Fluvial Erosion Measurements of Streambanks Using Photo-Electronic Erosion Pins (PEEPs)

I. Introduction

Bank erosion remains a major research topic among water scientists and engineers due to its frequency and detrimental effects on human life. This natural process often threatens infrastructures such as bridges, houses, roads, dams, and other structures built near the river bank or in the vicinity of river flood plain. The damage caused by bank erosion to the Midwestern infrastructure has been estimated to be nearly $1.1 billion during the last decade (Papanicolaou et al. 2008). Also, the volume of eroded bank could settle on the river bed and reduce the depth making the stream not navigable. In addition, a large amount of eroded soil originated by the bank can increase the turbidity of water at the downstream reach of a river and further disturb the ecosystem of streams. Odgaard (1987) reported that 40% of the suspended sediments found in streams came from the riverbanks. Bank erosion, also, results to a large amount of loss of fertile agricultural soil. Thoma et al. (2005) stated that the averaged loss rate is about 0.5 feet/year in the upper Minnesota River. In Iowa, bank erosion has been exacerbated by the conversion of nearly 80% of prairies to agricultural fields (Burkart et al. 1994), which resulted to increased streambank failure.

Bank erosion occurs when some portion of soil is removed from the bank surface of a river due to shearing action of the water, seepage effects and bank pop-up failure. The removal of soil from a river bank is triggered by two different mechanisms known in the literature as “mass failure “and “fluvial erosion” (ASCE 1998). The first term refers to the collapse of a large portion of soil due to the instability of a river bank. “The stability of a bank with regard to the
mass failure depends on the balance between gravitational forces that tend to move soil downslope and the forces of friction and cohesion that resist movement.” (ASCE 1998). This balance can be disturbed by the change of pore-water pressure in the soil. As the soil is fully saturated, positive pore-water pressure acts to reduce the friction forces, which can lead to mass failure. Conversely, as the bank soil is unsaturated, negative pore-water pressure occurs, which can increase the inter-particle bonding forces developed among soil particles and consequently enhance the stability of the river bank. Mostly, a portion of a river bank located above the water surface is unsaturated, while the lower portion affected by the rapid drawdown and upraising of the water level is saturated. This means that in general the upper soil (soil near the bank crest) tends to be more stable than the soil located in the lower bank profile (near the bank toe).

The second mechanism of bank soil removal is fluvial erosion, which refers to the removal of individual soil particles or aggregates by flow-induced forces, including drag force, and lift force that act on the bank surface. This erosion mechanism continuously occurs on the immersed bank surface during a period when the flow induced forces exceed a surrogate measure of cohesion, known as the critical erosional strength ($\tau_{cr}$).” The critical erosional strength denotes the cohesion strength provided by interparticle forces of attraction or repulsion acting at the microscopic level, including electrostatistic forces, van der Waals forces, hydration forces and biological forces”(Papanicolaou et al. 2007). Seasonal changes in temperature and humidity of air and earth surface can contribute to the weakening of soil and further inducing the fluvial erosion. “Swelling and shrinkage of soils during repeated cycles of wetting and drying can contribute to cracking that significantly increase erodibility and reduces soil shear strength.” (ASCE 1998). Besides, the presence of ice in the soil pore interstices during winter is responsible for the increase of fluvial erosion. “Heaving, due to the 9% increase in water volume
on freezing, and the growth of needle ice wedges and needles during thawing of soil moisture, are highly effective in increasing the susceptibility of cohesive bank materials to flow erosion” (ASCE 1998). Moreover, vegetation can also increase the erosion resistance of the soil. The roots of plants bind the soil and introduce “added” cohesion over the intrinsic cohesion of the bank material.

Mass failure has been studied earlier than fluvial erosion. Researches focused on mass failure have been conducted frequently and literature that discusses the concept and analysis on this topic is plenty. This is because mass failure analysis has a similar basic concept with slope stability analysis which has been previously well developed and understood by researchers. It is acknowledged that treatment of river bank stability shares a common origin with that of engineered slopes and embankments which is the fundamental work of researchers, such as Bishop (1955), Bishop and Morgenstern (1960), Fredlund and Krahn (1977), and Poulos et al. (1985). More specific investigations on mass failure have been conducted by many researchers such as Lawler et al. (1997), Simon and Rinaldi (2000), and Papanicolaou (2001).

