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A Radio Frequency IDentification (RFID) Detection System for Assessing Scour Countermeasures and the Stability of Hydraulic Structures

Final Report for
NCHRP IDEA Project 183

Prepared by:
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Knoxville, TN
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A.N. Thanos Papanicolaou

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GLOSSARY

Antenna – The excitation antenna is a standard component of an RFID systems, which ensures the two-way communication between the reader and a transponder.

Anti-collision – An improvement to an RFID that allows for simultaneous reception of signals from multiple transponders within the excitation antenna magnetic field.

Barbs – Unique hydraulic structures for protecting streambanks and transportation infrastructure. They incorporate beneficial geometric attributes of other existing hydraulic structures, which include a trapezoidal shape with inclined sides and a wide-sloped crest.

Department of Transportation (DOT)

Dolos - a reinforced concrete block in a complex geometric shape weighing up to 80 tonnes and used as a form of coastal management to build revetments for protection against the erosive force of waves.

ELJ Engineered Log Jams (ELJs) – interlocking components of large woody material, root wads, and concrete dolos used for stream bank protection.

Federal Highway Administration (FHWA)

Innovations Deserving Exploratory Analysis (IDEA)

Inclinometer – A sensor that measures the angle of inclination of the transponder relative to the antenna loop plane.

Knickpoint – Upstream-advancing steps in the stream bed.

Multiplexer – component added to an RFID system that allows a single reader and a single workstation to support three antennas for triangulation measurments.

National Cooperative Highway Research Program (NCHRP)

PAPTSAK – Radio frequency smart particle detection software package developed by the PI, which is enhanced for use in the RSDS.

Probability density functions (PDF)

Radio Frequency IDentification (RFID)

Radio frequency identification Scour Detection System (RSDS)

Reader – A standard component of an RFID system, which is the base station that transmits radio waves through an excitation antenna to a transponder.

Received Signal Strength Indication (RSSI) – The RSSI is a measure of the returned radio wave energy transmitted from the transponder to the reader. This signal decays inversely with the cube of the distance, $\sim d^{-3}$, where d is the distance of the buried transponder relative to the antenna loop plane.

Reduction equation – A mathematical expression that relates the variable of interest (measured) with the input quantities

Smart rock – Rocks with transponders inserted into them")

Texas Instruments (TI)

Transponder – A standard component of an RFID system which is the receiving sensor with a unique ID embedded in its memory. It is short for "trans-mitter" and "re-sponder".

Triangulation – Method to determine the x-, y-, and z-coordinates of each transponder. This functionality involves the use of three antennas.

EXECUTIVE SUMMARY

Although scour monitoring is of prime importance, currently the Federal Highway Administration requires assessments of a bridge's scour condition only on a biannual basis due to financial and labor constraints. To address this concern, a novel Radio Frequency IDentification (RFID) Scour Detection System (RSDS) has been developed herein to monitor scour hole evolution autonomously, continuously, and remotely near bridge piers and abutments, thus providing repeatable and reliable 3D scour data for both clear-water and live-bed scour conditions.

Current scour monitoring is typically performed by physically probing the scour hole. These time- and resource-intensive methods suffer from low accuracy and limited applicability during high and debris-laden flows, as well as under icy conditions. The relatively new RFID technology automates the collection of scour data to ensure the safety of maintenance/monitoring crews. It eliminates the need for onsite measurements during hazardous conditions, especially floods. The technology can improve manager insight and decision-making by facilitating an organizational paradigm shift to condition-based management that offers a substantial cost reduction in bridge scour monitoring through timely recognition of scour related problems and a reduction in the required man-hours for physical monitoring.

The RFID system is comprised of a reader, which is the base station that transmits radio waves through an excitation antenna to a transponder. The transmitted radio waves trigger a response in the transponder, which then transmits its unique ID, as well as other stored data, back to the excitation antenna, which relays this information to the reader and eventually a host computer. The RFID technology has proven useful at detecting the movement of transponder-tagged sediment particles atop channel beds, but in these studies the RFID systems used could not provide the geospatial location of the particles in space and over time, especially when the particles were buried. Also, only a single transponder can be detected within the range of the antenna due to radio signal collision effects, further limiting their applicability for scour measurements.

