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Original Research Article

# Erosion risk assessment: A case study of the Langat River bank in Malaysia☆

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## ABSTRACT

River bank erosion is one of the major and unpredictable hazards worldwide including in Malaysia. Soil detachment at river banks is due to two processes: 1) hydraulic erosion imposed by channel flow and 2) sub aerial erosion due to the weakening and weathering of bank materials. This paper is focused on the second aspect of the erosion process which mainly depends on the combination of rainfall intensity and the ability of the soil to withstand the raindrop effects. The relative combination of sand, silt and clay in a soil is argued to have an impact on erosion resistance. In cohesive soil composition, sand forms the largest size ranging from 0.05 to 2 mm whereas silt is adequately moderate (ranging from 0.002 to 0.05 mm) and clay is the smallest of all three (less than 0.002 mm). With the knowledge that soil composition does indeed have an effect on erosion resistance, this paper will attempt to relate risk assessment index of river bank erosion specifically to soil composition. Thus, the objectives of this document are as follows; 1) to produce risk assessment index for river bank erosion and 2) to carry out a case study for selected rivers in Malaysia pertaining to river bank assessment. The index is produced by inferring the previously developed scale on soil erodibility. Past researchers created the “ROM” scale (named after the researchers, Rolan and Mazidah) to assess degree of soil erodibility into five classes namely “critical”, “very high”, “high”, “medium” and “low”. Instead of using semi empirical formula from the “ROM” scale, a percentage of soil composition was inferred to produce risk assessment index. It was found that as the percentage of clay decreased, susceptibility index became higher and approached a critical level. Application of the newly developed index is verified by conducting a case study at the Langat River, Kajang, Malaysia. The soil composition was classified and form fitted into the index. It was found that the middle reach of the Langat river is susceptible to severe erosion due to low percentage of clay. This finding agreed well with the visual observation of these reaches as a large portion of gully type of erosion had been observed throughout the study. The establishment of risk assessment index which firmly indicates the relationship between soil composition and river bank erosion can be used as a tool in forecasting the risk levels. This formulation is well proven to assess river bank conditions and the associated critical shear stress is very much close with the previously published shear stress.

## 1. Introduction

Over the past decade, there has been a dramatic increase of causes related to soil erosion. Soil erosion, is a natural process that continuously occurs without any symptoms or warning signs, and has been identified as a serious issue for decades. It is predicted to become even more critical in the future as a result of uncontrolled development. Julien (2012) hypothesized that the natural processes of erosion and sedimentation have been active throughout geological time and have shaped the present landscape of our world. River bank erosion would cause the riverbed to degrade and dump particles and sediments into receiving water body. The bedform particles, along with river bank particles, would be detached from their interlocking due to the action of water flow. The transportable particles would the start to move and deposit at the downstream part of a river section (see Fig. 1). This process would cause severe engineering and environmental problems if monitoring programs are not well-managed and practiced.

Based on past researches, two major agents of erosion were found; wind and water (Musa, Abdulwaheed, & Saidu, 2010). Water is perceived in many parts of the world as the most common agent of soil erosion. The influence of water as an agent includes the degradation of river basin, landform and seashore. Water erodes soil and

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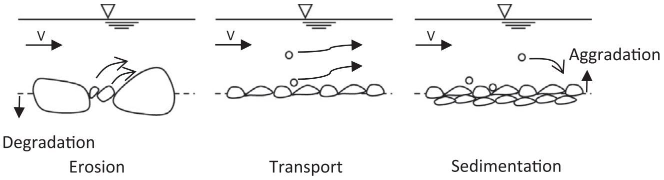


**Fig. 1.** The sequential process of erosion, transport and sedimentation.

**Table 1**
The "ROM" Scale (Zainal Abidin & Mukri, 2002).

| 'ROM' scale | Soil erodibility category |
|---|---|
| < 1.5 | Low |
| 1.5–4.0 | Moderate |
| 4.0–8.0 | High |
| 8.0–12.0 | Very high |
| > 12.0 | Critical |

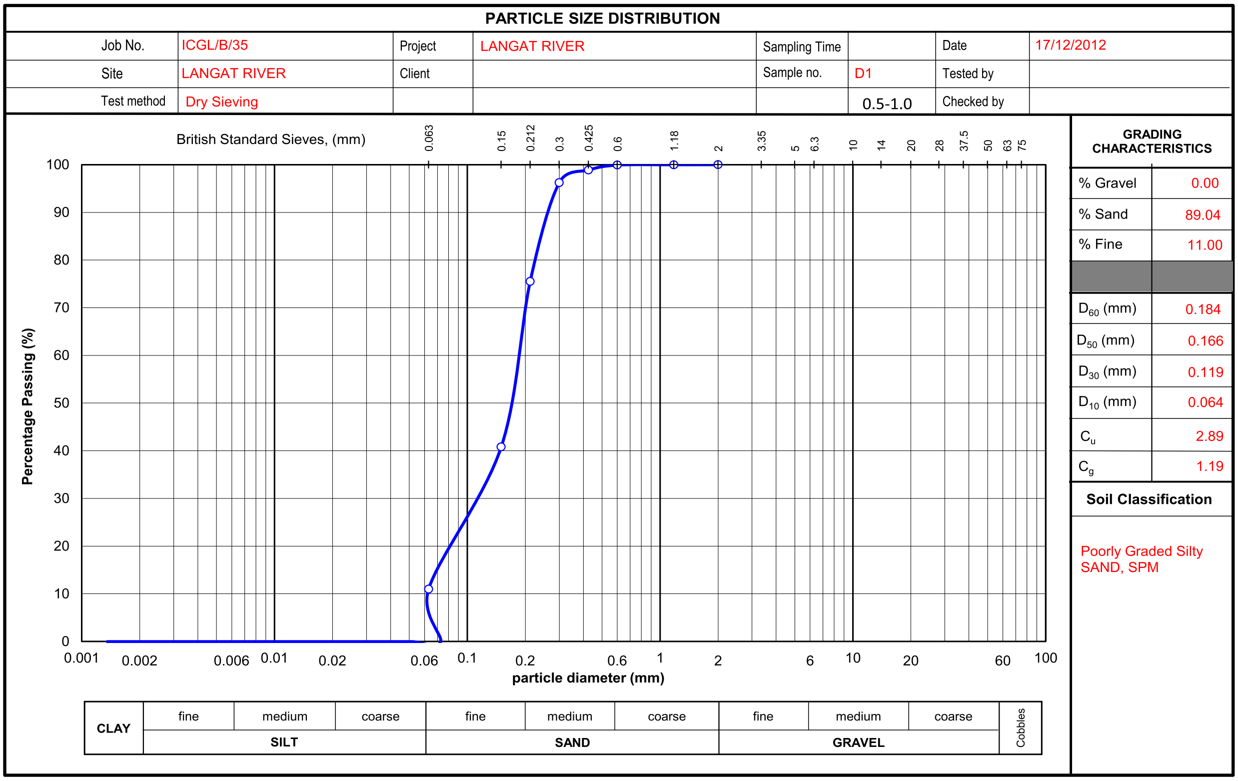
transports soil particles from higher altitudes and deposits them in low lying areas. Water has been identified as a major cause of soil erosion problems, compared to wind (Singer & Munns, 1999).

