Low amplitude of streambank erosion: distinguishing mass and surface fluvial erosions

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Abstract. The purposes of this manuscript are in two folds e.g.: first, to promote two novel techniques using field-laboratory protocols, each for quantifying surface and mass fluvial erosion, second, to capture and highlight the regime change in the mode of bank erosion from surface to mass fluvial erosion based on real monitoring and measurements on a streambank face. In this study, conduit erosion flume and Photo Electronic Erosion Pin (PEEP) sensor technique were used for monitoring and measuring surface and mass fluvial erosions, respectively. Using those techniques the $\tau_{c,sf}$ and $\tau_{c,mf}$, two key parameters which determine the onset of surface and mass fluvial erosion, can be determined successfully. The PEEP sensor can measure the mass fluvial erosion occurred under water, even capture the quasi-continues nature of erosion. More importantly, using these two methods, the presence of two regimes in the low amplitude of bank erosion, e.g. surface fluvial erosion and mass fluvial erosion can be captured. Starting from low to high shear stress, the onset of surface fluvial erosion as well as the transition from surface to mass fluvial erosion can be depicted.

1. Introduction

Streambank erosion or known as bank erosion is a dynamic process with effects on channel morphology [1, 2] and significant contributions to the total sediment budget within a watershed [3, 4, 5]. Bank erosion manifests in different modes, namely mass failure, surface fluvial erosion, and mass fluvial erosion [6] which are described in detail below.

The upper limit of bank erosion, as shown in Figure 1a, is mass failure which is a “high amplitude” erosion process in terms of its rate or size. Mass failure refers to the breakdown of large part of streambank soil when its bulk weight exceeds its shearing strength with the latter being much dependent on the soil friction angle, $\phi'$, and the soil mechanical strength, $c'$ [7]. Mass failure is a product of various but interconnected processes, such as, the presence of positive and negative pore water pressures within the bank soil [8], bank toe undercutting or basal erosion [9], tension crack [10], desiccation crack [10], rapid drawdown of water stage [11], occurrence of high seepage gradient forces [12], and influence of riparian vegetation [13]. Mass failure can manifest in the form of planar failures, cantilever failures, rotational failures, piping and sapping failures, all of which occur in discrete times.
The lower limit of bank erosion refers the “low amplitude” erosion processes regarding to their size or rate. This mode of erosion can be subdivided into surface fluvial erosion and mass fluvial erosion (see Figure 1a). Surface fluvial erosion manifests in the form of dislodgement of individual grains or grain flocks from the surface of bank soil caused by the shearing action of flow [14, 15]. Unlike mass failure, surface fluvial erosion is a quasi-continuous process which begins once the hydrodynamic shear stresses sweeping over the bank surface exceed the resistance promoted by the inter-particle cohesion bond among soil grains or flocks. This resistance is represented by the term threshold shear stress for surface fluvial erosion or surface fluvial erosional strength, \( \tau_{c,sf} \) [16, 17] which, for cohesive bank soils, is mostly affected by an array of biogeochemical properties [18].

Another lower limit of bank erosion is mass fluvial erosion which also occurs as quasi-continuous processes [6]. However, the commencement of mass fluvial erosion corresponds to a higher flow shear stress and therefore its rate of erosion and bank retreat are also higher compared to surface fluvial erosion. During mass fluvial erosion, the bank retreats manifest by the removal of chunks or clods or thin sheets of soil from the bank face. Typically, surface fluvial erosion precedes mass fluvial erosion as the stream water stage rises and the hydraulic shear stress acting on the bank face gradually increases. This sequential occurrence of erosion [19] is illustrated in Figure 1b. Surface fluvial erosion is represented with the purple triangle-marked line while mass fluvial erosion with the green square-marked line. The onset of surface and mass fluvial erosions correspond to the first and the second threshold shear stresses which are denoted as \( \tau_{c,sf} \) and \( \tau_{c,mf} \) respectively. The latter is higher and also named as threshold shear stress for mass fluvial erosion or mass fluvial erosional strength. The change in gradient of the two lines demonstrates that the mode of bank erosion changes at a certain point as the flow shear stress acting on the bank gradually increases.

![Figure 1](image_url)

**Figure 1.** Conceptual figures showing different modes of bank erosion. (a) The ranges of hydraulic shear stress and retreat length for different modes of bank erosion. (b) An idealistic illustration of surface and mass fluvial erosions.

