AN ADAPTIVE FIELD DETECTION METHOD FOR BRIDGE SCOUR MONITORING USING MOTION-SENSING RADIO TRANSPONDERS (RFIDs)

FINAL REPORT

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IIHR Hydroscience & Engineering

Iowa Department of Transportation

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16. ABSTRACT

A comprehensive field detection method is proposed that is aimed at developing advanced capability for reliable monitoring, inspection and life estimation of bridge infrastructure. The goal is to utilize Motion-Sensing Radio Transponders (RFIDS) on fully adaptive bridge monitoring to minimize the problems inherent in human inspections of bridges. We developed a novel integrated condition-based maintenance (CBM) framework integrating transformative research in RFID sensors and sensing architecture, for in-situ scour monitoring, state-of-the-art computationally efficient multiscale modeling for scour assessment.

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Iowa City, IA
February, 2014

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1. INTRODUCTION

1.1 Problem statement

Local scour of the river bed sediment near a bridge pier or abutment is due to the complex interactions (Figure 1) between the approaching streamflow and the bridge structure (e.g., Chiew and Melville, 1987; Melville and Coleman, 2000; Deng and Cai, 2010). Excessive scour can expose the bridge foundations and thus compromise their stability. As a result, scour can have significant economic impacts and potentially catastrophic consequences (Figure 2) on the safety of the traveling public, making it a problem of national importance (Federal Highway Administration, FHWA, 2012).

The FWHA has identified more than 150,000 bridges across the United States that are "vulnerable to scour" or have "undetermined foundation conditions" (Lagasse et al., 1995). A more recent study by Wardhana and Hadipriono (2003) revealed that of the 503 bridge failures between 1989 and 2000 in the United States, more than half (266 bridge failures) were related to scour. In 1993 alone, the scour accompanying the floods in the U.S. Midwest led to the failure of 23 bridges costing nearly $15 million in infrastructure damage (FWHA, 2012). In the following year, scour triggered by Hurricane Alberto damaged more than 500 bridges in Georgia and burdened the state with $130 million of needed infrastructure repair (Mueller and Landers, 1999; FWHA, 2012).

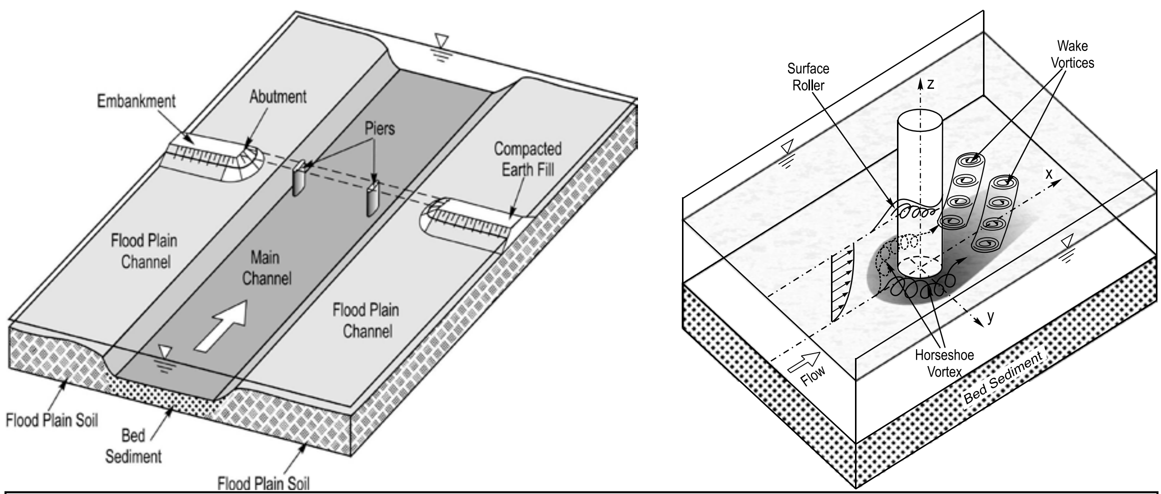

Figure 1. Flow through a bridge site produces complex interactions between the flowing water, bed sediment, and bridge pier causing hydraulic erosion and scour. These sketches illustrate some of these flow complexities around an abutment or pier.

To monitor scour the FWHA requires assessment of a bridge's scour condition only on a biannual basis. These inspections are typically performed by physically probing the scour hole. However, this physical probing is a time- and resource-intensive process with low accuracy and limited applicability, especially during high-flow, debris-laden, or icy conditions (e.g., Lagasse et al., 1998; Fukui and Otuka, 2002; Ettema et al., 2006). Recently, sonar, sound reflectometers (i.e., fathometers and acoustic depth sounders), and Time-Domain Reflectometers (TDR) have been used to measure bridge scour. Despite their advantages comparatively to physical probing, the sonar and reflectometers are costly and may also provide questionable measurements during high-flow or highly turbulent conditions (Yankienlun and Zabilansky, 1999; Nassif et al., 2002; Lin et al., 2004; Schall and Price, 2004; Ettema et al., 2006). Novel methods for measuring scour include the use of ground penetrating radar (e.g., Horne, 1993; Forde et al., 1999; Webb et al., 2000) and fiber bragg grating sensors (e.g., Lin et al., 2004; 2005); however, these methods have not been widely adopted, as of yet, in parts due to their relatively high acquisition costs.

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

Figure 2. A bridge pier collapsing due to scour during flood flows caused by a typhoon (Akabane River, Japan, September 2004).

In this study, we investigated the performance and applicability of Radio Frequency IDentification (RFID) technology for detecting the onset of scour and estimating the scour depth by uniquely relating radio signal strength to the distance and orientation of a submerged sensor in different river bed materials (e.g., sand and gravel). The RFID technology utilizes radio-waves as a means of information transfer between a base station and a sensor (Nichols, 2004; Roberts, 2006; Finkenzeller, 2010), in order to facilitate the collection of data remotely and provide information regarding scour hole development and depth that cannot be collected efficiently by other methods. The use of RFID techniques presents the potential for performing continuous monitoring of bridge scour in-situ but their application has been limited to the laboratory at best.

1.2 Background: Radio Frequency IDentification (RFID) technology

A typical RFID system (Figure 3) consists of the following three components: (i) the reader, which is the base station that transmits radio-waves through an excitation antenna to a transponder; (ii) the transponder (short for "*trans*-mitter" and "re-*sponder*"), which is the receiving sensor encapsulated in a protective shell (Figure 4) and has a unique ID embedded in its memory; and (iii) the excitation antenna, which ensures the two-way communication between the reader and a transponder (e.g., Lu et al., 2006; Dziadak et al., 2009; Finkenzeller, 2010).

The reader triggers the emission of radio-waves through the excitation antenna. These radio-waves, in turn, trigger a response in the transponder. The transponder then transmits its unique ID, as well as other potential, stored, energy-related data, back to the excitation antenna, which relays this information to the reader and eventually a host computer.

RFID systems can be distinguished based on either the power source used in the transponders or the frequency of the radio-waves used in the communication. The transponders are classified as passive and active (e.g., Roberts, 2006; Bailey et al., 2007; Tentzeris et al., 2007; Finkenzeller, 2010). Passive transponders are powered by an integrated capacitor, which is charged from the energy of the magnetic field generated by the excitation antenna. In contrast, active transponders are powered by an internal battery. Furthermore, based on the frequency of the radio-waves used in the communication, RFID systems can operate in the following three frequency ranges: (i) Low Frequency (LF; 9-195 kHz); (ii) High Frequency (HF; 3-300 MHz); and (iii) Ultra-High Frequency (UHF; 700 MHz - 3 GHz) (e.g., Hassan and Chatterjee, 2006; Roberts, 2006; Bailey et al., 2007; Tentzeris et al., 2007). Typically, active RFID systems operate in the HF band, while passive systems in the LF band.

RFIDs have been used in many applications, including sediment transport studies (e.g., Habersack, 2001; Nichols, 2004; Lamarre et al., 2005; MacVicar and Roy, 2011; Bradley and Tucker, 2012; Liebault et al., 2012; Liedermann et al., 2012); monitoring and control of the movement of machinery, equipment, and construction material (e.g., Goodrum et al., 2006; Lu et al., 2006; Wang et al., 2007; Ko, 2010); traffic management to alleviate congestion, especially in metropolitan areas (Wen, 2008; 2010; Chattaraj et al. 2009); and wildlife monitoring (e.g., Fischer et al., 2012). Other studies have used RFIDs for determining the location of tagged objects with respect to the excitation antenna (e.g., Zhao et al., 2006; Choi et al., 2009; Dziadak et al., 2009; Joho et al., 2009; Khan and Antiwal, 2009; Ko, 2010; Parlak and Marsic, 2011) by establishing quantitative relations with the Received Signal Strength Indicator (RSSI), which is a measure of the power in the RF signal transmitted from the transponder to the reader and is a function of the distance between the transponder and the excitation antenna (e.g., Ko, 2010). Most of these studies though were performed in air and used active RFIDs (e.g., Lu et al., 2006; Ko, 2010) due to their larger detection distance in air.

RFID utilizes radio-waves to transfer information between a base station (i.e., reader) and a sensor (i.e., transponder) via an excitation antenna.

Only a handful of studies have more recently explored the possibility of integrating RFIDs into a bridge scour monitoring system (Hawrylak et al., 2009; Papanicolaou et al., 2010; Chen et al., 2011). In these studies, RFID transponders with unique IDs were inserted into natural/ human-made particles (e.g., smart particles) or float-out devices (e.g., scour balls) that were buried at known depths or placed on top of the sediment bed in the vicinity of the bridge pier where scour was expected to occur. These studies mostly focused on particle ID detection, but they also explored the role of the transponder long-axis orientation relative to the excitation antenna. To examine, the role of transponder orientation, Hawrylak et al. (2009) incorporated an inclinometer to the transponder whereas Chen et al. (2011) performed a simulation study. Papanicolaou et al. (2010) conducted experiments with the transponder being both perpendicular and parallel relative to the excitation antenna, which are the two extreme cases. In most of these studies, passive RFID transponders were used for the following reasons: (i) passive transponders are less costly (~$300/ active transponder vs. ~$20/ passive transponder); (ii) they are smaller and require less maintenance, as they have no battery; (iii) the smaller size makes them easier to install in the field; and (iv) there is less backscatter of the LF waves as they travel through water or sediment (Choritos, 1998; Personnal communication with Telonics). The LF passive RFID technology offers other important advantages, namely the ability to use the RSSI measurements mentioned above and spatial orientation between the excitation antenna and the transponder to develop an advanced bridge scour monitoring system.

