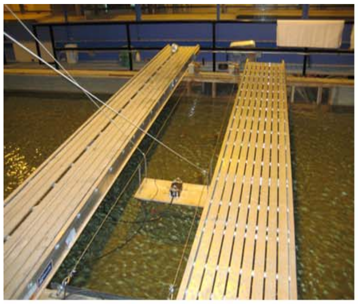
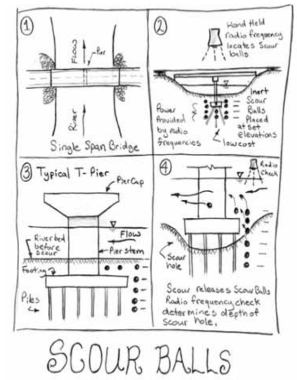
Autonomous Measurements of Bridge Pier and Abutment Scour using Motion-Sensing Radio Transmitters

FINAL REPORT: PROJECT TR-595





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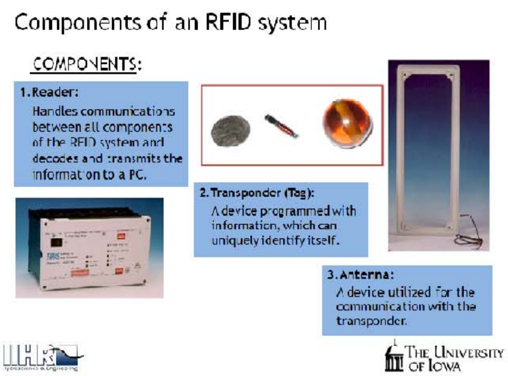

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IIHR Hydroscience & Engineering — IHRB Iowa Highway Research Board

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IIHR, a unit of The University of Iowa's College of Engineering, is one of the nation's premier and oldest environmental fluids research and engineering laboratories. Situated on the Iowa River in Iowa City, Iowa, IIHR seeks to educate students to conduct research in the broad fields of river hydraulics, sedimentary processes and watershed scale non-point source pollution processes. IIHR has on board 40 engineers and scientists that bring together a wide range of expertise.

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Technical Report Documentation Page

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15. ABSTRACT

Two portable **R**adio **F**requency **ID**entification (RFID) systems (made by Texas Instruments and HiTAG) were developed and tested for bridge scour monitoring by the Department of Civil and Environmental Engineering at the University of Iowa (UI). Both systems consist of three similar components: 1) a passive cylindrical transponder of 2.2 cm in length (derived from transmitter/responder); 2) a low frequency reader (~134.2 kHz frequency); and 3) an antenna (of rectangular or hexagonal loop). The Texas Instruments system can only read one smart particle per time, while the HiTAG system was successfully modified here at UI by adding the anti-collision feature. The HiTAG system was equipped with four antennas and could simultaneously detect 1,000s of smart particles located in a close proximity. A computer code was written in C++ at the UI for the HiTAG system to allow simultaneous, multiple readouts of smart particles under different flow conditions. The code is written for the Windows XP operational system which has a user-friendly windows interface that provides detailed information regarding the smart particle that includes: identification number, location (orientation in x,y,z), and the instance the particle was detected.. These systems were examined within the context of this innovative research in order to identify the best suited RFID system for performing autonomous bridge scour monitoring. A comprehensive laboratory study that included 142 experimental runs and limited field testing was performed to test the code and determine the performance of each system in terms of transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum inter-particle distance and antenna sweep angle. The two RFID systems capabilities to predict scour depth were also examined using pier models. **The findings can be summarized as follows:**

1) The first system (Texas Instruments) read one smart particle per time, and its effective read range was about 3ft (~1m). The second system (HiTAG) had similar detection ranges but permitted the addition of an anti-collision system to facilitate the simultaneous identification of multiple smart particles (transponders placed into marbles). Therefore, it was sought that the HiTAG system, with the anti-collision feature (or a system with similar features), would be preferable when compared to a single-read-out system for bridge scour monitoring, as the former could provide repetitive readings at multiple locations, which could help in predicting the scour-hole bathymetry along with maximum scour depth.

2) The HiTAG system provided reliable measures of the scour depth (z-direction) and the locations of the smart particles on the x-y plane within a distance of about 3ft (~1m) from the 4 antennas. A *Multiplexer* HTM4-I allowed the simultaneous use of four antennas for the HiTAG system. The four Hexagonal Loop antennas permitted the complete identification of the smart particles in an x, y, z orthogonal system as function of time. The HiTAG system can be also used to measure the rate of sediment movement (in kg/s or tones/hr).

3) The maximum detection distance of the antenna did not change significantly for the buried particles compared to the particles tested in the air. Thus, the low frequency RFID systems (~134.2 kHz) are appropriate for monitoring bridge scour because their waves can penetrate water and sand bodies without significant loss of their signal strength.

4) The pier model experiments in a flume with first RFID system showed that the system was able to successfully predict the maximum scour depth when the system was used with a single particle in the vicinity of pier model where scour-hole was expected. The pier model experiments with the second RFID system, performed in a sandbox, showed that system was able to successfully predict the maximum scour depth when two scour balls were used in the vicinity of the pier model where scour-hole was developed.

5) The preliminary field experiments with the second RFID system, at the Raccoon River, IA near the Railroad Bridge (located upstream of 360th street Bridge, near Booneville), showed that the RFID technology is transferable to the field. A practical method would be developed for facilitating the placement of the smart particles within the river bed. This method needs to be straightforward for the Department of Transportation (DOT) and county road working crews so it can be easily implemented at different locations.

6) Since the inception of this project, further research showed that there is significant progress in RFID technology. This includes the availability of waterproof RFID systems with passive or active transponders of detection ranges up to 60 ft (~20 m) within the water–sediment column. These systems do have anti-collision and can facilitate up to 8 powerful antennas which can significantly increase the detection range. Such systems need to be further considered and modified for performing automatic bridge scour monitoring. The knowledge gained from the two systems, including the software, needs to be adapted to the new systems.

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Final Report

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Iowa City January, 2010

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EXPANDED ABSTRACT

Two portable **R**adio **F**requency **ID**entification (RFID) systems (made by Texas Instruments and HiTAG) were developed and tested for bridge scour monitoring by the Department of Civil and Environmental Engineering at the University of Iowa (UI). These systems were considered based on prior research recommendations made in the broader discipline of Civil Engineering regarding sediment transport. Both systems consist of three similar components: 1) a passive cylindrical transponder of 2.2 cm in length (derived from transmitter/responder); 2) a low frequency reader (~134.2 kHz frequency); and 3) an antenna (of rectangular or hexagonal loop). The Texas Instruments system can only read one smart particle per time, while the HiTAG system was successfully modified here at UI by adding the anti-collision feature. The HiTAG system was equipped with four antennas and could simultaneously detect 1,000s of smart particles located in a close proximity. A computer code was written in C++ at the UI for the HiTAG system to allow simultaneous, multiple readouts of smart particles under different flow conditions. The code is written for the Windows XP operational system which has a user-friendly windows interface that provides detailed information regarding the smart particle that includes: identification number, location (orientation in x,y,z), and the instance the particle was detected.. These systems were examined within the context of this innovative research in order to identify the best suited RFID system for performing autonomous bridge scour monitoring. A comprehensive laboratory study that included 142 experimental runs and limited field testing was performed to test the code and determine the performance of each system in terms of transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum inter-particle distance and antenna sweep angle. The two RFID systems capabilities to predict scour depth were also examined using pier models. The findings/outcomes of this innovative study can be summarized as follows:

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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 1980's. 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 buried or driven rods, float-out devices, 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., piezo-electric probes), magnetic sliding collars and RFID systems (Lauth and Papanicolaou, 2008), 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. 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.

Buried rods, for example, can be equipped with a piezo-electric probe and driven vertically in the scour hole. The changes in the output voltage of the piezo-electric probe can be used to quantify the scour or deposition processes occurring around the rod. The change in the output voltage can then be converted into either scour or deposition depth and stored by means of a data logger. Magnetic sliding collars can be placed along each rod and driven vertically in the scour hole. As the scour depth increases, the magnetic sliding collar descends along the rod until it rests on the bottom of the scour hole. The traveling distance of the magnetic collar and the corresponding scour depth can be determined from the voltage change induced by the descent of the magnetic collar along the driven rod. This information can be transmitted to a data logger.

Scour holes that develop during a flood may refill with sediment during the flood recession; therefore, data must be collected during the flood and methods must be developed to determine the maximum scour depth that occurs during the flood prior to recession (Placzek and Haeni, 1995). Under these circumstances, 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 bridges failure by alerting traffic engineers to close the bridges during floods if the scour depth reaches a critical level. Advancements in sensor technology over the last half-decade warrant success towards the development of autonomous scour detection systems, which could 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.

2. OBJECTIVES

In this study the investigators proposed the use of Radio Frequency IDentification (RFID) technology to collect field data and remotely monitor bridge scour during floods. RFID is a wireless automated identification technology that utilizes waves at radio frequency (RF) to transfer information between a reader and a transponder (short for transmitter and responder) via an antenna. RFID technology has several advantages over other methods. Because it operates by transmission of RF waves rather than beams, the only requirement for detecting a transponder is that it falls within the detection field of the antenna, even if it is buried in the scour-hole. Another important feature of the RFID technology is that a unique identification number can be assigned to each transponder, allowing different transponders within the system to be identified. RFID systems are also cost effective and flexible because a reader/antenna system can be used with any number of transponders, which have low acquisition cost. The variety of sizes and shapes of the commercially available transponders and antennas enhance the flexibility of the RFID system. Finally, modern RFID systems can be completely controlled by a host computer and therefore be fully automated (Scher, 2005).

The overarching objective of this study is to develop an automated RFID system for monitoring bridge scour with the following four specific goals:

1. a. Configure an RFID system to facilitate multiple smart particle detection for monitoring bridge scour.
   b. Develop a computer code in LabView to enable simultaneous, multiple readouts of smart particles under different flow conditions. The code should provide the ID of smart particles, the x,y,z of the smart particles, and the instance of their detection in a user-friendly windows interface.

2. Evaluate the RFID system performance by conducting laboratory experiments to determine the maximum detection range of the system.
3. Provide the initial steps towards the development of an integrated bridge scour monitoring system using RFID technology based on the knowledge gained from goals 1 and 2 above.
4. Assess the applicability of the RFID system for monitoring bridge scour in the field and identify the areas needing improvement.

3. METHODOLOGY

The following methodological steps were undertaken to achieve the overarching objective of the study:

1. Select the appropriate reader and anti-collision hardware for the configuration of an RFID system for monitoring bridge scour. Identify the optimal set-up of the antennas, in terms of antenna spacing, orientation, size and shape.
2. Program the reader to transmit RF waves for charging the transponders for 50 msec, and listening for the transponder response for another 50 msec.
3. Write a computer code in Lab View to establish communication between transponders and reader at 10 reads per second for our TI reader, providing information regarding the ID of smart particles, the x,y,z of the smart particles, and the instance of their detection in a user-friendly windows interface. The data can be exported to Excel or any other plotting software.
4. Develop a custom code in C++ programming environment to allow for fully automating the use of the anti-collision feature and the switching between the antennas, when multiple antennas are connected to the reader.
5. Perform comprehensive laboratory study that includes 142 experimental runs and limited field testing to determine the performance of each system in terms of transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum inter-particle distance and antenna sweep angle. Develop an integrated system using the RFID technology to monitor bridge scour.
6. Evaluate the reconfigured RFID system at the field and suggest future directions for the development of a standalone, versatile system for performing bridge scour monitoring in-situ.

3.1 RFID System Configuration

RFID is a wireless automated identification technology that utilizes waves at radio frequency (RF) to transfer information between a reader and a transponder (short for transmitter and responder) via an antenna. The reader is a set of circuits converting the information transmitted by the transponders as RF waves to electric signals, which can then be transmitted to an output device (host), such as a computer. The antenna consists of circuits, which ensure the two-way communication between the reader and the transponder, viz. transmit the RF signal from the reader to the transponder and receive the return signal from the transponder. Transponders consist of a miniature antenna for two-way communication with the reader and circuits to store and send information to the reader. Transponders can be either active or passive according to the way that they are powered. An active transponder has a battery to provide power to its integrated circuits (IC) and transmit the information to the reader, whereas a passive transponder is powered by the energy stored in the RF wave that the transponder receives from the reader.