Malaysia, due to its tropical rainforest climate relatively has a hot and humid condition throughout the year and thus is identified to be prone to soil erosion. An average annual rainfall exceeding 2000 mm in Malaysia is above the global average. The highest annual rainfall ever recorded in the history of Malaysia was 5293 mm (NAHRIM, 2008). Heavy rainfalls can have adverse effects on soil particles because it heightens the ability of raindrops to detach particles. This phenomenon, also known as rainfall erositivity, greatly depends on rainfall intensity, kinetic energy and seasonal distribution of the rain as an impetus (Caracciola et al., 2012). Rainfalls with high intensities and low frequencies produces more erosion compared to rainfalls with high frequencies and low intensities (Wei et al., 2007). The amount of soil erosion loss depends upon the combination of the strength of the rain to cause erosion and the ability of the soil to withstand the rain.

**Table 2**
Percentage of occupy for clay, silt and sand.

| 'ROM' scale | Soil erodibility category | % Clay | % Silt | % Sand |
|---|---|---|---|---|
| 0.5 | Low | 50 | 30 | 20 |
| 3 | Moderate | 14 | 60 | 24 |
| 5.75 | High | 8 | 30 | 62 |
| 9.5 | Very high | 5 | 25 | 70 |
| 49.5 | Critical | 1 | 26 | 73 |

Soil resistance against erosion is termed as soil erodibility and its value greatly depends on several factors such as soil structure, infiltration levels and organic matter content. River bank erosions could lead to the accumulation of sediment which in turn increases river pollution problems. The capacity of sediments flushing depends on the rate of the river flow. The initiation of sediment movement is highly anticipated by the action of velocity, bedform conditions and kinetic energies at the river bed (Yang, 2006). If the shear stress imposed by the flow exceeds the particle shear stress, then the particles start to move (Sulaiman, Sinnakaudan, & Shukor, 2013). More particles are transported if the imposed shear by the flow action exceeds the particle shear stress. However, the imposed shear by the action water flow starts to decrease at the downstream portion of river network due to a tranquil flow (Cengal & Cimbala, 2006). This phenomenon could lead to deposition or sedimentation at the downstream part of the river network. In Malaysia, the average suspended sediment concentration in the rivers due to soil erosion rose by 34% in 1998 (Mastura, Al-Toum, & Jaafar, 2003). During rainfall, sediments and eroded soil are flushed out to downstream where sedimentation takes place, hence resulting in the downstream becoming shallower and waters to be milky. This situation leads to water scarcity, flash floods and other environmental problems. It is important to acknowledge that soil detachment and subsequent entrainment at river bank section originates from two main processes; hydraulic erosion and subaerial erosion. Julian and Torres (2006) provided an in-depth



PARTICLE SIZE DISTRIBUTION

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Job No. | ICGL/B/35 | Project | LANGAT RIVER | Sampling Time | | Date | 17/12/2012 |
| Site | LANGAT RIVER | Client | | Sample no. | D1 | Tested by | |
| Test method | Dry Sieving | | | | 0.5-1.0 | Checked by | |

GRADING CHARACTERISTICS

| | |
|---|---|
| % Gravel | 0.00 |
| % Sand | 89.04 |
| % Fine | 11.00 |
| $D_{60}$ (mm) | 0.184 |
| $D_{50}$ (mm) | 0.166 |
| $D_{30}$ (mm) | 0.119 |
| $D_{10}$ (mm) | 0.064 |
| $C_u$ | 2.89 |
| $C_g$ | 1.19 |