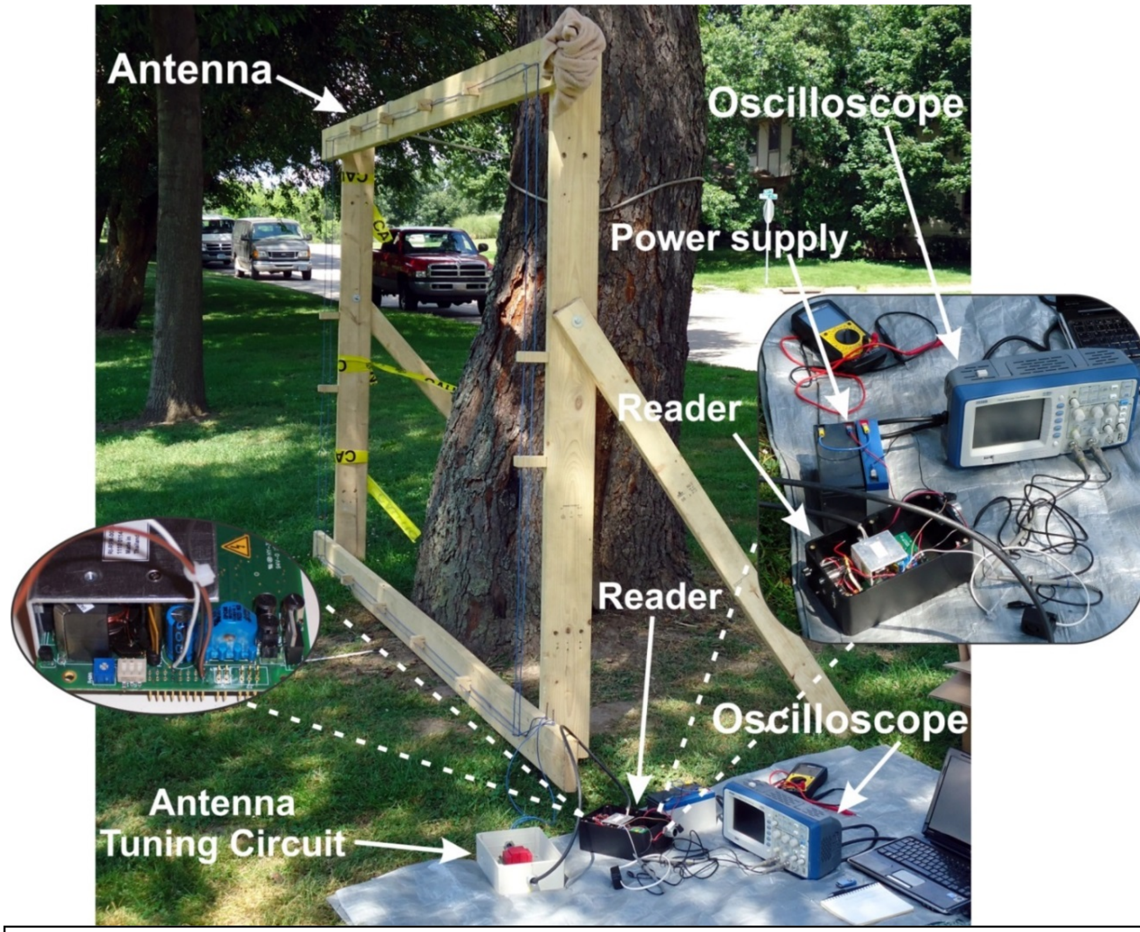

Figure 3. Setup of the Low Frequency, passive RFID system used in this study with the custom antenna.

1.3 RFID system for autonomous bridge scour monitoring

To capture fully the advantages of the LF passive RFID technology for autonomous bridge scour monitoring, the transponders were placed along a Leopold chain. The integrated RFID-Leopold chain system combines the established Leopold chain approach for scour measurement with the novel, automated, wireless RFID technology. Figure 5 depicts how the RFID-Leopold chain determines scour depth.

Figure 4. RFID transponders. (A) 23-mm glass encased transponder, with a penny for a size comparison; and (B) 120-mm long transponder. Both transponders are from Texas Instruments.

An RFID transponder with a unique ID (i.e., serial number, S/N) is attached at a known length along the Leopold chain. The Leopold chain length is then essentially electronically “marked” or “measured” by the RFID transponders. The Leopold chain with the RFID transponders is inserted vertically in the sediment bed near a pier where scour is occurring. The transponder is then located at a known depth within the bed. After installing the modified Leopold chain with the RFID transponders, a background survey will detect the buried transponders to provide the initial RSSI signal. For this background survey, the excitation antenna is placed horizontally at a fixed location directly above the transponders so that the transponders are perpendicularly oriented to the antenna (Figure 5a).

Measurement of the scour depth relies on the change in orientation of the RFID transponder(s) along the Leopold chain. Once scour occurs, the Leopold chain length above the scoured bed is exposed and folds over onto the scoured bed (Figure 5b). As a result, the transponders attached along the exposed Leopold chain are no longer perpendicular to the antenna. The change in orientation will result in a reduction of the transponder RSSI and possibly a complete inability to detect the transponder as the main focus of the return signal is now directed away from the antenna, hence signifying that the scour has reached the depth of that transponder. The progression of the scour depth can thus be monitored by inserting multiple Leopold chains in the river bed around a pier or abutments, each one integrated with a unique RFID transponder placed at different burial depth than the transponders of its neighboring Leopold chains (Figure 5).

2. OBJECTIVES & TASKS

A comprehensive field detection method was developed for the reliable monitoring, inspection, and life estimation of bridge infrastructure affected by scour that utilized state-of-the-art RFID sensors to minimize the problems inherent with manual monitoring techniques of the scour. The novel, condition-based maintenance (CBM) framework integrating the RFIDs for in-situ scour monitoring and computationally efficient, multi-scale modeling of scour will provide real-time, condition assessments that can be used in decision-making for down time, repair costs, and estimating the remaining useful life of critically scoured bridge structures. The results from this study will ultimately translate to an inexpensive, automated bridge monitoring system with the potential applications for other critical infrastructure, such as dams, levees or other near-shore structures.

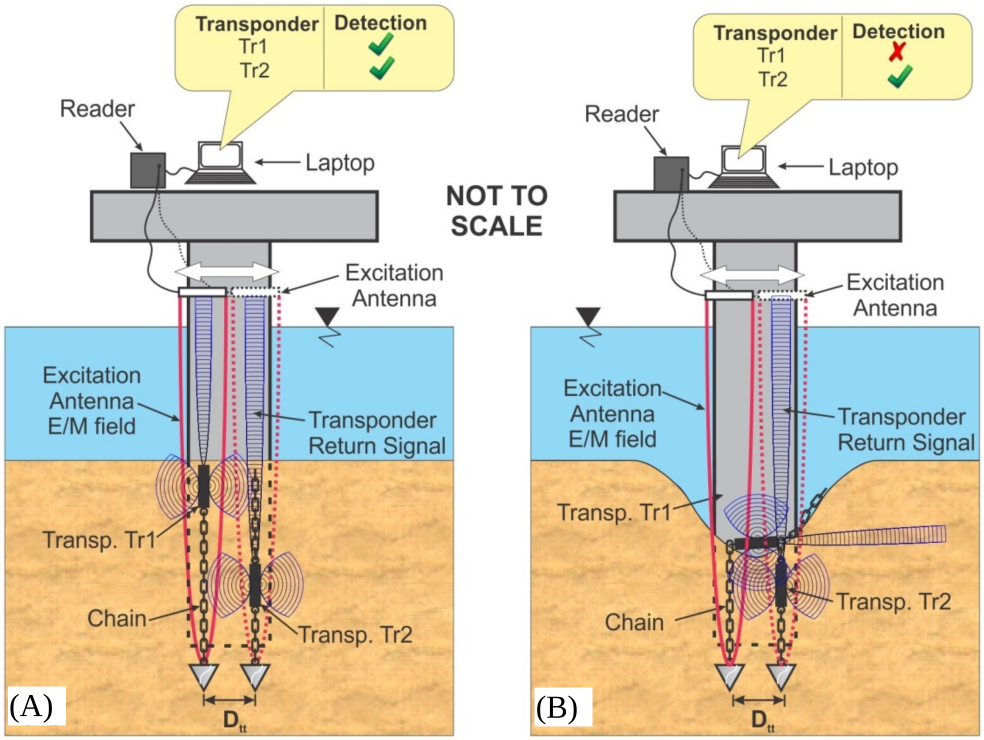

Figure 5. Application of the RFID technology for measuring scour via the transponder orientation: (A) prior to the occurrence of scour, and (B) after the occurrence of scour.

These scour assessment datasets using the RFIDs will help develop a *fundamental understanding of both clear water scour and live bed scour*. Clear water scour occurs when the amount of sediment transported from upstream of the scour hole is insufficient to fill the hole during the falling stage of the flood. Live bed scour occurs when sediments transported from upstream of a scour hole settle into the hole, sometimes completely refilling the hole, during the falling stage of the flood. *Live bed scour can be very difficult to detect by probing or visual inspection when the scour hole fills in after the process has occurred; however the use of the RFID monitoring systems discussed herein provides the ability to remotely monitor live bed scour.*

The corresponding tasks of this study can be summarized as follows:
Task 1: Construct a custom-made, excitation antenna optimized for a maximum read range and capable of providing detection ranges up to 60 ft. (~ 20 m) within the water-sediment column.

Task 2: Assemble waterproof, passive transponders capable of providing detection ranges up to 60 ft. (~ 20 m). This step had the following *2 addendum sub-tasks*: (i) Improve the waterproofing of the new developed transponders; (ii) Incorporate a Micro-Electro-Mechanical Sensor (MEMS) inclinometer to the transponders to quantify the orientation of the transponders to the excitation antenna and identify the moment when they is no longer perpendicular due to their "folding-over" from exposure during scour.

Task 3: Install water level loggers to measure stage at a monitoring site. Complement the stage measurements with standard channel cross-section surveys and sonar measurements for bathymetry.

Task 4: Install the modified Leopold chains with the RFIDs in the sediment at a monitoring site.

Task 5: Measure the scour depth, d_s, using the transponders mounted on the chain based on two approaches: (i) the change in orientation or "folding chain" method; and (ii) the RSSI or "signal strength" method.

Task 6: Prepare the RFID system for use by IDOT and County personnel to collect and analyze scour data by providing LABVIEW software developed at IIHR by the Papanicolaou research team, known as the PAPTSAK RFID software. An *addendum sub-task* for this step was to incorporate the magnetic properties of the river bed sediment (e.g., sand and gravel) and excitation antenna electromagnetic characteristics into the PAPTSAK RFID software.

Task 7: Incorporate the scour and flow data obtained in the previous tasks into the Finite-Element Surface-Water Modeling System (FESWMS) 2-D hydrodynamic model.

Task 8: Present the research products during state, regional, and national conferences (e.g., the Iowa County Engineers Association Annual Meeting; the biennial Midwest Transportation Conference), as well as the IHRB at a monthly meeting following the completion of the project. Compile the key results in this final report and an accompanying tech transfer document.