Thus, to improve the applicability of the RFID technology for measuring scour, an existing RFID system was enhanced through this project. The resulting RSDS has unique features & capabilities to provide repeatable and reliable 3D scour data autonomously, continuously, and remotely. The project was organized into two successive stages; Stage 1 involved enhancing the main components of the RSDS system (i.e. the transponder, reader, and software) and testing of the enhanced components in the laboratory. Stage 2 involved verification of the RSDS through applications in the laboratory and the field.

In Stage 1:

- The RSDS was enhanced by including the *Received Signal Strength Indication* (RSSI) concept, which is a measure of the returned radio wave energy transmitted from the transponder to the reader. The advantage to using the signal strength concept over other distance measuring approaches is that it provides considerably more accurate (i.e., with errors in the 2-cm range) distance data for the transponders, even when they are buried. It also has the capability of predicting whether or not transponders along a Leopold Chain that are buried or exposed (i.e., laying within the scour hole).
- The transponders used in the RSDS had built-in *inclinometers* to measure the angle of inclination of the transponder to the antenna loop plane. Changes in the transponder inclination affects the RSSI by affecting the likelihood of transponder detection (by as much as an 80% drop in some cases). By accounting for the changes in the RSSI with inclination, more accurate estimates of transponder distance are possible.
- An *anti-collision feature* was also developed to facilitate the detection of multiple transponders with a single reader. This was necessary to overcome the communication breakdown between a reader and the transponders that occurs when multiple transponders are located within the antenna's magnetic field. This anti-collision feature is needed to determine the distances of multiple transponders along a Leopold Chain.
- *Triangulation functionality* was incorporated into the RSDS to determine the x-, y-, and z-coordinates of each transponder. This functionality involves the use of three antennas with known positioning, along with the RSSI-determined distance and the anti-collision feature, to triangulate the location (i.e., depth + position) of each transponder and thus provide a 3D mapping of the scour hole geometry.
- The existing PAPTSAK radio frequency smart particle detection software package was enhanced to interrogate automatically multiple transponders in the vicinity of the scour hole using the three antennas connected to the reader supplemented with a multiplexer. The software has a built-in timer that triggers measurements of individual transponders with each antenna consecutively at user-specified time intervals, thus enabling continuous measurements.

Uncertainty analyses were performed in the laboratory after Stage 1 to evaluate the performance of the RSDS in different bed media. The RSDS gave consistent and reliable measurements, with the main source of uncertainty being the media in which transponders were buried. Gravel amplified detuning of the transponder antenna for short detection distances; however, for longer detection distances the RSSI was not affected. Sand absorbed the radio signal and was found to reduce the RSSI more than the other bed media, as much as 37%.

In Stage 2:

- The RSDS was verified at testing sites in Iowa and Tennessee. The Clear Creek, IA site is a sand bed river draining a 270 km^2 agricultural system. The Third Creek, TN site is gravel-bed stream draining a 7.5 km^2 urban system. During the study, only Clear Creek experienced measureable scour (7.6 cm of scour which compared well with physical measurements). At the site, four transponders were placed along a Leopold Chain at 0.6-m depth intervals below the bed surface. Each transponder was programmed with a unique identification serial number and wake-up pattern. Ten RSSI measurements were collected for repeatability and additional statistical analyses. The measured signal decay for each transponder was used to develop a curve relating the normalized decay to the depth of the transponder.
- Clear-water and live-bed scour experiments around engineered log jam (ELJ) prototypes were conducted in a laboratory flume to monitor the 3D evolution of the scour hole geometry. These tests followed the Lagrangian geospatial approach using a number of transponders that were released into the scour hole once it was detected.

