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Automated Erosion System to Protect Highway Bridge Crossings at Abutments

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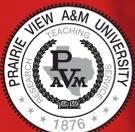THE UNIVERSITY OF IOWA

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Automated Erosion System to Protect Highway Bridge Crossings at Abutments

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15. ABSTRACT

A new instrument (Photo-Electronic Erosion Pin, or PEEP) was examined in collecting field data and remotely monitoring bank erosion near bridge abutments during floods. The performance of PEEPs was evaluated through a detailed field study to determine factors affecting their records. Proper calibration of the instrument was important in obtaining accurate erosion lengths. Calibration of the PEEPs within the banks nearby the study reach provided the most accurate erosion lengths. In addition, comparison with traditional, manual methods was recommended. Bank erosion was monitored at two study sites at the Clear Creek Watershed (CCW), IA between May 2009 and December 2009 using the continuously monitoring PEEPs and more traditional methods (e.g., geodetic channel surveys and standard erosion pins). The first site was located below an agricultural headwater of the CCW at the confluence of two 1st order streams downstream of the 190th Street Bridge near U.S. Highway 151 in Iowa County. Whereas, the second site (hereafter referred to as "Site 2") was located on a 4th order stream at Camp Cardinal Rd. in Coralville, Iowa near the CCW confluence (mouth) with the Iowa River. The area surrounding this reach is mainly urbanized. The monitoring period contained two significant runoff events on June 19 and August 27, 2009. The PEEPs provided a detailed time series of bank retreat during the study period. At Site 1, the flash flood of June 19, 2009 produced significant, mass failure of the channel banks, especially at the bank crest and mid-section. Bank retreats of ~ 25 cm were measured with the highest erosion rate being observed at the mid-section of the bank. The high erosion at the bank midsection over-steepened the bank height making the bank more susceptible to mass failure and slumping. At Site 2, flow was often higher than at Site 1 providing favorable conditions for more continuous fluvial erosion punctuated with irregular bank slumping. Erosion lengths up to 38 cm were detected at Site 2. The bank erosion monitoring at high resolution intervals due to the PEEPS allowed for better characterization the fluvial erosion occurring at this site. One limitation of the PEEPs was their inability to record data while submerged. The correlation between the submerged and unsubmerged data revealed that R^2 was higher for PEEPs at higher elevations above the free surface; hence, the PEEPs located at the bank mid-section or crest performed better than the PEEPs near the bank toe. Despite the above limitation, the PEEPs captured well the timing and magnitude of specific erosion events at both sites. The PEEPs were able to predict accurately bank erosion near bridge abutments during the flood. The maximum error between manual and automated measurements of the exposed length of the PEEPs was observed at site 1 and this error was less than 27%. The error between the channel survey and the automated PEEP measurements was less than 14%. The successful field experiments of the PEEPs at the study sites proved that the PEEPs technology is transferable to the field. The PEEPs present several advantages by providing real-time data of erosion in terms of magnitude and frequency, which is not possible with the traditional methods where only net changes from previous measurements are known. This real-time data coupled with the automated nature of the instrument made it ideal for certain sites that are not easy to access on a continuous basis. Automated and continuous real-time data are in great need for monitoring bank erosion near bridge abutments. The PEEPs provide valuable data on the timing of individual bank erosion events, especially the time lag between the peak erosion and the peak of the hydrograph. This information can also be of great importance to the field of geomorphology, as well as to numerical modeling.

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Chapter 1 Introduction

Scour around the foundations (piers and abutments) of a bridge due to river flow is often

referred to as "bridge scour" (Ettema et al. 2006). Bridge scour is a problem of national scope

that has dramatic impacts on the economy and safety of the traveling public. Bridge scour has

resulted in more bridge failures than all other causes in recent history (Murillo 1987).

In 1988, the Federal Highway Administration (FHWA) issued a technical advisory

mandating the evaluation of scour potential at all existing bridges and the scour-resistant design

of new bridges. Since this mandate, design engineers have repeatedly questioned the validity of

design methods and scour predictions based on laboratory studies. The experiences of many

design engineers indicated the need for collecting field data to verify the applicability and

accuracy of the current design procedure for different soils (sediments), streamflow conditions,

and bridges encountered throughout the United States (Richardson et al. 1993).

Despite the recognized need for the collection of field data (Culbertson et al. 1967; Shen

1975), very few scour data were collected until the late 1980s. This deficiency is primarily due to

the difficulty of performing accurate and complete field measurements of scour during floods,

the inability to get skilled personnel to perform the measurements, and the limitations associated

with existing methods and instruments.

Both portable and fixed instruments have been proposed to measure and monitor bridge

scour during floods. Portable scour-monitoring instruments include probing the streambed

adjacent to piers and abutments with long poles or lowering a tethered sounding weight from the

bridge deck (Shearman et al. 1986). A recent development of this technique involves the use of a

truck with a fully articulated arm that positions the instrument on the river from the side of the

bridge. Regardless of the detection mechanism, these methods require personnel to be physically

present at the bridge site during the measurements, which puts the operator at risk during a flood event. Also, these methods are expensive, time consuming, and require traffic control or bridge closings to be implemented, which is undesirable especially during high volumes of traffic.

Fixed instruments include float-out devices, buried or driven rods, and scour chains (Ettema et al. 2006). These techniques require considerable skills in installing, collecting, and interpreting the data. Recently, these instruments have been combined with other non-traditional techniques such as conductance (e.g., Radio Frequency IDs, RFIDs; and Photo-Electric Erosion Pins, PEEPs), in order to facilitate the collection of data remotely and provide information regarding scour development and maximum scour depth that cannot be efficiently collected by other methods. Buried rods, for example, can be equipped with Photo-Electric Erosion Pins (PEEPs) driven horizontally in the stream bank near the bridge abutment. The changes in the output voltage of the probe photovoltaic due to exposure can be used to quantify the scour occurring around the rod. The change in the output voltage can then be converted into scour depth and stored by means of a data logger. These techniques present the potential for performing continuous monitoring of bridge scour in situ but their application has been limited to the laboratory at best.

The FHWA, among other agencies (e.g., USGS), recognized the need to develop nontraditional methods and implement advanced instrumentation to collect field data and remotely monitor bridge scour during floods (Mueller and Landers 2000). Monitoring bridge scour can be a cost-effective approach for protecting the traveling public from potential bridge failure by alerting traffic engineers to close bridges during floods if the scour depth reaches a critical level. Advancements in sensor technology over the last half-decade have contributed towards the development of autonomous scour detection systems, which can minimize the

exposure of DOT crews to dangerous conditions (e.g., especially during floods). At the same time, these technologies have the potential to provide unique, rare data which can improve our predictive approaches for scour monitoring. All these elements combined can help move towards the development of a warning system for preventing loss of life and property due to catastrophic failures.

Chapter 2 Objectives

Stream bank degradation has resulted in approximately $1.1 billion in damages to US bridge infrastructure mainly due to abutment failure. Failure of stream banks near bridge abutments is due to climatic and hydrologic forces (e.g., high flows, seepage, freeze/ thaw) that weaken the bank soil's overall strength. The cumulative effects of these processes are difficult to capture with conventional monitoring methods (e.g., erosion pins, channel surveys), which provide only net bank retreat since the previous sampling. A more robust technique that systematically and continuously quantifies bank erosion, especially during extreme conditions when failure is most likely, is needed to determine the precise temporal distribution of the bank erosion.