Two RFID systems were configured for the purposes of the study (Figure 1). Both systems, namely the Texas Instruments system (system 1) and the HiTAG (system 2) operated at a low radio frequency band (134.2 kHz and 125 kHz for the first and second system, respectively). The response RF from the transponder can be in one of two frequencies: if the transmitted signal from the transponder corresponds to a "1", the RF wave is a 134.2 kHz, while if it corresponds to a "0" the RF is transmitted at 124.2 kHz (which is close to audio frequency). Low frequency RFID systems were preferred for this study, because low RF waves (LRF) present higher penetration into bodies of water and soil (including sand) than high RF (HRF) waves. Therefore, LRF systems are ideally suited for the detection of buried transponders. In addition, LRF waves are less affected by surrounding metal surfaces compared to HRF waves. This property could be of importance because many of the bridges are made of steel. Both RFID systems were passive, i.e., the integrated circuits (IC) of the transponders were powered by the energy of the RF wave emitted from the antenna. A passive RFID system was used in this study, because passive transponders have a more compact size than active transponders, practically unlimited lifetime, and have comparatively lower costs than active transponders. Moreover, passive RFID systems can handle multiple transponders more efficiently than active RFID systems within the detection range of an antenna.

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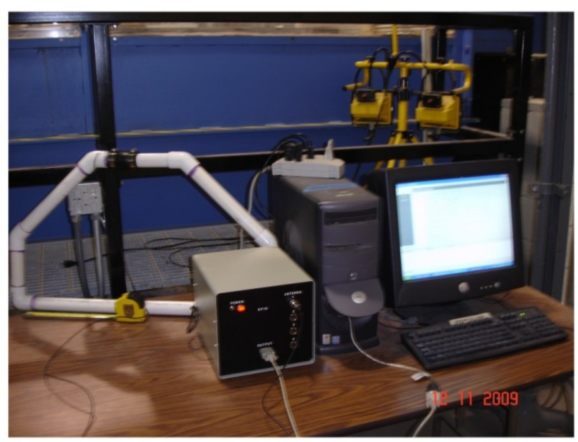

B

Figure 1. General view of the two configured RFID systems: (A) the TI system of 134.2 kHz; (B) the HiTAG system of 125 kHz.

3.1.1. Configuration of the first RFID system

The first system was an off-the-shelf, 134.2 kHz passive system developed by Texas Instruments (www.ti.com), which has configurations similar to the system of Nichols (2004). The reader of the system consisted of three modules, namely the frequency module, the control module, and the antenna tuning module. The frequency module (Figure 2A1) (RI-RFM-008B-00) converts the radio frequency signals emitted by the transponder to electric signals that can be processed by the control module. The control module (RI-CTL-MB2A-03) (Figure 2A2) is the interface between the frequency module and the PC used to control the system. Essentially the control module converts the RF signals received from the transponder to the serial number of the transponder and transmits this information over a serial line to the host PC. A custom code was developed in LabView software (www.ni.com), which records the serial number and the detection time of each transponder and exports the output in text format (Figure 3). The antenna tuning module (RI-ACC-008B-00) tunes the antenna so that the outgoing RF signals from the frequency module are emitted at the correct frequency to ensure communication with the transponders. Two antennas of different size were used in this study. The larger antenna (RI-ANT-G01E) has a rectangular loop shape with dimensions of 0.70×0.27 m (Figure 2B). The smaller antenna (RI-ANT-G02E) has a square loop shape with dimensions of 0.20×0.20 m (Figure 2B). The two antennas can be connected interchangeably to the reader by switching two pin type connectors. A 10 m long waterproof cable is used to connect the selected antenna to the reader. The entire RFID system is powered by a 12V power supply.

The final steps for the development of the first RFID system were the selection of the transponder and the production of a particle that would house the transponder and be suitable for monitoring bridge scour in sand bed rivers. The transponder selected for this study was the RI-TRP-WEHP-30, low radio frequency (132.4 kHz), passive transponder from the economy line of Texas Instruments with density of 2,223kg/m^3. The transponders are 23 mm long and 3.8 mm in diameter, protected by self-contained glass casings, thus allowing the use of the transponder without an additional casing (naked) if desired (Figure 2C). The low acquisition cost of each transponder permitted the purchase of large number of transponders. Each transponder came with 80 bit Read/Write memory, which enabled the coding of a unique identification number on each transponder.

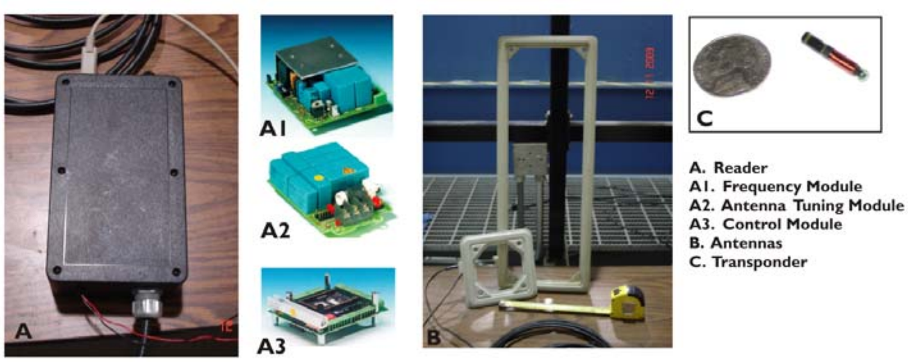

Figure 2. Components of the TI 134.2 kHz RFID system used in this study (A) RFID reader, (A1) reader frequency module, (A2) antenna tuning module, (A3) control module, (B) antennas (0.70×0.27 m and 0.20×0.20 m) and (C) transponder.

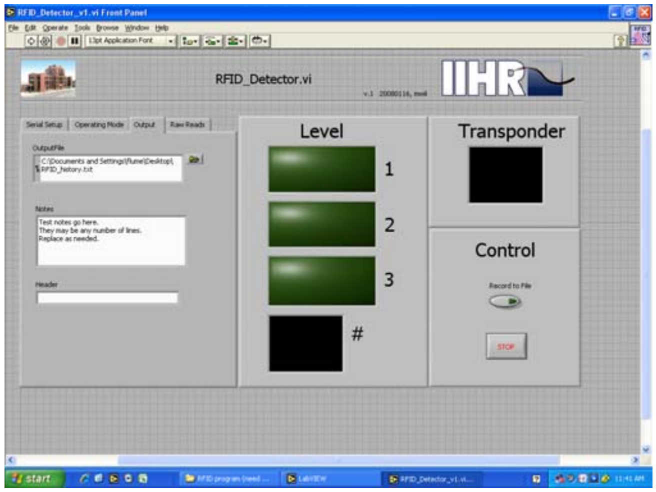

Figure 3. LabView™ program developed for the operation of the 134.2 kHz RFID system.

Two types of spherical particles were used to house the transponders, namely a glass particle and a particle made of concrete coated with tungsten (Figure 4). The particles used matched the density of the sand (measured here equal to 2658 kgr/m^3) with a diameter of 25.4 mm. The glass particles were drilled to provide an opening for the placement of one transponder. The glass particle was then sealed with silicon to protect the transponder. The concrete-tungsten particles were made by first casting concrete particles and subsequently coating them with a thin film of tungsten, in order to match the density of the sand for the known volume of the particle.

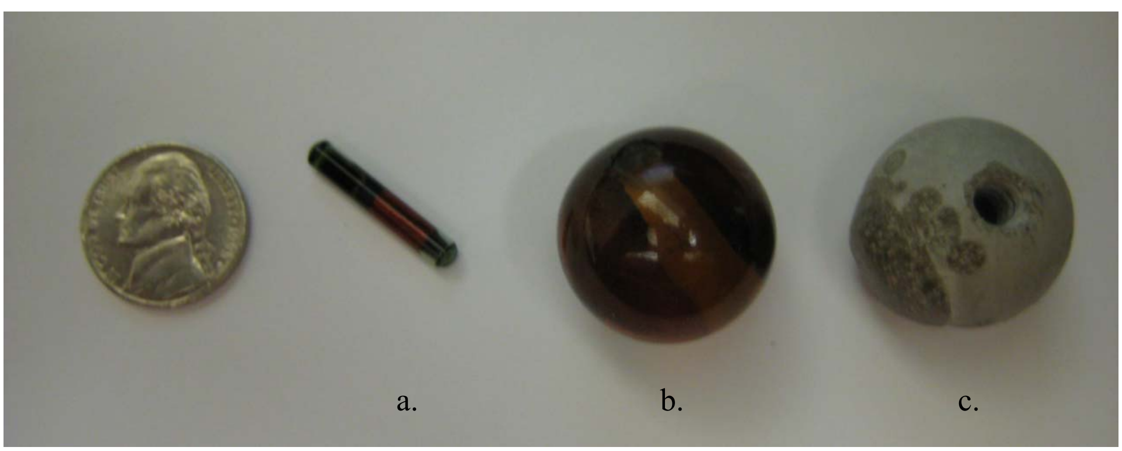

Figure 4. Size comparison for the transponder and particles used. From left to right: (a)naked transponder, (b)glass particle and (c)concrete-tungsten particle. The transponder density is 2,223kg/m^3.

3.1.2. Configuration of the second RFID system

The second RFID system was a 125 kHz passive system, which was developed by HiTAG and modified based on the test results acquired from the first RFID system (Lauth and Papanicolaou, 2009). The core of the system is the HiTAG HTRM-01 Long Range Reader module, which is offered by Phillips. The main advantage the reader module of the second RFID system offers when compared to the first RFID system is that it can support multi-tag operation or anti-collision. RFID systems that do not support anti-collision fail to establish communication between the reader and the transponders when multiple transponders are located within the electromagnetic field of the antenna (Figure 5A). In this case, all the transponders try to communicate with the antenna simultaneously. As a result, the signals coming from the multiple transponders "collide", thus impairing the communication between the antenna and all the transponders. The HiTAG HTRM-01 Long Range Reader Module incorporates the anti-collision feature, which is based on the RTF ("Reader Talks First") protocol. According to RTF protocol, the reader can prioritize the communication between the antenna and one transponder when multiple transponders are detected (Figure 5B). Once the first transponder is interrogated, the anti-collision function sets the already detected transponder in mute status and proceeds with the interrogation of the transponder detected next. The process is repeated until all transponders within the antenna electromagnetic field are interrogated.

Another advantage of the second RFID system over the first system (described in section 3.1.1) is that it can support the simultaneous connection of up to four antennas to the same reader (Figure 6A). This is achieved by the HiTAG HTM4-I multiplexer. A custom code was developed in C++ programming environment allowing the fully automated use of the anti-collision feature and the ability to switch between the antennas, when more than one antenna is connected to the reader. The custom C++ code records the serial number and the detection time of each transponder followed by the antenna number used for the detection and exports the output in text format. An integrated antenna tuning module offered by HiTAG (HT-OT840) is incorporated also in the reader system, which ensures that the antenna transmits the radio waves at the correct frequency for proper communication between the transponders and the reader. The second RFID system came with 4 identical antennas having the specifications of the HTLRX antenna offered by HiTAG. These antennas have a six-edged polygon shape and overall dimensions of 0.86×0.52 m (Figure 6B). The antennas are placed in PVC pipes, which make the antennas watertight such that they can be operated under water.