Soil Classification

Poorly Graded Silty SAND, SPM

**Fig. 2.** Grain size distribution.

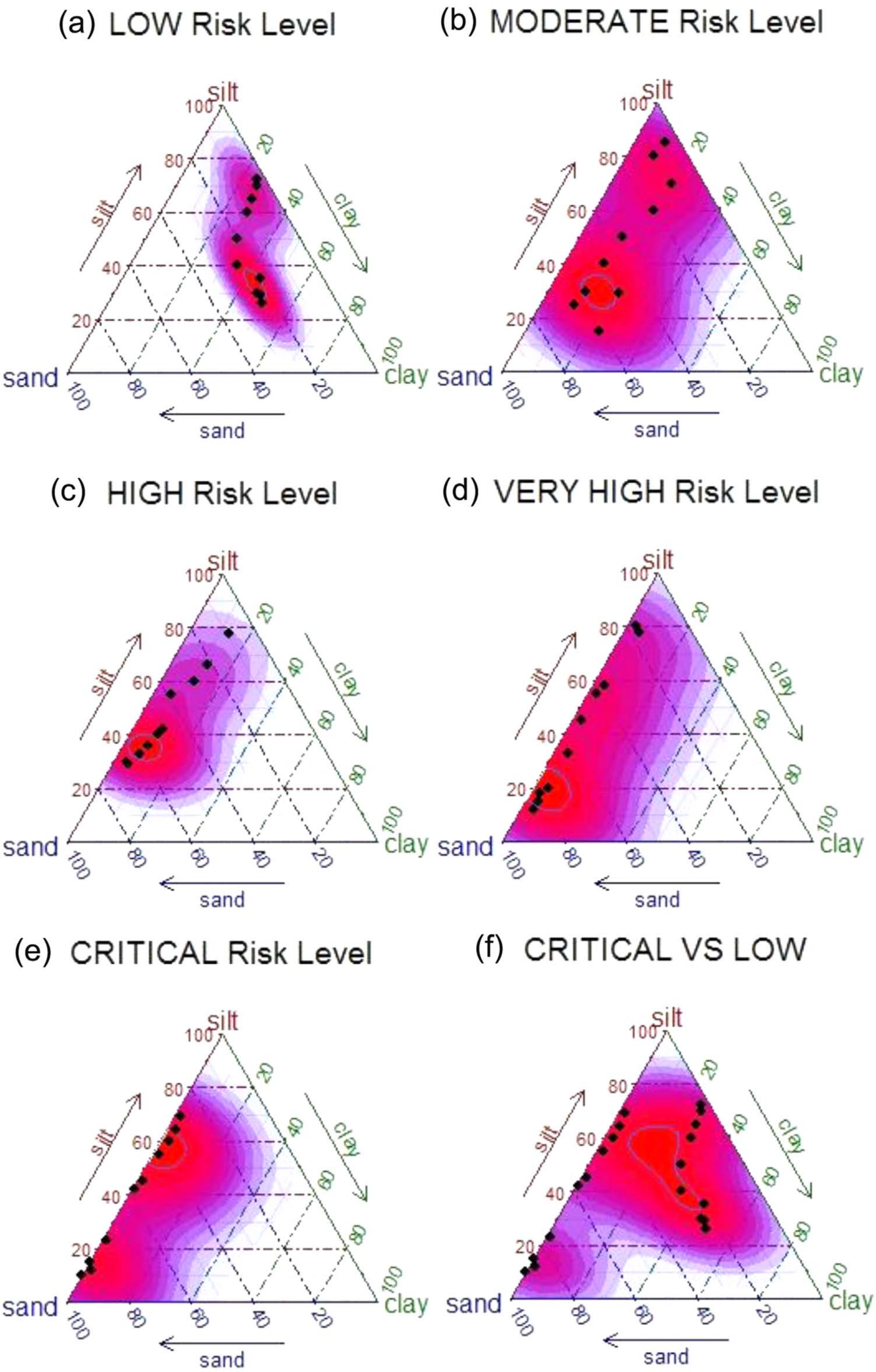


**Fig. 3.** Tri-plot for Sand, Silt and Clay Fraction; (a) Low risk level, (b) Moderate risk level, (c) High risk level, (d) Very high risk level, (e) Critical risk level (f) Critical vs Low level.

discussion on these two processes. They postulated that the lift and drag imposed by the flow can induce river bank erosions at toe section. This phenomenon is called hydraulic erosion. Another factor that contributes to soil detachment is subaerial erosion where the dynamics of soil moisture and soil composition play a key role at weakening and weathering bank materials. For this particular research, special attention was given to subaerial erosion rather than hydraulic erosion. Preceding researchers devoted their research work on characterizing river bank erosion by inferring soil properties and their associated parameterization. Lack of assessment index on river bank erosion led to the execution of this research.

Over the past decade, research on cohesive soil and various formulations on critical shear stress with regards to physical properties, chemical properties, mechanical properties, biological factors and environmental factor (Kimiaghalam, Clark, & Ahmari, 2016) was given special attention to. A good appraisal is due to Debnath and Chaudhuri (2010), Owen (1975), Thorn and Parsons (1980), Amos, Feeney, Sutherland, and Luternauer (1997) and Julian and Torres

**Table 3**
River bank assessment index.

| Erosion risk level | Min / Max | % Sand | % Silt | % Clay |
|---|---|---|---|---|
| Critical | Min | 22 | 8 | 0 |
| | Max | 90 | 69 | 3 |
| Very high | Min | 11 | 6 | 3 |
| | Max | 85 | 80 | 5 |
| High | Min | 9 | 23 | 4 |
| | Max | 66 | 78 | 13 |
| Moderate | Min | 9 | 8 | 9 |
| | Max | 63 | 85 | 24 |
| Low | Min | 0 | 26 | 25 |
| | Max | 32 | 72 | 50 |

(2006) who devoted their work on developing critical shear stress based on potential factors that may influence cohesive soil behaviour. These researched upon relationships indirectly relate the stability of river banks towards incisions and erosions. Knowledge of the shear stress at river banks and its associated critical shear stress provides estimates on river bank stability.

Instead of a critical shear stress, a few indexes were developed to relate the stability of river banks towards erosions. The most notable work on the index development was produced by Rosgen (2001). He made full use of Geomorphic Rapid Assessment (GRA) by analysing channel patterns, channel slopes, bank erosion potential and aggradation or degradation patterns. This grading method inferred the stream classification made by Rosgen (1994) where the range of application is broad spanning from lowland to highland streams. Heeren et al. (2012) extended the work of Rosgen (2001) to assess streambank stability by developing site specific index using the same approach. The Rapid Geomorphic Assessment (RGA) is rather simple and straightforward where there is no evidence on flow thresholds. It was developed to assess the current conditions of stability. However, these indexes require a few parameters to be sampled and observed such as primary bed materials, bank protection, degree of incisions, degree of constrictions, established riparian and many more. These tasks are time consuming and require on site-skills and proficient judgements to obtain the required upon data.

Thus, it is prudent to have an index with a simple and direct approach on erosion risk assessment at river bank sections. The aims of this research text are: 1) to produce risk assessment index for river bank erosion; and 2) to perform a case study using such index for the Langat River in Malaysia. The subsequent details of this manuscript entails brief introductory to erosion and the "ROM" scale that was developed by Zainal Abidin and Mukri (2002). The newly risk assessment index will be developed by inferring the percentage occupied for sand, silt and clay. The risk level is assigned by looking at the corresponding scale based on the "ROM" model. The final part of this manuscript elucidates the application and validation of the newly developed index by carrying a case study on the Langat River in Malaysia.

