urbanization purposes [1]. Runoff erosivity has been the most significant erosion factor due to high mean of annual rainfall, storm frequency and density [2]. The objectives of this research are to estimate and compare soil erosion rates and sediment yields during pre-construction, construction, and operation stages of a sanitary landfill at Sibu, Sarawak.

The proposed Level 4 Sanitary Landfill is located approximately 26 km from Sibu Town centre (Figure 1). It is a Level 4 Sanitary Landfill located at Jalan Kemuyang, Sibu, Sarawak. Comprehensive assessments on the rates of erosion and sediment yields were carried out during pre-construction, construction and post-construction stages. The topography of the region comprises of generally rolling and flat lands, well-drained by tributaries of Sg. Lukut running along the northeast boundary of the proposed landfill site (Figure 1). There are relatively lower spots at the north part of the landfill site, mainly swampy land. The landfill area is predominantly underlain by Tertiary Eocene sediments; namely Pelagus Formation and a small portion by Pleistocene-Holocene sediments.

The two main streams draining the site catchment are Sungai Lukut and Sungai Pasai, whereby Sungai Lukut is the tributary of Sungai Pasai. The annual rainfall pattern varies from year-to-year with distinct dry and wet seasons, which shows the characteristic influence of the monsoon seasons. The region experiences rather heavy rainfall during the peak of the Northeast monsoon, receiving more than 400 mm in December and 500 mm in January. The total annual rainfall is relatively high that varies between 110.2 mm during the El Nino years to above 4,500 mm during the wet years.

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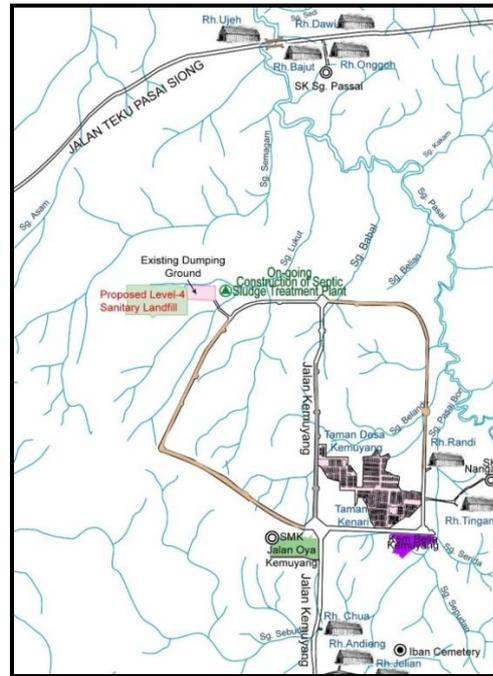[3] Law, P.L., Prof, Civil Engineering Department, Universiti Malaysia Sarawak (e-mail: puonglaw@feng.unimas.my)

Figure 1: Locality of Proposed Level 4 Sanitary Landfill, Jln Kemuyang, Sibu

Since, the early 1980s, the United States Department of Agriculture (USDA) has used the Universal Soil-Loss Equation (USLE) to estimate the severity of soil and sediment yield from disturbed land surface. Lately, a refined and revised equation called Revised Universal Soil-Loss Equation (RUSLE) that can be applied to many more field conditions, provides much more site-specific value than does the USLE, and to overcome major limitations of the USLE for predicting rainfall erosion losses. Generally, the RUSLE equation can be written as follow**:**

$$\mathbf{RUSLE = R \times K \times LS \times C \times P} \tag{1}$$

where,   RUSLE = Average annual soil loss in unit $[tons.(ha.yr)^{-1}]$
            R = Rainfall/runoff erosivity in unit $[Mj.mm.(ha.h.yr)^{-1}]$
            K = Soil erodibility in unit $[tons.ha.h.(ha.Mj.mm)^{-1}]$
            LS = Slope length and steepness factor
            C = Cover-management factor
            P = Erosion control practice factor

In this study, the R factor was estimated using Foster's Method according to the following equation [4]**:**

$$\mathbf{R = 0.276P \times \left(\frac{I_{30}}{173}.6\right)} \tag{2}$$

where,   P   = mean annual rainfall in mm, and
                  I_{30} = maximum 30-minute rainfall intensity.

Appropriate LS value could be obtained from the following equation**:**

$$\mathbf{LS = (0.065 = 0.045S + 0.0065S^2) \times \sqrt{\frac{L}{22}}.13} \tag{3}$$

where, *L* is in metre (m) and S in percent (%).