In this study the investigators proposed the utilization of a new instrument—Photo-Electronic Erosion Pin, or PEEP—to collect field data and remotely monitor bridge scour during floods. The main objective of this pilot study is to develop a monitoring protocol for bank erosion near bridge abutments using innovative technology, namely PEEPs. In order to accomplish the study objective, a rational approach has been performed with the three specific goals:

1. Evaluate the PEEPs efficiency by conducting field experiments to determine the factors affecting their performance.

2. Provide the initial steps towards the development of an integrated bridge scour monitoring system using the PEEPs technology.

3. Assess the applicability of the PEEPs for monitoring bridge scour in the field and identify the areas needing improvement.

Chapter 3 Methodology

The following methodological steps were undertaken to achieve the overarching

objective of the study:

1. Perform a comprehensive field study to evaluate the performance of the 2 different

    models of PEEPs.

2. Implement the PEEPs technology at the field for monitoring bank erosion and suggest

    future directions for the development of a stand-alone, versatile system for

    performing bridge scour monitoring in situ.

3.1 Evaluation of the PEEPs Performance

The principles of operation, description of the instruments, and calibration of both PEEP

models are described in this section.

3.1.1 Principles of operation

The Photo-Electronic Erosion Pin, which was originally described in Lawler (1991),

provides automated and continuous monitoring of erosion and deposition. The PEEPs are

essentially a series of photovoltaic/ photo-resistance cells (or diodes) encased in a transparent

waterproofed acrylic tube (Lawler 1991, 1992); thus, the PEEPs are light dependent. The

photovoltaic PEEP provides a voltage as light (e.g., from the sun) strikes the diodes. The voltage

is sent along a cable and is recorded on a datalogger. With the photo-resistance PEEP, an

external voltage is supplied to the PEEP but is stopped when reaching the photo-resistors. As

light strikes the photo-resistors their resistance drops, which allows a higher voltage to pass

through to the datalogger, where the value is recorded. Figure 3.1 illustrates the principle of the

PEEP sensors.

Figure 3.1 Illustration of the Principles of Operation of the PEEP

Essentially for both PEEP models, an increase in the number of exposed diodes (i.e., struck by light) corresponds to a higher voltage sent to the datalogger. When the PEEPs are initially inserted into the bank face parallel to the water surface, all the diodes are covered by the bank sediment and the voltage received by the datalogger is low. However, as the bank face retreats, more diodes are exposed and the voltage received by the datalogger increases. This voltage is normalized against a reference value, which corresponds to the voltage if all PEEP diodes are exposed. This ratio is then related to an erosion length. The ratio between the reference voltage and the voltage received by the datalogger is considered to account for the fluctuations of sunlight or temporary shadows.

3.1.2 Description of the instruments

For this study, two PEEP models were used: a photovoltaic PEEP and a photo-resistance PEEP. The photovoltaic PEEP is a PEEP 200 series by Hydro Scientific Limited, as shown in figure 3.2a. The model consists of 20 photovoltaic cells in series over a 20 cm section that constitutes the active length of the sensor. The diodes are encased in an acrylic tube. The whole instrument is 66 cm long and is terminated by a 15 m cable, which can be connected to a datalogger. The outer diameter of the protective acrylic tube is 16 mm. Two of the diodes located at either end of the active length are considered reference cells. The other eighteen diodes are

used to evaluate the location of the bank face. The accuracy of the instrument is $\pm\, 2 - 4$ mm with a 95 % confidence level (Hydro Scientific Limited 2004). Two PEEPs of this model were used in this study and are identified as L230 and L231.

The second PEEP model is produced by Rickly Hydrological Company and is based on the principle proposed by Lawler (1991), however, these PEEPs use photo-resistors. In addition, these PEEPs are shorter: only containing 13 diodes as seen in figure 3.2 b. The diodes are encased in an acrylic tube. These PEEPs require an additional, fully exposed PEEP for the reference values. Ten PEEPs of this model were used in this study and identified as A1, A2, A3, A4, A5 and B1, B2, B3, B4, B5.

Two Campbell Scientific data loggers, CR 800 and CR 1000, were used to store the data. The dataloggers were set to receive voltages in the range of 0-225 mV every 15 minutes (Lawler 2005) and a computer was used to download the data. The dataloggers use solar power to operate of the datalogger is sufficient to send the initial voltage required by the Rickly PEEPs.
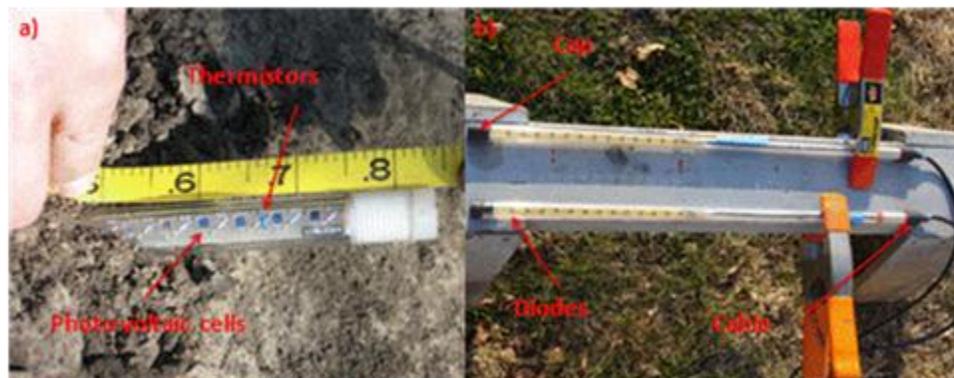

Figure 3.2 a) Picture of the PEEP Sensors (Lawler et al. 2001); b) Picture of the Rickly PEEP Series

3.1.3 Calibration

A calibration process was required before installing the PEEPs, which relates the exposed active length of the PEEP and the voltage received by the datalogger. An outdoor, site-specific

calibration is recommended (Lawler, 1991); therefore, a field calibration was conducted at study sites for the PEEPs on a sunny day with some fluctuations in light intensity. Initially, the PEEPs were laid horizontally adjacent to one another on floodplain at each site in alignment with the sun, as demonstrated in figure 3.3 a. Steel wire stakes were used to fix the PEEPs to the ground to prevent tilting of the PEEPs, which would produce invalid data. A dark tube was placed over all the diodes of each PEEP. The tube was moved back at defined intervals exposing the diodes, which simulated bank erosion. The interval between the exposure of subsequent diodes was 4 minutes and the measurement window for each diode was every fifteen seconds. The calibration process lasted about 2 hours. The corresponding voltage recorded by the datalogger after each consecutive movement of the tube was correlated to the measured exposed length for the calibration. The exposed length was measured using a measure tape.

However, this method proved insufficient when recorded voltages after installation were lower than the calibrated values. It was assumed that the tubes did not block all the light reaching the diodes and was not accurately simulating the field situation; therefore, a second calibration was conducted by incrementally sliding the PEEPs out of the pre-drilled holes in the stream bank (see fig. 3.3b). This calibration proved successful since all subsequent values were within the calibration range.

To determine the relationship between the exposed length of the PEEP and the received voltage (i.e., the bank retreat), the exposed length was plotted on a graph against the ratio of the voltage received by the datalogger normalized against the reference value. A linear relationship was used for the photovoltaic PEEPs and a polynomial equation was used for the best fit line of the photo-resistance PEEPs.

For the photovoltaic sensor, the ratio between the voltage of any cell "i" to the voltage of the front reference cell was calculated (Equation 3.1) and termed the photovoltaic ratio (Rpp), which is expressed as a percentage.

$$R_{pp} = \frac{voltage\ cell\ i\ (mV)}{voltage\ front\ reference\ cell\ (mV)} \tag{3.1}$$

The erosion length of the PEEP was then determined using a linear egression (Equation 3.2) that relates the Rpp (%) and measured exposure length:

$$L\ = c + d \times Rpp \tag{3.2}$$

where c = 17.83 and d = 2.1743 are coefficients determined from the manual (User Guide for Models PEEP 110, PEEP 200, and P-LITE 200, 2004).