Building on the Lagrangian geospatial approach developed, the movement of sediment particles in the Elwha River was monitored under various flow conditions. Randomly placed transponders in "smart particles" representative of the sediment characteristics in the river were monitored. Their locations and pathways were tracked over time to understand general sediment movement. The wake-up function, anti-collision features, and the PAPTSAK software were tested in this study and used to track the transponders. The particle tracking is a critical part of the Trinity River Restoration Program that is designed to help understand coarse sediment movement and how it affects aquatic habitats and infrastructure under peak restoration flows.

The information from the RSDS verification will be helpful for field monitoring of scour using the RSDS, which is being discussed for two ELJs installed on the Skagit River near Rockport, WA. A series of transponders along a Leopold Chain will be inserted into the sediment bed around the ELJs, the locations of which will be based on observations of scour hole formation from these experiments.

Finally, applications of the RSDS related to monitoring an advancing knickpoint in Iowa are being discussed. Leopold Chains at different locations along the river channel and randomly placed transponders will actively monitor knickpoint migration rates, scour depths, and geometry of the scour hole formed from knickpoint migration. In addition, the RSDS can be used to monitor scour volumes and geometry at the barbs protecting bridges and other road infrastructure crossing waterways. This application also involves the use of Leopold Chains and the Lagrangian geospatial approach to capture the evolution of the scour depth with time using the anti-collision and triangulation features added to RSDS.

In the end, these applications can lead to an advanced formulation that estimates scour depth and volume at hydraulic structures. The continuous, real-time measurements of the RSDS can capture the modification to bed shear stress as the scour hole evolves and the resultant effect on the growth rate and extent of the scour hole. This resulting formulation is a decay function, where the shear force applied by the flow decays as the scour hole develops. The maximum depth of scour is reached when the shear force applied by the flow no longer exceeds the erosion resistance of the bed. This formulation has not been examined for a

1 IDEA PRODUCT

A novel Radio Frequency IDentification (RFID) Scour Detection System (RSDS) was developed in this study for the following purposes:

- To monitor scour hole evolution autonomously, continuously, and remotely near bridge piers and abutments; and
- To provide repeatable and reliable 3D scour data for both clear-water and live-bed scour conditions for developing an advanced formulation that estimates scour depth and volume at hydraulic structures.

RFID technology is relatively new and cost-efficient. It uses radio waves for the non-line-of-sight transfer of information between a base station (i.e., a reader) and different sensors (i.e., transponders or tags) through an antenna (*1*, *2*). Building on this technology, an easy-to-use scour detection system (Figure 1) was developed that can provide unmanned, real-time, 3D measurements of scour evolution to help assess hydraulic structure stability.

The RSDS incorporates principles from electromagnetic theory, hydraulics, and sediment transport to transcend the disciplines of civil & environmental engineering, electrical engineering & computer science, and sensor development. This unique system can continuously provide real-time net scour depth measurements that can capture both erosion and deposition, using the Leopold Chain concept (*3*), as well as the 3D scour hole volume evolution.

The continuous, real-time measurements of the RSDS will allow for advanced formulation of scour depths by capturing the modification to the bed shear stress as the scour hole evolves and the resultant effects on the growth rate and extent of the scour hole. This resulting formulation is a decay function, where the shear force applied by the flow decays as the scour hole develops. The maximum depth of scour is reached when the shear force applied by the flow no longer exceeds the erosion resistance of the bed. This formulation has not been examined for a wide range of flow conditions, and thus, existing scour equations do not capture the scour hole evolution.

Moreover, the RSDS will save money as the continuous, real-time measurements can facilitate a shift to a condition-based maintenance program and even potentially save lives by offering an early warning system for scour-threatened bridges. The RSDS also measures scour development remotely and autonomously to ensure the safety of Department of Transportation (DOT) maintenance/monitoring crews, as it eliminates the need for onsite measurements under hazardous conditions, especially flooding.