The knowledge on mass failure has been much more mature compared to the two other modes of erosion due to the fact that it is more observable and measurable. On the other hand, measurement of surface and mass fluvial erosion are very challenging due to the following reasons: 1) they are difficult to monitor as they occur under water surface involving the entrainment of soil chunks or clods or soil layers from the bank profile, 2) both erosion modes have quasi-continuous nature which cannot be captured by customary techniques, for instance periodical measurement of stream cross-sections, terrestrial photogrammetry and scanning [20] and bank retreat measurement using erosion pin, which are manual and discrete in time, 3) the two key parameters e.g., \( \tau_{c,sf} \) and \( \tau_{c,mf} \) are delicate and difficult to measure as they are affected by an integral of various physical, bio-chemical, and biological aspects [18, 21, 22].
Most of the time the lower limit of bank erosion is insufficiently represented by single erosion process named as fluvial or surface or hydraulic erosion [12, 15]. This is not fully correct since there are two distinctive sequential processes namely surface and mass fluvial erosion, each with different onset time and erosion rate.

The purposes of this manuscript are in two folds e.g.: first, to promote two novel techniques using field-laboratory protocols, each for quantifying surface and mass fluvial erosion, second, to capture and highlight the regime change in the mode of bank erosion from surface to mass fluvial erosion based on real monitoring and measurements on a streambank face.

2. Methodology
2.1. Surface fluvial erosion quantification
This study was performed near the mouth of Clear Creek, which is located in Iowa City, U.S.A. The Clear Creek is subjected to frequent flash floods and prominent bank erosion. It drains a watershed area of approximately 270 km² to Iowa River.

The quantification of surface fluvial erosion can be expressed with an excess shear stress formula [16] as follows:

$$E = M_{sf} \left( \frac{\tau_w}{\tau_{c,sf}} - 1 \right)^m$$

Here, $E$ is the erosion rate (kg/m²/s), $M_{sf}$ is the soil erodibility coefficient (kg/m²/s) for surface fluvial erosion, $\tau_w$ is the flow shear stress (Pa) acting on the bank face, and $\tau_{c,sf}$ is the surface fluvial erosional strength (Pa) of the bank soil. The $m$ is 1 for homogeneous consolidated cohesive soils [6].

To determine the $\tau_{c,sf}$ and $M_{sf}$ values of the bank soils, a laboratory conduit erosion flume was developed [23, 24, 25]. Soil samples were cut into beam shape and excavated from the bank and tested in the laboratory. The sampling extractions were conducted between the months of July and October during which the freeze-thaw effects were minimum. The samples were collected from the crest, midbank, and toe of the bank face at the right bank (looking downstream). Each soil block has a length of 35 cm, a width of 20 cm, and a height of 15 cm.

Initially, soil blocks were carefully carved and lifted up from the bank surface using two wide spatulas and a wire saw. To maintain soil structure and to avoid loss of soil water, the extracted soil samples were covered in cheese cloth, coated with wax, and stored in plastic boxes. The samples were then delivered to the laboratory and deposited in a room with a constant temperature of 20°C before being tested.

In the laboratory, each soil samples were tested using a recirculating conduit erosion flume (Figure 2a) for obtaining their $\tau_{c,sf}$ and $M_{sf}$ values. The flow in a conduit erosion flume is fully controlled by an attached pump, allowing an application of higher shear stress. The pump was connected to a variable frequency control, enabling the operator to vary the discharge. The conduit section of the flume was made of flexi glass and has a length of 180.34 cm, a width of 10 cm, and a height of 5 cm. Before running the test, the soil sample was carefully cut and trimmed to fit the sample box (Figure 2b). The box was mounted atop the flume bed at the distance 180 cm from the upstream end of the conduit. The test protocol was initiated by filling the conical tank with tap water. A low flow rate, $Q$, was applied as a precursor to testing. The flow rate was increased every 10 (ten) minutes by doing so periodically amplified the flow shear stress on the soil sample. This regulated increment of flow was conducted by adjusting the variable speed control. The flume water was collected in a 1-liter plastic bottle respectively 8 and 9 minutes after a flow rate increment for obtaining its average concentration, $C_{av}$, by filtration. Each test run for at least 5 (five) flow increments, in other words, each soil sample were subjected to 5 (five) or more stress levels before the flume run was terminated. A test run can also be stopped if a local scour was witnessed on the surface of the sample or when the water in the flume starts to be murky.
As a result of a flume test, a time series of average concentration, \( C_{av} \), and applied flow rate, \( Q \), were coupled in one plot to demonstrate clearly the response in concentration to the stepwise increase in flow rate. For each applied flow rate, \( Q \), a corresponding hydraulic shear stress, \( \tau_w \), can be determined as:

\[
\tau_w = \frac{\rho U^2}{8} f
\]

where \( \tau_w \) is the hydraulic shear stress (Pa), \( \rho \) is the water density (kg/m\(^3\)), \( U \) is the bulk velocity (m/s) obtained by dividing \( Q \) in m\(^3\)/s with \( A_f \) the cross sectional area of conduit flume (0.005 m\(^2\)), and \( f \) is the friction factor \[26\]:

\[
\frac{1}{\sqrt{f}} = -1.8 \log \left[ \frac{6.9}{Re_{eff}} + \left( \frac{e}{3.7d_{eff}} \right)^{1/11} \right]
\]

Herein \( e \) is the wall roughness (0.0002 m in this case); \( Re_{eff} \) is the Reynolds number calculated as \( Re_{eff} = Ud_{eff}/\nu; \nu \) is water kinematic viscosity (1.01 x 10\(^{-6}\) m\(^2\)/s); \( d_{eff} \) is the effective diameter (m) of the rectangular conduit, \( d_{eff} = 1.029d_h \); and \( d_h \) is hydraulic diameter of the conduit (0.0667 m in this case).

\( \Delta C_{av} \) is the concentration increase (kg/m\(^3\)), \( Q \) is the corresponding discharge (m\(^3\)/s), and \( A_s \) is the area of soil surface (0.03 m\(^2\)).

For each applied flow rate, the erosion rate equals to the change in water concentration times the corresponding flow rate divided by the area of soil surface, or:

\[
E = \frac{\Delta C_{av} * Q}{A_s}
\]

where \( E \) is the erosion rate (kg/m\(^2\)/s), \( \Delta C_{av} \) is the concentration increase (kg/m\(^3\)), \( Q \) is the corresponding discharge (m\(^3\)/s), and \( A_s \) is the area of soil surface (0.03 m\(^2\)).

Next, the \((E, \tau_w)\) pairs obtained from all flume runs were plotted, the surface fluvial erosional strength, \( \tau_{c,sf} \) can be obtained by creating a best fit line on the \((E, \tau_w)\) plot, the \( \tau_{c,sf} \) corresponds to the shear stress at which the fitting line intercept shear stress axis.

To determine the erodibility coefficient, \( M_{sf} \), a graphical procedure was used similar to that applied by \[16\]. A linear fitting line was drawn in the plot of excess shear stress \( (\tau_s/\tau_w - 1) \) vs. \( E \). The gradient of the line represents the \( M_{sf} \) value.

2.2. Mass fluvial erosion quantification

To determine mass fluvial erosional strength, \( \tau_{c,mf} \) and soil erodibility coefficient for mass fluvial erosion, \( M_{mf} \), a field technique was developed using Photo Electronic Erosion Pin (PEEP) sensor \[27,
28, 29]. Four PEEP sensors, noted as B1 until B4 were placed at four point locations, e.g. the crest, upper midbank, lower midbank, and toe of the right bank respectively, at the selected site near the location where soil samples were extracted.

The main component of a PEEP sensor is a line of 13 (thirteen) photo-resistance diodes/cells placed on a motherboard with a space of 1.65 cm between two consecutive cells (Figure 3). The system is enclosed in a transparent, water-proof acrylic tube. Before being deployed on a bank, each sensor needs to be calibrated in an open space under the sunlight. To start an erosion monitoring, the sensor was fully inserted into the observed bank face with horizontal position. Sufficient number of solar panels was used to supply electric power to the PEEP sensor. As the bank soils gradually retreat by erosion, the PEEP tube and the cells inside slowly exposed to the sunlight. The more number of cells exposed, the higher voltage can be produced and delivered through a wire to a data logger which was set up to record data every 15 minutes. Using the calibration equation and a developed data processing protocol, the time series of voltage output were converted to time series of exposure length of PEEP sensor and retreat length of bank soil.

The PEEP monitoring was complemented with water stage, $h$, measurement using a pressure transducer, the data logger was adjusted to record $h$ data every 15 minutes, following the logging rate of PEEP data. The time series of $h$ were used for quantifying hydraulic shear stress, $\tau_w$, near the bank in order to obtain a time series of $\tau_w$ which coincide with the time series of exposure length of PEEP.