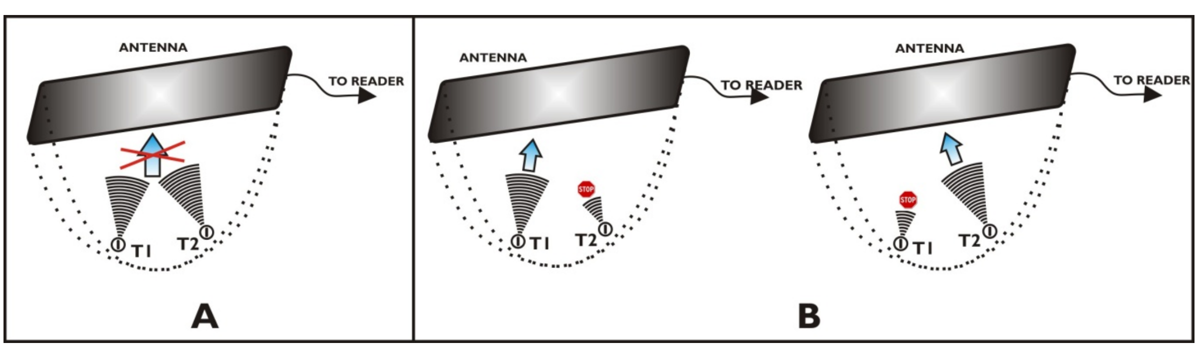

Figure 5. Communication between the antenna and multiple transponders (A) without the anti-collision capability and (B) with the anti-collision capability.

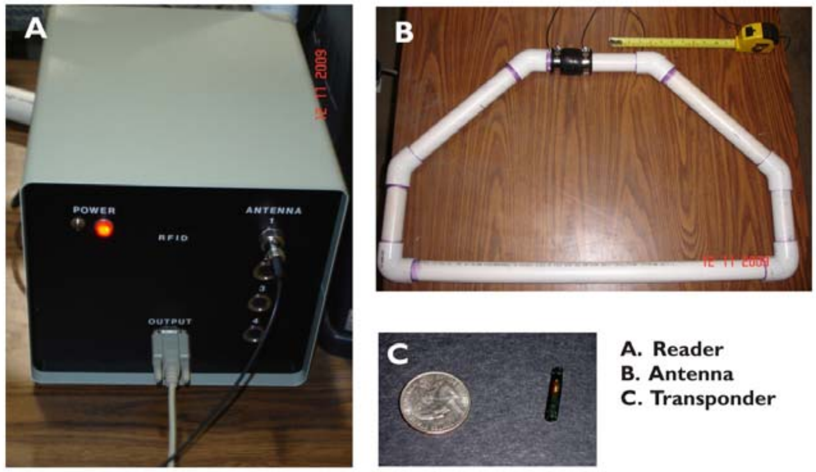

Figure 6. Components of the second RFID system used in this study: (A) reader with the four ports for the antenna connections, (B) antenna and (C) transponder.

The transponders used with the second RFID system are of Read/Write type, model HTS2048 manufactured by HiTAG (Figure 6C). The HTS2048 transponders come with 2048 bits of memory and are encased in a glass casing 22 mm long and 4 mm in diameter. These transponders support the anti-collision feature (RTF protocol).

Two types of spherical particles were used to house the transponders, namely glass particles similar to the ones used with the first RFID system and plastic particles to float on the water surface. However, each particle used with the second RFID system houses two transponders instead of one, because these particles were used mainly in the field (Figure 7). The second transponder acts as a spare in the case that the first transponder malfunctions. The glass particles used in the field have a diameter of 25.4 mm, whereas the plastic particles have a diameter of 100 mm and are red in color to easily locate them in the field (Figure 7). A small number of plastic particles 40 mm in diameter with one transponder were also used with the second RFID system for laboratory experiments. The transponders were sealed inside the particles with silicone.

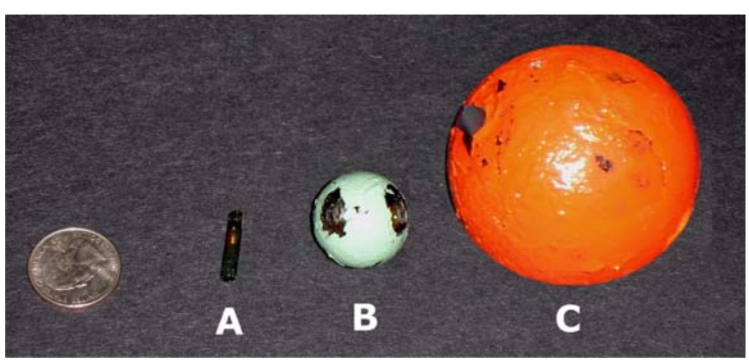

Figure 7. (A) HITAG HTS2048 transponder, (B) glass particle with 2 holes for the 2 transponders, and (C) plastic particle containing 2 transponders (used in the Raccoon River).

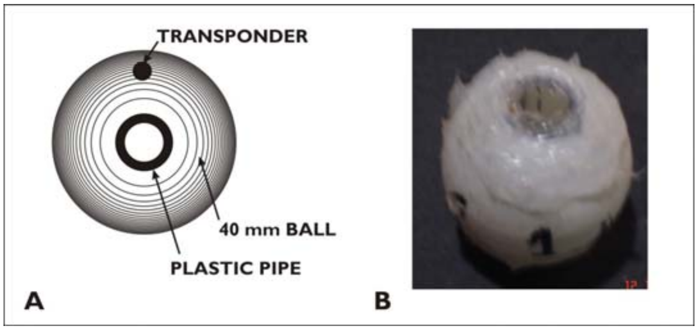

Figure 8. (A) Plan view sketch (not to scale) of the scour ball, (B) Perspective of the scour ball.

3.2 Laboratory Experiments Using RFIDs

The performance of the two configured RFID systems was evaluated by conducting laboratory and field experiments to determine the maximum detection range of each system. Factors that affect the detection range of an RFID system and will be examined in this study are: the transponder orientation, the transponder housing material (or particle type), the transponder distance from the antenna, and the minimum distance between two transponders. Laboratory experiments were conducted in order to first maintain controlled conditions during the tests, followed by a limited number of field experiments to assess the applicability of the RFID technology in the field. The findings of these experiments will facilitate the development of an integrated system to monitor bridge scour.

3.2.1. Detection Range of the two RFID Systems

The effects of orientation and transponder housing material on the detection range of the two RFID systems were investigated through a series of comprehensive experiments (overall 142 experimental runs were performed).

The permissible distance between a transponder and the antenna for the transponder to be successfully detected were examined in a water recirculating flume using the first RFID system. Additional experiments were performed in a small acrylic sand box to examine the anti-collision capability of the second RFID system.

Preliminary experiments were performed first using a naked transponder to determine the optimal orientation of the transponder with respect to the antenna plane, at which the distance for a successful detection of the transponder is maximum. The transponder was placed at different orientations with respect to the antenna plane and the largest distance corresponding to successful detection was recorded.

It was sought that the HiTAG system with the anti-collision (or a system with similar features) will be preferable compared to a single-read-out system for bridge scour monitoring, as the former could provide at multiple locations repetitive readings which could lead towards the detection of a scoured location (depth and aerial dimensions of scour hole).

The maximum antenna detection distance occurred when the transponder long axis was perpendicular to the plane of the antenna. For this orientation the intensity of the electromagnetic field created by the transponder due to the action of the antenna obtained its highest value, which is hereafter termed *as the favorable transponder orientation*. On the contrary, when the transponder long axis was parallel to the plane of the antenna (unfavorable orientation), the minimum antenna detection distance was observed. Other orientations provided intermediate detection distances. The maximum and minimum transponder detection distances of the RFID system were 0.68 m and 0.43 m, respectively. The detection distance decreased by 37%, when the transponder was at its unfavorable orientation compared to the favorable orientation. This finding has implications for the design of a scour monitoring device.

The orientation experiments were repeated for the transponders by placing them in glass, concrete-tungsten, and plastic spherical particles to examine the effect of these housing materials on the detection distance of the RFID system. **The concrete-tungsten tagged particles had the smallest detection distance. Instead the plastic tagged particles had the highest detection distance out of the three tested housing material. The RF reduction for the plastic tagged particles was less than 3% when are compared to the naked passive transponders.** The low detection distance observed for the concrete-tungsten particles was attributed to the tungsten coating, which weakened the RF signal that reached to the housed transponder. The glass particles had 6% reduction in the detection distance compared to the naked transponders. *Table 1 summarizes the results of the orientation and housing tests*. The detection distance values given in Table 1 are the outcome of 10 iterations for each tested condition.

Based on the preliminary experiment findings, only glass and plastic particles were used for the remaining laboratory and field experiments. The laboratory experiments were conducted in a recirculating flume to determine the permissible distance for a transponder to be successfully detected when it is buried in a sand-bed.

The maximum antenna detection distance occurred when the transponder long axis was perpendicular to the plane of the antenna. The detection distance decreased by 37%, when the transponder was at its unfavorable orientation compared to the favorable orientation. This finding has implications for the design of a scour monitoring device.

Table 1. “**Orientation & Housing Preliminary Experiments**”: Effects of transponder orientation and housing material on the detection distance (summary of 120 total experimental runs).

Housing material	**Naked**		**Glass**		**Concrete-Tungsten**		**Plastic**	
Orientation	Perp.**	Parallel	Perp.	Parallel	Perp.	Parallel	Perp.	Parallel
Detection distance (m)*	0.68	0.43	0.65	0.41	0.53	0.28	0.66	0.42

*Average of 15 iterations, the deviation was ± 2% in the reported average values; **Perp. = Perpendicular

The flume experiments were conducted in the Hydraulics Laboratory of the Iowa Institute of Hydraulic Research (IIHR), at the University of Iowa in a recirculating flume 21.3 m long, 4 m wide, and 1.21 m deep (Figure 9). Only the first RFID system was used for these flume experiments. The sidewalls of the flume are made of waterproofed opaque bricks. The flume has a side glass-section 3.05 m long and 1.21 m tall, to allow for visual observations. A wooden honeycomb structure was installed at the headbox of the flume to ensure rectilinear flow. At the flume entrance, 1.5 m long section was paved with concrete blocks to avoid excessive sand scour. A sandtrap with a fine opening screen was installed at the downstream end of the flume near the tailbox to prevent sand from entering the recirculating system. The flume had a closed operating system, which involved two pumps with a maximum discharge of 0.211 m^3/ s to recirculate the flow. The first pump (60 HP) was used to fill the flume to the desired water level, while the second pump (30 HP) was used to recirculate the water in the flume. Water discharge was controlled using a butterfly valve and measured via a calibrated side-contraction orifice located in the return flow pipe.

Figure 9. View looking upstream of the 21.3 m long, 4.0 m wide recirculating flume.

The working section of the flume was filled with a 61 cm layer of natural, near uniform sand with a median diameter d_{50} = 0.47 mm and specific weight of 2.658. The slope of the sand surface was set equal to S = 0.1% before each experimental run by leveling the sand surface with a scraper. The test section in the flume, where the antenna and the transponders were placed, was 0.70 m long by 4.0 m wide, and was located approximately 12.0 m downstream of the flume entrance. Two steel cables, placed 0.64 m apart from one another traversed the flume test section. The RFID antenna was mounted on a wooden board attached to the cables via four metal hooks. The antenna could therefore sweep the entire test section of the flume, when towed along the cables. The initial water depth in the flume was 0.30 m for all experiments, and the bottom of the antenna was just above the water surface to keep it dry.

Three main sets of flume experiments were conducted to identify: 1) the maximum distance between a buried transponder and the antenna; 2) the minimum distance between buried transponders to avoid collision effects between the signals of the transponders; and 3) the optimal angle between the antenna (rectangular in shape) longitudinal axis and the antenna sweep direction to minimize collision effects. Additional runs with a pier model were conducted to assess the applicability of the RFID system for monitoring bridge scour.

The first set of flume experiments consisted of 8 experimental runs to determine the maximum detection distance between a buried transponder and the antenna. Four glass particles with different serial numbers were used for each experimental run (Table 2). In each run, the 4 particles were buried in the test section at a certain depth below the sand bed surface and were spaced 0.38 m apart from each other along the flume width (Figure 10A). During the placement of the particles it was ensured that the transponders were placed vertically, i.e. at their favorable orientation with regards to the antenna plane as found from the preliminary experiments.

Table 2. "Burial Depth Experiments": Transponder burial depths, D_b, and resulting antenna particle distances, D_{ap}, per experimental run for the first set of experiments.