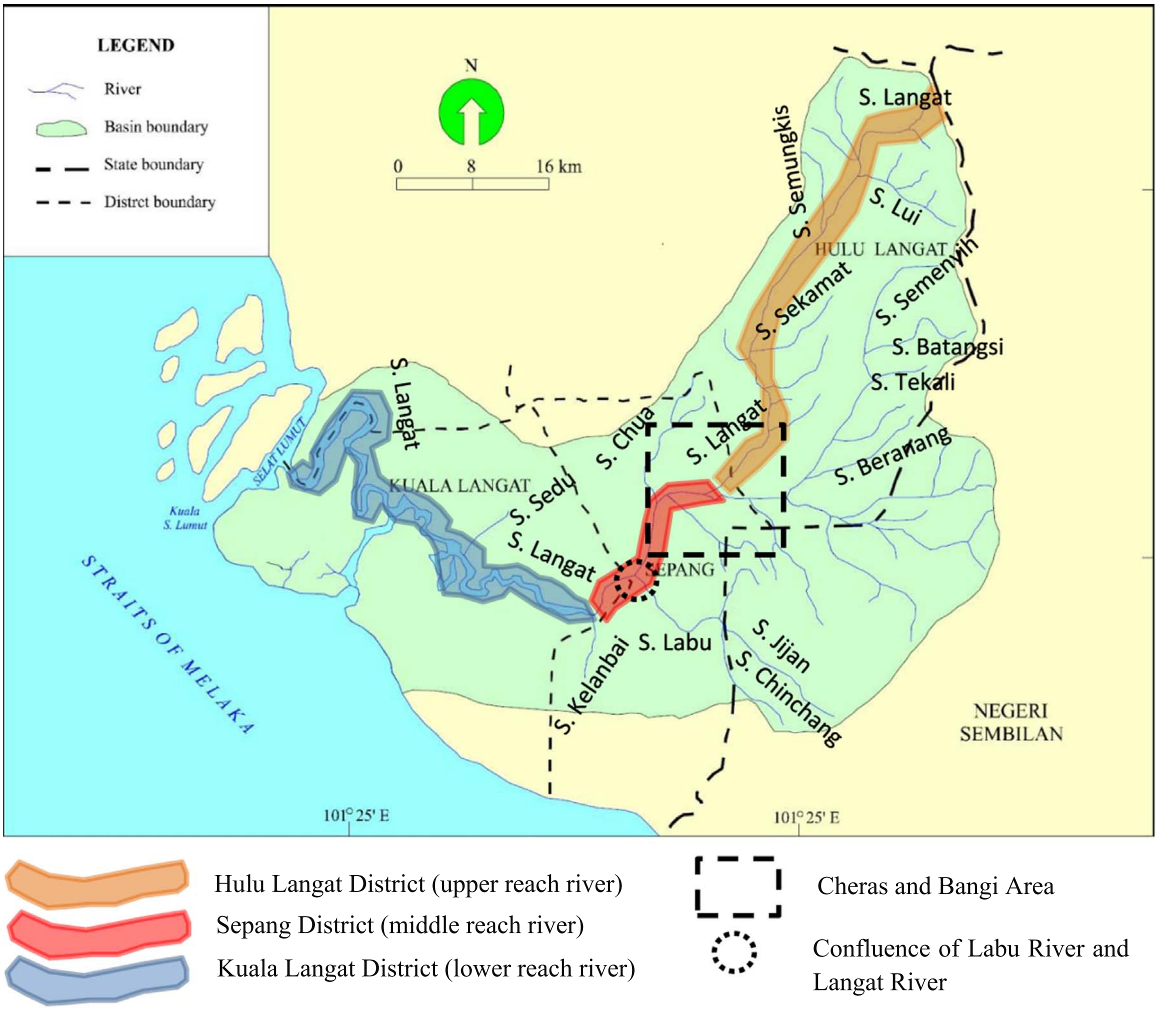
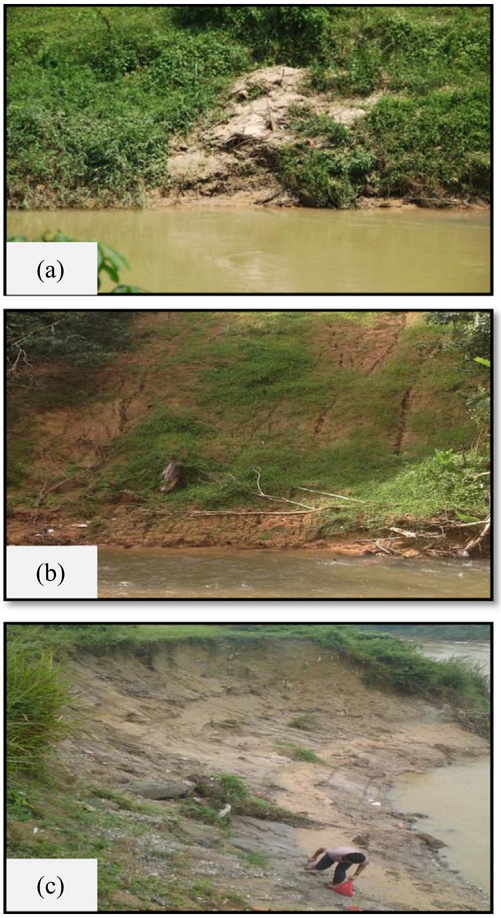


**Fig. 4.** Langat river basin.



Sheet erosion – the most common and less damaging erosion

Rill erosion – this type of erosion can be classified as moderate type of erosion and range between sheet and gully. The soil erodes downward and may extend into the subsoil and leading to gully in a short time

Gully erosion – is the most erosive process compared to sheet and rill. Gully mostly causes a great amount of soil loss and then contributes to shape the earth surface

**Fig. 5.** Types of erosion features (a) Sheet erosion (b) Rill erosion (c) Gully erosion.

## 2. Methods of erosion assessment

### 2.1. Soil erodibility and the 'ROM' scale

Soil erosion can defined as a general destruction of soil structure by the action of water and wind (Beasley, 1974). It can be divided into two categories, namely: geological and accelerated erosion. Geological erosion is an essential process of forming the earth landscape. This process takes place for a long period of time and shapes the natural topographic features. As a result, the process of soil formation and erosion is considered to be in a balance state. The natural vegetative cover is of vital importance in the maintenance of this balanced state while anything which disturbs this state would tend to produce accelerated erosion (Bache & MacAskill, 1984).

Erosion takes place when the force provided by the flow on a surface exceeds the resistance of the soil (Leopold, Wolman, & Miller, 1964). The force provided by the flow can be inferred as a result of raindrops, slope and depth. Depth is however, very much related to rainfall intensity and infiltration rates, velocity of flow and length of slope. Rainfall or raindrop effects may have two impacts; a direct impact which promotes dislodges of the particles from their interlocking bonding and an indirect impact which reduces the infiltration and stimulates surface runoff.