On the other hand, little attention has been given to fluvial erosion comparatively to mass failure and other processes that affect bank erosion. Rinaldi and Simon, in their literature review on bank erosion articles of the last four decades, have summarized the proportion of each sub topic in the substantial development of bank erosion research. There is a growing number of bank erosion investigations and a shift in the pattern of “hot” sub topics in the discipline, but few studies have been concerned with the process of fluvial erosion, and little progress has been made in understanding fluvial erosion of cohesive bank (Bertrand & Papanicolaou, 2010). In addition, the fluvial erosion has been underestimated and considered less significant when compared with the mass failure in term of production of eroded material. Fluvial erosion,
comparatively to mass failure results to less erosion on an event scale and for this reason has received much less attention compared to mass failure.

In this study, more attention is given to the fluvial erosion process. A field observation for studying the relative importance of fluvial erosion (compared to mass failure) is presented. Two different sites in Clear Creek, Iowa were selected as study locations. As previously described, fluvial erosion is typically a continuous process that commences at the bank for conditions above threshold whereas the mass failure is an event based process triggered by the rapid change of pore water pressure in the bank soil. The pore water pressure itself is affected by the water level in the stream. Referring to this fact, it is reasonable to expect that the dominant erosion mechanism would be different at each selected site. It is hypothesized that mass failure is dominant in the headwater site where the water level could rapidly change, while fluvial erosion is ubiquitous at the downstream site where the flow is considerable to erode the streambank.

II. Objective

The goal of this study is to identify and quantify the dominant erosion mechanism (mass failure or fluvial entrainment) affecting two stream reaches of different stream order, flow condition, and land-use. First, erosion rates of two selected locations in the Clear Creek were continuously measured using Photo Electronic Erosion Pins (PEEPs) connected to a data logger that can record the measurement each 15 seconds. The first location was South Amana (upstream reach of Clear Creek), and the second one was Camp Cardinal (downstream reach of Clear Creek). Later, the recorded erosion rates were analyzed to reveal the dominant erosion process of the corresponding location.
III. Study Area

Clear Creek is a 40-km long water body ideal for studying bank erosion. Soils in this watershed are mainly loess-derived and highly erodible. The soil texture varies from sandy loam to clay loam. Move to the downstream, the dominant soil texture changes from a silty-clay loam in the headwaters to a silty-loam near the mouth. Approximately 65% of the upland slopes in the Clear Creek Watershed (CCW) range between 2 and 9%. According to Abaci and Papanicolaou (2009), the combination of extensive agricultural activities, increased urbanization, 20 highly erodible soils, and steep slopes within CCW have influenced the fluvial processes and stream bank erosion in the watershed.

Furthermore, two sites were selected based on their position in the Clear Creek and evidence of previous bank erosion. First, South Amana was referred to as “site 1” located at the upstream reach of Clear Creek, representing an agricultural headwater system of the CCW (Fig. 1). It was expected that mass failure was the dominant erosion mechanism here due to the flashiness of the system. Camp Cardinal was then selected as “site 2” situated at the downstream reach of Clear Creek, where the flow condition is similar to that of 4th order stream (Fig. 2). The area surrounding this reach is mainly urbanized and the fluvial erosion was expected as the dominant process at this site.

IV. Field Observations

First, PEEP sensors and conventional erosion pins were fully inserted into the observed banks at site 1 and site 2. As an initial condition, no active-length of those pins was allowed to be exposed to sun light and their positions should construct a mesh-like formation on the surface of the bank (Fig. 2.a). A PEEP is an optoelectronic device consisting of an array of photovoltaic
cells (photodiodes) connected in series and enclosed within a transparent acrylic tube. When the bank is eroded, the portion of the PEEP exposed to the light increases, resulting in more intensive incident light striking the PEEP (Fig. 2.b). With the photodiodes, the received incident light is converted to milivolt signal and sent through a cable to a data logger that will record the signal continuously with a time step of 15-minute. It is logic to state that the magnitude of the signal is proportional to the erosion length. The PEEP method offers a capability of conducting continuous monitoring; thereby the timing, magnitude and frequency of the specific erosion events at the site can be clearly identified. On the other hand, conventional, manual methods like erosion pins and resurvey techniques can only reveal net change to a site since the previous field visit. They cannot therefore reveal the “true” temporal distribution of erosional activity. Although the conventional pin is less preferred, in this research both types of pins were used in order to compare their performances.