The hydraulic shear stresses near the bank, $\tau_w$, were determined for the crest, upper midbank, lower midbank, and toe layers corresponding to the PEEP locations. The magnitude of $\tau_w$ experienced by each bank layer $i$ was approximated following the method explained in [30] with the shear stress formula:

$$\tau_{wi} = \rho g R_i S$$  \hspace{1cm} (5)

where $\tau_{wi}$ is the hydraulic shear stress (Pa) at bank layer $i$, $\rho$ is the density of water (kg/m$^3$); $g$ is the gravitational acceleration (m/s$^2$); $R_i = A_i/P_i$ is the hydraulic radius (m) of the flow subsection affected by layer $i$, $A_i$ is the area (m$^2$) and $P_i$ is the wetted perimeter of the subsection, and $S$ is the channel slope. $A_i$, $P_i$, and $S$ were quantified using water stage data and channel cross-sectional shape. The latter was obtained from survey performed before PEEP sensor installation. Equation (5) is suitable for approximating the shear stress near the bank regarding that the secondary currents were limited in the study reach which is characterized with a relatively straight corridor, less expansions/constrictions, and less compound cross sections.

3. Results and Discussion

3.1. $\tau_{sf}$ and $M_{sf}$ values for surface fluvial erosion

Table 1 shows the flume test conditions for four soil samples. For each test, the flow rate, $Q$, were increased 5 (five) times gradually (see column 3) except for test no. 2 and 4 which were terminated earlier due to a scour hole was observed. The friction factor, $f$, and the shear stress, $\tau_w$, were determined using equation (3) and (2) respectively. The average concentration, $C_{av}$, was obtained by collecting the flume water in two 1-liter bottles and filtrating them. The on $\Delta C_{av}$ is the increase in
concentration corresponds to the increase of flow rate. The erosion rate, $E$, was quantified using equation (4).

Table 1. Flume test conditions and results

| Test No. | Sample Identifier | $Q \times 10^3$ (m$^2$/s) | $U$ (m/s) | $Re_{eff} \times 10^3$ | $f$ | $\tau_w$ (Pa) | $C_{avg}$ (kg/m$^3$) | $AC_{avg}$ (kg/m$^3$) | $E \times 10^{-3}$ (kg/m$^2$s) | $\tau_w/\tau_{c,sf}$ - 1 |
|----------|-------------------|-----------------------------|-----------|------------------------|-----|--------------|----------------------|----------------------|-----------------------------|------------------------|
| 1        | Crest, CC-R-C5    | 3.47                        | 0.69      | 47.16                  | 0.0284 | 1.71         | 0.178                | 0.101                | 12.92                       | 1.09                   |
|          |                   | 3.85                        | 0.77      | 52.30                  | 0.0282 | 2.09         | 0.279                | 0.101                | 12.92                       | 1.09                   |
|          |                   | 4.16                        | 0.83      | 56.59                  | 0.0280 | 2.43         | 0.216                | 0.000                | 0.00                        | 1.43                   |
|          |                   | 4.73                        | 0.95      | 64.31                  | 0.0278 | 3.11         | 0.347                | 0.130                | 20.53                       | 2.11                   |
|          |                   | 5.49                        | 1.10      | 74.60                  | 0.0276 | 4.15         | 0.423                | 0.077                | 14.05                       | 3.15                   |
|          |                   | 5.99                        | 1.20      | 81.46                  | 0.0275 | 4.93         | 0.531                | 0.108                | 21.50                       | 3.93                   |
| 2        | Midbank, CC-R-M1  | 3.05                        | 0.61      | 41.50                  | 0.0287 | 1.34         | 0.652                | -                   | -                            | -                      |
|          |                   | 3.15                        | 0.63      | 42.87                  | 0.0286 | 1.42         | 0.548                | 0.000                | 0.00                        | 0.42                   |
|          |                   | 3.28                        | 0.66      | 44.59                  | 0.0285 | 1.54         | 0.592                | 0.043                | 4.74                        | 0.54                   |
|          |                   | 3.47                        | 0.69      | 47.16                  | 0.0284 | 1.71         | 0.638                | 0.046                | 5.32                        | 0.71                   |
| 3        | Midbank, CC-R-M2  | 2.67                        | 0.53      | 36.27                  | 0.0290 | 1.03         | 0.099                | -                   | -                            | -                      |
|          |                   | 3.05                        | 0.61      | 41.50                  | 0.0287 | 1.34         | 0.079                | 0.000                | 0.00                        | 0.34                   |
|          |                   | 3.41                        | 0.68      | 46.30                  | 0.0284 | 1.65         | 0.145                | 0.066                | 7.53                        | 0.65                   |
|          |                   | 3.53                        | 0.71      | 48.02                  | 0.0284 | 1.77         | 0.120                | 0.000                | 0.00                        | 0.00                   |
|          |                   | 3.79                        | 0.76      | 51.45                  | 0.0282 | 2.02         | 0.143                | 0.024                | 3.01                        | 1.02                   |
|          |                   | 4.16                        | 0.83      | 56.59                  | 0.0280 | 2.43         | 0.212                | 0.068                | 9.48                        | 1.43                   |
| 4        | Toe, CC-R-T1      | 3.06                        | 0.61      | 41.59                  | 0.0287 | 1.34         | 0.388                | -                   | -                            | -                      |
|          |                   | 3.15                        | 0.63      | 42.87                  | 0.0286 | 1.42         | 0.395                | 0.007                | 0.69                        | 0.42                   |
|          |                   | 3.28                        | 0.66      | 44.59                  | 0.0285 | 1.54         | 0.402                | 0.007                | 0.76                        | 0.54                   |
|          |                   | 3.41                        | 0.68      | 46.30                  | 0.0284 | 1.65         | 0.500                | 0.098                | 11.13                       | 0.65                   |
|          |                   | 3.85                        | 0.77      | 52.30                  | 0.0282 | 2.09         | 0.630                | 0.130                | 16.69                       | 1.09                   |