3. METHODOLOGY

3.1 TI RFID system configuration

In this study, a Low Frequency (134.2 kHz), passive RFID system was used (Figure 3). This RFID system consists of three main parts: The reader, the antenna, and the transponder.

The reader encodes specific commands into radio-waves, which are then transmitted to the transponder through an electromagnetic field generated by an excitation antenna. The reader also decodes the information received from the transponder (i.e., S/N; RSSI; inclination) passed back through the excitation antenna and relays it to a host computer through standard communication protocols. Additionally, a 25 MHz digital storage oscilloscope was connected to the RFID reader to record and export the shape and form of the RF signal.

The excitation antenna is typically a wire loop that creates an electromagnetic field for transmitting information from the reader to the transponder (Texas Instruments, TI, 2003; Finkenzeller, 2010). The excitation antenna also intercepts the radio-waves from the transponder and relays them to the reader. Two different excitation antennas were used in this study, which were an off-the-shelf, square loop (0.70 m x 0.70 m) antenna from TI and a custom-made large rectangular (3.00 m x 1.83 m) loop antenna. The use of a custom-made excitation antenna in this study is considered an advantage. By developing a custom-made antenna, the size, shape, and material can be manipulated to increase the maximum detection distance. A 10-m long waterproof twinax cable was used to connect the selected excitation antenna with the reader. The length of the twinax cable can be up to 120 m, after which, though, the increased resistance reduces the antenna voltage, thereby affecting the maximum antenna-transponder detection distance (Oregon RFID, 2012). The excitation antenna was tuned with the reader using an antenna tuning module so that the outgoing RF signal was at the correct frequency to achieve the maximum detection distance.

An advantage of this RFID system is that a custom-made excitation antenna can be connected to the reader. This allows the user to optimize the antenna size, shape, and material to increase the maximum detection distance.

The transponder, which is also commonly called a “tag”, is the data-carrying device of an RFID system (TI, 2001; Wilding and Delgado, 2004; Roberts, 2006; Finkenzeller, 2010). Transponders are mostly cylindrical and can range in sizes from a few millimeters to several centimeters. All transponders consist of a miniature antenna, a set of “memory” circuits where the S/N and other user-programmed data are stored, and a set of transmitting circuits. These transponder components are encased in a thin glass or plastic housing for protection. As mentioned previously, the transponders are either characterized as “active” or “passive” (Winding and Delgado, 2004; Finkenzeller, 2010) depending on their power source. Active transponders have a battery, while passive transponders have a built-in capacitor, which is charged by the electromagnetic field from the excitation antenna. The energy stored in this capacitor powers the transponder circuits and transmits the stored information back to the reader.

In this study, passive transponders were used. The operation of a passive transponder consists of the three following phases (TI, 2002; Finkenzeller, 2010): (i) the “transmit” (or charge) phase; (ii) the “read” (or listen) phase; and (iii) the “synchronization” phase.

During the *transmit phase*, the reader applies a voltage to the excitation antenna, V_{ant}. The voltage, V_{ant}, produces an electrical current, I_{ant}, through the excitation antenna wire loop, which is given as:

$$I_{ant} = \frac{V_{ant}}{2\sqrt{2}\cdot\sqrt{R_{ant}^2 + \left(2\pi f L\right)^2}} \quad (1)$$

where R_{ant} is the resistance of the excitation antenna wire in Ohms; f is the radio-wave frequency in Hz; and L is the inductance of the excitation antenna, which is measured in Henries (H). The excitation antenna inductance, L, is a measure of the ability of the excitation antenna loop to store energy within its electromagnetic field, and is given as:

$$L = \frac{1}{4\pi^2 f^2 C} \quad (2)$$

where C is the excitation antenna capacitance in Farads. In this study, the antenna inductance did not exceed 80 μH (TI, 2002).

The electromagnetic field of the excitation antenna is characterized by its strength, $H(d)$ at a distance from the antenna, d, and is given by the equation:

$$H(d) = \frac{n_{ant} \cdot r_{ant}^2 \cdot I_{ant}}{2 \cdot \left(d^2 + r_{ant}^2\right)^{1.5}} \quad (3)$$

where n_{ant} is the number of wire loops (or windings) in the antenna, and r_{ant} is the antenna loop radius defined as:

$$r_{ant} = \sqrt{\frac{h_{ant} \cdot w_{ant}}{\pi}} \quad (4)$$

with h_{ant} and w_{ant} as the height and width of the antenna loop and $\pi = 3.14$. The strength of the electromagnetic field, *H(d)*, (Eq. 3), of the excitation antenna provides the energy for charging the built-in capacitor of a passive transponder. Once the transponder capacitor is charged, the read phase of the RFID system cycle commences. The transponder powers up its circuits and transmits the encoded information stored in its memory to the reader through its miniature antenna. The excitation antenna receives the transmitted information and relays it to the reader, where it is decoded and communicated to the host computer. After the transponder transmits back to the reader, the reader enters a synchronization mode, where it remains idle and is re-initialized for the following cycle. During the synchronization period, there is no communication between the reader and the transponder.

An important characteristic of the *read and transmit phase* is the way that the "transferring" of information (radiowaves in Voltage) occurs from the transponder to the excitation antenna. The RSSI is dependent on the orientation of the transponder longitudinal axis in relation to the antenna plane. The detection distance of a transponder reaches its maximum when the long transponder axis is perpendicular to the excitation antenna loop plane (i.e., a favorable condition), whereas the detection distance of a transponder having its long axis parallel to the excitation antenna loop plane reaches a minimum value (i.e., an unfavorable condition).

- **The antenna inductance (L) signifies its ability to store energy within the created electromagnetic field.**
- **The antenna quality factor (Q) indicates the strength of the generated electromagnetic field.**
- **The excitation antenna electromagnetic field strength (H) generated by the charge supplied by reader to the excitation antenna, is a measurement that shows the maximum distance at which the antenna can successfully activate a transponder.**

3.2 Experimental design and setup

Task 1: Construct a custom-made, excitation antenna optimized for a maximum read range and capable of providing detection ranges up to 60 ft. (~ 20 m) within the water-sediment column.

The maximum detection distance of an RFID systems is a function of the following parameters: (i) the power transmitted by reader; (ii) the physical dimensions of the excitation antenna; (iii) the transponder antenna size and housing material; (iv) the transponder orientation with respect to the excitation antenna; (v) the media between the excitation antenna and the transponder; and (vi) the level of electromagnetic noise in the surrounding environment (Papanicolaou et al., 2010; Li and Becerik-Gerber., 2011). The reader power and the transponder characteristics are fixed based on their configurations. The transponder orientation, the type of the media between the antenna and the transponder, and the level of electromagnetic noise are determined by conditions at the site. Thus, customizing the physical dimensions of the excitation antenna (Figure 6) offers the user the best control to maximize the detection distance of the transponder (Hassan and Chatterjee, 2006; Dziadak et al., 2009).

Along with the inductance, *L*, (Eq. 2) and the resonance capacitance of the antenna, which is set by a series of jumpers (TI, 2002), the antenna quality factor, $Q_{ant,}$ is another important parameter that can affect its performance in terms of the strength of the generated electromagnetic field. Q_{ant} quantifies the bandwidth of the RF signal, as well as the sharpness and selectivity of the circuitry. It is dependent on the inverse of the antenna's resistance, *R*. The antenna quality can be computed using the formula:

$$Q_{ant} = \frac{2\pi fL}{R_{ant}} \tag{5}$$

One direct way to manipulate Q_{ant} is by selecting the appropriate wire gage. In this study, three different wire gages were tested, namely AWG 12, AWG 14, and AWG 18. The electromagnetic field strength, *H(d)*, of the excitation antenna is generated by a charge from the reader to the excitation antenna, I_{ant}, and quantifies the maximum distance at which the excitation antenna can successfully activate a transponder. The *H* at a distance *d* away from the excitation antenna is given by Eq. 3. As the transponder is moved laterally away from the center of the excitation antenna, the strength of the excitation antenna's electromagnetic field decays with distance by a factor of 3 (Finkenzeller 2010). The strength of the excitation antenna electromagnetic field is then given by:

$$B_{coil} = \frac{\mu \times N \times I}{2 \times \Lambda} \tag{6}$$

where μ is the effective permeability of the excitation antenna coil; Λ is the length of the coil solenoid. Having determined all the antenna parameters that affect the antenna's electromagnetic field strength, the "theoretical" maximum antenna-transponder detection distance $(D_{a\text{-}t,max})$ can be calculated using the excitation antenna electromagnetic field strength formula (Eq. 3) combined with the minimum level of energy that the transponder requires in order to be activated (Personal communication with TI engineers).

Task 2: Assemble waterproof, passive transponders capable of providing detection ranges up to 60 ft. (~ 20 m). 2 addendum sub-tasks: (i) Improve the waterproofing of the new developed transponders; (ii) Incorporate a Micro-Electro-Mechanical Sensor (MEMS) inclinometer to the transponders to quantify the orientation of the transponder to the excitation antenna.

Current RFID transponders are not designed to be submerged in water. Thus, this task was instituted to identify a suitable encasing material that would satisfactorily waterproof the transponders without diminishing their detection range.

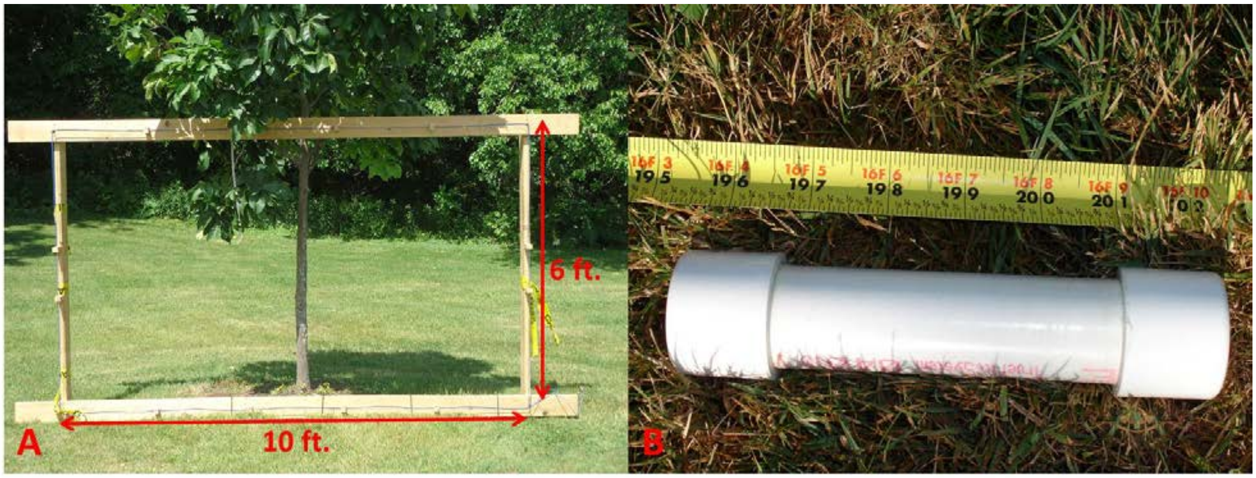

Figure 6. (a) Custom-made excitation antenna and (b) PVC-encased transponder.