In additional to RUSLE equation, another soil loss equation was established in 1975, namely the Modified Universal Soil Loss Equation (MUSLE) or also called Single Event Sediment Yields [5]. In this equation, the rainfall energy or runoff erosivity factor, R in the USLE was replaced with a term that includes both the peak discharge and total amount volume of runoff applied to the field to determine the sediment yield during a specific storm event [5]. Generally, the MUSLE equation is expressed as:

$$\text{MUSLE} = 11.8 \times \left(\left(V \times Q_p \right)^0 .56 \right) \times K \times LS \times C \times P \tag{4}$$

where

$$
\begin{aligned}
\text{MUSLE} &= \text{Sediment yield (tons)} \\
V &= \text{Runoff volume (m}^3) \\
Q_p &= \text{Peak runoff rate (m}^3.\text{sec}^{-1})
\end{aligned}
$$

The peak runoff rate can be determined by using rational formula with the equation described as follow:

$$Q_p = \frac{CIA}{360} \tag{5}$$

The runoff coefficient, C, represents the percentage of rainfall which is related to multiple hydrologic processes. In a non-homogeneous drainage area, C should be calculated as an area-weighted composite of the different land uses in the watershed. The intensity, I can be obtained from Rainfall Intensity, Duration and Frequency Curve (IDF Curves) [6]. A is the drainage area. The IDF curve summarizes the conditional probabilities or frequencies of rainfall depth or average intensities at a particular location. These variables, i.e. intensity, duration and frequency are all related to each other [7].

The SCS Curve Number Runoff relates a calculated Runoff Curve Number (CN) to runoff, accounting for initial abstraction losses and infiltration rates of soils. The fundamentals rainfall-runoff equations are as follows [8]:

$$Q_p = \frac{([P - I_a)]^2}{(P - I_a) + S} \tag{6}$$

Initial abstraction (I_a) is all losses before runoff begins, which includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover factors. From the previous studies on small agricultural watersheds, I_a can be approximated by the following empirical equation:

$$I_a = 0.2S \tag{7}$$

While I_a is an independent parameter, this approximation allows the use of a combination of S and P to produce a unique runoff amount. Substituting (7) into (6) gives:

$$Q_p = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{8}$$

S is related to the soil and cover conditions of the watershed as represented by the value of Runoff Curve Number (CN). Generally, CN values range from 0 to 100, and S is related to CN by:

$$S = \left(\frac{1000}{CN} \right) - 10 \tag{9}$$

For a given CN and precipitation depth, the volume of runoff can be calculated using Equation 8 and Equation 9. The CN value can be expressed as a function of soil characteristics, hydrologic condition and cover or land use. For watersheds with multiple soil types or land uses, an area-weighted CN should be used. When significant differences in land use or natural control points exist, the watershed should be divided up into smaller drainage areas for modeling purposes. Many factors can affect the erosion and sedimentation processes especially in construction development. In this study, the RUSLE and MUSLE concepts were used as measurements of soil erosion for specific combinations of physical and

management conditions in the proposed landfill site, in addition to taking into consideration the suitability and data dependant factors.

During construction stage, the Erosion and Sedimentation Control Plan (ESCP) is generally regarded as a comprehensive plan designed to address the temporary and permanent mitigation of erosion and sedimentation hazards on disturbed soil surfaces. The objectives of ESCP are to implement temporary or permanent erosion and sedimentation mitigation measures. The plans also aim to identify, reduce, eliminate, or prevent the pollution of stormwater as well as the water quality of nearby watercourses by controlling peak rates and volumes of runoff outfalls and downstream of the outfalls.