For the photo-resistance PEEPs, the ratio between the reference PEEP and the measuring PEEP was initially determined from the data (Equation 3.3) and then applied to a polynomial equation (Equation 3.4); namely, the 2D NIST HAHN Model, was used to calculate the erosion length. The coefficients: a, b, c, d, e, f, and g were obtained for each sensor using the commercially free, web-based software at Zunzun.com.[1]

$$x = \frac{voltage\ measuring\ PEEP\ (mV)}{voltage\ reference\ PEEP\ (mV)} \tag{3.3}$$

$$y = \frac{a + bx + cx^2 + dx^3}{1 + ex + fx^2 + gx^3} \tag{3.4}$$

After calibration, the values from the dataloggers can be converted to erosion lengths using Equations 3.2 and 3.4, however, visual confirmation is also recommended.

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[1] The specific URL for the equation is: http://zunzun.com/Equation/2/NIST/NIST%20Hahn/
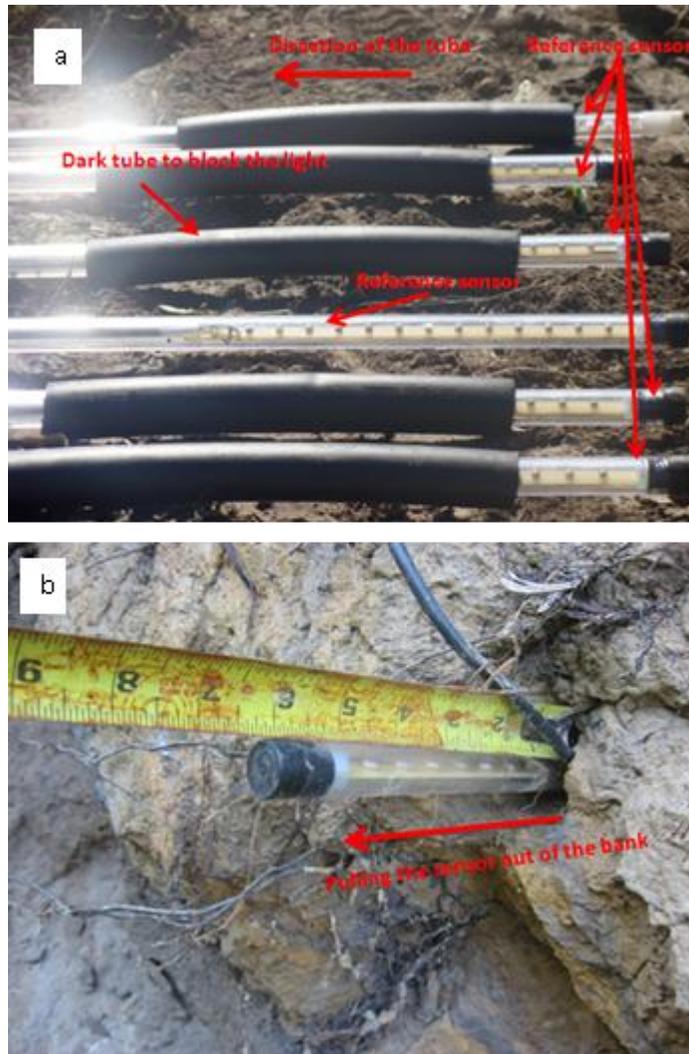
Figure 3.3 Calibration of the PEEPs: a) Floodplain; b) In-bank

3.2 Monitoring Bank Erosion using the PEEPs

This section describes the field study performed for monitoring bank erosion near bridge abutments using the PEEPs.

3.2.1 Study sites description

Two study sites at the Clear Creek Watershed (CCW), IA were selected based on evidence of previous bank erosion. The first site, hereafter referred to as "Site 1," is located below an agricultural headwater of the CCW at the confluence of two 1st order streams

downstream of the 190th Street Bridge near U.S. Highway 151 in Iowa County. The reach drains a 26-km^2, agricultural sub-watershed of the CCW. The mean annual stream flow discharge for this reach is 5.9×10^6 m^3/yr with an annual sediment discharge of 5×10^3 tons (Abaci and Papanicolaou, 2009). Six cross-sections were established every 15 m within the reach to determine the reach geometry and for extensive monitoring (see fig. 3.4). The average bank height of each cross section was 3.3 m and the average bank angle was 23°. It is expected that mass failure is the dominant erosion mechanism here due to the flashiness of the system.

The second site, hereafter referred to as "Site 2," is located on a 4th order stream at Camp Cardinal Rd. in Coralville, Iowa near the CCW confluence (mouth) with the Iowa River (see fig. 3.5). The area surrounding this reach is mainly urbanized. Flow at Site 2 is less flashy than site 1 and the sustained high flows facilitate fluvial erosion. The average bank height was 5.8 m and the average bank angle was 47°. The reach is at a bend in the river, so the study was focused on the right bank (looking downstream), which receives the impinging flow. The average annual flow is 7.2×10^7 m^3/ yr and the sediment discharge from this site is 7.8×10^4 tons. Figure 3.5 shows the bank height is steep and greater than 2 m. This bank had obvious signs of bank erosion. Fluvial erosion is expected to be the main erosion process at Site 2.

Soils at both study sites are mainly loess-derived and highly erodible. The soil texture varies from sandy loam to clay loam in the CCW. Moving 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 CCW were in the range between 2 and 9%. The combination of extensive agricultural activities, increased urbanization, highly erodible soils, and steep slopes within CCW has influenced the fluvial processes and stream bank erosion in the watershed (Abaci and Papanicolaou 2009).
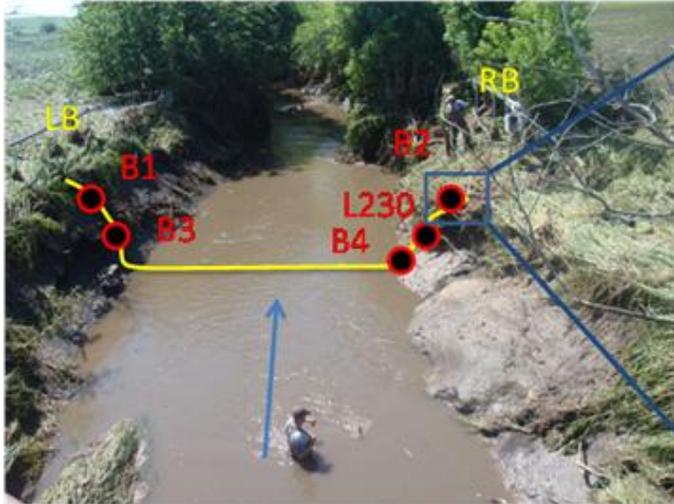
LB: Left bank RB: Right bank
● **PEEPs** —— **Cross-section**
—— **Flow direction**