The soil erodibility can be described as resistance of soil towards the detachment and transportation by erosive agents (Houghton & Charman, 1986). It is an important index to determine soil sensitivity towards erosion. Zhang et al. (2004) conducted a study on erodibility soils on the Loess Plateu of China. It was found that the $K$ factor in the USLE is more appropriate for this region. This factor is able to isolate the effects of soil properties on soil loss and does not depend on topographical factors such as slope steepness. In this study, the $K$ factor values were derived by using nomograph and field measurements that involved laboratory analysis of soil samples. Singh and Khera (2008) conducted a study on soil erodibility under various categories of land use in Lower Shiwaliks, India. It was found that the soils under the forest cover had more levels of water retention and a higher infiltration rate with a lower level of dispersion and erosion rates. Similarly, Kukal, Khera, and Hadda (1993) observed that the soils in the forest land were more secured compared to the soils of agriculture and this finding were credited to the higher organic carbon content resulting in more stability of soil aggregates.

Many attempts have been made to develop an index of erodibility. Those efforts spanned from the properties of soils to the response of the soil to rainfalls. A soil scientist Bouyoucos (1962) suggested that erodibility is proportional to the following ratio:

$$Bouyou\cos\ Erodibility\ Index = \frac{(\%\ \text{of Sand}\ +\ \%\ \text{of Silt})}{(\%\ \text{of Clay})} \quad (1)$$

The work of Bouyoucos (1962) has been expanded by Zainal Abidin and Mukri (2002) in order to take into account the erodibility risks in Malaysia. Eventually, the "ROM" scale (named after the researchers, Roslan and Mazidah) was created using the basis of logical predictive calculation to indicate the degree of soil erosion tragedies. It was developed in year 2001 and had received an international recognition. Apart from that, it has also won a Global Medal award with distinction at the 30th International Exhibition on new inventions, innovations, designs, technologies and products in 2002, Geneva, Switzerland. The establishment of the "ROM" Scale was based merely on soil grading characteristics. This is the first ever scale created to grade the degree of erosions with regards to soil erodibility in Malaysia. The "ROM" Scale

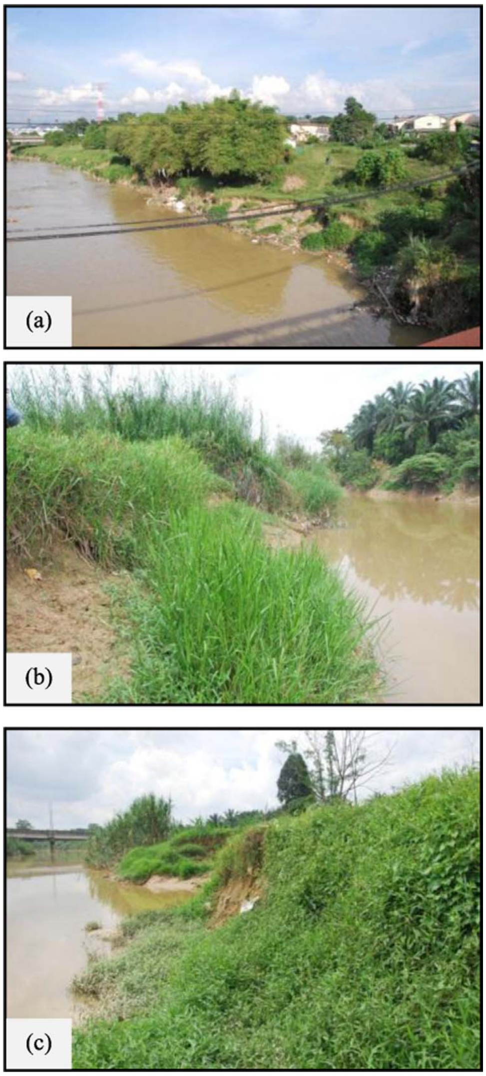


**Fig. 6.** Typical View of Erosion Features at Langat River Basin (a) Upper part river- Langat River at Persiaran Bangi, Hulu Langat District, (b) Middle part river- Langat River at Lebohan Dagang, Sepang District (c) Lower part river- Langat River at Jenjaron, Kuala Langat District.

equation is given as:

$$EI_{Rom} = \frac{(\%\text{ of Sand} + \ \%\text{ of Silt})}{2(\%\text{ of Clay})} \qquad (2)$$

From Eq. (2), the erodibility index can only be determined if the soil's textural composition of sand, silt and clay are known. If the clay content is very low, the “ROM” Scale will be at a very high value and vice versa. The digit 2 at the denominator is used after considering the range of values to be categorized with respect to other standards of international values such as the Richter scale for earthquake intensity. The scale range of “ROM” and the degree of soil erosion risk are shown in Table 1. This scale ($EI_{Rom}$) has been successfully applied to erosion induced landslide study in Malaysia and mostly cited in Zainal Abidin (2009).

### 2.2. Development of assessment index

The result from the sieve test and hydrometer test will lead to the construction of grain size distribution. A sample of the final construction of grain size distribution can be perused from Fig. 2. For the sake of discussion, an exemplary percentage of silt, clay, sand and gravel used is 14%, 60%, 24% and 2% each. And since the percentage of gravel is insignificant (2%), thus the percentage of sand taken is then increased to 26%. By using Eq. (2), the ROM scale can be calculated as follows:

$$EI_{ROM} = \frac{26\ \ \% + 60\ \ \%}{2(14\%)} = 3 \qquad (3)$$

According to Table 1, soil sample can be categorised as a moderate degree of erosion risk. The calculation was expanded to another sample with the main aim of observing the percentage of occupy for clay, silt and sand. Table 2 shows some samples of calculation using the ROM scale and its associated percentage of occupy for clay, silt and sand.

Based on the level of soil erodibility category, a tri-plot was created against clay, silt and sand to observe the distribution of occupy with regards to the risk level. Ten data types were fitted into each category and were plotted using the statistical R package. The tri-plot is able to give an estimate whether there is a distinct segregation between the risk levels as proposed by the ROM scale. As shown in Fig. 3, there is an existence of two distinct belts; segregation towards the clay (→100%) and segregation towards the sand (→100%). At the low risk level, it can be observed that the percentage of occupy for clay is higher (approximately 60%) and the percentage of occupy for sand is weakened (approximately 30%). As the risk level rises from moderate to very high, the percentage for clay decreased and the percentage for sand increased higher. At the critical level, the fitted points were moving towards zero percentage of clay (→0%) and the ultimate percentage of sand (→100%). This observation leads to the development of river bank assessment index, by looking at the percentage of sand and clay as a reference threshold. Table 3 shows the river bank classification index with regards to the percentage of sand, silt and clay.