II.   MATERIALS AND METHOD

An integrated approach for the assessment of the soil erosion rate and sediment yield for different construction stages, and recommended appropriate mitigation measures for the project site is shown in Figure 2. Preliminary investigation and identification of the study area were carried out prior to the erosion analysis. In this study, RUSLE and MUSLE equations were used to estimate the soil erosion rates and sediment yields at the project site. The equations and the relevant factors are shown in Equation 1 to Equation 9.
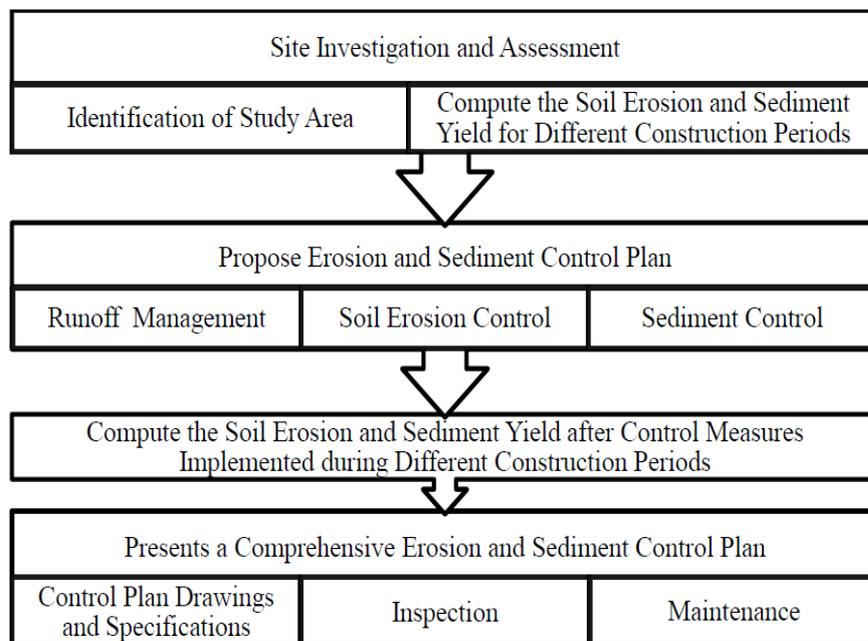

Figure 2: Erosion Rate and Sediment Yield and Mitigation Measures

Since comprehensive rainfall records are not available, the rainfall observations obtained from Jabatan Kerja Raya, Sibu, Sarawak was used to represent the rainfall condition at the landfill site, as it is the nearest rainfall station in Sibu Division or Central Zone of Sarawak. The R factor was estimated using Foster's Method as shown in Equation 2 [4]. The monthly average rainfall was used to determine the mean annual rainfall and the *Rainfall Intensity-Duration-Frequency Curve* for 30 minute in 5 years return period was used to estimate the R factor [6].

Due to the absence of empirical value, the K factor of a soil was determined from *USDA Soil Erodibility Nomograph* during pre-construction, construction, and operation stages [9]. The K factor is related to the class of land-component map on the basis of percentages of sand, silt, very fine sand, organic matters, soil structure and permeability [9]. The basis of percent of sand, percent of silt plus very fine sand parameters was determined from the soil particle size distribution analysis for the landfill site. The percentage of organic matters was obtained from the *Test Report* of the landfill site by taking the average percentage of organic matters content of the 16 borehole log data in the disturbed samples. The soil structure categories were determined from the *USDA Soil Structure Classes* [9]**.** The permeability value

was estimated using borehole drilling test method and the results were compared to the *USDA Soil Permeability Classes* [9]**.**

The landfill site is located on existing ground levels between 8.5–16.0 meters contour levels, and the site will be elevated to a design elevations ranging from 10.0 – 22.5 meters contour level. Site stripping, excavation, and grading on exposes soil shall alter slope gradient and slope length. Therefore, the potential erosion and sedimentation shall most likely to occur along the project alignments during construction stage. During operation stage, slope length is generally not significant as the elevation is same as the design level. Therefore, the slope length (LS) during construction stage and operation stage shall be considered the same.

As shown in Figure 4 and Figure 5, a total of 13 different slope lengths for the individual "micro-catchments" had been estimated in the process of determining the value of C during pre-construction, construction, and operation stages with reference to *Cover Management Factor (C) for Construction Sites* [10]. However, the P value was determined by using the *Surface Condition for Construction Sites* [10].

The peak flow, Q_p was determined using *Rational Formula* by delineating the watershed boundary and computing the landfill area. Then the rainfall intensity, *i* for the 5-Yr design storm was determined with reference to the *IDF Curve* [6]. The runoff coefficient was adopted from the *Runoff Coefficients for Rational Equation* to determine the peak flowrate, Q_p [11].