Past studies (e.g., Papanicolaou et al., 2010) have shown that schedule-40 PVC is essentially "transparent" to LF radio-waves and is robust enough to be submerged. Additionally, different products were tested as the appropriate "filling" material inside the PVC. Different materials specifically designed for electronic packaging (e.g., aviation electronics grade silicon; silicon grease; epoxy; urethane) proved most useful for minimizing the impedance of the electrical current across the transponder circuits and the displacement of the circuit components, while maximizing the protection against moisture buildup, vibrations, and temperature gradients (e.g., Tummala et al., 1989).

Along with the encasing material, additional improvements were needed to the transponders to facilitate their use in estimating bridge scour depth using the "folding chain" approach, which is conceptually based on the angle (or inclination), ϕ, between the transponder long axis and the excitation antenna plane (Figure 7). Measurements of the transponder inclination were achieved by integrating a MEMS inclinometer on the transponder circuit boards. Furthermore, the existing software programmed in the transponder memory was modified to read the inclination measurement and transmit the measurement to the reader.

Task 3: Install water level loggers to measure stage at a monitoring site. Complement the stage measurements with standard channel cross-section surveys and sonar measurements for bathymetry.

The Camp Cardinal Rd. bridge in Coralville, IA that crosses over Clear Creek (N 41^{o} 40' 35"; W 91^{o} 35' 54") was selected as a test site for this study. The water stage at this site was obtained using the existing USGS stream gage (#05454300; Clear Creek near Coralville, IA) and the discharge (i.e., volumetric flow rate) was determined using the established USGS rating curve. Additionally, a vented pressure transducer (i.e., Global Water WL16 Water Level Logger), with an accuracy of ±0.2%, and an enclosed datalogger was placed upstream of the USGS stream gage to measure the water level of the approach flow to the bridge. The pressure transducer was installed 10 cm above the streambed within a stilling well to minimize the effects of waves and water current on the measurements. Four additional T-posts were placed in front of the stilling well to capture debris flowing downstream thereby protecting the pressure transducer. The stage measurements were complemented with standard channel cross-section surveys and Eagle FishElite® 480 sonar measurements for bathymetry. The stage values were correlated with the scour depth values to develop scour-depth relations with flow.

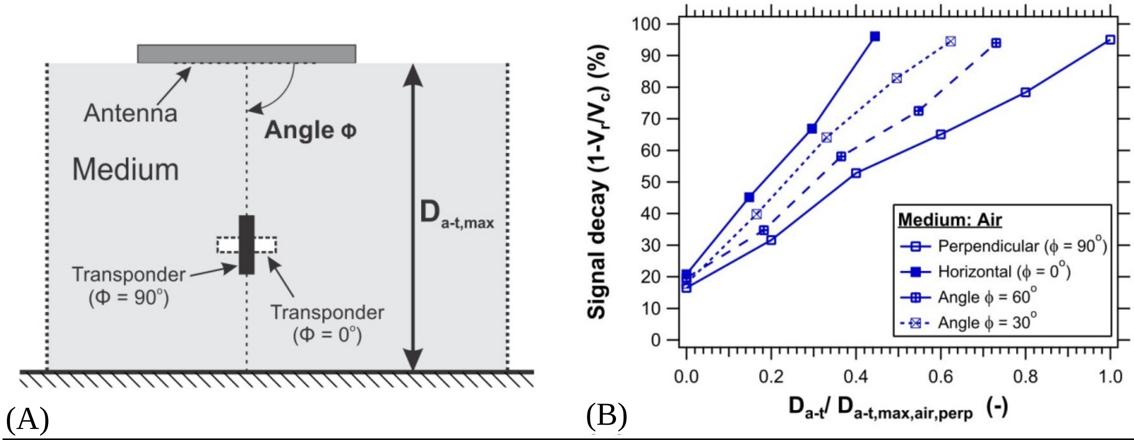

Figure 7. (A) Inclination angle, ϕ, between the transponder antenna axis and the excitation antenna plane, (B) Dependence of the transponder signal strength decay on ϕ.

Task 4: Install the modified Leopold chains with the RFIDs in the sediment at a monitoring site.

A series of four transponders were placed along a Leopold chain at distances of 2, 4, 8, and 12 ft. The transponders were then buried into the sediment bed at the Camp Cardinal Rd. bridge site by simply hammering a PVC tube into the bed, by hand, with the transponders attached to a chain and then removing the tube. The chain was then run along the stream bed and up the bank, where it was secured to a ground anchor.

Through this installation we were able to refine and document the necessary procedures for placing these RFID Systems at other field locations. The use of a vibracore was also tested for feasibility and proved useful but at times cumbersome, especially in a small system like Clear Creek. The vibracore installation method would be more useful in larger systems with deeper projected scour depths.

Figure 8 illustrates the steps involved in using the vibracore to install the RFIDs. Thin-walled (7.6 to 10.2 cm in diameter; 3.2 mm in thickness) metal tubes without liners would be most effective for vibracoring because they conduct vibrational energy most efficiently. An anchoring cone placed at the lower end of the chain is helpful in order to drive the chain with ease into the bed.

Task 5: Measure the scour depth, ds, using the transponders mounted on the chain based on two approaches: (i) the change in orientation or "folding chain" method; and (ii) the RSSI or "signal strength" method.

The folding chain method is based on the orientation experiments of Papanicolaou et al. (2010) for the IHRB seed project TR-595. According to these experiments the maximum intensity of the return electromagnetic signal from the transponder is received by the antenna when the long axis of the transponder antenna is perpendicular to the plane of the excitation antenna (i.e., the favorable orientation). On the contrary, when the long axis of the transponder antenna is parallel to the plane of the excitation antenna (i.e., the unfavorable orientation), the antenna receives a minimum (i.e., no) signal from the transponder. This occurs when the chain folds over after being exposed by scour. Because the transponders are placed at a known distance along the chain, the depth of scour can be determined by seeing which transponders have a loss of their return signal. Transponders with nearly zero detection signal correspond to the segments of the chain that are folded over, which is indicative of the scour depth. See Transponder Tr1 in the folding segment of the chain in Figure 9b and 9c.

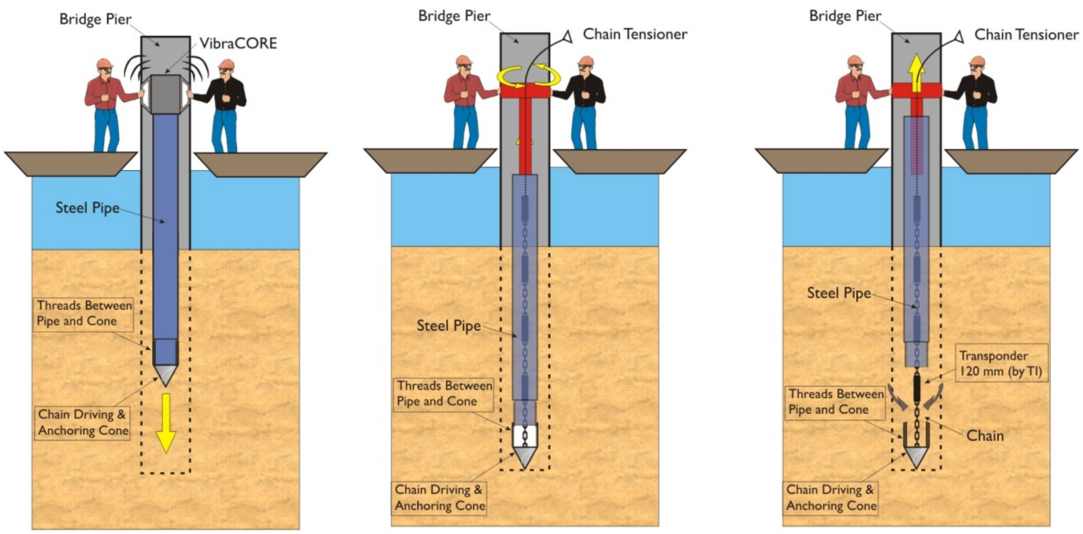

Figure 8. The pile/chain driving mechanism with vibracoring. Transponders are mounted to the chain at predetermined distance.

The principle behind the signal strength method is outlined in Figure 10. In this case, the upper end of the chain is fixed with a support to prevent folding. Transponders exposed in water (e.g., Tr1 and Tr2 in Figure 10b) have an intensity that is well represented by a peaky function. On the contrary, as the burial distance of the transponders in the bed increases, the distribution of its return signal diffuses or widens. This distinct difference in the distribution of the intensities between transponders in water and those in the sediment can also provide an estimation of scour depth.

Task 6: Prepare the RFID system for use by IDOT and County personnel to collect and analyze scour data by providing LABVIEW software developed at IIHR by the Papanicolaou research team, known as the PAPTSAK RFID software. One addendum sub-task: Incorporate the magnetic properties of the river bed sediment (e.g., sand and gravel) and excitation antenna electromagnetic characteristics into the PAPTSAK RFID software.

The PAPTSAK RFID software was developed by the Papanicolaou Research Team to calculate the distance between a buried transponder and the excitation antenna, based on the user input information for the antenna type. The software allows the user to initiate an electromagnetic field from the reader and the antenna and query the individual transponders one at a time. The response of each buried transponders to the queries provides the necessary information for this measurement.