In addition, periodical field visits at site 1 and site 2 were conducted during the period of the project that coincided with some flood events. The visits are important to upload the data from data logger into computer, to measure the exposed length of conventional pins, and to inspect the position of PEEPs after a flood event occurs.

Finally, the collected data was analyzed by statistical method i.e., moving average method and Shewhart graph capable to identify the dominant trend of the data and the variability of the erosion lengths at the two sites based on the work of Bertrand and Papanicolaou (2010).
V. Result and Discussion

V.1. Site 1

The recorded data provided by the PEEPs were plotted in the graphs and evaluated using moving average technique and the Shewhart graph. Figure 3 illustrates the time series data for the 15-minutes interval with the stage measured at Site 1 for the period of May 18th – June 22nd, 2009. Figure 4 is similar to figure 3, except that the time window in figure 4 is narrowed to focus on the flood event of June 19th, 2009. As shown by Figure 3, bank toe erosion occurred on a continuous basis and presented high variability. This behavior was attributed to the variability in the stress exerted by the flow. According to Simon and Collison (2001), Papanicolaou et al. (2007), and Fox et al. (2007), bank toe erosion is triggered by the significant excess or apparent shear stress, which can lead to bank undercutting near the toe region. Therefore, it was most probable that bank toe erosion at Site 1 was governed by the fluvial erosion process.

On the other hand, the erosion at the crest of the bank look has less variability comparatively to the erosion near toe location; however, the mean magnitude of erosion near the crest was higher than that near the toe for most of the period of observation. This behavior indicated that erosion process at the crest was governed by the subaerial processes and potentially by the swelling that occurred at this location. A similar behavior has been reported in the literature by Lawler et al. (1999) and more recently by Pizzuto (2009). Shortly, fluvial erosion is the dominant mode of erosion at the bank toe, whereas the subaerial processes are the governing process at the crest of the bank. This finding agrees with the observations by Prosser et al. (2000) that stated 80% of the time, bank erosion at the toe is dominated by fluvial hydraulic forces. Similarly Lawler et al. (1999) postulated through decadal observations that subaerial
processes have a significant contribution to bank erosion starting from the midsection of the bank and extending to the bank crest.

It was also recognized from figure 4 that the middle part of the bank (L230) experienced the highest erosion comparatively to the other two locations (crest and toe) for the period the activity has been recorded. This kind of behavior has also been reported by Harden et al. (2009).

Figure 5 described a mass failure occurred at site 1 after the flood event of June 19th, 2009. After that peak event, the erosion length increased significantly to the value of 20.5 – 22 cm at all points in the bank. Such a large magnitude of erosion that occurred in a short period can only be explained by the occurrence of mass failure. Also, there was a time lag between the peak of hydrograph and the occurrence of the mass failure during which the water level drew down as illustrated by the falling limb of the hydrograph. This drawdown of stream water affected the stability of the stream bank. Water level in the bank soil did not decrease in the same speed as that in the stream. When the stream water drew down, the water level in the soil was still high, making the bank soil in saturated condition. This condition created high pour water pressure in bank soil, and consequently lowered the soil shear strength that induced bank instability.

The moving-average technique is a useful technique of filtering data series for visually depicting the dominant trends within the data series. The variability of data is filtered out but the dominant trend remains. Figure 5 demonstrated the result of a moving-average technique applied to time series data of erosion length at site 1 with a sampling interval of 11.25 hours. Although the data fluctuation was less prominent in figure 5 compare to figure 4, both figures illustrated a similar erosion pattern. In figure 5, the data trend was clearer. Fluvial erosion ensued in the period between May 18th and June 18th, 2009, and mass failure was clearly depicted by the June 19th event.
As demonstrated by figure 5, the dominant erosion process that governs the bank geometry was the mass failure. Although the fluvial erosion process took place during most of the time of observation and the mass failure occurred only in one incident after the flood event, but the erosion length resulting from mass failure were more significant determining the bank retreat and the geometry of the bank.