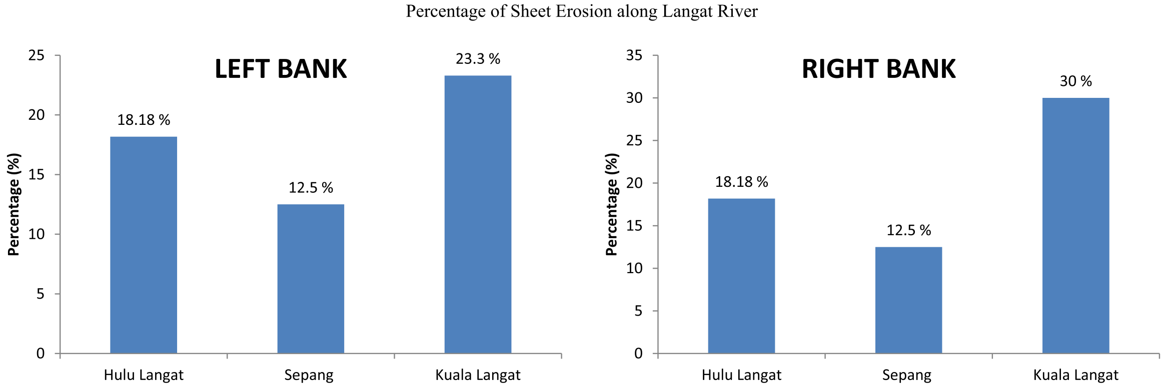


**Fig. 7.** Percentage of sheet erosion on the left and right bank of Langat River.

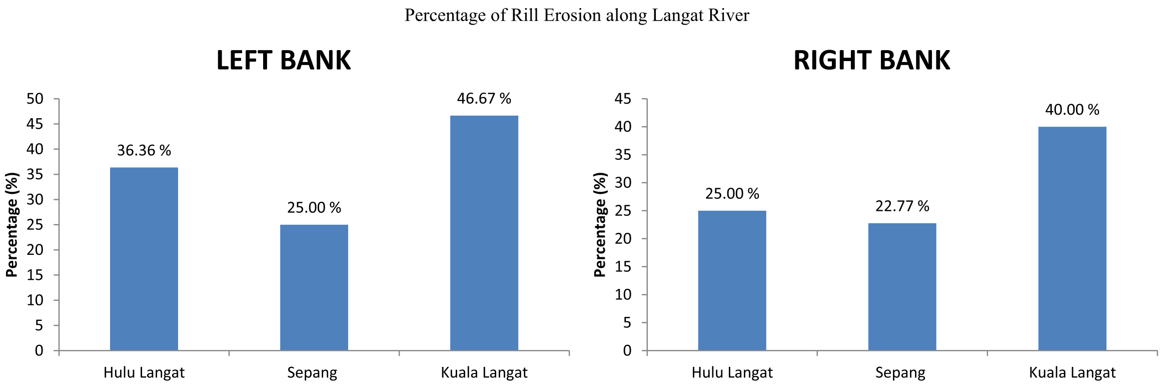


**Fig. 8.** Percentage of rill erosion on the left and right bank of along Langat River.

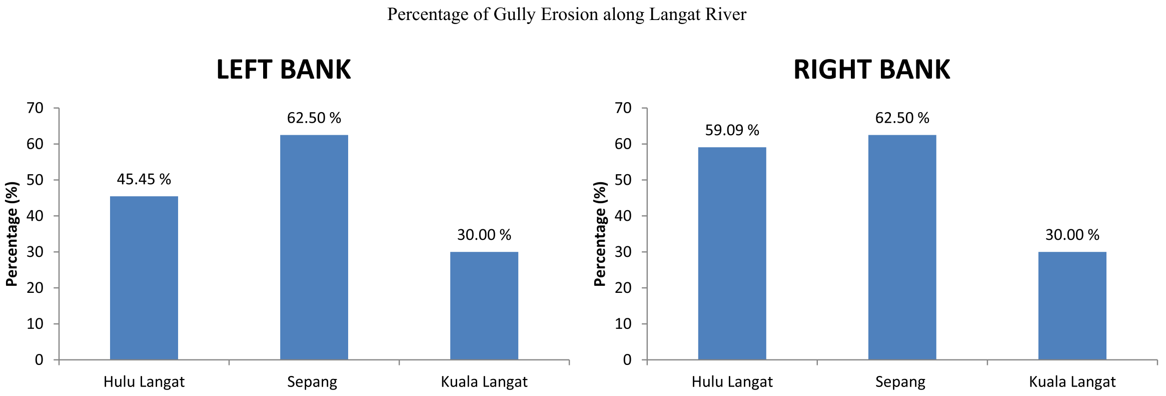


**Fig. 9.** Percentage of gully erosion on the left and right bank of along Langat River.

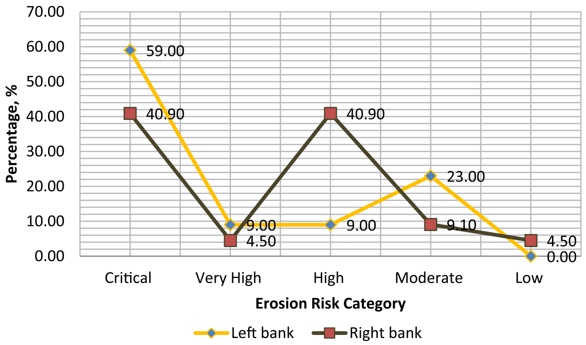


**Fig. 10.** Erosion Risk Categorisation along Langat River in Hulu Langat District according to Assessment Index.

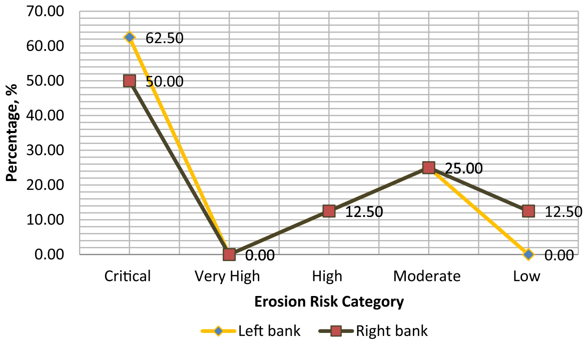


**Fig. 11.** Erosion Risk Categorisation along Langat River in Sepang District according to Assessment Index.

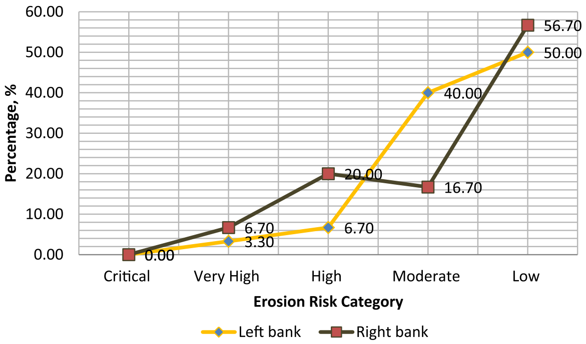


**Fig. 12.** Erosion Risk Categorisation along Langat River in Kuala Langat District according to Assessment Index.

**Table 4**
Upperbound and lowerbound critical shear stress.

| Erosion risk level | Min / Max | % Sand | % Silt | % Clay | $\tau_c$ |
|---|---|---|---|---|---|
| Critical | Min | 22 | 8 | 0 | 0.11 |
| | Max | 90 | 69 | 3 | 0.23 |
| Very high | Min | 11 | 6 | 3 | 0.12 |
| | Max | 85 | 80 | 5 | 0.25 |
| High | Min | 9 | 23 | 4 | 0.15 |
| | Max | 66 | 78 | 13 | 0.26 |
| Moderate | Min | 9 | 8 | 9 | 0.13 |
| | Max | 63 | 85 | 24 | 0.29 |
| Low | Min | 0 | 26 | 25 | 0.19 |
| | Max | 32 | 72 | 50 | 0.32 |

**Table 5**
Different of critical shear stress between present study and previous research.

| Erosion risk level | Researcher | $\tau_c$ | Erodibility class | Researcher | $\tau_c$ |
|---|---|---|---|---|---|
| Critical | | 0.11–0.23 | Very erodible | | 0.11–0.499 |
| Very high | Current study | 0.12–0.25 | Erodible | Navarro | 0.5–3.49 |
| | | | | Hobson | |
| High | | 0.15–0.26 | Moderately resistant | Wang | 3.5–7.79 |
| Moderate | | 0.13–0.29 | Resistant | | 7.8–20.99 |
| Low | | 0.19–0.32 | Very resistant | | ≥21.00 |

## 3. Case study of risk assessment index to Langat River

### 3.1. Langat River

The site for this case study is the Langat River which flows from the main range of Banjaran Titiwangsa from the east of the Selangor state in Malaysia. It drains through three districts in the Selangor state namely Hulu Langat, Sepang and Kuala Langat. The average annual precipitation is 2316 mm with a range of 1800–3000 mm. The upstream of the Langat River has a steep river bed gradient and a fast flowing velocity due to bed adulations. Riverbed material consists mainly of rock and stones, and the banks are gentle and covered with vegetation. Just downstream from the town of Hulu Langat, sedimentation and occurrence of minor bank erosions can be observed. Just between Cheras and Bangi area, the Langat River flows through a highly urbanised area with many features of bank erosions. Sand mining and dredging activities can be seen along the Bangi stretch of the Langat River thus resulting in severe processes of sedimentations and depositions. Apart from that, distinctive evidence of heavy sedimentations and severe riverbed erosions can be also observed along the river network. The Langat River then passes through the Kuala Langat district and the riverbed gradient and velocity becomes gentler and tranquil. In addition to that, the merging of the Labu River and the Langat River at the Kuala Langat district depicts less erosion and sedimentation issues. Fig. 4 shows the Langat River basin for investigation purposes.