Top PEEP B2 completely exposed

—— **Slumping of materials at the left bank**

Figure 3.4 Site 1 Study Reach Showing the Location of the Peeps
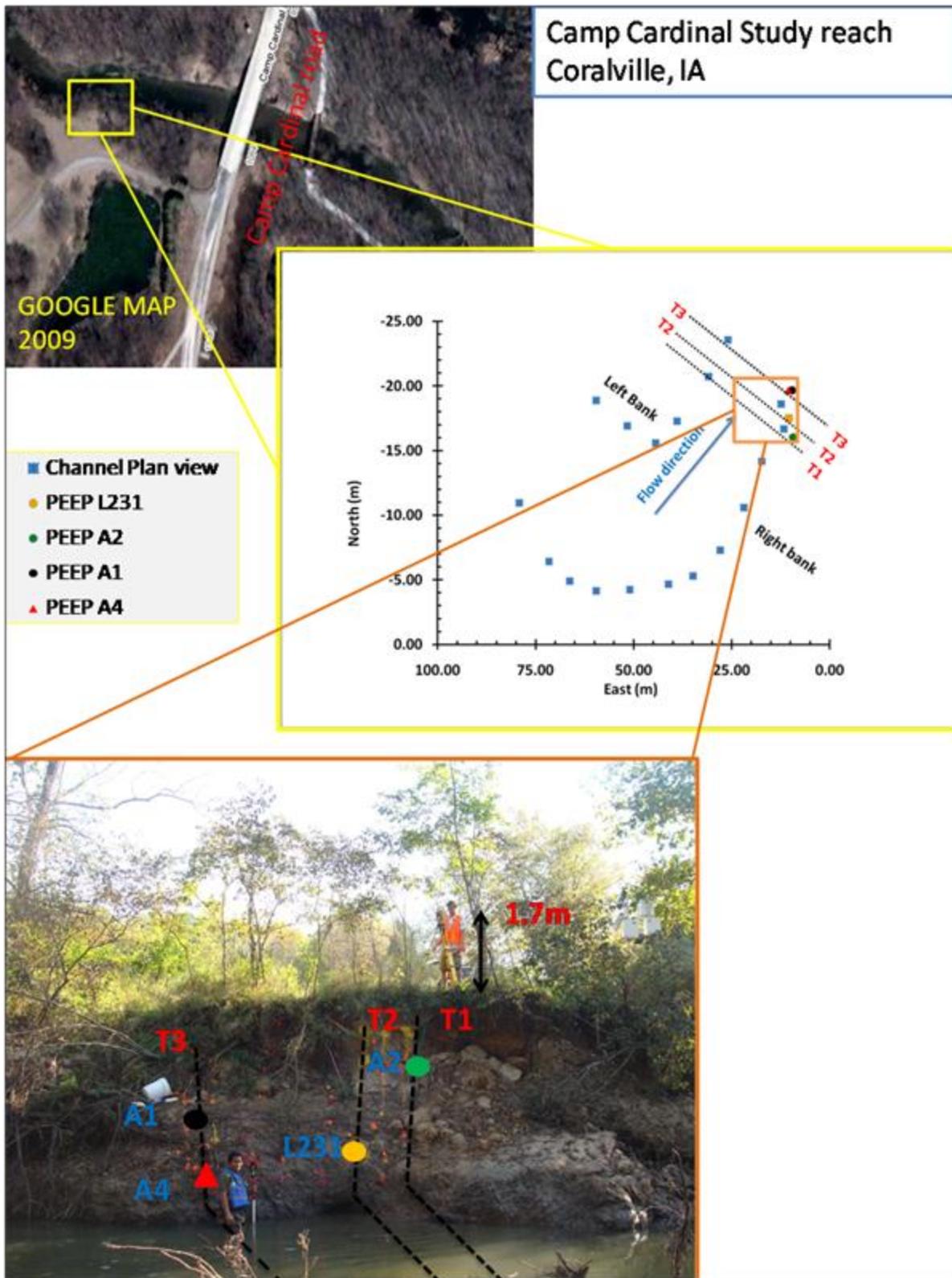
Figure 3.5 Site 2 Study Reach Showing the Location of the Peeps

3.2.2 PEEPs Installation

The recommended procedure for installing the PEEPs calls for drilling two 16 mm diameter holes. The first hole is into the bank face, parallel to the water surface. The second hole must be vertical from the top of bank some distance from the edge to avoid disturbing the bank. The two holes must intersect perfectly so that the PEEP cable can be passed through the holes. This technique proved difficult and was modified.

The modified procedure for installing the PEEPs required auguring a 16 mm hole parallel to the water surface only about 1 m into the bank face. The hole was carefully drilled to avoid significant disturbance to the surrounding bank soils (see fig. 3.6a). Moreover, the diameter of the hole was kept close to the outer diameter of the sensor itself (see fig. 3.3b).

Before inserting the PEEP into the hole, the cable at the end of the sensor was attached to the side of acrylic tube using plastic cable ties. Care was taken not to cover the diodes with the cable. In addition, sufficient slack was maintained at the tube/ cable interface to avoid snapping the cable. The PEEP and attached cable were then inserted in the bank so that only one diode was initially exposed (see fig. 3.6b and c). This configuration allowed the cable to exit the front of the hole so that the cable may travel up the bank face to the datalogger. The cable along the bank face was inserted into a garden hose for additional protection and the hose was fixed to the bank surface using bent steel wire stakes.

The data loggers were attached to 3 m aluminum poles that were driven at least 1 m into the ground. These poles were positioned approximately 2 m from the bank edge to avoid slumping. The cables were wired into the dataloggers and the remaining slack wire was bound to these poles (see fig. 3.6d).

At Site 1, five photo-resistance PEEPs (B1, B2, B3, B4, and B5) and one photovoltaic PEEP (L230) were installed on May 18, 2009. For the photo-resistance PEEPs, B5 was considered as the reference PEEP and secured at the flood plain as shown in figure 3.6d. On the right bank (looking downstream), PEEPs B2, L230, and B4 were respectively inserted into the bank face from the top of the bank to the toe, while on the left bank B1 and B3 were installed at the top and bank toe, respectively (see fig. 3.4). These PEEP sensors were removed shortly after the high event of June 19, 2009. The left bank experienced significant mass failure and PEEPs B1 and B3 were completely exposed. No data were recorded for these PEEPs due to a substantial battery drain. The PEEPs on the right bank remained in-place, but significant erosion had also occurred. The reference PEEP, B5, was moved from its original location due to over bank water flow.

At Site 2, four photo-resistance PEEPs (A1, A2, A4, and A5) and 1 photovoltaic PEEP (L231) were installed. Three transects were established on only the right bank (looking downstream), which is the side that received the impinging flow around the bend. PEEP A2 was installed in Transect 1 (T1), PEEP L231 in Transect 2 (T2), and PEEPs A1 and A4 in Transect 3 (T3). T1 was the most upstream transect followed by T2 and T3 moving downstream. The sensors A4 and A1 were installed, respectively, at the toe and mid bank section. L231 and A1 were installed, respectively, at mid and top bank.

Figure 3.6 Installation Procedure of the Peeps

3.2.3 Programming and data processing

The dataloggers required specific programs in order to receive and record the voltage signals from the PEEPs. The programs were created using the Short Cut software provided by Campbell Scientific. For the photovoltaic PEEPs, a differential voltage reading was used. With the photo-resistance PEEPs, however, a half bridge program was used, which allowed for an excitation voltage to be sent across the wires through the resistors.

The PEEP data were downloaded weekly at both sites. Data were collected from May 18, 2009 to June 22, 2009 at Site 1 and from June 4, 2009 to December 1, 2009 at Site 2. Using the calibration relationships, the recorded voltages from the PEEP data (in mV) were converted to erosion length (in mm).

The data collected during darkness (i.e., at night) were filtered from the dataset because no artificial light was used in this study. A limitation of the PEEPs is that they only provide valid data in daylight. The daily period of observation was from 7 am to 7 pm during the summer and

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from 8 am to 5 pm during fall and winter seasons. Information about daily sunrise and sunset were found at the "U.S. Naval Oceanography website."[2]

The data were further filtered to remove values outside the calibrated range, such as negative numbers. In addition, values recorded while the PEEPs were submerged were removed from the dataset. The lack of data accuracy while the instrument is submerged is reported in the literature on PEEPs (Lawler 1991; Lawler 2005; Lawler et al. 1999; Lawler et al. 2001). This filtering is commonly done especially in coastal engineering applications (Couperthwaite et al. 1998; Mitchell et al. 1999; Mitchell et al. 2003). In these applications, authors filtered the original dataset and smoothed the remaining values with a daily mean approximation.