V.2. Site 2

A similar procedure was adopted to present the results for the absolute erosion length for Site 2 with the one considered for Site 1. The moving average technique was used to reveal the dominant trend of erosion during the observation period as shown by figure 6. Two storm events were identified at site two e.g., June 19\textsuperscript{th} and August 27\textsuperscript{th} storm events. A large discrepancy in the stage recorded at Sites 1 and 2 can be revealed by comparing figure 5 and 6. Other than the June 19\textsuperscript{th} event that triggered a historic upper limit value of 300 cm, most of the stage values at Site 1 are of a single or at best double order of magnitude. On the other hand, the minimum observed stage at site 2 was of a three orders of magnitude, nearly 100 cm. This fact suggested that Site 2 was more actively eroded than site 1. According to figure 6, there was no significant change of erosion length during the period of observation that can indicate the occurrence of mass failure except at L231. The single noticeable significant change of erosion length occurred after the storm June 19\textsuperscript{th} at middle part of the bank (L231), more obviously presented in figure 7, and could not be an indication of mass failure because mass failure was characterized by the occurrence of significant erosion at all points of observations as demonstrated at site 1.
To observe the possibility of mass failure that could happen after the storm event, the recorded data series were plotted in a narrowed time window focusing on the two storm event as shown in figure 7 and 8. Figure 7 and 8 supported the previous explanation that describes the absence of mass failure after the storm event. Accordingly, the dominant erosion process at site 2 was fluvial erosion as expected before the observation was conducted.

VI. Conclusion

The PEEP technique can successfully reveal the trend and the dominant erosion processes in the bank due to the capability of this device to continuously monitor the erosion length resulting to an important data series. Information of erosion patterns in the bank can be identified by analyzing the data series of the recorded erosion length. Anyhow, this method needs to be accompanied with geodetic survey and traditional erosion pin as the control agents to the result proposed by PEEP and as the second alternative source of data when the PEEP is washed out by the storm flow.

Fluvial erosion is the dominant mechanism in a stream reach of third or fourth order stream characterized by a quasi-steady and continuously high base flow, an ideal condition for fluvial erosion to occur. Further, the weathering processes accompanied by mass failure are more prominent at the upstream reach (near the headwaters) where the flow condition is unsteady, flushy and low base flow, analogues to that of first order stream.

Acknowledgements

I am grateful to Dr.Papanicolaou for his permit to use the erosion data and his continuous support on my research. I would like to thank Fabienne Bertrand, my colleague in Dr.Papanicolaou’s research group, for her tremendous effort on collecting and analyzing the recorded erosion data.
Figures

**Fig 1.** (a) Initial condition at site 1 South Amana, Iowa on the beginning of the study period (May 28, 2009). (b) A survey was conducted at the same site after the June 19- flood even. To monitor the erosion rate, five PEEP s were positioned at different observation points as labeled in the picture.

**Fig. 2.** (a) Survey was conducted at Camp Cardinal, Iowa on September 9, 2009 after the flood event. Four PEEP sensors denoted by A1, A2, A4, L231 and some traditional pins signed with flags were attached into the bank to measure the erosion. (b) Both the conventional pin and PEEP are used to measure the erosion length. During the erosion process the exposed length of PEEP increases, resulting in a higher voltage signal. The recorded voltage signal is logically proportional to the length of erosion.

**Fig. 3.** Stage and bank erosion data series of 15-minute interval recorded at site 1. The symbol B2, L230, and B4 respectively denote the point of observation at the crest, middle part, and toe of the bank. The blue line described the change of water stage or hydrograph. The x-axis is the 15-minute interval, the primary y-axis is the absolute erosion measurements in cm and the secondary y-axis is the water stage in cm.
Fig. 4. Erosion length recorded before, during and after the June 19th storm event at site 1.

Fig. 5. Time series of erosion recorded at site 1 after moving average method with time interval 11.25 hours.

Fig. 6. Time series of erosion recorded at site 2 after moving average method. The symbol A1 and A2 denote the point of observation at the crest of the bank, L231 for middle part of the bank and A4 for the toe of the bank.

Fig. 7. Erosion length recorded before, during and after the June 19th storm event at site 2.

Fig. 8. Erosion length recorded before, during and after the August 27th storm event at site 2.
Reference