Note:
- $A_t = 0.005$ m$^2$
- $d_{eff} = A_t/m$
- $A_c = 0.03$ m$^2$
- $E = 0.0002$ m
- $R = 1000$ kg/m$^3$
- $\tau_{c,sf} = 1.00$ Pa
- $d_h = 0.0067$ m
- $V = 1.01E-06$ m$^2$/s

Figure 4a shows the $(E, \tau_w)$ plot of the entire flume tests presented in Table 1. A fitting line was extrapolated on the plot. The fitting line intercepts the shear stress axis at 1 Pa which means $\tau_{c,sf}$ equals to 1 Pa. The term $(\tau_w/\tau_{c,sf} - 1)$ in Table 1 column 11 was quantified after the value of $\tau_{c,sf}$ was obtained. To obtain erodibility coefficient, $M_{sf}$, a fitting line was drawn on the plot of $E$ vs. $(\tau_w/\tau_{c,sf} - 1)$ as shown in Figure 4b. The gradient of the fitting line represents the erodibility coefficient, $M_{sf}$, which was equal to 0.0068 kg/m$^2$s.

3.2. Mass fluvial erosion events

Figure 5 demonstrates the time series of water stage during the period between June 4th and December 1st (Figure 5a), the corresponding estimated exposure length, $L_e$ for PEEP B1 installed at the crest of the bank (figure 5b), and the corresponding shear stress exerted on the crest of the bank (Figure 5c). As mentioned earlier, the time series of $L_e$ was obtained by converting the time series of voltage output produced by the sensor using the calibration equation and a developed data processing protocol. This monitoring activity successfully captured the increase in sensor exposure length (figure 5b) due to the bank retreat between June 4 and December 1, 2009 during which at least 6 (six) flood events occurred (Figure 5a). Each staircase in the solid red line (Figure 5b) indicates the occurrence of a bank retreat event. Eight retreat events were identified at the crest of the bank (see Figure 5b) with the retreat lengths, $\Delta L$, were 9.2 cm, 4.9 cm, 2.7 cm, 6.8 cm, 7.8 cm, 5.9 cm, 1.6 cm, and 2.1 cm, respectively. More interestingly, Figure 5c reveals that only three retreat events ($\Delta L=9.2$ cm, 2.7 cm, and 6.8 cm)
can be attributed to the shearing action of flow or mass fluvial erosion, while the others were coincide with \( \tau_w = 0 \).

![Figure 4](image)

**Figure 4.** (a) The fitting line in \( E \) vs. \( \tau_w \) plot intercepted the shear stress axis at 1 Pa. (b) The gradient of the fitting line in \( E \) vs. \( (\tau_w/\tau_{c,sf}-1) \) plot was equal to 0.0068 kg/m\(^2\)/s.