Additionally, the *SCS Curve Number Runoff Method* was used to determine the volume of runoff by using the *Runoff Curve Numbers for Undeveloped Land* [10]. The *Hydrologic Soil Groups* (HSGs) in *USDA Manual, 1986* describes the water absorption in soil after a period of prolonged wetting and the data were used to determine the CN values [10].
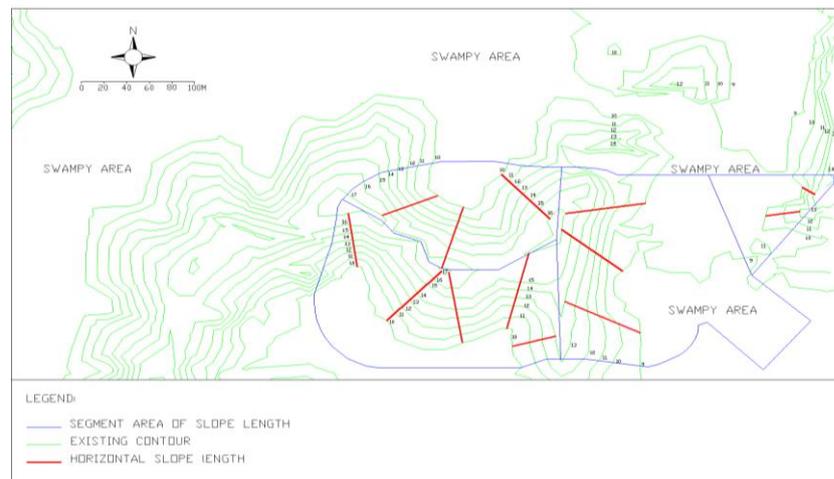

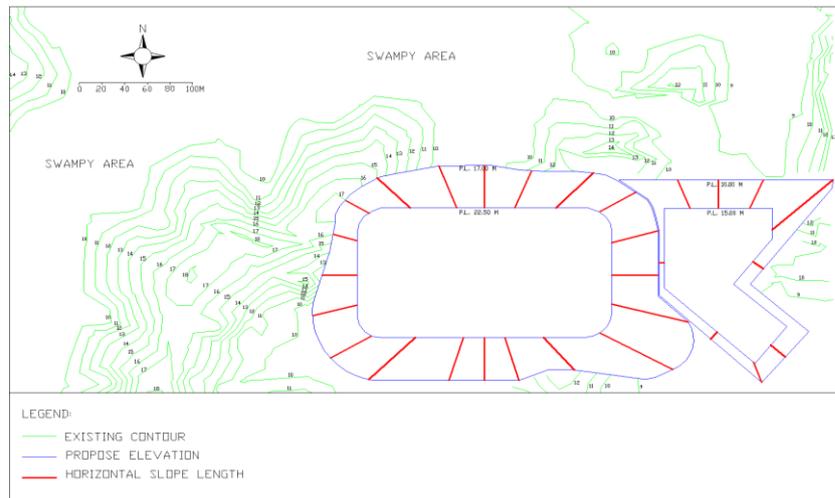Figure 3: Estimated Slope Lengths during Pre-Construction Stage

Figure 4:   Estimated Slope Lengths during Construction Stage

III. RESULTS AND DISCUSSION

Soil erosion rates were estimated using the Revised Universal Soil Loss Equation (RUSLE), while sediment yields were predicted using the Modified Universal Soil Loss Equation (MUSLE). The mean annual rainfall in Year 2003 recorded at *Sibu JKR Water Board* Station was 270.54 mm for the region [6]. From the *Rainfall Intensity-Duration-Frequency Curve*, it was determined that the value of rainfall intensity, *I* for 30-minute 5 years return period was approximately 99 mm.hr^{-1}. From Equation 2, the rainfall runoff erosivity, R was found to be 42.58 Mj.mm.(ha.h.yr)$^{-1}$.

Analysis on the soil samples collected from project site showed that the soil types ranged from very soft clay, clayed silt to firm sandy silt. The particle size distribution analysis showed that the average percentage of silt (including very fine sand), sand and organic matters were 78.59%, 1.22% and 0.128%, respectively. The average soil permeability at landfill site was found to be 1.15 x 10^{-5} cm.s^{-1}, and the K factor for the landfill site was 0.46 tons.ha.h.(ha.Mj.mm)$^{-1}$.

The maximum LS values at site were found to be 3.16 during pre-construction stage and 3.59 during construction and operation stages. The soil at site would be disturbed during earthwork and the existing vegetation would have to be cleared and removed for cut-and-fill activities. Based on the *Cover Management Factor (C) for Construction Sites*, the C value of 0.01 would be used during pre-construction stage as an undisturbed condition [10]. During construction and operation stages, C value of 1.0 would be used for cleared or bare soil surfaces and no re-vegetation conditions.

Based on the *Surface Condition for Construction Sites*, *w*hen no activities are carried out on the landfill site, a default P value of 1.0 would be used [10]. During construction stage, construction activities such as grading, excavating, cutting and filling would disturb the soil by loosening the particles of soil and thus reducing the soil's shear strength, which may lead to surface runoff caused by heavy rain water. Thus, a P value of 1.3 would be used. After the construction period, considering the project site is rough, irregular surface equipment tracks in all directions, P value of 0.9 would be used.