Exp. Run #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
D_b (m)	0.30	0.33	0.36	0.38	0.41	0.43	0.46	0.48
D_{ap} (m)	0.60	0.63	0.66	0.68	0.71	0.73	0.76	0.78

Sand was removed partially from the test section and the glass particles were placed at a certain burial depth. The particles were covered with sand and the test section was leveled. For all the experimental runs, the discharge and water depth were 0.211 m^3/s and 0.30 m, respectively. The total distance between the antenna and the particles was calculated as $D_{ap} = D_b + H$, where H is the water depth and D_b is the distance between the buried transponder and the sand bed surface. The antenna was swept over test section 16 times with an average speed of 0.06 m/sec to detect the particles. It was determined that this was the optimal antenna sweeping speed to have sufficient time for successful detection. The serial numbers of the detected and undetected particles during each pass were recorded. The burial depth of the particles was increased in each run until no particles could be detected, which corresponded to the maximum detection distance between a buried particle and the antenna.

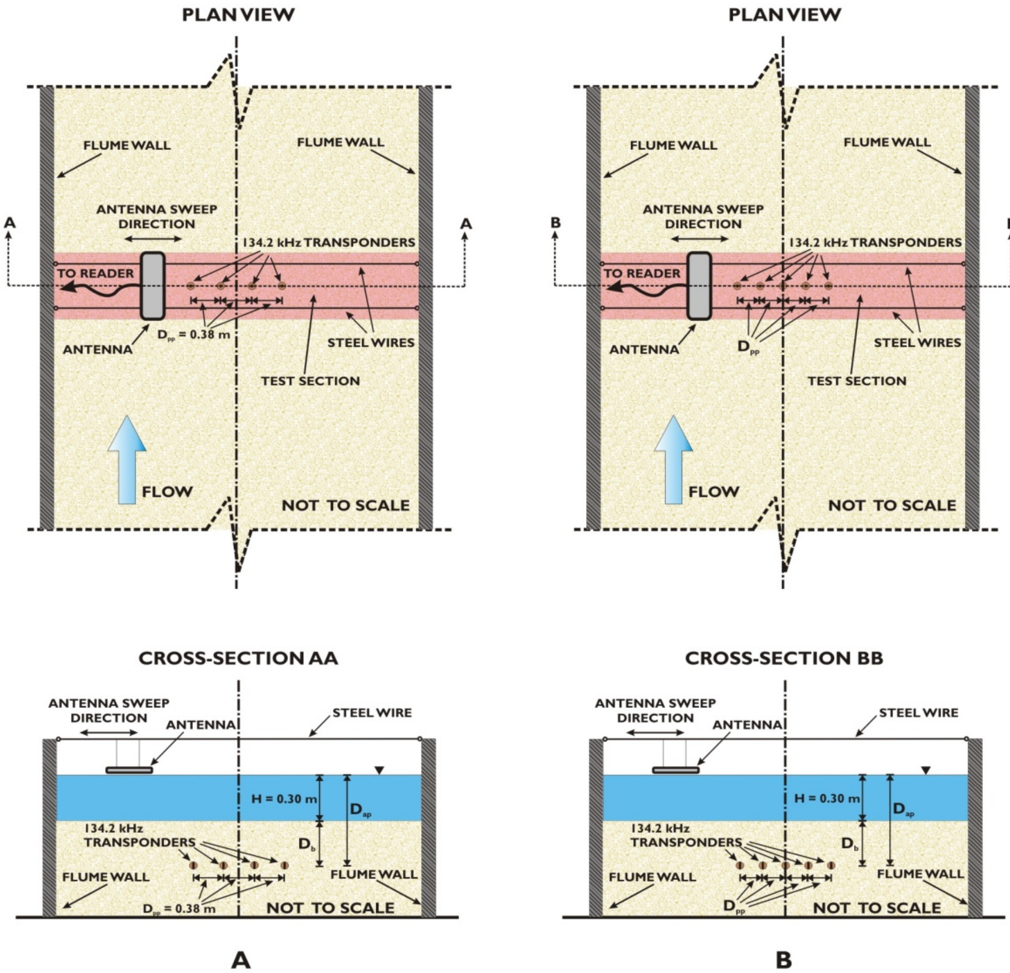

Figure 10. Flume setup for (A) the first set of experiments, and (B) for the second set.

The second set of experiments consisted of 7 experimental runs to determine the minimum distance between buried transponders (D_{pp}) to avoid collision effects between the signals of the transponders. Five glass particles with different serial numbers were used for each experimental run. In each run, sand was removed partially from the test section and the particles were placed at equal distances from each other along the flume width (Figure 10B). The distance between the particles was varied for each run (Table 3). The particles were covered with sand and the test section was leveled. The particles were buried 0.3 m below the sand bed surface, which was within the detection distance of the RFID system. The particles were also placed such that the transponders were vertically oriented. For all the experimental runs, the discharge and water depth were 0.211 m^3/s and 0.30 m, respectively. The antenna was swept over test section 12 times with an average speed of 0.06 m/sec to detect the particles. The serial numbers of the detected and undetected particles during each pass were recorded. The spacing between the particles was decreased in each run until a minimum number of particles was detected by the antenna, which corresponded to the minimum detection distance between the buried particles.

Table 3. "Collision Effects Experiments": Separation distance, D_{pp}, between each transponder for each run of the second set of experiments.

Run #	1	2	3	4	5	6	7
D_{pp} (m)	0.15	0.18	0.20	0.23	0.25	0.28	0.30

The third set of experiments consisted of 5 collision runs. These runs were conducted using the same setup as the second set of experiments (Figure 10B), with five particles placed along the flume width. However, the distance between the particles was kept 0.28 m. *The angle, φ, between the antenna longitudinal axis and the antenna sweep direction was varied (Figure 11).* Table 4 summarizes the values of the angle φ selected for these runs. The antenna was swept over test section 18 times during each run, with an average speed of 0.06 m/sec to detect the particles. The serial numbers of the detected and undetected particles during each pass were recorded. The angle φ was decreased in each run until the number of detected particles was minimum, which corresponded to the worst sweeping angle.

Table 4. "Antenna Angle Sweep Experiments": Angle between the antenna longitudinal axis and the antenna sweep direction, φ, for each collision run of the third set of experiments.

Exp. Run #	1	2	3	4	5
Angle φ (^{o})	0	30	45	60	90

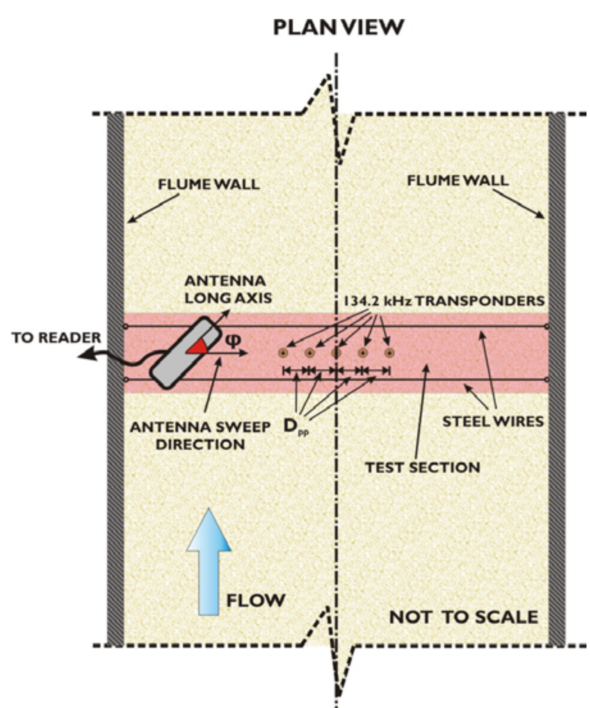

Figure 11. Flume setup for the third set of experiments.

3.2.2. Pier scour monitoring system

The experiments described so far to evaluate the detection range of the RFID system were conducted without any structure in place. In this last phase of the experiments, pier models were used to assess the applicability of the two RFID systems ability in monitoring bridge scour. The proposed pier scour experiments with the RFIDs were based upon two principles, namely the particle signal-loss and the particle float-out.

Two sets of pier model experiments were conducted to monitor bridge scour using both rectangular and cylindrical pier models. The first set of experiments was conducted in the flume with a rectangular pier model. This set of experiments was based on the particle signal-loss principle, and used the first RFID system with a single glass particle. The second set of experiments was conducted in a sandbox with a cylindrical pier model. This set of experiments was based on the float-out principle and utilized the second RFID system consisting of multiple plastic particles. The second RFID system was preferred for this set of experiments, because it could handle anti-collision between multiple particles.

The first set of experiments with the first RFID was conducted in the flume using a rectangular pier model 1.33 m long with a cross-section of 0.22×0.41 m. The pier was made of wood with an intermediate 0.15 m glass section to allow the placement of a video camera to monitor the scour occurring around the pier (Figure 12A). The pier was fixed into the bottom of the flume and buried in the sand up to 0.61 m of its height. The small antenna with a cross-section area of 0.20×0.20 m was fixed at the upstream face of the pier model as shown in Figure 12B. The sand bed surface was leveled around the pier and one glass particle was placed on the sand bed surface directly below the center of the antenna. The distance between the antenna and the particle was 0.20 m, which was 0.11 m less than the maximum detection distance of the antenna. It was anticipated that the antenna would lose contact with the particle, when the scour exceeded 0.11 m, thus providing an estimate of the maximum scour depth. The maximum anticipated scour around the pier (0.11 m) was determined from previous experiments with the pier model. The discharge and water depth during the test were 0.168 m^3/s and 0.18 m, respectively. The particle remained stationary under this flow condition, while scour commenced underneath the particle. As the scour developed, the particle started to drop down into the scour-hole. When the distance between the particle and the antenna exceeded the maximum detection depth of the antenna (0.31 m), the contact between the particle and the antenna was lost. This indicated that the scour-hole had reached the anticipated maximum scour depth of 0.11 m. The scour at the end of the experiments did not change significantly from the reported 0.11 m depth.

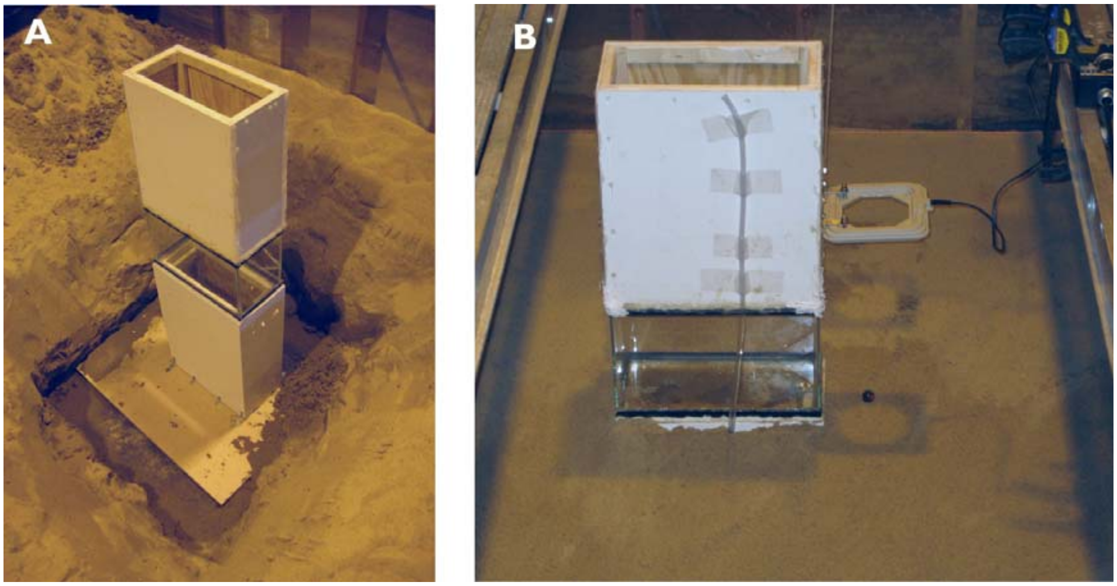

Figure 12. Setup for the set of experiments with the rectangular pier: (A) pier resting on the flume bed and (B) final pier setup with the antenna placed on the pier upstream face and the RFID particle underneath. Flow is from right to left.