The “ROM” Scale was used as a basis for the creation of a river bank assessment index. Prior to index development, the Langat River in Selangor, Malaysia was identified as a case study for index creation. The Langat River banks (both left and right) were monitored and classified accordingly to the levels of erosiveness; stability of the banks, sheet erosions, rill erosions and gully erosions (see Fig. 5). For sampling work, the hand auger sampling device was used to take hold of the soil samples. This undisturbed soil samples were then taken to a lab for sieve analysis and a hydrometer test. The combination results of the sieving and hydrometer test enabled a continuous creation of the particle size distribution curve. Sieve analysis was performed to determine the percentage of grain size distribution within a soil. BS 1377 Part 2:1990 is the standard of reference for this test and is applied worldwide (Sulaiman, Sinnakaudan, Ng, & Strom, 2014). Physical properties of soil are affected by the distribution of different grain sizes. To perform this experiment, the sieve shaker should have a nominal sieve size of 6.3 mm, 5 mm, 3.35 mm, 2 mm, 1.18 mm, 0.6 mm, 0.425 mm, 0.3 mm, 0.212 mm, 0.15 mm and 0.063 mm. Before beginning the sieving test, soil samples must first, be oven dried at a temperature of 105–110 °C overnight (between 16 and 24 h). After that, a portion of the dried sample is weighted amounting to 50–100 g. This amount of soil mass is adequate to represent the percentage of grain distribution at one (1) sampling point. The hydrometer test must be performed to obtain the clay and silt percentage, if should there be more than 10% of the soil mass retained on the pan (final pan after 0.063 mm sieve pan).

### 3.2. Results

A case study was conducted at three main districts representing the whole Langat basin namely the Hulu Langat district (upstream), the Sepang district (middlestream) and the Kuala Langat district (downstream). A few stretches of the Langat River basin showed a glimpse of erosion features at river banks and some photographs were taken as evidence of the mentioned above issues. Fig. 6 illustrates the typical view of the studied area.

A total number of 120 soil samples were collected at every 2 km intervals using a hand auger at the depth of 1 m along the Langat River. In this study, the disturbed samples were required for a detailed lab testing of particle size in order to determine the amount of sand, silt and clay. Therefore, the hand auger sampling method was selected to suit the purpose of the testing requirements. The laboratory testing which consists of sieve analysis and hydrometer test were performed to analyse the percentage of soil texture composition.

An observation via visual surveillance revealed that sheet erosion and rill erosion dominated the Kuala Langat district whereas gully erosion dominated the Sepang district. As for the Hulu Langat district (left river bank), 18.18% of erosion features were due to sheet erosions, 36.36% were due to rill erosions and 45.45% were due to gully erosions. Meanwhile, at the Sepang district (left river bank), 12.5% of erosion features were due to sheet erosions, 25% were due to rill erosions and 65.5% were due to gully erosions. Finally, at the Kuala Langat district (left river bank), 23.33% of erosion features were due to sheet erosions, 46.67% were due to rill erosions and 30% were due to gully erosions. Figs. 7–9 showed the distribution of erosion features at three main districts for both the left and right banks. Since gully is the most severe type of erosion, an early conclusion can be made that the middle stream of Langat basin is undergoing the process of active erosion along the river banks.