The runoff coefficient, *C* and the peak flow, Q_p used in the Rational Formula was computed in Table 1 whilst the Runoff Curve Number, CN and Runoff Volume, V were calculated in Table 2 for different construction stages. Table 3 and Table 4 show the predicted soil erosion rates and sediment yields without control measures onsite during different construction stages, whilst Table 5 and Table 6 show the estimated soil erosion rates and sediment yields with BMP control measures onsite. The BMP control measures proposed for this research are stated in Table 7 for different construction stages whilst the proposed locations and methods of application are shown in Figures 5, 6, 7, 8 and 9.

As shown in Tables 2, 3, 4, 5 and 6, the potential soil erosion rates and sediment yields after implementation of BMPs control measures during different construction stages could effectively reduce the impacts from 91.4 and 954.8 to 1.62 and 24.8 tons.(ha.yr)$^{-1}$, respectively. During operation stage, the

soil erosion rates and sediment yields would decrease from 63.3 and 1042.4 to 0.54 and 14.9 tons.(ha.yr)[-1], respectively. According to the *Classification of Soil Erosion Risk* under *Department of Environment* [12], BMP is very effective and able to reduce the potential soil loss from Moderate-High Soil Loss Risk to Low Risk, as shown in Table 8. With BMP onsite, it was showed that a decrease of 97.4% in soil erosion rate and more than 98% sediment reduction during both the construction and operation stages.

Table 1: Runoff Coefficient, C and Peak Flow, Q_p vs Construction Stage

Stage	Area (m^2)	Area (ha)	Average slope	Coefficient, C	Rainfall Intensity, I (mm.hr^{-1})	Peak Flow, Q_p (m^3.s^{-1})	Total
Pre -Construction	14720.64	1.472	0.11	0.2	99	0.081	
	24302.70	2.430	0.10	0.2	99	0.134	0.415
	36493.17	3.649	0.12	0.2	99	0.201	
Construction	17426.68	1.743	0.17	0.5	99	0.240	1.038
	58089.83	5.809	0.17	0.5	99	0.799	
Operation	17426.68	1.743	0.17	0.6	99	0.288	1.246
	58089.83	5.809	0.17	0.6	99	0.958	

Table 2: Runoff Curve Number, CN and Runoff Volume, V vs Construction Stage

Stage	Rainfall Depth (mm)	Rainfall Depth (in)	HSGs	CN	S	Runoff Depth, Q (in)	Runoff Depth (m)	Area of Site (m^2)	Runoff Volume (m^3)
Pre-Construction	49.5	1.95	D	86	1.628	0.811	0.021	75516.51	1556.24
During Construction	49.5	1.95	D	74	3.514	0.327	0.008	75516.51	626.81
Operation	49.5	1.95	D	82	2.195	0.616	0.016	75516.51	1181.61

Table 3: Predicted Soil Erosion Rates vs Construction Stages (without Control Measures)

Stage	R [Mj.mm.(ha.h.yr)$^{-1}$]	K [tons.ha.h.(ha.Mj.mm)$^{-1}$]	LS	C	P	RUSLE (tons.{ha.yr}$^{-1}$)
Pre-construction	42.58	0.46	3.16	0.01	1	0.619
During Construction Without Control	42.58	0.46	3.59	1.0	1.3	91.412
Operation Stage	42.58	0.46	3.59	1.0	0.9	63.285

Table 4: Predicted Sediment Yields vs Construction Stages (Without Control Measures)

Stage	Q_p (m^3.s^{-1})	V, (m^3)	K [tons.ha.h.(ha.Mj.mm)$^{-1}$]	LS	C	P	MUSLE (tons)
Pre-construction	0.415	1556.24	0.46	3.16	0.01	1	6.43
During Construction Without Control	1.038	628.81	0.46	3.59	1.0	1.3	954.81
Operation Stage	1.246	1181.61	0.46	3.59	1.0	0.9	1042.44

Table 5: Soil Erosion Rates with Implementation of BMP Control Measures

Stage	R	K	LS	C	P	Effectiveness of Sediment Control Factor					RUSLE (tons.{ha .yr}$^{-1}$)
						Earth Bund	Silt Fence	Silt Trap	Check dams	Stabilized Construction Exit	
During Construction Without Control	42.58	0.46	3.59	0.1	1.0	0.95	0.95	0.85	0.4	0.75	1.618
Operation Stage	42.58	0.46	3.59	0.01	0.9	-	-	0.85	-	-	0.538