In the second set of the pier model experiments the second RFID system (HiTAG) was used to overcome the limitation of the first system with regards to collision, when more than one transponder was found around the pier. The experiments with the second RFID system were conducted in a sandbox using a cylindrical pier model 0.6 m long, and 0.07 m in diameter. The sand box was 0.34 m tall, 0.25 m wide, and 0.38 m long (Figure 13). The sandbox and the pier were made of acrylic to allow monitoring the scour occurring around the pier via a video camera. The pier was fixed vertically at the bottom of sandbox as shown in Figure 15. A rod 0.006 m in diameter was also fixed vertically at the bottom of sandbox 0.037 m away from the pier model (Figure 14). This rod served as a guide for the two 40 mm plastic particles (or “scour balls”) used in these experiments. Two parallel holes were drilled in each scour ball as shown in Figure 9A. The first hole was bored through the center of the scour ball to guide the balls through the rod, while the second hole was bored at the edge of the scour ball to place one transponder. This design enabled the transponder to remain vertical at all times. The two scour balls were placed one atop the other, along the rod that the lower ball rest on the bottom of the sandbox (Figure 15A), and the sandbox was filled with near uniform sand (d_{50} = 0.47 mm) up to a depth of 0.125 m. The burial depths of the lower and upper balls measured from the sand bed surface were 0.08 and 0.04 m, respectively. The weight of the 0.02 m sand layer above upper scour ball was sufficient to retain the balls buried in the sand bed. An antenna was placed at a distance of 0.45 m above the sandbox bottom such that it could not detect the scour balls when they were buried within the sand bed, but it could detect the scour balls when they floated on the water surface. The maximum detection distance of the used antenna was 0.3 m (Figure 15B).

Water was recirculated in the sandbox at constant discharge of 0.00074 m^3/sec through a jet nozzle using a 1/3 HP pump, while the water depth was maintained at 0.04 m. The jet nozzle 0.004 m in diameter was pointed towards the pier model, where the scour balls were located to create scour around the pier. Two acrylic plates of dimensions 0.05x0.15 m were inserted vertically into the sand bed on each side of the pier forming a funnel with an angle of 60^o to prevent the surrounding sand from infiltrating the developed scour hole (Figure 13). The particles, which were exposed due to excessive scour, rose to the water surface. The detection of a particle by the antenna at the water surface indicated that scour had reached the depth, where the particle was initially buried. The second RFID system was able to successfully detect multiple transponders (anti-collision), when they were within the antenna detection distance.

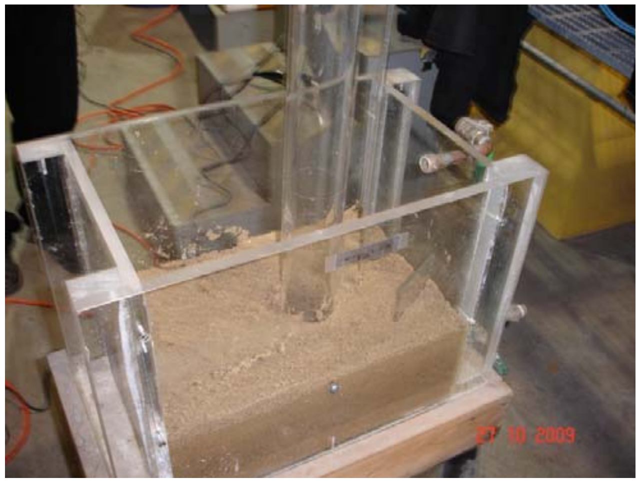

Figure 13. Perspective of the sandbox used for the second set of the experiments with the pier models.

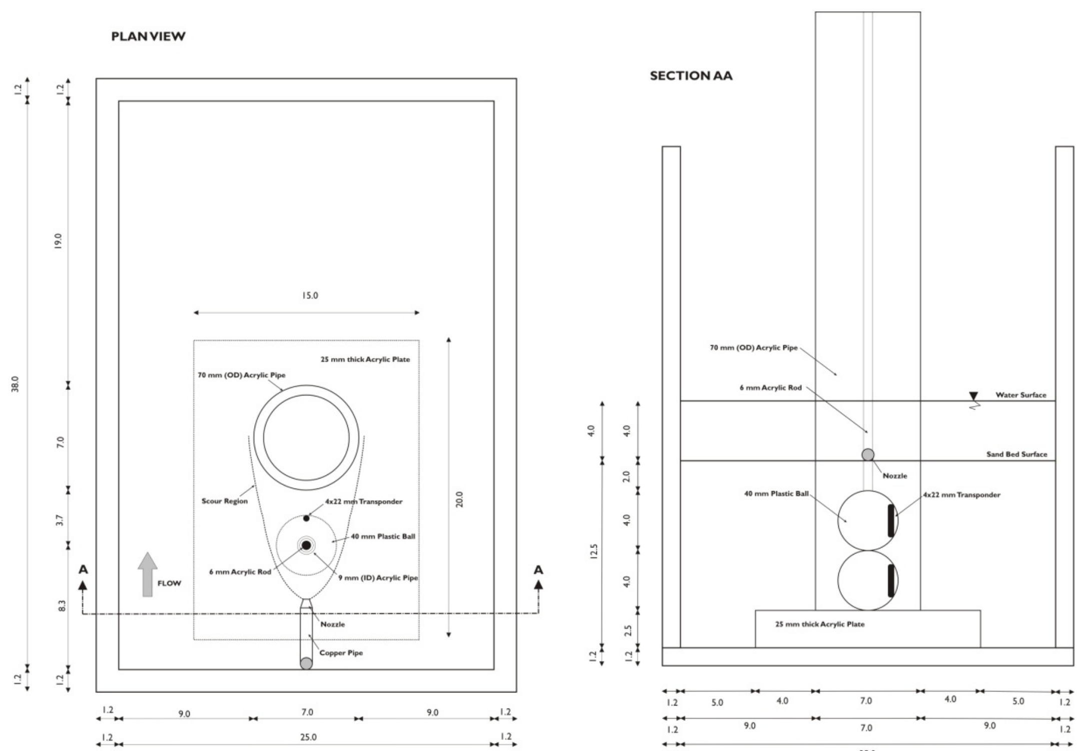

Figure 14. Plan and cross-sectional view of the acrylic scour tank.

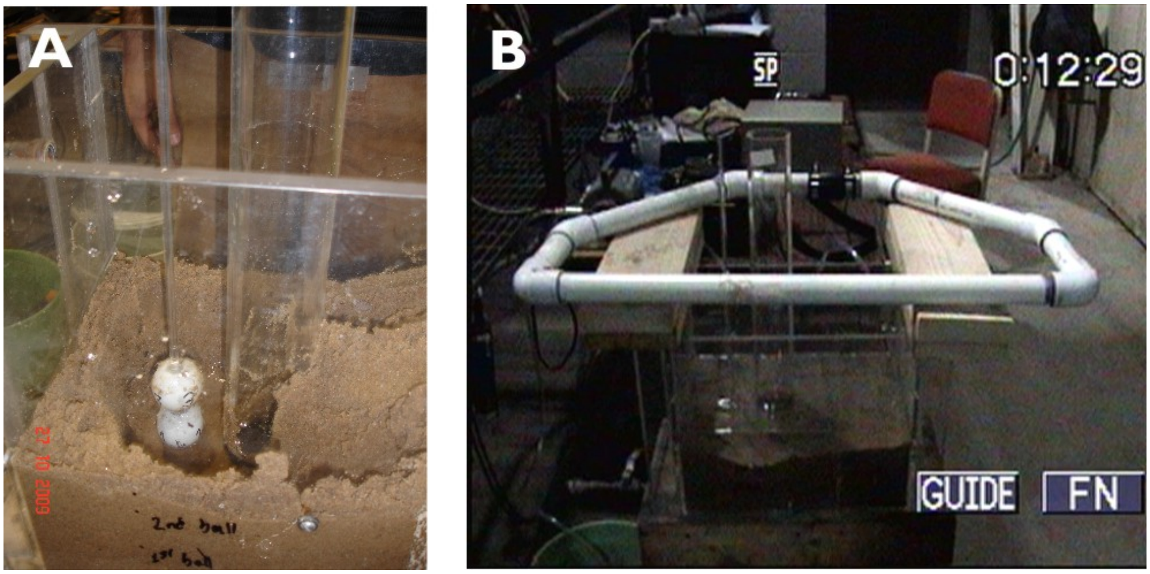

Figure 15. (A) Placement of two scour balls through the guiding rod in the acrylic sandbox (B) Placement of the antenna above the sandbox.

Summary of the Number of Laboratory Experiments Performed:

Group 1: 120 Orientation & Housing Preliminary Experiments
Group 2: 8 Burial Depth Flume Experiments (repeated at least 16 times)
Group 3: 7 Collision Effects Flume Experiments (repeated at least 18 times)
Group 4: 5 Antenna Angle Sweep Experiments (repeated at least 18 times)
Group 5: 2 Pier scour monitoring system (repeated at least twice)

142 Total Number of Laboratory experiments

3.3 Field Experiments Using RFIDs

Limited field experiments were conducted at the Raccoon River, IA to assess the applicability of the RFID technology in the field. Only the HiTAG RFID system was used in the field experiments. The Raccoon River has inherently a very active planform geometry, which typically translates to lateral migration of the river banks causing scour around the foundations of many bridges along the river. Specifically, the field experiments were conducted at the Railroad Bridge (Figure 17A), located on the Raccoon River upstream of 360th street Bridge near Booneville, which constricts the flow and thus increases the approach velocity. This condition leads to accelerated scour around the Railroad Bridge piers and abutments.

The field experiments took place during August of 2009 at low flow conditions and involved two visits to the field site before and after a major flood event. The flow depth at the study site was less than 0.60 m during both visits. A total of 15 red plastic scour balls 100 mm in diameter, each containing 2 transponders (Figure 7C) were used at the study site. The second transponder acted as spare, just in case the first transponder malfunctions. The serial numbers of the transponders in each scour ball were pre-recorded in order to identify the scour balls when they were buried at different locations and depths. During the first visit, 3 scour balls were buried one on top of each other at 5 different locations around one abutment and one pier of the Railroad Bridge. The scour balls were buried at depths of 0.05, 0.2, and 0.35 m below the bed surface. The locations of the scour balls were also recorded using an RTK GPS with accuracy of 2 cm to easily find their burial locations at the second visit after the flood. In the second visit, the locations around the selected pier and abutment of the Railroad Bridge where the scour balls were buried were scanned with an antenna mounted on a floater. The inability to detect 7 of the scour balls with the antenna at the targeted locations indicated that these balls were exposed because scour had reached their burial depths. This was verified by finding some of these balls floating on the water surface downstream of the bridge. By this approach we were able to estimate the scour that occurred at the selected locations during the flood, which ranged between 0.05 and 0.45 m.

In addition during the first visit, a total of 48 glass particles 25.4 mm in diameter, each containing also 2 transponders (Figure 7B) were seeded around the selected pier and abutment of the Railroad Bridge from a boat. The boat was equipped with an antenna and an RTK GPS mounted on towed a floater (Figure 16). The serial numbers of the transponders in each particle were recorded with the antenna in order to identify the particles and trace their locations. The initial seed locations of the particles were also recorded using the RTK GPS. During the second visit after the flood, the river was traversed with the boat for a distance of 200 m downstream of the particle seed location in order to detect and locate the particles. The boat speed was 0.10 m/sec, which is comparable to the ultimate speed needed in order to detect the transponders. The inability to detect most of these particles with the antenna at their original seed locations indicated that these particles had moved downstream. We were able to recover 25 of the 48 particles within the scanned 200 m reach. From the flood duration and average travel distance of the particles, we were able to predict the bedload rate near the bridge during the flood.

Figure 16. Detection of the particles in the Raccoon River via the floatable antenna towed by the boat.