During the period of observation both sites experienced high flow events, which produced significant erosion that exposed many of the PEEP diodes. This required the PEEPs to either be reset into the bank or completely removed. The flash flood event of June 19th facilitated the removal of the PEEPs at Site 1. At Site 2 on July 7, 2009 all PEEPs were reset into the bank. Finally, on August 27, 2009 another flash flood event occurred at Site 2, which required PEEP A2 to be reset. After the resetting of a PEEP, the absolute erosion length was calculated by adding the previous daily mean value of erosion to the newly recorded data after the instrument was reset. This explains why the recorded erosion lengths are greater than the active length of the PEEP.

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[2] The full web address is: http://aa.usno.navy.mil/data/docs/RS_OneDay.php

Chapter 4 Results

The results were organized as follows. First, the PEEPs performance was evaluated; second, the time series data obtained from the PEEPs were presented; and third, the change in the cross section area of the stream due to bank erosion during the recorded period was demonstrated.

4.1 PEEPs Performance

The statistical tests performed to evaluate the performance of PEEPs A1, A2, and A4 located at the three transects at Site 2 are summarized in figure 4.1. On the vertical axis all the data were plotted, when the PEEPs were submerged and unsubmerged. To determine the impact of submergence on the instrument's performance, we correlated all data defined earlier with unsubmerged data. Figure 4.1 reveals that there is a positive correlation between unsubmerged condition and all data with the poorest performance exhibited by PEEP A4 located near the stream bed (see fig. 3.5). Figure 4.1 incorporates regression lines and confidence intervals for the best fit lines of the real data. The closer the PEEPs were to the free water surface, the poorer the performance of the PEEP. This was reflected with the correlation coefficient R^2 value recorded for the three PEEP transects. The higher the elevation of the sensor, the higher the R^2 obtained from the best fit analysis. We believe PEEPs located near the toe of the bank perform poorer than the remaining PEEPs for the following reasons: (1) light availability and penetration corresponding to the submergence period of the PEEPs, and (2) disturbance caused by the bank inundation and the formation of forbay areas in the proximity of the bank toe.

In terms of light availability, several authors (Effler et al. 2007; Lin et al. 2009) noted and quantified the role of water transparency on light penetration. They demonstrated that suspended sediment triggers light scattering and, in some cases, absorption. As a result, the light penetrating

the water may not reach the photovoltaic cells of the instrument. Transparency measurements performed by Loperfido (2009) in Clear Creek show that the average transparency is less than 40 cm. Therefore, it is safe to say that attenuation of light due to traveling in the water phase is further amplified by the presence of suspended material, which affects water transparency.

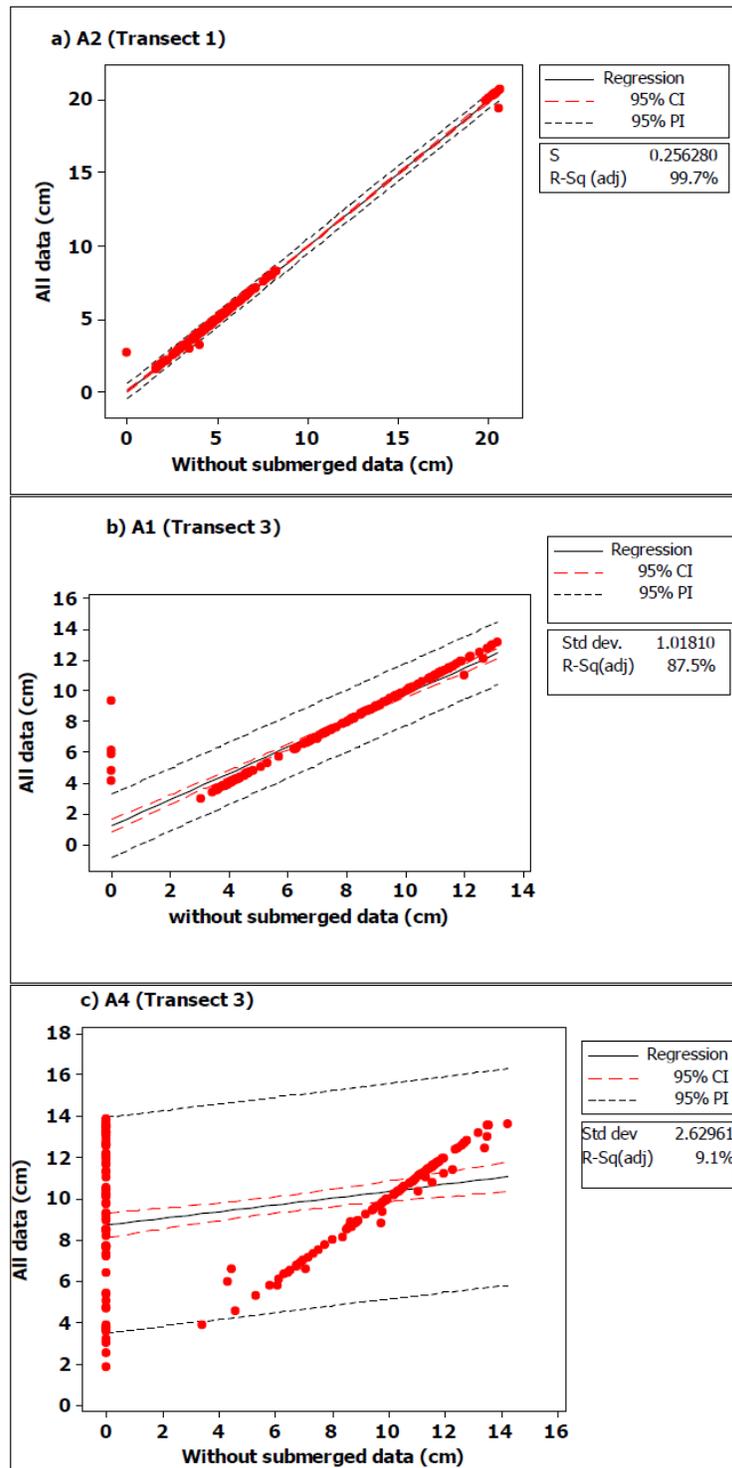**Figure 4.1** Examination of Peeps Performance for Periods that Peeps are Submerged to the Flow and Unsubmerged. The datasets are recorded from PEEPs: a) A2; b) A1; and c) A4 located at Camp Cardinal (Site 2) for summer and fall of 2009. The x-axis includes data when PEEPs A2, A1, and A4 are fully submerged. The y-axis includes all the data without removing the data when PEEPs A2, A1, and A4 are submerged.

Table 4.1 offers a comparison of the automated bank measurements with the traditional measurements (i.e., tape measure and surveys) at Site 2. The surveys were performed on July 30th and September 30th. There is an excellent agreement between the measurements for PEEP A2. The maximum error observed was about 20% and was recorded for PEEP L231. Figure 4.2 complements the results summarized in table 4.1, and demonstrates the performance of all PEEPS against the measuring tape measurements referred to in the horizontal axis as manual measurements. The closer to the bank toe, the higher the departure is between the automated and manual measurements. Several authors in the literature have attributed this trend to the intense inundation that takes place near the toe. Vibration caused by the potentially induced spiral motion of the impinging flow must also be considered (Couperthwaite et al. 1998; Lawler 1991; Lawler 1992; Lawler et al. 2001; Lawler 2005; Mitchell et al. 1999; Prosser et al. 2000).