Table 6: Sediment Yields with Implementation of BMP Control Measures

Stage	Q_p	V	K	LS	C	P	Effectiveness of Sediment Control Factor					MUSLE (tons)
							Earth Bund	Silt Fence	Silt Trap	Check dams	Stabilized Construction Exit	
During Construction Without Control	1.038	628.81	0.46	3.59	0.1	1.0	0.95	0.95	0.85	0.4	0.75	24.806
Operation Stage	1.246	1181.61	0.46	3.59	0.01	0.9	-	-	0.85	-	-	14.928

Table 7: Proposed Erosion and Sediment Control Measures

BMPs Control Measures	Construction Stage	Operation Stage
Sediment Control		
Silt Fence	√	
Check Dams	√	
Silt Trap	√	√
Stabilized Construction Exits	√	
Erosion Prevention Controls		
Seeding / re-vegetation / turfing	√	√
Appropriate Earthwork Operation	√	

Table 8: Classification of Potential Soil Loss

Classification of Soil Loss	Potential Soil Loss/Erosion Rate (tons/ha/yr)
Low	0 – 10
Moderate	10 – 50
Moderate High	50 – 100
High	100 – 150
Very High	Above 150

Source: State Environmental Conservation Department (ECD), Sabah, Malaysia
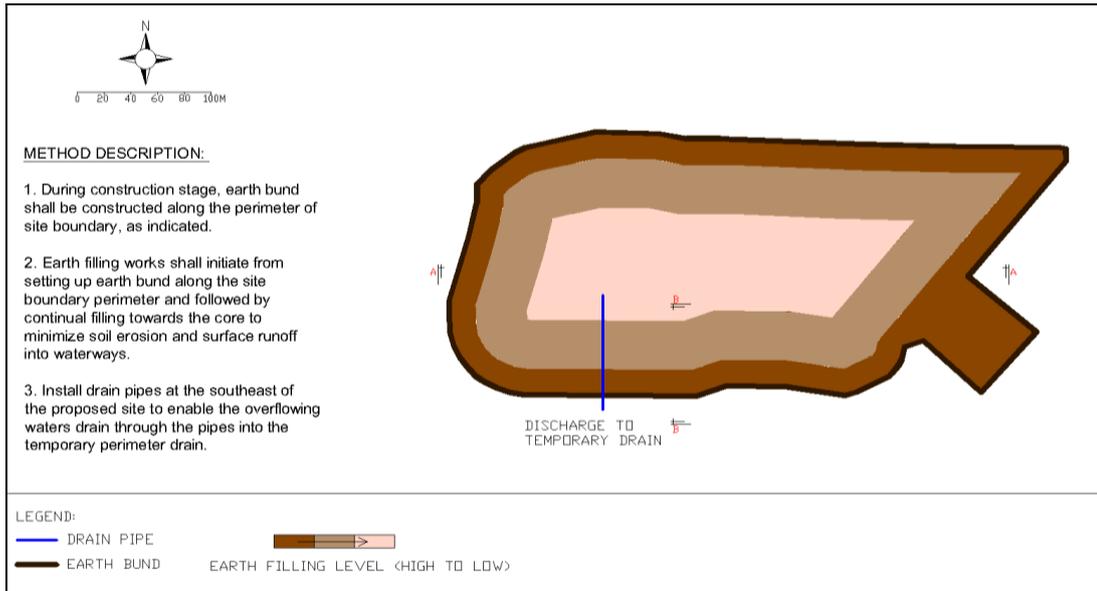
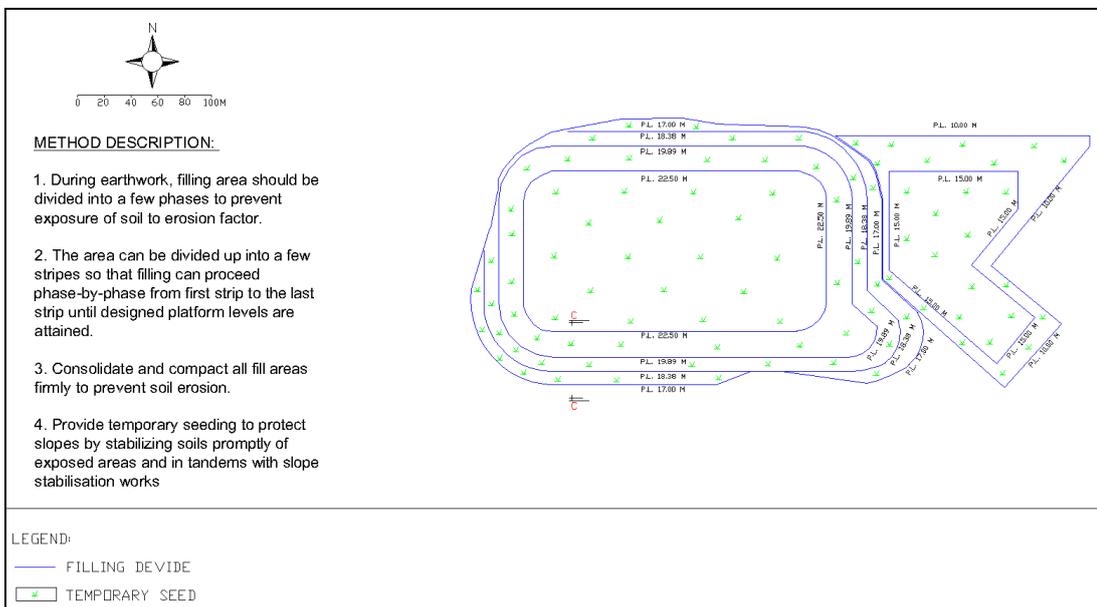