4. RESULTS

This section of the report describes the results of laboratory and field experiments with the two RFID systems. The laboratory results were presented first focusing on the RFID detection range and the pier model experiments, followed by the findings from the field experiments.

4.1. Laboratory Results

4.1.1 RFID detection range

The maximum detection distance between the transponders and the antenna was determined from iterative experiments with 4 buried glass particles each containing a transponder. The antenna-particle distance was increased until no particles can be detected by the antenna. For each tested distance, the antenna was swept over the particles 16 times providing a total of 64 iterations to detect the particles. The percentage of the particles detected as a function of the antenna - particles distance, D_{ap}, is shown in Figure 17. This figure showed that the particles can be successfully detected 95% of the time, when the antenna - particles distance is less than 0.71 m. This value was considered the maximum antenna-particle detection distance for the first RFID system. An abrupt reduction in the percentage of particles detected took place when the antenna-particle distance was larger than 0.73 m. This abrupt reduction was attributed to the fact that most of the particles were outside the electromagnetic field of the antenna.

In order to demonstrate the variability of the antenna-particle detection distance for each particle individually, the results were broken down, in Figure 18, showing how many times each particle was detected for the 16 sweeps (as a percentage) under various antenna-particle distances, D_{ap}. Four particles were used to perform this exercise. The particles are numbered 1, 3, 5 and 7, with particles 1 and 7 being the outermost particles. Each particle was successfully detected at all times, when their distance from the antenna is less than 0.68 m. When the antenna-particle distance increased to 0.71 m, only the two outermost particles (namely particles 1 and 7) were detected at all times, while the detection success of the two intermediate particles (particles 3 and 5) dropped to 81% and 94%, respectively. The average detection success for all the 4 particles is 80 % for antenna-particle distance up to 0.71 m. When the distance between the antenna and the particles was increased to 0.73 m, all particles could be successfully detected at least 60% of the time. For a distance larger than 0.76 m, the signals between the antenna and particles 1 and 5 were lost.

The results obtained from the group and individual particles analyses have shown that the maximum antenna-particle detection distance for the current setup is 0.73 m. In order to detect the particles beyond this distance (0.73 m) either a larger/stronger antenna or larger transponder must be used. Some of the commercially available low frequency RFID systems can have antenna-particle detection distance between 10 and 20 m. It was also found that the maximum detection distance of the antenna did not change significantly for the buried particles compared to the particles tested in the air (Lauth and Papanicolaou, 2008). Thus, the low frequency RFID systems are appropriate for monitoring bridge scour because their waves can penetrate water and sand bodies without significant loss of their signal strength.

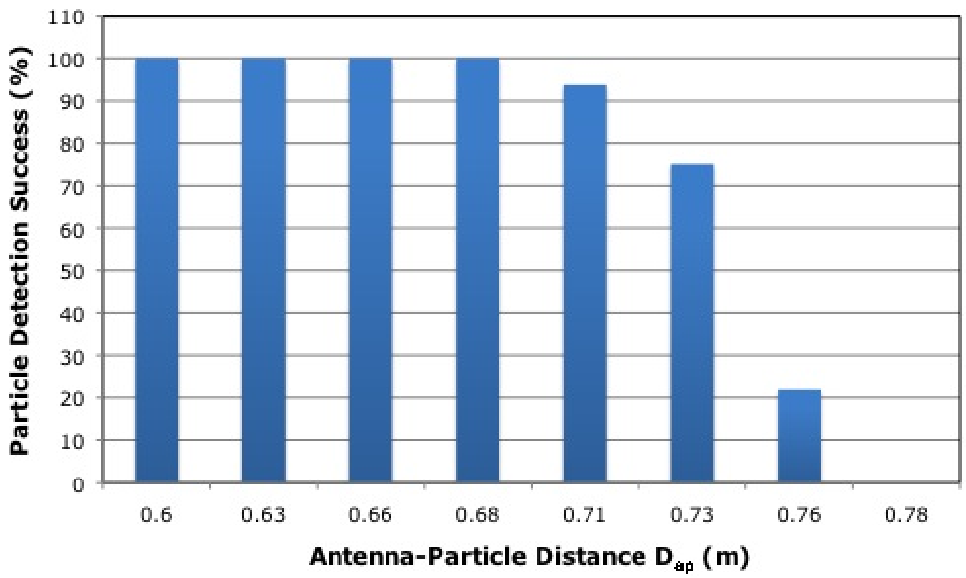

Figure 17. Particle detection success rate as a function of the antenna-particle distance, D_{ap}.

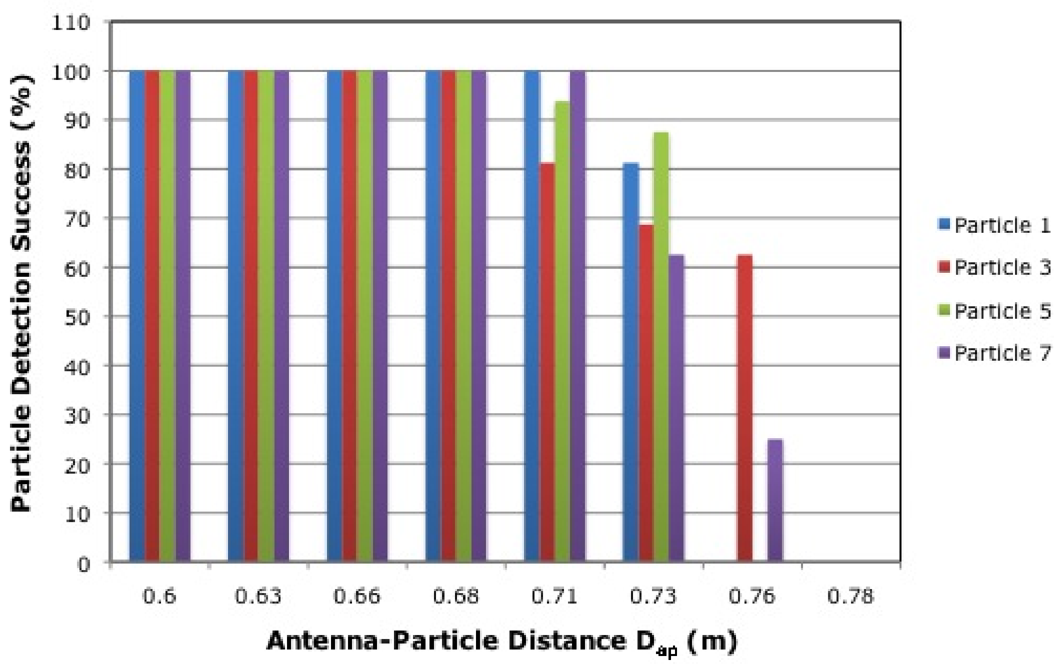

Figure 18. Particle detection success percentage as a function of the antenna-particle distance, D_{ap}, for each particle used in the test.

The minimum distance between transponders in order to be detected via the antenna (avoid signal collision) was determined from iterative experiments with 5 buried glass particles each containing a transponder. The spacing between the particles (interparticle distance) was decreased in each run until a minimum number of particles was detected by the antenna, which corresponded to the minimum detection distance between the buried particles. For each run, the antenna was swept over the particles 12 times providing a total of 60 iterations to detect the particles. The percentage of the particles detected as a function of the interparticle distance, D_{pp}, is shown in Figure 19. As the distance D_{pp} increases, the total detection success increases linearly albeit with some scatter. Figure 19 showed that all 5 particles can be successfully detected at all times (100 % detection), when the interparticle distance is greater than 0.3 m. This value was considered the minimum interparticle detection distance for the first RFID system. When the interparticle distance was smaller than 0.18 m, the antenna failed to detect the particles 50 % of the time.

Figure 19 was the outcome of the total number of particles (5 particles) used in experiments. In order to examine the variability of the interparticle distance for each particle individually to be detected, the results were broken down in Figure 20 showing how many times each particle was detected for the 12 sweeps (as a percentage) under various interparticle distances, D_{pp}. The particles were numbered 1, 3, 5, 7 and 9, with particles 1 and 9 being the outermost particles. Each particle was successfully detected at all times, when the interparticle distance was larger than 0.3 m. When the interparticle distance decreased to 0.15 m, only the two outermost particles (namely particles 1 and 9) were detected at all times, while the other three intermediate particles (particles 3, 5 and 7) were undetectable. This discrepancy in the particles detection success was attributed to the fact that at a certain instance during the antenna sweep, particle 1 or 9 was the only particle within the antenna electromagnetic field that allows its detection without signal interference from the neighboring particles. This condition can not be satisfied for the other intermediate particles. It was noted that the intermediate particles (3, 5, and 7) had an erratic detection pattern, when interparticle distance was less than 0.25 m due to the increased signal collision from the neighbor on each side. Therefore, minimum interparticle detection distance was estimated to be 0.25 m for the first RFID system. This minimum interparticle detection distance was approximately equal to the dimension of the antenna (0.27 m) parallel to sweep direction. The results obtained from the group and individual particles analysis have shown that the minimum interparticle detection distance for the current setup is 0.25 m.

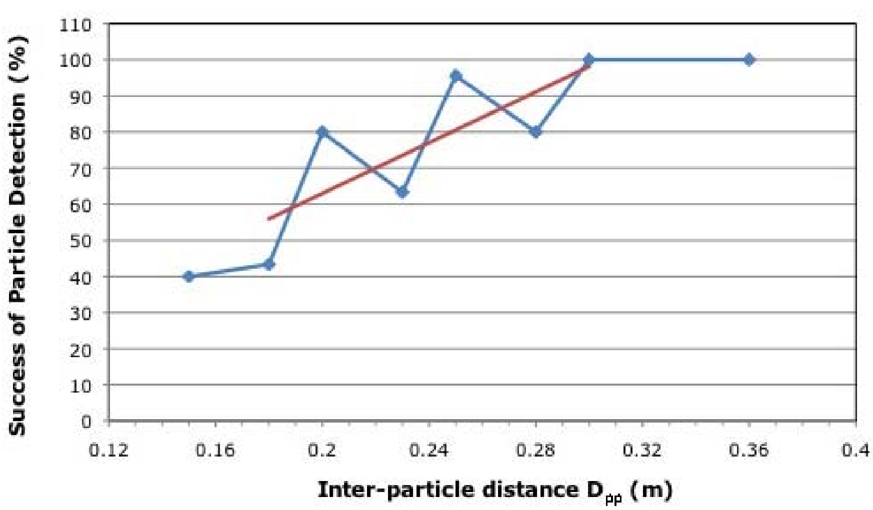

Figure 19. Success rate of particle detection as function of the distance between consecutive transponders, D_{pp}.

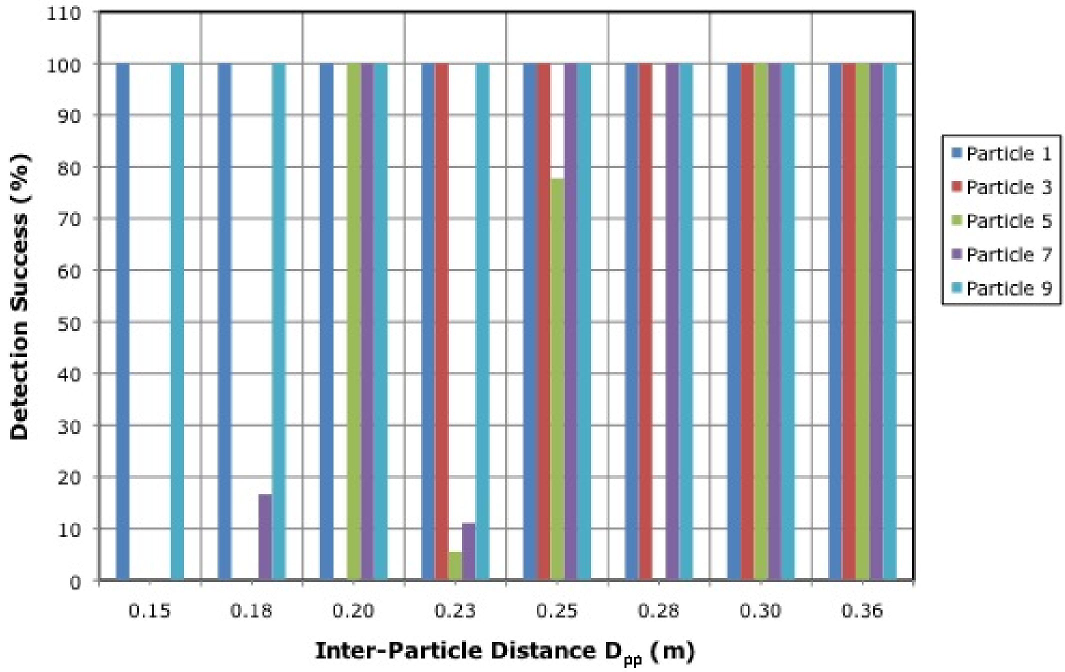

Figure 20. Particle detection success for each particle as function of the interparticle distance, D_{pp}.