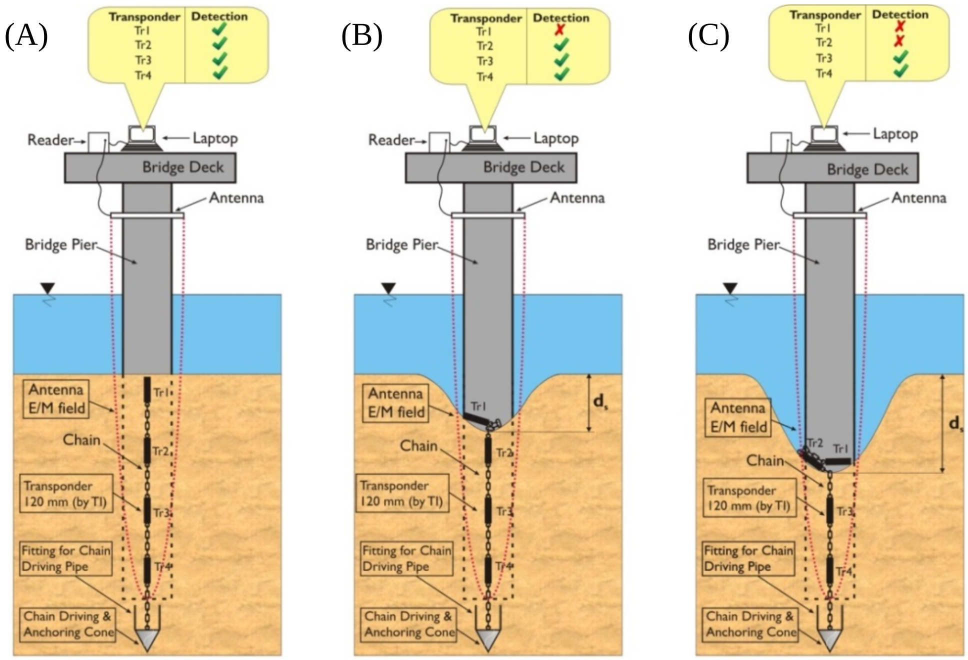

Figure 9. Detection of the scour depth using the "folding chain" approach. (A) No scour. (B) Scour exposes transponder Tr1. (C) Scour increases and exposes transponders Tr1 and Tra2

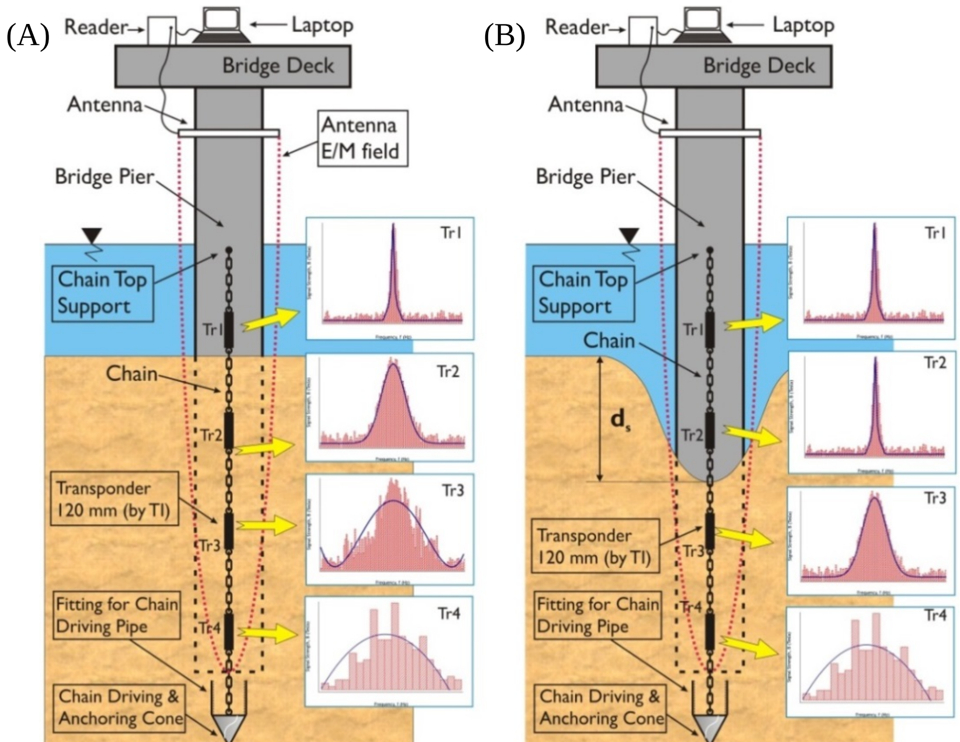

Figure 10. Detection of the scour depth using the "signal strength" approach. (A) No scour. (B) Scour

For a given distance, *d*, between the transponder and the excitation antenna, the signal strength input voltage, V_{IN}, at the receiver of the RFID reader is dependent on the following: (i) the electromagnetic characteristics of the excitation antenna, such as the excitation antenna radius and number of wire loops, r_{ant} and N_{ant}, respectively, and (ii) the electromagnetic properties (i.e., the relative magnetic permeability, μ_r) of the river bed material in which the transponder is buried (e.g., sand, gravel, or mixtures of these).

The Papanicolaou team continues to refine the PAPTSAK RFID software to determine scour depths from the returned, attenuated RF signal of the buried transponders. The software was also modified to contain an input box where users can manually enter the relative magnetic permeability (μ_r) of the surrounding medium (e.g., water, sand, gravel). Magnetic permeability is the ability of a specific medium to support the formation of a magnetic field within itself and affects the decay of the RF signals between the antenna and transponders. The relative magnetic permeability is the ratio of the magnetic permeability of the specific medium to the permeability of air.

Task 7: Incorporate the scour and flow data obtained in the previous tasks into the Finite-Element Surface-Water Modeling System (FESWMS) 2-D hydrodynamic model.

The Finite-Element Surface-Water Modeling System (FESWMS) 2-D hydrodynamic model is a modular set of computer programs that simulates two-dimensional, depth-integrated, surface-water flows. The conservative forms of the FESWMS equations can solve critical and transcritical flows under both low- and high-flow conditions by allowing for dry elements to exist within the computational mesh, which would be expected around piers and abutments (Chaudhry, 1993). The flow data from the installed pressure transducers, coupled with the channel surveys and sonar data were used as inputs to the model to develop a velocity flow field for Clear Creek at the Camp Cardinal Rd. bridge site.

Task 8: Present the research products during state, regional, and national conferences (e.g., the Iowa County Engineers Association Annual Meeting; the biennial Midwest Transportation Conference), as well as to the IHRB at a monthly meeting following the completion of the project. Compile the key results in this final report and an accompanying tech transfer document.

The key results from this study have been compiled herein and the accompanying tech transfer document. In addition, these results have been summarized into presentations for the upcoming the 2014 World Environmental & Water Resources Congress in Portland, OR.

4. RESULTS

Task 1: Construct a custom-made, excitation antenna optimized for a maximum read range and capable of providing detection ranges up to 60 ft. (~ 20 m) within the water-sediment column.

A key parameter for achieving the maximum possible detection range between the antenna and transponder is the number of the wire loops in the antenna as it affects the antenna inductance, *L*. The antenna inductance is a measure of the energy storage capacity in the antenna's generated electromagnetic field. The antenna inductance was measured via an inductance meter that was connected to the two ends of the antenna wire. Custom-made excitation antennas that were built using only 1 loop had low inductance values and thus a limited energy storage capacity and short antenna-transponder detection distances. Conversely, Three-loop antennas had high antenna inductance values that were close to or exceeded the maximum limit of the RFID reader used in this study, ~ 80 μH. Therefore, the 3-loop antennas were not considered due to potential damage to the reader. With the 2-loop antennas, the maximum detection distance was 45 ft., or ~13.716 m (Figure 11) with moderate inductance values (L = 45 μH).

The quality factor, *Q*, of the custom-made antenna was also determined for the custom-made antenna. The thickness of the wire used to build the antenna loops also affected the antenna performance. Thicker wires (12 AWG Stranded) had higher electrical conductivity and therefore more energy could be stored in the electromagnetic field of the antenna. Additionally, adjusting the loop spacing parameter (e.g. 1.375 in. for a 2 loop antenna) helped obtain the maximum antenna-transponder detection distance (45 ft.). One important fact that became evident during the antenna testing was that the type of nails used to attach the wire on the antenna wooden frame could significantly affect the performance of the RFID antenna. In this case, blank nails were used.

Figure 11. Construction of the custom-made antenna. (A) the 10 x 6 ft.^{2} 2-wire loop custom RFID antenna developed by Papanicolaou research team; and (B) The LCR meter used to measure the custom RFID antenna inductance, L (45 µH).

Task 2: Assemble waterproof, passive transponders capable of providing detection ranges up to 60 ft. (~ 20 m). 2 addendum sub-tasks: (i) Improve the waterproofing of the new developed transponders; (ii) Incorporate a Micro-Electro-Mechanical Sensor (MEMS) inclinometer to the transponders to quantify the orientation of the transponder to the excitation antenna.

Because the passive transponders used in this study were not designed to be buried in a river bed, there was a need to further protect them from the added external pressures of the water, sediment and weather conditions by encapsulating them into specially developed potting compound (Figure 12). The potting compound used herein was specially designed to protect circuits from vibrations and any moisture build-up that might affect the performance of the transponder internal circuits in the long run. Once the transponders were encapsulated, the detection distance between the excitation antenna and transponders was re-evaluated to determine any reduction in the RF signal strength due to the potting compound. These tests showed no change in the RF signal strength; therefore, the potting compound was essentially “transparent”. Additionally, the encapsulated transponders were placed into a pressurized water tank for 10 days to test the ability of the potting compound to prevent moisture build-up. The detection distance between the excitation antenna and transponders was again tested and no loss in signal strength was observed. Finally, the encapsulated transponders were placed into PVC tubes and attached to a plastic Leopold chain (Figure 13).

As part of the addendum to this project, a Micro Electro Mechanical Sensor (MEMS) inclinometer was incorporated into the transponders to detect changes in orientation that may occur during scour. Slight changes in the angle of the transponder with respect to the excitation antenna loop plane signify the development of the scour hole as the exposed transponder begins to tip over as the support of the surrounding sediment erodes away. Hence, this feature can also provide the rate at which the scour hole develops providing unique data without the need for DOT personnel to be present on the bridge during a flood event. Table 1 shows the changes in the return RF signal strength from the transponder as the inclination angle between the transponder and the excitation antenna loop plane changes at different antenna-transponder distances. Therefore, the incorporation of the inclinometer to the RFID transponders is an important addition for the proposed bridge scour monitoring system.

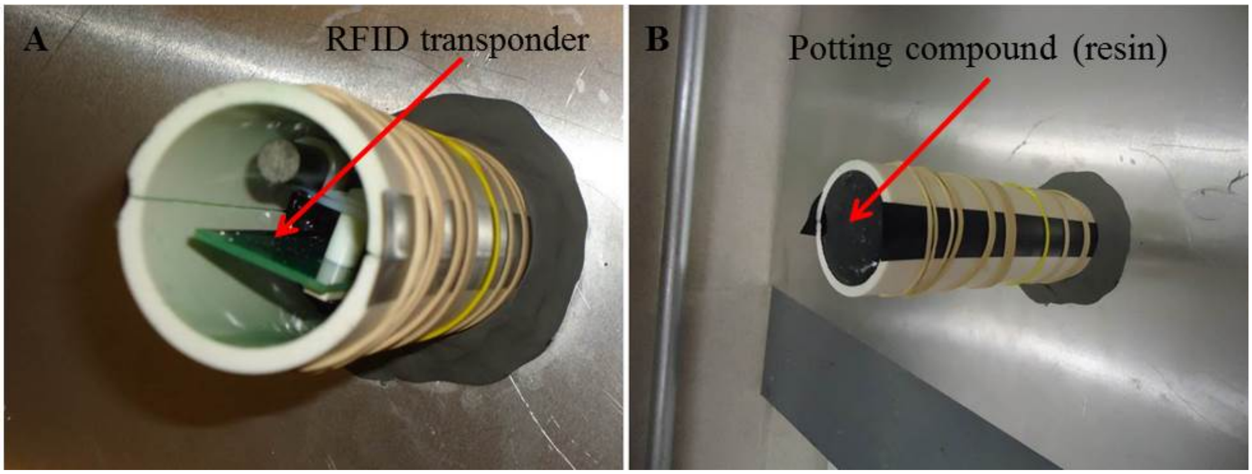

Figure 12. Encapsulating the transponder. (A) The transponder was carefully placed into a mold and potting compound was added to encapsulate the transponder circuitry; and (B) The transponder is fully covered, or encapsulated, into the potting compound.