Table 4.1 Comparison of the Automated Bank Measurements to the Traditional Methods (Manual Measurements and Resurvey Bank Lines) at Camp Cardinal

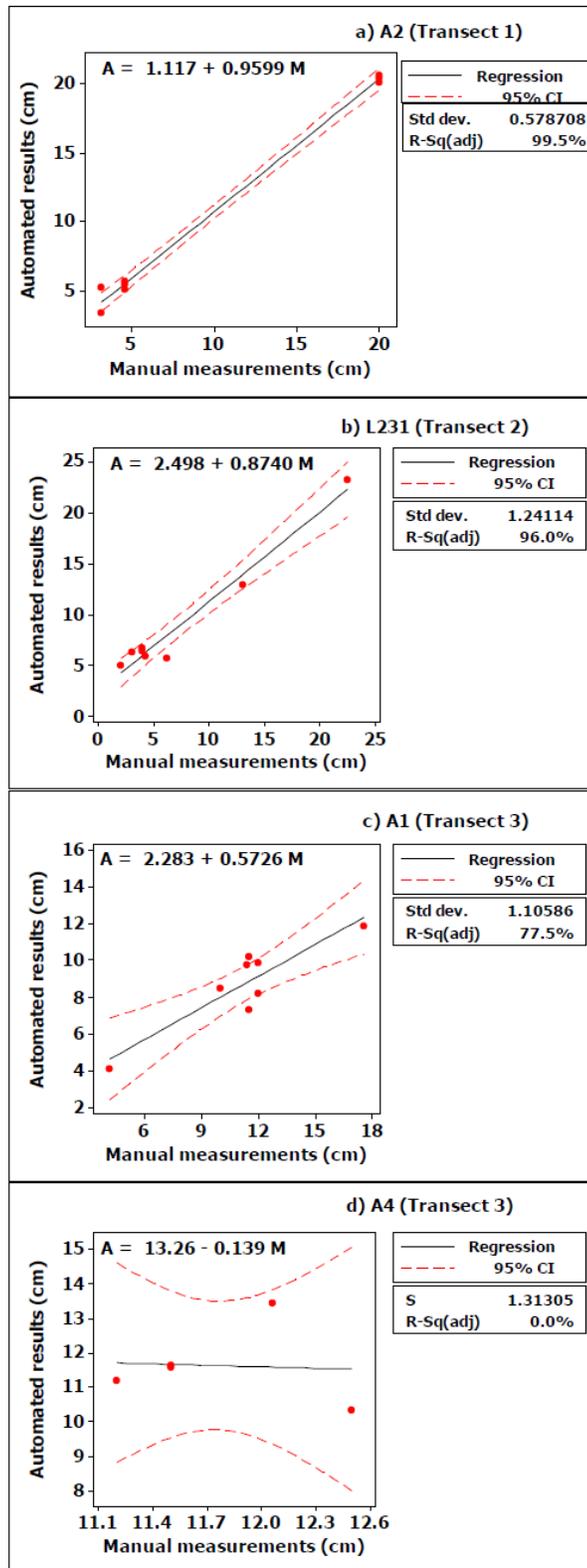| Erosion length (cm) after the August 27th event (cm) at Site 2			
	Survey	**PEEP SENSORS**	
		Automated	**Manual measurement with tape**
PEEP A2	23.9	23.7	20.5
PEEP L231	4.3	5.7	6.2
PEEP A1	8.7	10.6	12.0
PEEP A4	16.6	11.6	11.5
Bank cross-section survey before the event : July 30th			
Bank cross-section survey after the event : September 30th			

Figure 4.2 Regression Plot between the PEEP Results and Measuring Tape Measurements. On the x-axis are the manual measurements of the protruding length of the sensor and on the y-axis the results of the PEEP sensor: a) A2; b) L231; c) A1; and d) A4 for the same date.

The daily time series data for the PEEPs records are presented along with the stage measured in figure 4.3 for Site 1 during the period of May 18 to June 22, 2009. The figure shows continuous toe erosion activity for the period of observation. Bank toe erosion has been observed to occur on a continuous basis and presents high variability that is attributed to the variability in the stress exerted by the flow. According to Simon and Collison (2001), and Papanicolaou et al (2007), bank toe erosion is triggered due to significant excess or apparent shear stress, which can lead to bank undercutting near the toe region. Therefore, it is most probable that bank toe erosion at Site 1 is triggered by the fluvial shear stress.

Near the bank crest (location of sensor B2), bank erosion presented less variability as compared to the near bank toe location; however, the mean magnitude of erosion near the crest was higher in magnitude for most of the observation period. For the period of May 21 to May 26, 2009, which coincides with a drop in the stage, high variability was pronounced near the crest compared to the remaining period of observation. This variability was attributed to subaerial processes and potentially to 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). In short, the time series data at the toe and crest reveal, that the toe fluvial erosion was the dominant mode of erosion, whereas at the crest there was a cumulative action of fluvial erosion and subaerial processes. This finding agreed with the observations by Prosser et al. (2000) that stated 80% of the time, bank erosion at the toe was 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.

The midsection of L230 experienced the highest erosion compared to the other two locations (crest and toe) for the recorded period. It is not unusual for bank midsections to exhibit the highest erosion rate as those are the locations where the bank experiences a change in its overall gradient. This rather typical behavior has been reported in the literature (Simon et al., 2003).

As the stage increased and we approached closer to the June 19th event, the erosion rates increased at all locations. A maximum retreat of 20.5 cm was recorded along the bank face (see fig. 4.3). This was an indication that mass failure occurred during the rising and falling limbs of the hydrograph. In other words, the erosion process at the bank boundary lost its spatial randomness and occurred simultaneously at the same rate for all locations.

In addition, figure 4.3 provides unique information about the time lag between the peak of the hydrograph and the highest erosion rate for all locations. The maximum retreat was observed roughly 21 hours after the occurrence of the hydrograph peak. It was clear that swelling and subsurface flow within the bank soil have contributed to the delayed response of the bank to the June 19th event. Both subsurface flows and swelling are key components of subaerial processes confirming our earlier suggestion that mass erosion remains the controlling agent during and after the June 19th event at Site 1. A similar trend to the one observed at site 1 was also observed at Site 2.
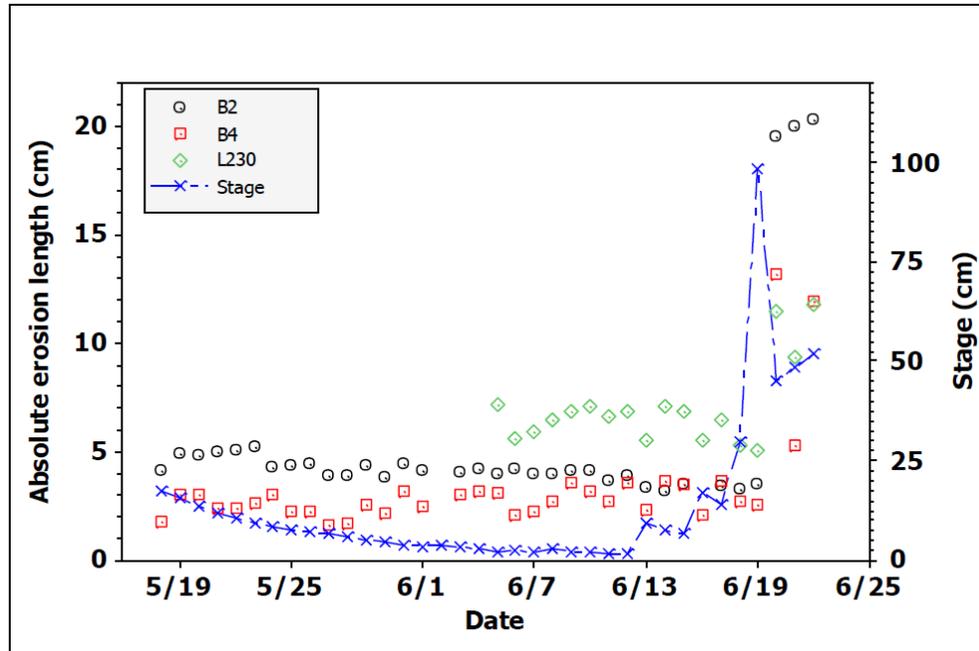
Figure 4.3 Times Series of Daily Interval, Stage and Bank Erosion Measurements Using the Sensors B2, B4, L230 at South Amana (Site 1)