The optimal sweeping angle, φ, between the antenna longitudinal axis and the sweep direction was determined from iterative experiments with 5 buried glass particles each containing a transponder. The sweeping angle was decreased from 90^o to 0^o until a minimum number of particles were detected by the antenna, corresponding to worst sweeping angle. For each tested sweeping angle, the antenna was swept over the particles 18 times providing a total of 60 iterations to detect the particles. Figure 21 shows the number of times each individual particle was successfully detected from the 18 sweeps (as a percentage), for a given sweeping angle, φ.

The particles were numbered 1, 3, 5, 7 and 9, with particles 1 and 9 being the outermost particles. The figure showed that the particles can be successfully detected 98% of the time, when the sweeping angle was 90^o. When the sweeping angle decreased to 30^o, only the two outermost particles (namely particles 1 and 9) were detected at all times, while the detection success of the next intermediate two particles (particles 3 and 7) and the middle particle (number 5) dropped to 50% and 10%, respectively. Only the outermost particles were successfully detected 100% of the time while the other particles showed less than 10% detection success, when the sweeping angle was 0^o which corresponded to worst sweeping angle.

This difference in the particle detection success was attributed to the fact that at an instant during the antenna sweep with a certain angle, particle 1 or 9 is the only particle within the antenna electromagnetic field that allows its detection without signal interference from the neighboring particles (Figure 21). This condition can not be satisfied for the other intermediate particles.

The trends in Figure 19 revealed that varying the sweeping angle of the antenna was closely interrelated to the collision between the signals of the transponders found at the same instant within the antenna electromagnetic field (Figure 22). As the sweeping angle decreases, the overlap between the antenna electromagnetic field and the particles in series increases (Figure 22). Therefore, the chance that more than one particle fall within the antenna electromagnetic field increases (Figure 22). Ultimately, when the antenna longer dimension is parallel to the sweep direction ($\varphi = 0^o$), there will always be at least two intermediate particles within the antenna electromagnetic field (Figure 22), which cause signals to collide.

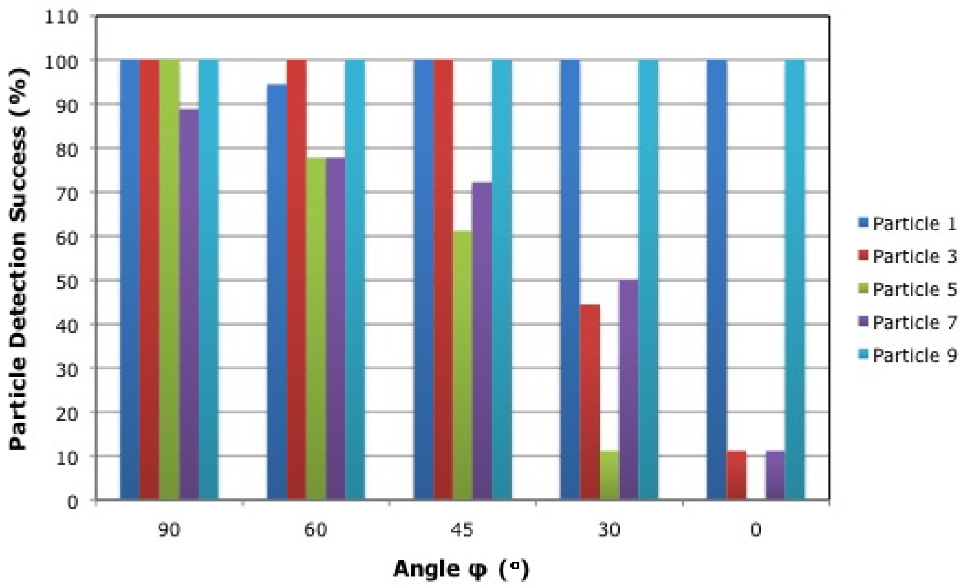

Figure 21. Particle detection success rate as function of the angle, φ, between the antenna longitudinal axis and the sweep direction for each particle.

The results obtained from the interparticle distance and sweeping angle with the first RFID system have shown that the minimum interparticle detection distance is 0.25 m and the optimal sweeping angle is 90^o, respectively. In order to overcome these limitations and detect multiple particles at distance smaller than 0.25 m, the second RFID system which supports anti-collision was used. The second system was equipped with multiple antennas and can detect 1,000s of particles located in close proximity, simultaneously.

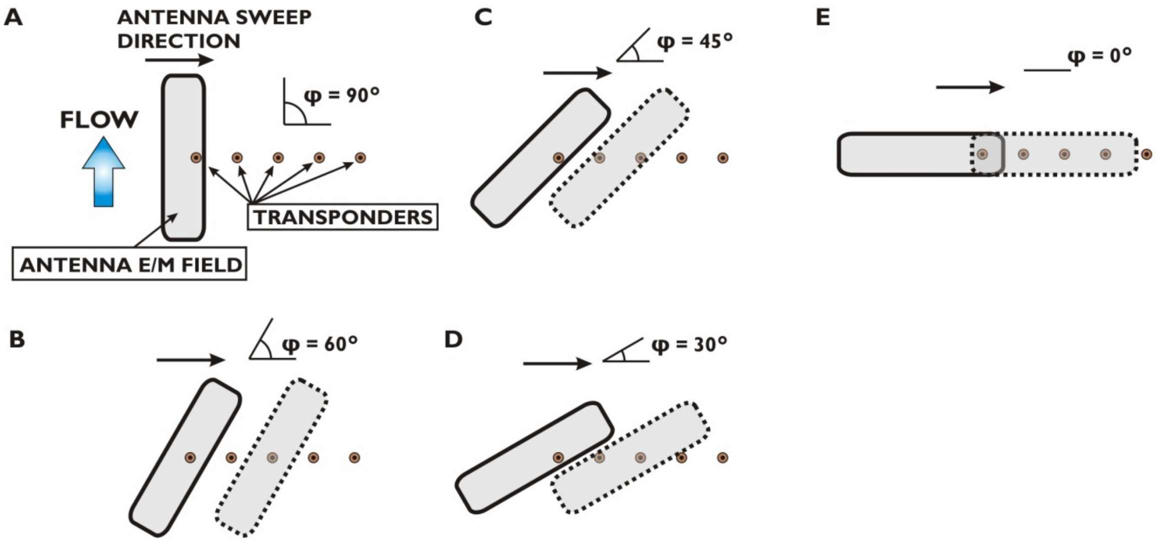

Figure 22. (A-E) Particle detection with an antenna inclined at various angles, φ, with respect to the sweep direction. Characteristic locations of the antenna electromagnetic field that allow the detection of the outermost particles are depicted with solid lines and locations that do not allow detection of the inner particles are depicted with dotted lines.

Summary of the Outcomes of the Laboratory Experiments Performed:

Group 1: Transponders with their long axis perpendicular to the plane of the antenna offer the best detection of 3ft; Plastic housing is the most suited for protecting the transponders (provide <3% reduction in the RF signal).
Group 2: For the RFID systems utilized herein the maximum burial depth for allowing detection is about 2-3ft. .
Group 3: Collision Effects between tags can be significant within a distance of ~20 cm; an anti-collision system by HiTAG is recommended and tested here.
Group 4: Antenna Angle Sweep φ<30 degrees results to zero detection
Group 5: The HiTAG system with anti-collision and the guiding rod are potential designs for future studies

4.1.2 Pier model results

The rectangular pier model results in the flume have shown that the TI RFID system was able to successfully predict the maximum scour depth when the system was used with a single particle in the vicinity of pier model where scour-hole was expected. The distance between the antenna and the particle was 0.20 m, which was 0.11 m less than the maximum detection distance of the antenna. The maximum detection distance of the antenna corresponded to the maximum scour depth of the pier model, which was determined from previous experiments. The particle in the scour-hole was detected via the antenna and also monitored via a video camera from glass section of the pier. Figure 23 shows a sample of images captured at different time instances during the experiment, while the particle was in communication with the antenna. When the scour-hole had reached the maximum scour depth of 0.11 m, the contact between the particle and the antenna was lost (Figure 23D). In Figure 23-D, the particle also went out of the camera field of view due to the scour. It was noted that the particle came closer to the pier model and the camera as the scour depth increased.

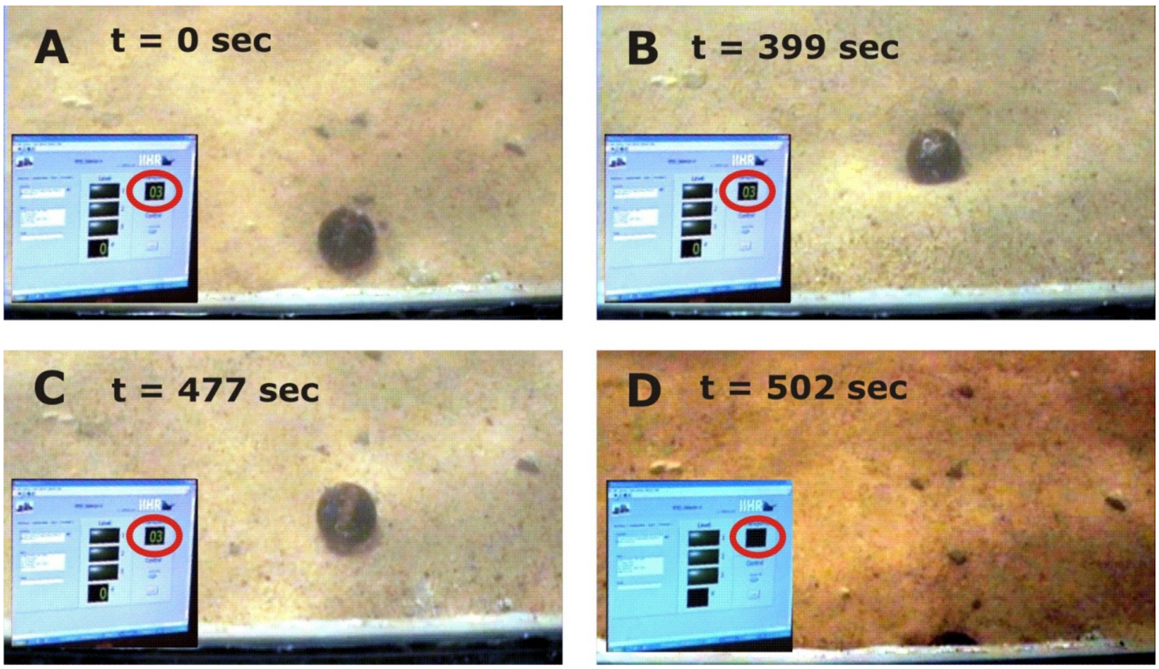

Figure 23. (A-D) Snapshots of the movement of the transponder around the rectangular pier at characteristic time instances during the experiment.

The cylindrical pier model results in the sandbox have shown that the HiTAG RFID system was able to successfully predict the maximum scour depth when the system was used with two (or multiple) scour balls in the vicinity of pier model where scour-hole was developed. The two scour balls were buried at depths 0.08 and 0.04 m from the sand bed surface, and they were detectable when they floated on the water surface. The particles were released due to excessive scour and detected by the antenna at the water surface, indicating that scour had reached the depths, where these particles were initially buried. The scour process around the pier model and the particles were monitored via a video camera.