Task 3: Install water level loggers to measure stage at a monitoring site. Complement the stage measurements with standard channel cross-section surveys and sonar measurements for bathymetry.

The current USGS stream gage at the site is located only a few meters upstream of the bridge (USGS 05454300; Clear Creek near Coralville, IA). However, to accurately measure the approach flow, it is recommended that the measurement location should be upstream approximately 30 times the bridge width. The approach flow is a key parameter for many scour formulas that can be used at the site.

A pressure transducer (e.g., water level logger sensor) was installed 300 m upstream of the road bridge at Clear Creek near Camp Cardinal, IA site to measure the water depth of the approach flow (Figure 14). The pressure transducer was attached to a T-post driven into the stream. The transducer was positioned 10 cm above the bed. A stilling well consisting of a slotted pipe was placed around the T-post to minimize the effects of waves. Four additional T-posts were placed in front of the stilling well to capture debris flowing downstream thereby protecting the pressure transducer.

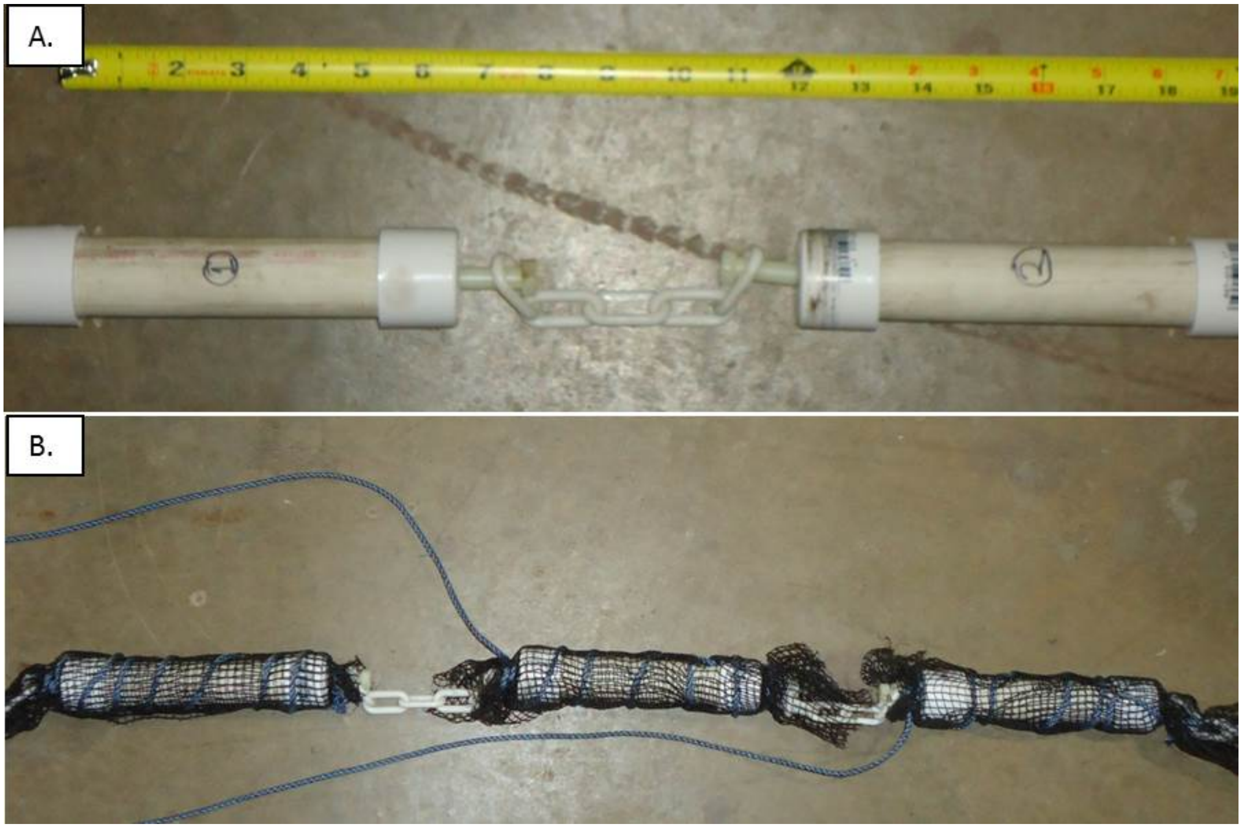

Figure 13. Leopold Chain. (A) A close-up image of the Leopold chain with two encased transponders and a plastic chain to minimize interference; and (B) The encased transponders were also placed in a is before the fishing net and secured with paracord were added.

A 350-m long reach of Clear Creek near Camp Cardinal in Johnson County, IA (Figure 15) was surveyed using both a Total Station and sonar. Six cross-sections and numerous points on the floodplain were surveyed with the Total Station. Figure 16 shows one of the measured cross-sections using the Total Station. The stream channel at this site is approximately 25 m in width and has a bank height of around 3.5 m.

Additionally, a bathymetric survey of the channel bed was conducted using sonar that collected depth measurements at a frequency of 1 Hz. A GPS was attached to the sonar device and measured the geographic location with a frequency of 4 Hz. Sonar measurements were collected in order to provide more detailed measurements of bathymetry in the stream channel.

Table 1. Inclination angle of the RFID transponder to the excitation antenna loop plane vs. RSSI.

Distance (ft)	**Inclination angle (degree)**	**RF signal strength (RSSI)**	**Success rate (%)**
15	0	385.6	100%
	15	374	100%
	30	359.5	100%
	45	336.9	100%
	60	303.8	100%
	75	215.75	40%

	90	N.A.	0%
25	0	266.8	100%
	15	263.5	100%
	30	253.2	100%
	45	229	80%
	60	188.7	70%
	75	106.5	20%
	90	N.A.	0%

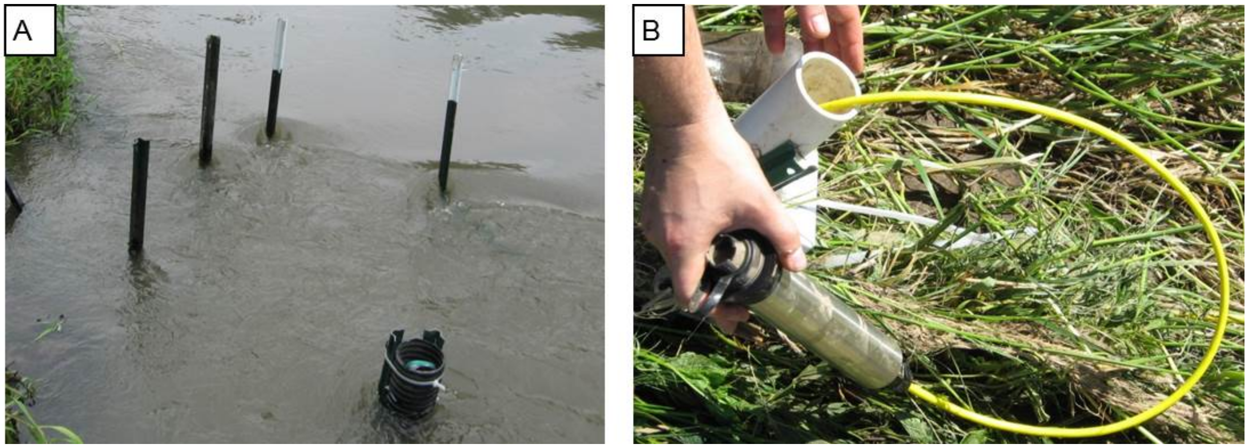

Figure 14. Pressure Transducer. (A) The pressure transducer was installed in stilling well in Clear Creek near Camp Cardinal, IA site; and (B) The datalogger of the pressure transducer was secured on the bank.

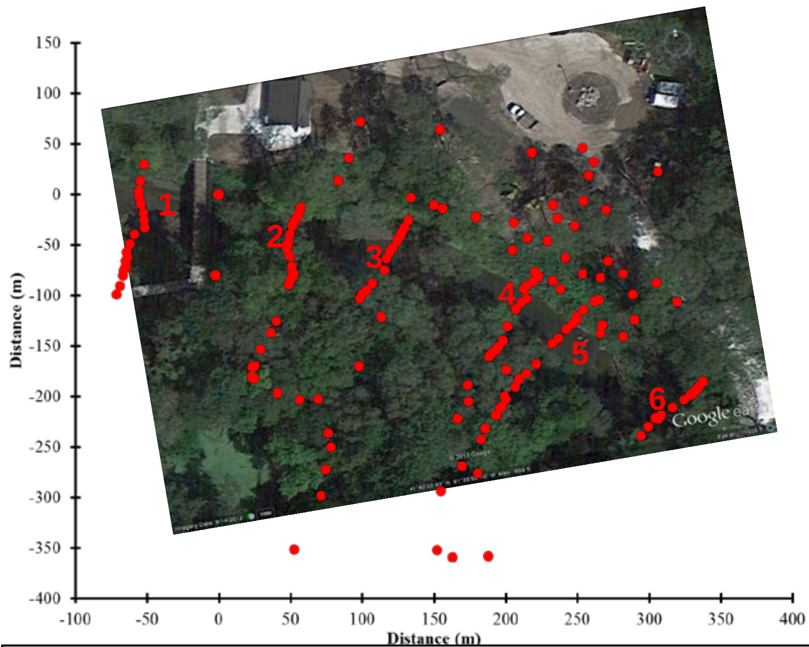

Figure 15. Survey points using a Total Station along Clear Creek near Camp Cardinal Rd. in Coralville, IA.