### 3.3. \( \tau_{c,mf} \) value for mass fluvial erosion

Mass fluvial erosion occurred during a short time of initial flood surge when the bank soils were punched by the rapidly increasing shear stress, \( \tau_w \), that goes higher than the threshold \( \tau_{c,mf} \) [31], [32], [33]. The time of mass fluvial erosion, \( \Delta T \), coincided with the change in gradient of the time series of \( \tau_w \). The change in gradient was determined as the “change in \( \tau_w \) between two consecutive time intervals” divided by the “change in time between two intervals” [31]. Applying this procedure, it was found that there were a total of 10 (ten) surges which corresponded to the mass fluvial erosion events (see Table 2) with 2 (two) of them resulted in no bank retreat (\( \Delta L = 0 \)).

In Table 2, the mass fluvial erosion rate, \( E \) (kg/m\(^2\)/s), was quantified as:

\[
E = \frac{\Delta L}{100 \Delta T} \rho_{bulk}
\]  

(6)

where \( \Delta L \) is the retreat length (cm), \( \Delta T \) is the duration (s) of erosion, and \( \rho_{bulk} \) is the soil bulk density (kg/m\(^3\)).
The \((\tau_w, E)\) data points from conduit erosion flume test (Table 1) were plotted along with data from PEEPs (Table 2) as shown in Figure 6. Two fitting lines were extended on the plot. Those two fitting lines had different gradient signifying two different erosion regimes e.g. surface and mass fluvial erosion. Surface fluvial erosion occurred at lower shear stresses compared to mass fluvial erosion. The turning point between surface and mass fluvial erosion corresponded to the turning point between the two fitting lines (Figure 6) or when the \(\tau_w = 14.65\) Pa. This \(\tau_w\) value represented the threshold shear stress for mass fluvial erosion or \(\tau_{c,mf}\). In other word, \(\tau_{c,mf}\) was equal to 14.65 Pa. This finding also provides a convincing evidence that the conduit flume and PEEPs are two suitable techniques for capturing and distinguishing two low amplitude of bank erosions in the nature e.g. surface and mass fluvial erosions.

Figure 5. Results of field monitoring during the period between June 4th and December 1st. (a) Time series of water stage. (b) Moving-averaged and estimated exposure length, \(L\), for PEEP B1. (c) Estimated exposure length, \(L\), coupled with corresponding shear stress at the crest of the bank.

Table 2. Mass fluvial erosion events detected by PEEPs

| PEEP | \(\Delta L\) (cm) | \(P_{bulk}\) (kg/m\(^3\)) | \(\Delta t\) (s) | \(E\) (kg/m\(^2\)s) | \(\tau_w\) (Pa) |
|------|-----------------|-----------------|---------------|-----------------|-------------|
| B1   | 9.2             | 1299            | 900           | 0.1328          | 14.5        |
|      | 6.8             |                 | 900           | 0.0981          | 13.8        |
|      | 2.7             |                 | 900           | 0.0390          | 5.81        |
| B2   | 12.4            | 1618            | 1200          | 0.1672          | 18.1        |
|      | 6.1             |                 | 750           | 0.1316          | 17.4        |
| B3   | 4.7             | 1618            | 900           | 0.08450         | 15.5        |
|      | 3.4             |                 | 900           | 0.06112         | 13.4        |
|      | 1.9             |                 | 900           | 0.03416         | 6.46        |
| B4   | 0               | 1880            | 0             | 0.00000         | 12.7        |
|      | 0               |                 | 0             | 0.00000         | 11.5        |
4. Conclusions

In this study, conduit erosion flume and PEEP sensor techniques were used for monitoring and measuring surface and mass fluvial erosions, respectively. Using those techniques the $\tau_{c, sf}$ and $\tau_{c, mf}$, two key parameters which determine the onset of surface and mass fluvial erosion, can be determined successfully. The PEEP sensor can measure the mass fluvial erosion occurred under water, even capture the quasi-continues nature of erosion. These are the advantages which cannot be found with other methods such as cross-sectional survey, streambank scanning, aerial imaging, and erosion pin. More importantly, using these two methods, the presence of two regimes in the low amplitude of bank erosion, e.g. surface and mass fluvial erosion can be captured and distinguished. Starting from low to high shear stress, the onset of surface fluvial erosion as well as the transition from surface to mass fluvial erosion can be depicted.

Acknowledgment

This study was mainly sponsored by Fulbright Indonesia Presidential Scholarship Program. Also, the author would like to acknowledge IIHR- Hydrosience and Engineering University of Iowa and Prof. Papanicolaou Research Team for providing valuable advice and field and laboratory facilities.

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