A series of images was taken at different time instances during the experiment (Figure 24). Figure 24A shows the sandbox setup prior to the commencement of the experiment at time t = 0 sec. As the material eroded above the first scour (plastic) ball, the ball was released to the water surface and detected by the antenna (Figure 24C). The scour-hole was approximately 3.0 cm, when the first scour ball was detected. As scour increases, the second scour ball was also released to the water surface and detected by the antenna after t = 99 sec from the commencement of the experiments (Figure 24D). The scour depth was approximately 7.0 cm at the detection time of the second scour ball. The antenna was able to detect the two the scour balls simultaneously at the water surface because of the anti-collision feature of the second RFID system.

Figure 24. (A-C) Snapshots of the scour ball experiment at characteristic time instants.

4. 2 Field Results Using The RFID System

The success of this relatively inexpensive RFID technology to remotely monitor scour in the laboratory motivated us to examine its applicability at the field. The following describes the field results with the HiTAG RFID system, which were conducted on the Raccoon River, IA near the Railroad Bridge located upstream of 360th street Bridge, near Booneville.

A total of 15 plastic scour balls were buried at 5 different locations around one abutment and one pier of the Railroad Bridge (Figure 25) at depths of 0.05, 0.2, and 0.35 m, during a low flow event. After a flood, the scour balls burial locations were scanned with an antenna and only 8 scour balls were detected. The number of released scour balls from each location is shown in Figure 25. This was also verified from the 4 scour balls found floating on the water surface downstream of the bridge (Figure 26). The scour that occurred at these locations during the flood ranged between 0.05 and 0.45 m.

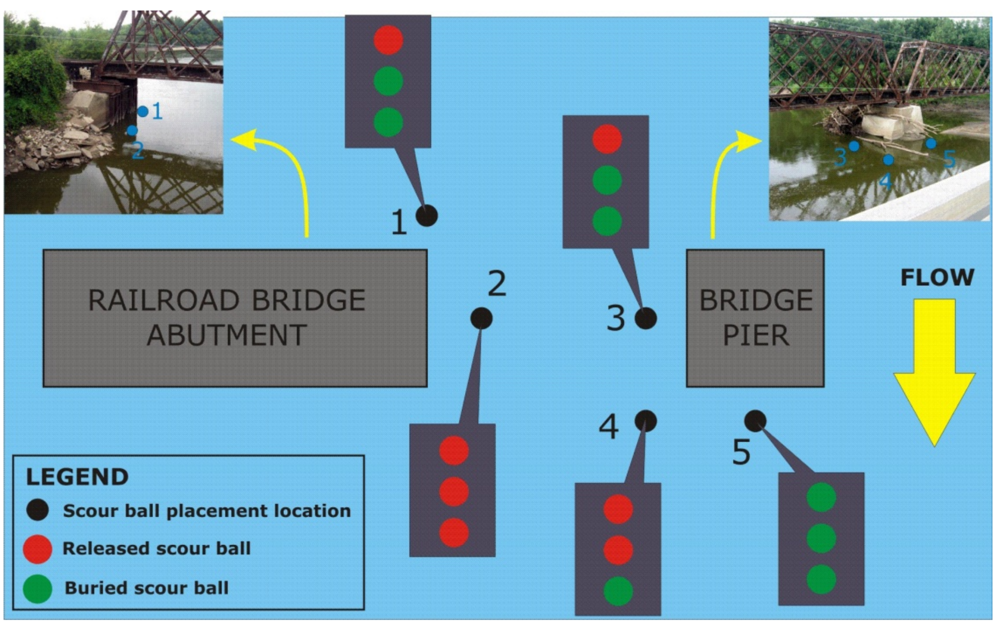

Figure 25. Locations of the buried scour balls around the abutment and pier and released scour balls.

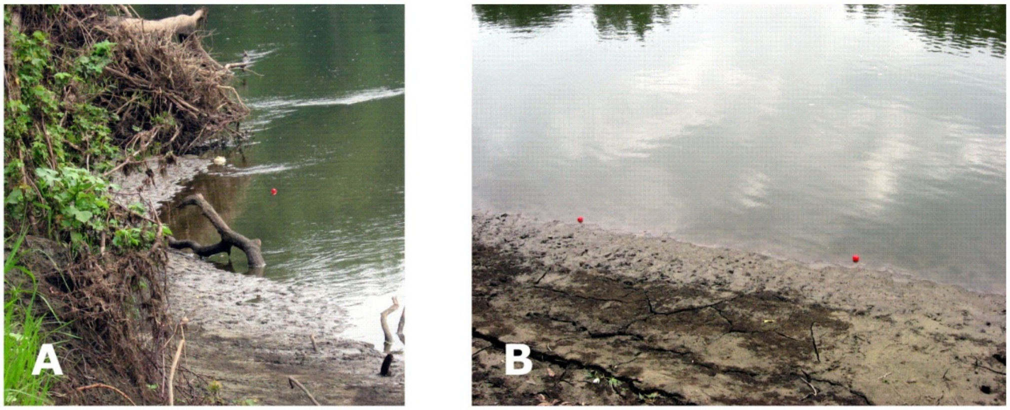

Figure 26. (A & B) Scour balls found floating in the river during the second field site visit.

The seeded 48 marble particles (tagged particles) near the Railroad Bridge during a low flow event were detected and located after the flood. Figure 27 shows the displacement distance of the 25 recovered particles. The average particle displacement distance was 9.45 m with a standard deviation of 12.55 m. The recovery of only 6 particles at their original locations (see in Figure 27) suggests that 42 of the 48 original particles were displaced by the flood. Figure 27 shows also that 1 particle was able to move as far as 50 m.

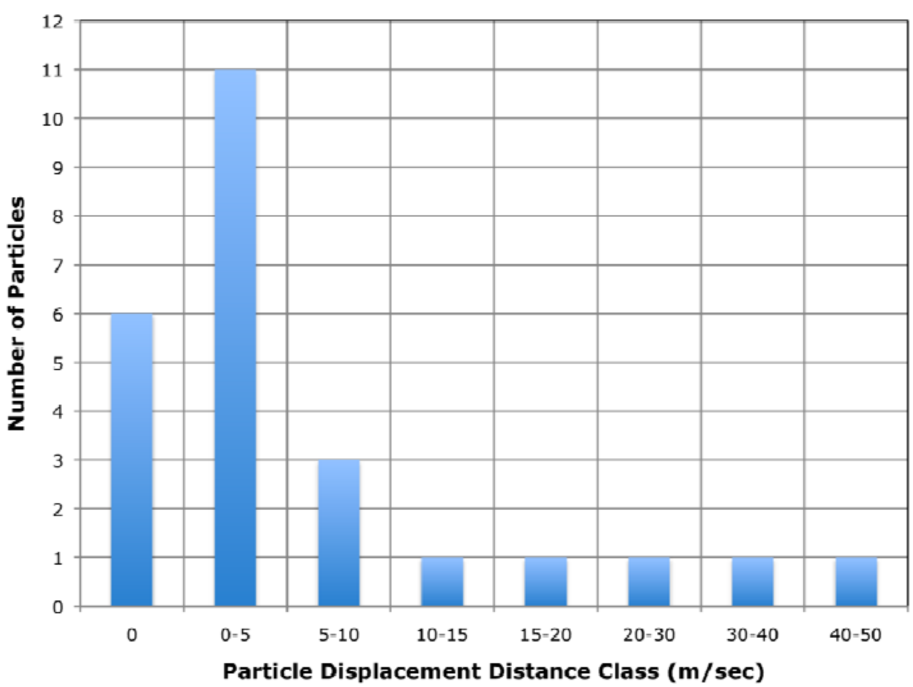

Figure 27. Particle displacement distance for the field experiments.

The bedload rate near the bridge during the flood was calculated as a function flood duration, average scour depth, and average travel distance of the particles from the following sediment continuity equation (Haschenburger and Church, 1998):

$$q_b = u_p \cdot d_s \cdot w_s \cdot (1-n) \cdot \rho_s \qquad (1)$$

where, q_b is the bedload rate, u_p the particle velocity, d_s the active layer depth, w_s width, n the porosity and ρ_s the sand density. The calculated bedload rate agreed with values obtained from the Meyer-Peter and Mueller equation:

$$\frac{q_b}{\sqrt{R \cdot g \cdot D_{50}} \cdot D_{50}} = 8\left(\tau^* - 0.047\right)^{1.5} \qquad (2)$$

where, q_b is the bedload rate, R is the submerged specific weight of the sand, g the acceleration of gravity, D_{50} the median sand diameter and τ^* the dimensionless bed shear stress, given as:

$$\tau^* = \frac{H \cdot S}{R \cdot D_{50}} \qquad (3)$$

where, H is the water depth, and S is the reach bed slope.

The field experiments showed that the RFID technology is transferable to the field, which promote the use of this technology for remotely monitoring bridge scour. This was proved from this limited scale field study performed via the second RFID system, which was able to measure scour around bridge foundations during a flood. Also, the bedload rate was estimated from the data collected via the system during the flood. The promising results of the field experiments warrant future development of the RFID technology.

5. CONCLUSIONS AND SUMMARY

Two RFID systems were configured for bridge scour monitoring. The performance of two RFID systems were evaluated through a comparative laboratory study to determine the maximum detection range of each system in terms of transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum interparticle distance and antenna sweep angle.

Analysis of the experimental results showed that the maximum antenna-particle detection distance was 0.73 m. It was also found that the maximum detection distance of the antenna did not change significantly for the buried particles when compared to the particles tested in the air. Thus, the low frequency RFID systems are appropriate for monitoring bridge scour because their waves can penetrate water and sand bodies without significant loss of their signal strength. The experiments from the first RFID system showed that the minimum interparticle detection distance is 0.25 m and the optimal sweeping angle is 90^{o}. These limitations were overcome with the configuration of the second RFID system which supports anti-collision. The second system was equipped with multiple antennas and can detect 1,000s of particles located in close proximity, simultaneously.

The pier model experiments in a flume with first RFID system showed that the system was able to successfully predict the maximum scour depth when the system was used with a single particle in the vicinity of pier model where scour-hole was expected. The pier model experiments conducted in a sandbox with the second RFID system showed that system was able to successfully predict the maximum scour depth when two scour balls was used in the vicinity of the pier model where scour-hole was developed.

The successful field experiments with the second RFID system at the Raccoon River, IA near the Railroad Bridge located upstream of 360th street Bridge, near Booneville proved that the RFID technology is transferable to the field. The second RFID system was able to measure scour around bridge foundations during a flood. Also, the bedload rate was estimated from the data collected via the system during the flood, which included flood duration, average scour depth, and average travel distance of the particles. These promising results of the field experiments warrant future development of the RFID technology.

6. OUTCOMES AND RECOMMENDATIONS

The following points summarize the outcomes of this research study:

1. Two RFID systems were configured through a comparative laboratory study by evaluating the maximum detection range of each system in terms of transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum interparticle distance and antenna sweep angle.
2. The applicability of the RFID system for monitoring bridge scour was assessed with a set of laboratory experiments using pier models of different geometries. These experiments ultimately led to the development of an integrated RFID-based system for monitoring bridge scour.
3. A scientifically-based approach was established for monitoring bridge scour in the field at low cost. Especially since some of the commercially available low frequency RFID systems can have detection distances up to 20 m.
4. Other relevant hydraulic fields that may be benefit from the RFID technology are sediment transport, and river morphology. For example, this approach took advantage of the data collected by the RFID system to predict bedload rate during a flood.

The methods and applications presented in this study are limited to the investigated laboratory and field conditions. The proposed method was successful to estimate bridge scour at the Raccoon River, IA and can be applicable to other bridges on rivers having similar planform geometry and flow conditions, mostly in 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 RFID method 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, capable of providing the public with vital real-time information regarding the structures integrity. The proposed approach in this study can provide information regarding scour development and maximum scour depth that cannot be efficiently collected by other methods.

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