4.3 PEEPs Predictions

The fluvial and mass erosion at Site 1 before and after the June 19th event is shown in figure 4.4. In general, the survey data (see fig. 4.4a) confirms the PEEPs observations. Figure 4.4b provides a plan view of the study reach before and after the June 19th event. There are discernable differences between the pre- and post-event cross-sectional areas in Site 1. The pictures strongly confirm the mass erosion triggered by the June 19th event with the widening of the channel and the removal of the pre-existing vegetation along the bank face. Note also that the pre-event picture was only taken 2 hours before the initiation of the June 19th event, while the post-event picture was taken the day after the event. Figure 4.5 shows the before and after conditions for two transects at Site 2. At Transect 1 the stream is active near the bed and the left bank where impingement of the incoming flow took place, whereas in Transect 3 the stream migrates towards the left bank.

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The maximum error between manual and automated measurements of the exposed length of the PEEPs was observed at site 1 and this error was less than 27%. The error between the channel survey and the automated PEEP measurements was less than 14%.
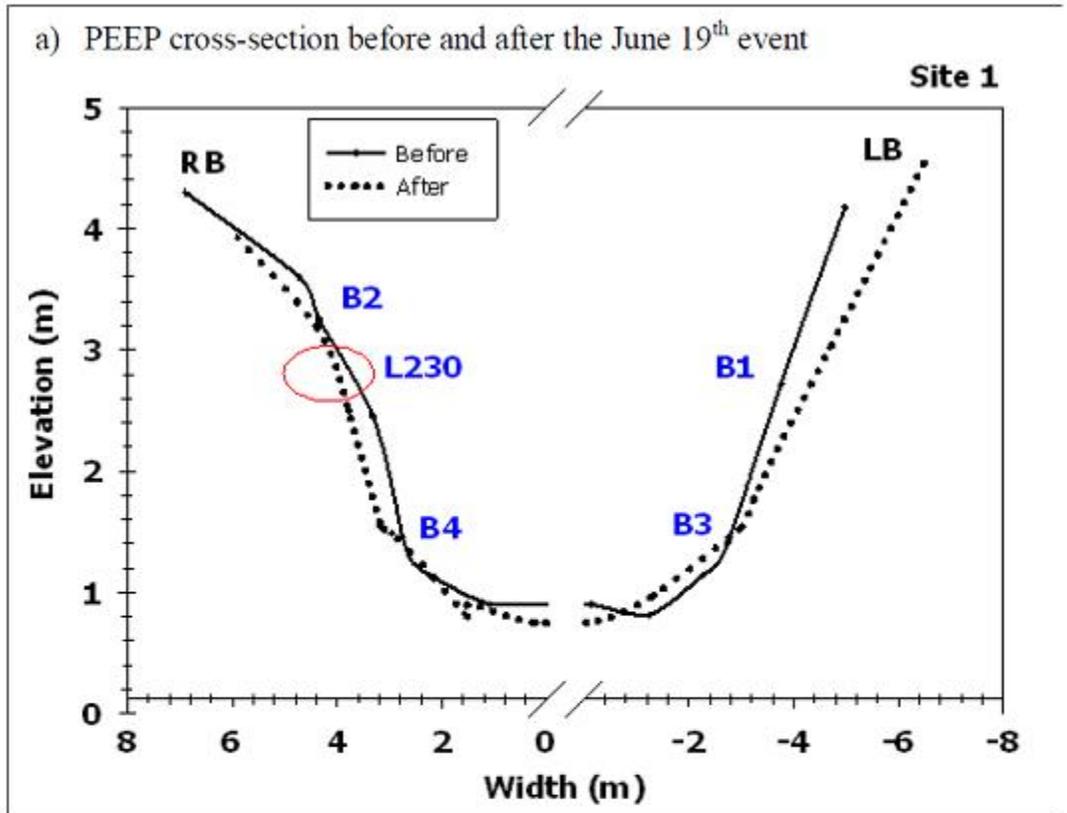
Figure 4.4 a) PEEP Cross-Section before and after the June 19th Event*; b) Plan View of the Study Reach Pre-event and Post-Event. If facing downstream, "RB" stands for Right bank and "LB" for left bank. The bank profile is delimitated using the survey data of May 28th and June 23rd 2009.
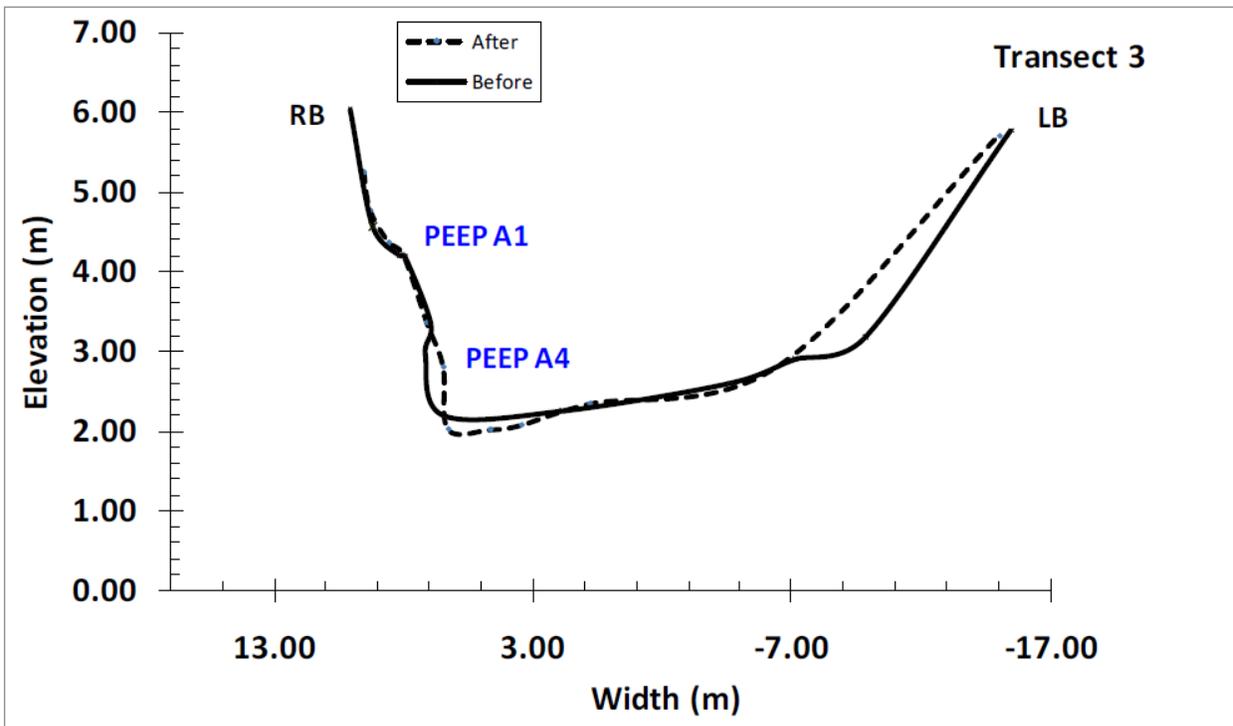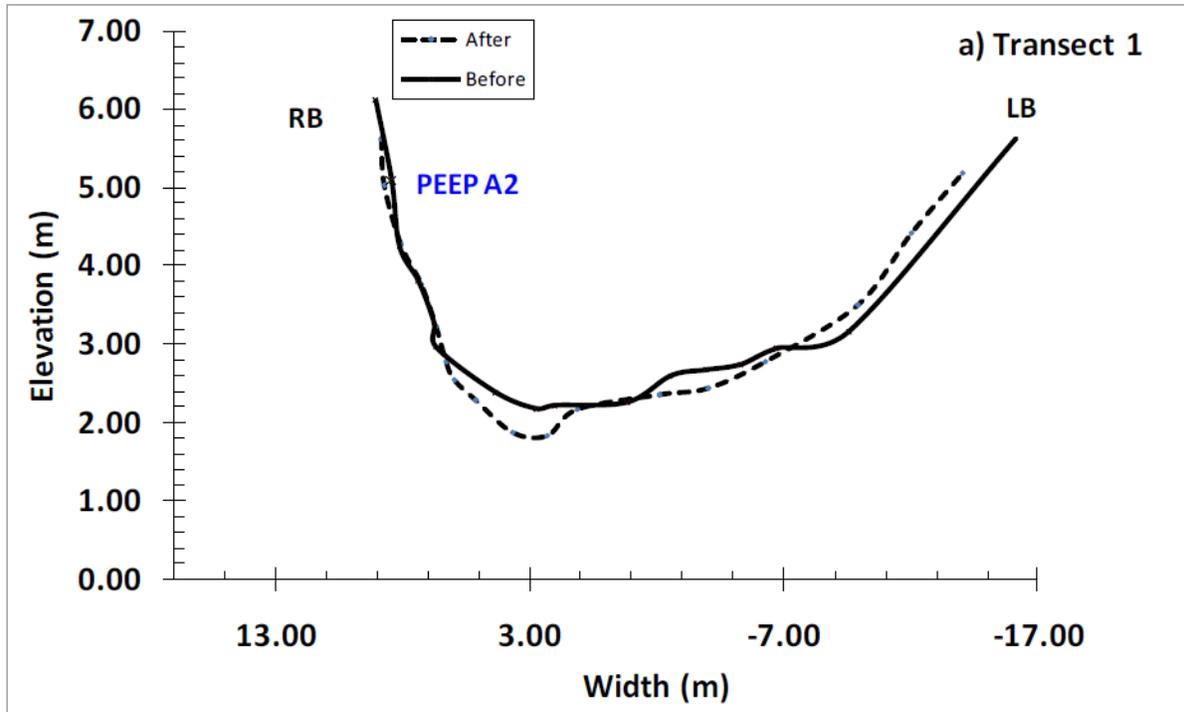
Figure 4.5 Bank Profile Delimitation before and after the August 27th Event Using the PEEP Data: (a) Transect 1 and (b) Transect 3. The bank profile is delimitated using the survey data of July 30th and September 30th 2009. If positioned facing downstream, "RB" stands for Right bank and "LB" for left bank.