Figure 5: Temporary Earth Filling Method

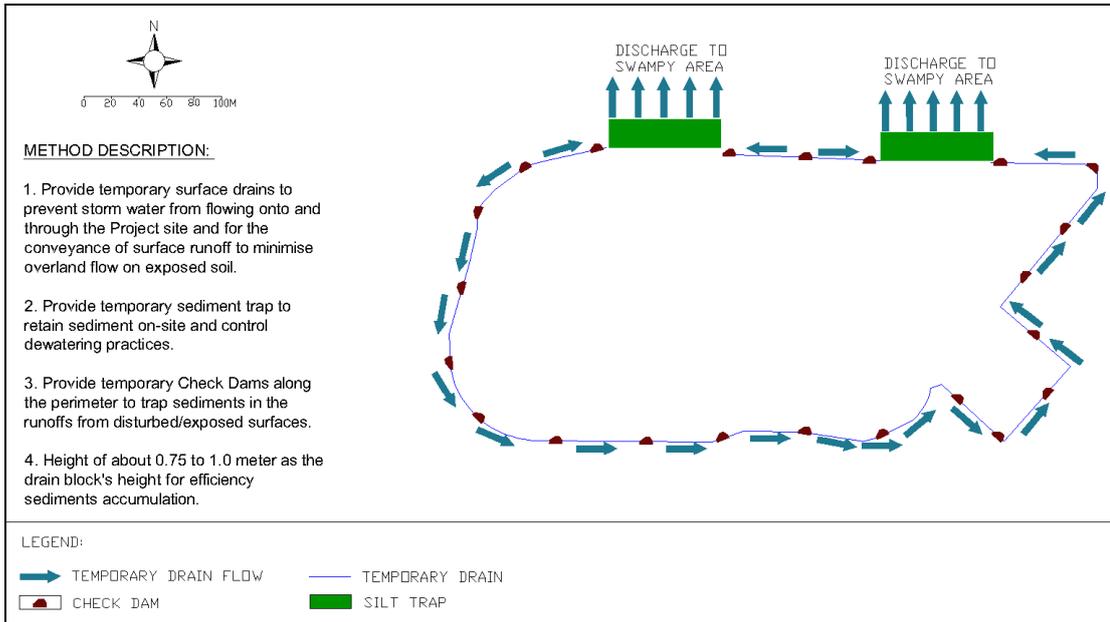Figure 6: Temporary Phasing of Filling & Seeding Area