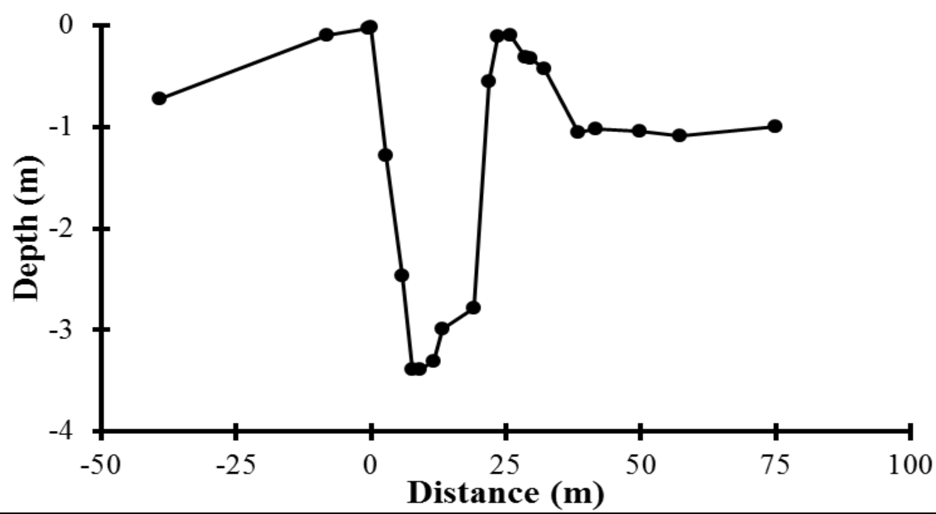

Figure 16. Channel Survey. One of the six cross-sections surveyed along Clear Creek near Camp Cardinal.

Task 4: Install the modified Leopold chains with the RFIDs in the sediment at a monitoring site.

Four transponders were placed along a Leopold chain at distances of 2, 4, 8, and 12 ft and they were buried into the sediment bed at the Camp Cardinal Rd. bridge site (Figure 17) by hammering a PVC tube into the bed with the transponders attached to a chain and then removing the tube. The chain was then run along the stream bed and up the bank, where it was secured to a ground anchor.

Figure 17. RFID transponders location in Clear Creek near Camp Cardinal Rd. in Coralville, IA (Location coordinates: 41°40’35.16” N 91°35’55.10” W).

The use of a vibracore (Figure 18, Table 2) was also tested for installing the transponders into the sediment bed. The vibracore proved useful but at times cumbersome; it would work best in larger or deeper river systems. As the vibracore drill head penetrates the sediment, it vibrates at high frequencies to liquefy the sediment particles allowing for the core tube to push down into the soil under the weight of the drill head. The penetration depth is limited only by the height of the metal structure (tripod) that accommodates the vibracore drill.

Table 2. Vibracore Components.	
1	Vibracore drill head
2	Electrical winch to move the vibracore up and down
3	Power source; 2 12-V heavy duty marine batteries connected in parallel
4	3-in. (inner diameter) acrylic tube attached to the bottom of the drill head
5	2-in. (inner diameter) PVC tube attached to the bottom of the acrylic tube. The length of the PVC tube is dictated by the maximum installation depth of the Leopold chain and the stream flow depth
6	A metal base (i.e., tripod) to support and accommodate for the vibracore. Extension rods can be attached to the tripod legs to facilitate deeper RFID transponder installation depths.

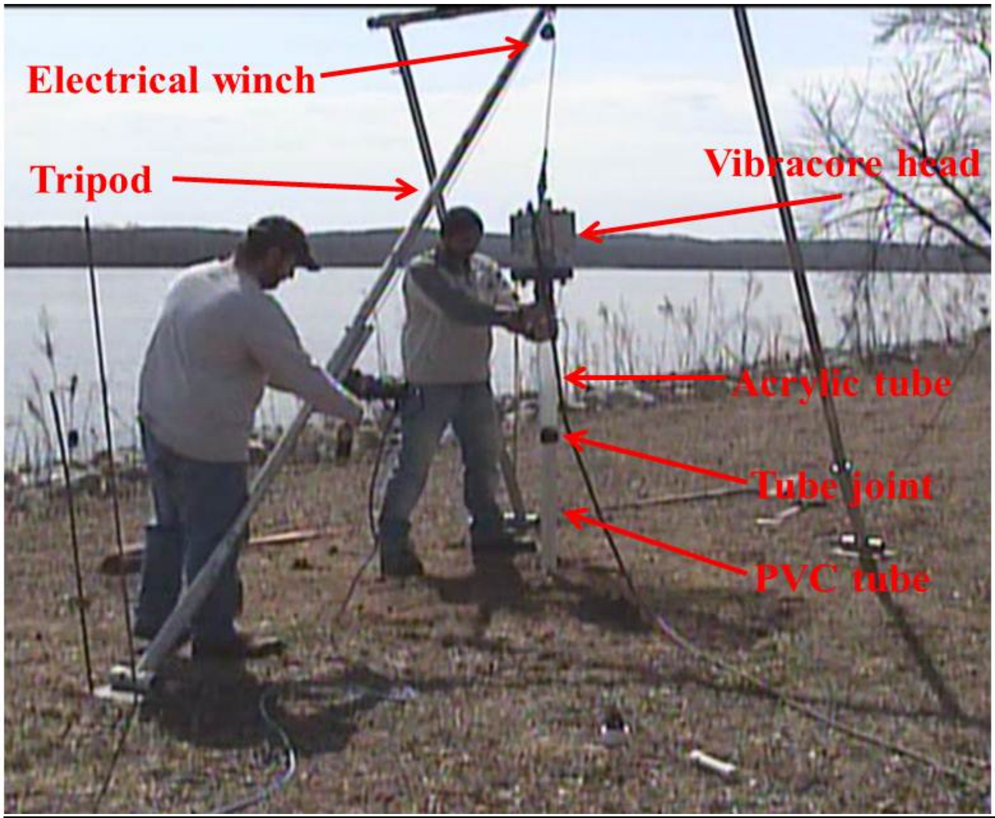

Figure 18. Vibracore drill components and field setup. The field installation process of the transponders shows the vibracore being driven into the sediment.

The process for setting up the vibracore and transponder installation is detailed below.

1. Set the tripod to the appropriate height for achieving the desired installation depth.
2. Attach the drill head to the tripod using the electrical winch.
3. Connect the acrylic and PVC tubes using a PVC joint (Figure 19). If needed wrap the PVC joint with electrical tape to increase the friction between the acrylic and the PVC tubes.
4. Place the Leopold chain with the transponders into the vibracore tubes. Secure the RFID transponders by passing the chain through the drilled hole on the upper part of the acrylic tube.
5. Attach the connected acrylic and PVC tubes to the vibracore drill head.
6. Make sure that the vibracore is perpendicular with respect to the stream bed. A level can be attached to the vibracore drilling head to ensure that the vibracore is always perpendicular.
7. Lower the vibracore drill head. Once the installation depth is achieved, loose the secured chain and slowly pull up the vibracore. As the vibracore tubes come out of the stream bed, the walls of the drilled hole will collapse and bury the transponders.
8. Once the Leopold chain has been successfully installed and the vibracore drill has been pulled up, carefully remove the acrylic and PVC tubes. Disassemble the vibracore drill head and tripod.

Figure 19. Using the vibracore. (A) The transponder is placed into a PVC core tube and secured with a "pointy" PVC cup. (B) The PVC joint is wrapped up with electrical tape to increase friction between the acrylic and the PVC tubes. Once the desired depth is reached, the vibracore is pulled up, while the RFID transponders have been buried into the stream bed.

Task 5: Measure the scour depth, ds*, using the transponders mounted on the chain based on two approaches: (i) the change in orientation or "folding chain" method; and (ii) the RSSI or "signal strength" method.*

Two different methods were developed through this study to determine the scour hole depth using the RFID technology. The first method, the "folding chain" method, utilizes the loss of the return signal from a specific transponder to determine scour depth. The second method, the "signal strength method, relies on a distinct difference in the distribution of the intensities between transponders in water and those in the sediment to provide an estimation of scour depth.

As scour removes the sediment from around a transponder attached to a Leopold Chain at a defined depth, the transponder will tip over. The change in orientation results in a redirection of the return signal away from the excitation antenna, hence a reduction in (and possibly complete loss of) the return signal (V_{RSSI}) will be observed. In comparison to a baseline measurement of the return signal strength from the transponder to the reader performed using an oscilloscope, the return signal strength there will be deviations to either a reduced signal strength compared to the baseline measurement ($V_{RSSI,1} < V_{RSSI,0}$), or even the loss of communication between the transponder and the reader. Figure 20 shows the processed signal strength decay curves developed for the four installed transponders corresponding to the two measurement dates. The decay curve for the transponders on 04/05/2013 follows the expected linear pattern indicating little to no scour. Conversely, the decay curve for the transponders on 06/07/2013 shows that the transponder buried initially 2 ft. below the stream bed (marked with the red circle) significantly deviates from the linear trend indicating an abrupt change in transponder orientation resulting from its exposure due to scour. After the flood event, the 2 ft. installed transponder changed orientation due to excessive scour (erosion), which led to significantly increased RF signal strength decay. The RF signal strength decay values for the rest of the buried transponders did not significantly change compared to the baseline measurements. Knowledge of the unique relationship between the RSSI and the distance of the transponder from the excitation antenna, for a given transponder orientation, will allow the estimation of the transponder position relative to the excitation antenna after a scour event and hence of the resulting scour depth, d_s.

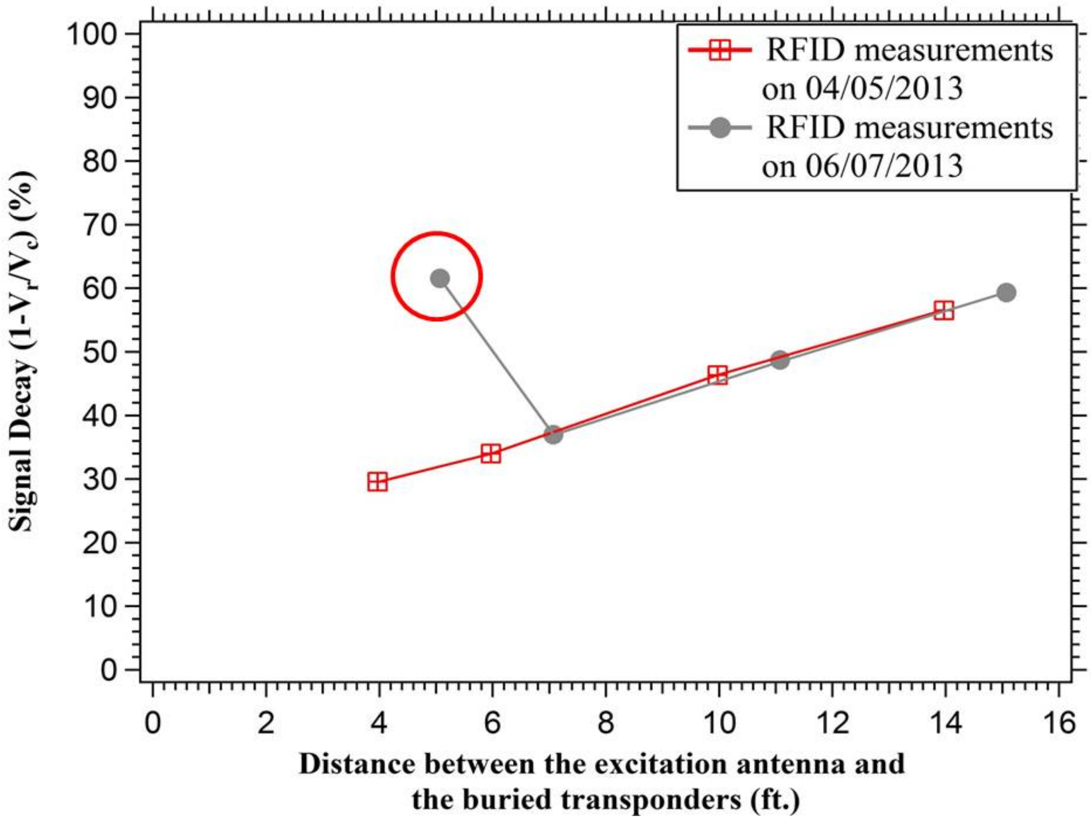

Figure 20. Processed RF signal strength decay curves corresponding to the two measurement dates during the period of 04/05/2013 and 06/07/2013.