Chapter 5 Conclusions and Summary

A new instrument Photo-Electronic Erosion Pin, or PEEP, was examined in collecting field data and remotely monitoring bank erosion near bridge abutments during floods. The performance of PEEPs was evaluated through a detailed field study to determine factors affecting their records. Proper calibration of the instrument was important in obtaining accurate erosion lengths. Calibration of the PEEPs within the banks nearby the study reach provided the most accurate erosion lengths. In addition, comparison with traditional, manual methods was recommended.

Bank erosion was monitored at two study sites at the Clear Creek Watershed (CCW) in Iowa between May 2009 and December 2009 using continuously monitoring PEEPs and more traditional methods (e.g., geodetic channel surveys and standard erosion pins). The first site was located below an agricultural headwater of the CCW at the confluence of two 1st order streams that were downstream of the 190th Street Bridge near U.S. Highway 151 in Iowa County. The second site, referred to as "Site 2," was located on a 4th order stream at Camp Cardinal Road in Coralville, Iowa near the CCW confluence (mouth) with the Iowa River. The area surrounding this reach is mainly urbanized.

The monitoring period contained two significant runoff events on June 19 and August 27, 2009. The PEEPs provided a detailed time series of bank retreat during the study period. At Site 1, the flash flood of June 19, 2009 produced significant mass failure of the channel banks, especially at the bank crest and mid-section. Bank retreats of ~ 25 cm were measured with the highest erosion rate being observed at the mid-section of the bank. The high erosion at the bank midsection over-steepened the bank height making the bank more susceptible to mass failure and slumping. At Site 2, flow was often higher than at Site 1 which provided favorable conditions for

more continuous fluvial erosion punctuated with irregular bank slumping. Erosion lengths up to 38 cm were detected at Site 2. The bank erosion monitoring at high resolution intervals due to the PEEPS allowed for better characterization the fluvial erosion occurring at this site.

One limitation of the PEEPs was their inability to record data while submerged. The correlation between the submerged and unsubmerged data revealed that R^2 was higher for PEEPs at higher elevations above the free surface; namely, the PEEPs located at the bank mid-section or crest performed better than the PEEPs near the bank toe. Despite the above limitation, the PEEPs captured well the timing and magnitude of specific erosion events at both sites. The PEEPs were able to predict accurately bank erosion near bridge abutments during the flood. The maximum error between manual and automated measurements of the exposed length of the PEEPs was observed at site 1 and this error was less than 27%. The error between the channel survey and the automated PEEP measurements was less than 14%.

The successful field experiments of the PEEPs at the study sites proved that the PEEPs technology is transferable to the field. The PEEPs present several advantages by providing real-time data of erosion in terms of magnitude and frequency, which is not possible with the traditional methods where only net changes from previous measurements are known. This real-time data coupled with the automated nature of the instrument made it ideal for certain sites that are not easy to access on a continuous basis. Automated and continuous real-time data are necessary for monitoring bank erosion near bridge abutments. The PEEPs provide valuable data on the timing of individual bank erosion events, especially the time lag between the peak erosion and the peak of the hydrograph. This information can also be of great importance to the fields of geomorphology and numerical modeling.

Chapter 6 Outcomes and Recommendations

The following points summarize the outcomes of this research study:

1. The PEEPs provided real-time monitoring of erosion events in terms of magnitude and frequency, which is not possible with the traditional methods where only net changes from previous measurements are known.

2. The applicability of the PEEPs for monitoring bank erosion near bridge abutments led to the development of a scientifically-based approach for monitoring bank erosion in the field at a low cost.

3. Other relevant hydraulic fields that may benefit from the PEEPs technology are sediment transport, and river morphology. For example, this approach took advantage of the data collected by the PEEPs to predict mass failure of bank material during a flood.

The methods and applications presented in this study are limited to the investigated field conditions. The proposed method was successful to estimate bank erosion near bridge abutments at two study sites in CCW, IA and can be applicable to other bridges on rivers with similar planform geometry and flow conditions (mostly applicable to Iowa). Nonetheless, it would be advisable to repeat this study at different bridges and rivers in the state to transfer its findings to other bridges in the Midwest. As the proposed PEEPs technology proved to be reliable in estimating bridge scour, future work based on this effective approach should continue. This can contribute to the development of remote bridge scour monitoring systems for the whole nation that are capable of providing the public with vital real-time information regarding the structures integrity. The approach proposed in this study can provide information regarding fluvial erosion and mass failure of streambank material that cannot be efficiently collected by other methods.

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