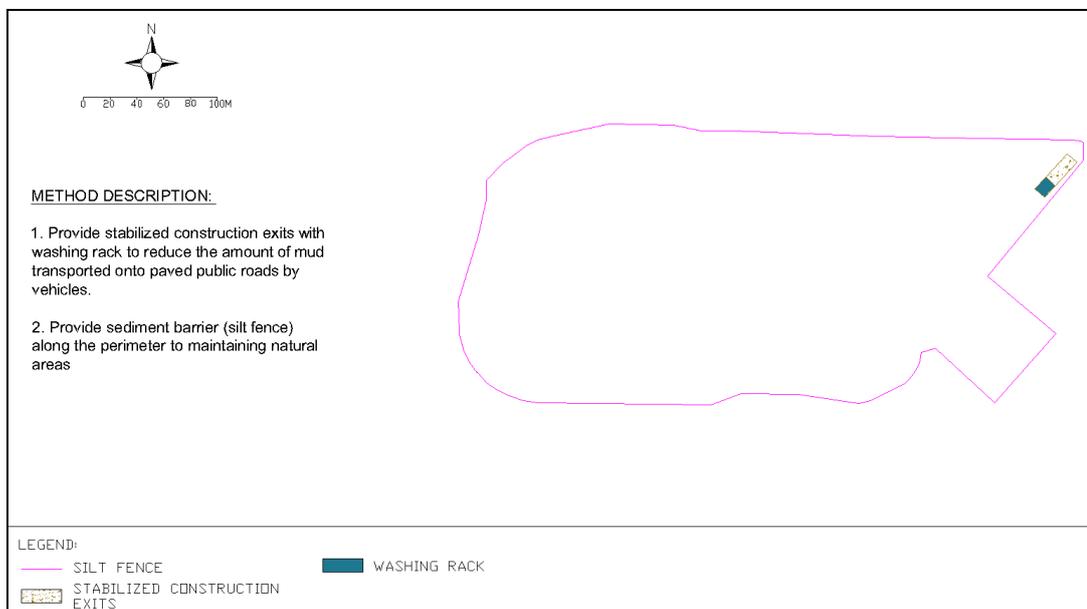Figure 7: Temporary Earth drain, Silt Trap and Check Dams

Figure 8: Temporary Stabilized Construction Exits and Silt Fence along Site Boundary
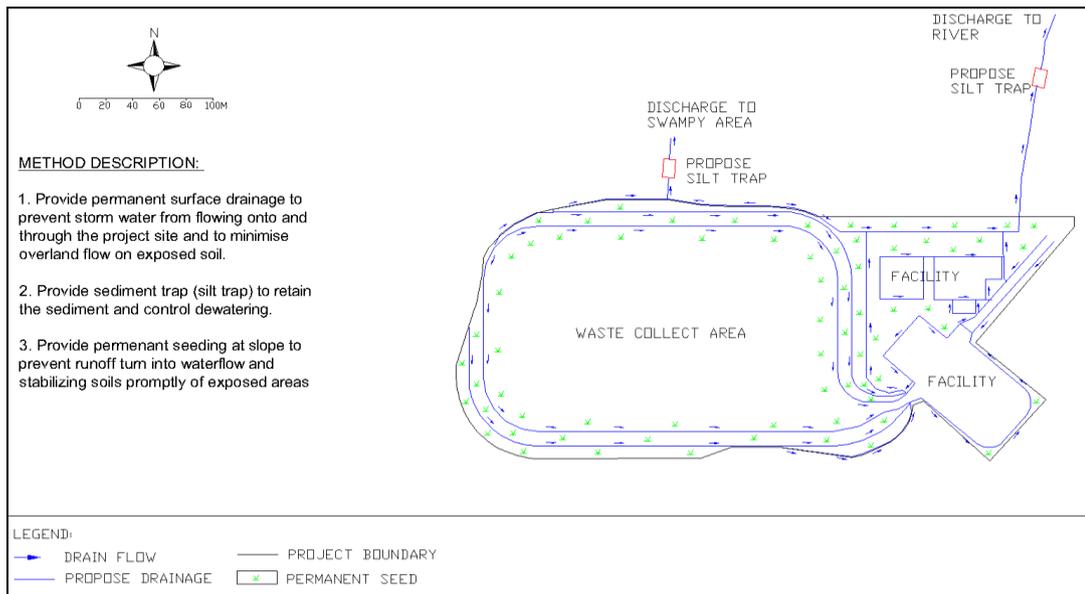
Figure 9: Permanent Seeding, Drainage, and Silt Trap Systems

IV. CONCLUSIONS

With BMP control measures onsite, the soil erosion rates during construction and operation stages could be reduced from "Moderate-High Soil Loss Class" (between $50 - 100$ tons.{ha.yr}$^{-1}$) to "Low Soil Loss Class" (between $0 - 10$ tons.{ha.yr}$^{-1}$). Similarly, after implementing BMP control measures onsite, sediments yields on a single storm event during construction can be reduced from 954.81 to 16.90 tons/storm event, and during operation stage from 1,042.44 to 8.86 tons/storm event. It can also be concluded that the most effective factor to reduce the potential of soil erosion rates and sediment yields was proper cover management. The implementation of seeding has shown a significant decrease in soil erosion rate and sediment yield due to its effectiveness in resisting rainfall impact through soil stabilizing effects caused by roots, and thus enhance sediment trapping capability and finally slowing down the runoff of both water and sediments.

ACKNOWLEDGMENT

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