Task 6: Prepare the RFID system for use by IDOT and County personnel to collect and analyze scour data by providing LABVIEW software developed at IIHR by the Papanicolaou research team, known as the PAPTSAK RFID software. One addendum sub-task: Incorporate the magnetic properties of the river bed sediment (e.g., sand and gravel) and excitation antenna electromagnetic characteristics into the PAPTSAK RFID software.

The PAPTSAK RFID software (Figure 21) that was developed by the Papanicolaou research team was modified to incorporate the following: (i) the transponder orientation angle with respect to the excitation antenna loop plane; and (ii) magnetic properties of a medium.

The magnetic permeability and especially the relative magnetic permeability, which is the ratio of the magnetic permeability of a specific medium to the magnetic permeability of air, μ_r, is a key parameter that affects the performance of the RFID system (see Eq. 3) and needs to be considered in calculating the actual distance between the excitation and the transponder antennas (in this study, this distance is related to the scour depth). In this task, we improved the "Distance Calculator" function of the PAPTSAK RFID software by incorporating an input box, where the user can manually insert the relative magnetic permeability of a medium or mixture of mediums (i.e., water and sand-clay mixture) that is in between the excitation and the transponder miniature antennas. Thus, by including the relative magnetic permeability, the accuracy of the estimated excitation antenna-transponder distance (related to the scour depth) increases significantly (i.e., the error is less than 7% of the real excitation antenna-transponder distance).

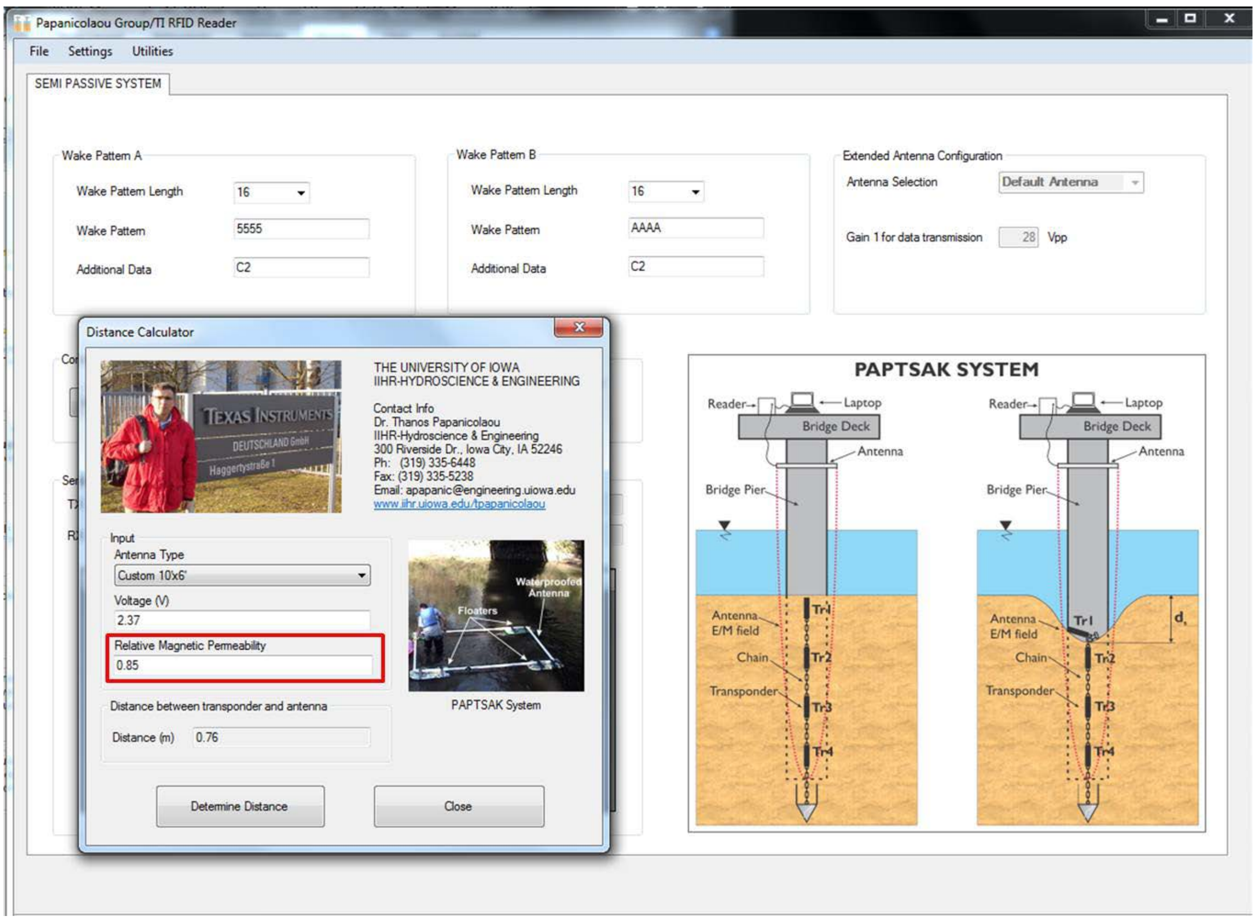

Figure 21. Screen shot of the PAPTSAK RFID software "Distance Calculator". The user can insert the relative magnetic permeability of the medium or mixture of mediums in between the excitation and the transponder miniature antennas, as well as to select the excitation antenna type from the drop down menu.

Task 7: Incorporate the scour and flow data obtained in the previous tasks into the Finite-Element Surface-Water Modeling System (FESWMS) 2-D hydrodynamic model.

The streamflow data and channel surveys and sonar measurements were input into the FESWMS 2-D hydrodynamic model to determine the velocity flow field through the channel reach at the Clear Creek-Camp Cardinal Rd. bridge site. Figure 22 shows the representative flow field the Clear Creek reach and reveals areas of accelerating flow (i.e., blues areas) and decelerating flow (i.e., red areas). As more scour data using the RFIDs is collected, these data will be correlated to the flow field through the stream in hopes of developing a scour-flow relationship for this site. Due to recent low flows more data are needed to develop a robust relationship at this site.

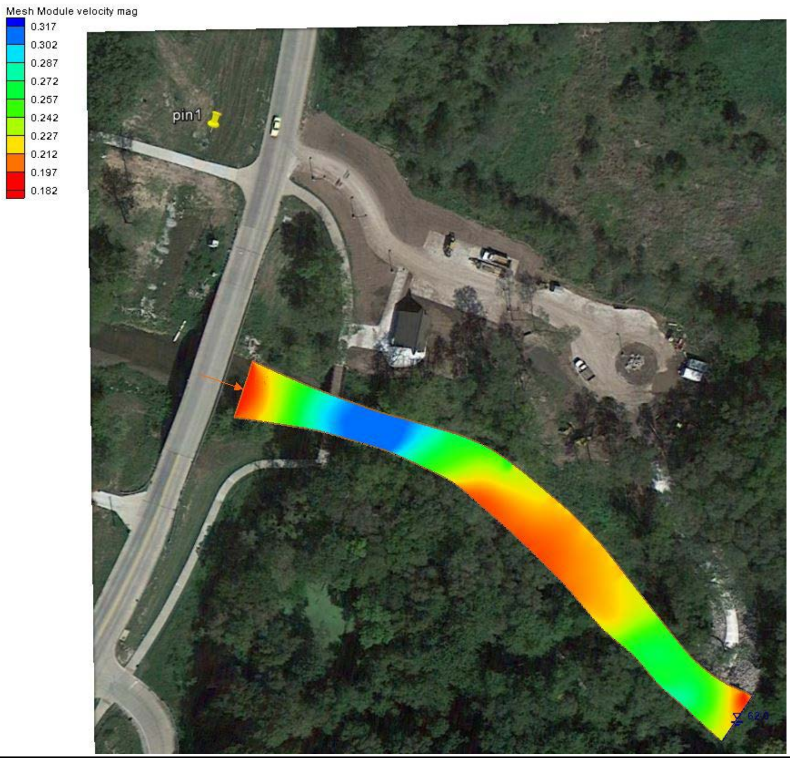

Figure 22. FESWMS simulation. The velocity flow field for Clear Creek near Camp Cardinal developed using FESWMS and the sonar-measured bathymetry data. Blue colors represent faster velocities and red colors represent slower velocities.

Task 8: Present the research products during state, regional, and national conferences (e.g., the Iowa County Engineers Association Annual Meeting; the biennial Midwest Transportation Conference), as well as to the IHRB at a monthly meeting following the completion of the project. Compile the key results in this final report and an accompanying tech transfer document.

The key results from this study have been compiled herein and the accompanying tech transfer document. In addition, these results have been summarized into presentations for the upcoming the 2014 World Environmental & Water Resources Congress in Portland, OR.

5. CONCLUSIONS, OUTCOMES AND RECOMMENDATIONS

An improved passive low-frequency system was developed to relate radiowave signal strength intensity or RSSI to distance. In addition, the role of orientation of the transponder to the excitation antenna plane was assessed via an inclinometer. The transponders were chained into a Leopold Chain that has been used in the past for scour monitoring. This time, the Leopold Chain is “smart”. Whenever the chain folds, the transponder changes its orientation with respect to the excitation antenna and sends a signal to the reader for the onset of scour. The PAPTSAK software provides to the user this information, as well as the ID of the transponder and the number of transponders detected from the RFID system. This study provided improved coating technique through the use of foam powder to protect the transponder electronic circuit from condensation. The first steps for the commercialization of this system have been addressed in this research.

The system can be used also for assessing the stability of hydraulic structures such as riprap, rocks and barbs, and provide unique information of the elements of those hydraulic structures. That may require further stabilization or improved design. Future research should explore the use of immersion techniques of the transponders into gravel-bed rivers. Currently, the system has been tested in sand-bed rivers where placement of the transponders within the sediment bed was not so challenging.

We recommend the use of both detection methodologies for determining the location of the transponders. This is the orientation method as well as the RSSI magnitude method (Figure 20). As part of this research, we have also identified the role of medium properties on RSSI. Future research should examine this issue in a more detail for different areas of the country.

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