The samples were then form fitted according to the percentage of occupies to fit the risk assessment index. Twenty points (20) were tagged along to the Hulu Langat district (upstream) spanning from both right and left banks at an interval of 2 km. A total of 44 samples were processed in order to obtain a percentage of the occupy for sand, silt and clay. The same process was performed at the Sepang district (middlestream) and the Kuala Langat district (downstream). At the Sepang and Kuala Langat district, 8 points and 30 points were tagged from the left and right banks' sample data.

Overall, upstream, middlestream and downstream comprised of 44, 16 and 60 data consecutively. The percentage for sand, silt and clay is fitted against the assessment index to obtain the risk level for the whole Langat Basin. Figs. 10–12 shows the level of risk assessment at Hulu Langat, Sepang and Kuala Langat district. The data reveals that the Sepang district has a higher percentage of critical risks opposed to other districts. The percentage of critical risk stood at 62% and 50% at both the left and right banks. The higher percentage of the critical level at the Sepang district is in agreement with the percentage of gully erosions that are present at this river section. The plausible reason for the higher percentage is the rapid growth of development in this area. The Kuala Langat district recorded the lowest percentage of the critical level which stood at almost 0% at both left and right river banks. It is because of high content of clay present at the Kuala Langat district.

## 4. Discussion

The detachment and subsequent entrainment of cohesive bank material can result from two processes: hydraulic erosion and subaerial erosion (Thorne, 1982). The sub aerial erosion includes the weakening and weathering of bank material imposed by dynamic soil and moisture conditions (Julian & Torres, 2006). Therefore, it is very crucial to understand and recognize the controlling predictor of cohesive riverbank erosion. Critical shear stress $\tau_c$ has become major predictor controlling riverbank erosion. Applied bank shear stress ($\tau_b$) can be calculated using the following equation as proposed by Flintham and Carling (1988).

$$\tau_{bank} = \tau^{*} SF_{bank}\left(\frac{B + P_{bed}}{2^{*} P_{bank}}\right) \tag{4}$$

$$SF_{bank} = 1.77\left(\frac{P_{bed}}{P_{bank}} + 1.5\right)^{-1.4} \tag{5}$$

where $SF_{bank}$ is the proportion of the total cross-sectional shear force acting on the bank, $P_{bed}$ and $P_{bank}$ are the wetted perimeters of the bed and banks respectively, B is the water surface width, and $\tau$ is the cross sectional shear stress. The river bank is considered stable if the applied shear is less than the critical shear stress (Millar, 2005). A handful number of empirical equation was developed by former researchers to relate the critical shear stress with the properties of cohesive soil behaviour. Julian and Torres (2006) found a correlation between the critical shear stress and clay silt fraction and it is shared as follows:

$$\tau_c = 0.1 + 0.1779(SC\%) + 0.0028(SC\%)^2 - 2.34 \times 10^{-5}(SC\%)^3 \tag{6}$$

where SC is the percentage of sand and clay combined. This empirical equation is form fitted in Table 3 to observe the critical shear stress for each levels of risk. In Table 4, it is observed that as the risk level increased, the critical shear stress decreased. A high applied shear is required to dislodge the particle at low level risk. At the critical level, the range of critical shear stress ranges from 0.11 to 0.23. A minimum of 0.11 of applied shear stress will lead to erosion risk at area of interest.

For comparison, this critical shear stress is then matched to previously published critical shear stresses. As such, Navarro (2004), Hobson (2008) and Wang (2013) predicted the critical shear stress of soils using distinct experimental datasets, each representing fundamentally different soil types. Navarro (2004) and Hobson (2008) proposed the same empirical equation as given below:

$$\tau_c = 0.664\text{x}10^{2.68} \times fines \times d_{*}^{-0.409} \tag{7}$$

where *fines* is the decimal fraction of the percent of fines and $d_*$ is the non-dimensional grain size. Conversely, Wang (2013) produced the following equation:

$$\tau_c = 8.46 - 27.76 \times w + 73.69 \times \text{clay} + 83.32 \times (w \times clay) \tag{8}$$

where $w$ is the water content as the decimal fraction and *clay* is the percent of clay given in decimal value. The similarity between Eqs. (7) and (8) is that the upper bound and lower bound limit of shear stress for erodible class is almost similar with proposed river bank assessment index.

A comparison between the critical shear stress made is shown in Table 5. The 'Critical level' and the 'very erodible class' is almost similar should the range of value be taken into consideration. However, as the range of class descends to very resistant, the critical shear stress is larger than the range provided by the erosion risk level. The difference is almost 65 times between one another. It is elucidated that the equation produced by the Navarro (2004), Hobson (2008) and Wang (2013) spans from very fine clay to very coarse gravel and cobble. It is sensical that the presence of gravel and cobble require higher applied shear stress to dislodge the particles. However, the present study only considers the sand, silt and clay fraction in creating the index. Nevertheless, the similarity at the critical and very erodible level provides a basis towards the maintenance of the applied shear.

## 5. Conclusion

River bank erosions are serious issues in a humid tropical climate country like Malaysia. Identification and early warning mechanism is very crucial before mitigation work can take place. With the existing "ROM" scale in place, the newly developed risk assessment index (critical, very high, high, medium and low) can accelerate the risk identification at river bank sections. The application of this index is direct and simple. Users and practitioners need to have the soil composition of the section of interest. The soil composition should be in recorded in percentage term; as such % clay, % clay and % sand. It is postulated that the risk will become higher if the percentage of occupy for clay decrease and percentage of occupy for sand increase. The risk will become critical should the percentage of clay range between 0–3% and percentage of sand range between 22–90%.

The plausible elucidation towards this consequence is that clays are pastier and stickier hence are able to provide an 'adhesive pattern' to interlocking particles. The least resistant particles are silts and sands; thus soils with high silt and sand content are more erodible than soils with clay content. A minimum of 0.11 N/m$^2$ applied shear stress is adequate to erode the particle and this is proven to be consistent with preceding findings.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.iswcr.2017.01.002.

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