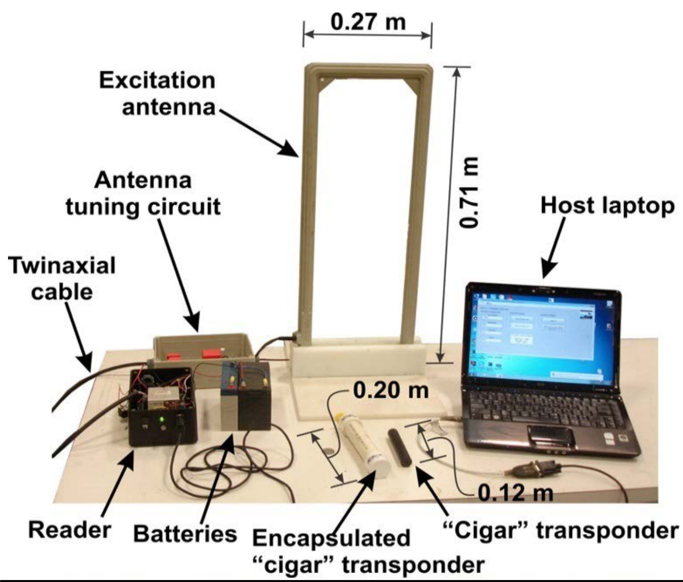


FIGURE 1 The RFID Scour Detection System (RSDS). RSDS includes a remote base station (i.e., a reader) that communicates with buried sensors (i.e., transponders or tags) through an antenna.

1.1 UNIQUE FEATURES & CAPABILITIES OF THE RSDS

This novel RSDS builds on an existing RFID framework (*4*) and also incorporates the following *unique features & capabilities* to provide repeatable and reliable 3D scour data autonomously, continuously, and remotely:

- The RSDS uses the *Received Signal Strength Indication* (RSSI) concept borrowed from electromagnetic theory. The RSSI is a measure of the returned radio wave energy transmitted from the transponder to the reader. This signal decays inversely with the cube of the distance, $\sim d^{-3}$, where d is the distance of the transponder relative to the antenna loop plane. The advantage to using the signal strength concept over other distance measuring approaches is that it provides considerably more accurate (i.e., with errors in the 2-cm range) distance data for the transponders, especially when they are buried. The RSSI also facilitates the development of probability density functions (PDFs) for the distance between the antenna and the transponder, which are used to differentiate those transponders on the Leopold Chain that are buried or exposed (i.e., laying within the scour hole). PDFs with a wide spread are still buried and those with a very peaky function are exposed (Figure 2).

- The transponders used in the RSDS have built-in *inclinometers* that measure the angle of inclination of the transponder to the antenna loop plane. Knowledge of the transponder inclination improves the accuracy of the distance estimates from the antenna to transponders. If the orientation of a transponder relative to the antenna changes after it moves or is exposed, the likelihood of detecting the transponder significantly drops from 100% to nearly 20%, in some cases, thus affecting the RSSI. By accounting for the changes in the RSSI with inclination, more accurate estimates of transponder distance are possible.

- An *anti-collision feature* was developed to facilitate the detection of multiple transponders with a single reader. Without this feature, the reader is unable to distinguish nearby transponders due to signal interference, leading to a breakdown in communication between the transponders and the reader. This improvement was necessary to overcome the interference caused by the signals from multiple transponders located within the excitation antenna magnetic field. This anti-collision feature, in conjunction with the RSSI concept, is needed to determine the distances of multiple transponders along the Leopold Chain.

- *Triangulation functionality* was incorporated in the RSDS to determine the x-, y-, and z-coordinates of each transponder. This functionality involves the use of three antennas with known positioning, along with the RSSI-determined distance and the anti-collision feature, to triangulate the location (i.e., depth + position) of each transponder and thus provide a 3D mapping of the scour hole geometry. A *multiplexer* has been added to the system that allows a single reader and a single workstation to support three antennas, thereby minimizing the cost.

<u>Enhancements for the RSDS</u>

- **The *RSSI* concept provides more accurate distance measurements, even when the transponders are buried.**
- ***Inclinometers* measure the angle between the transponder to the antenna loop plane.**
- **An *anti-collision feature* facilitates the use of multiple transponders with a single reader.**
- **A *triangulation functionality* determines the x-, y-, and z-coordinates of each transponder.**
- **The *PAPTSAK RFID detection software package* interrogates consecutively multiple transponders using the three antennas connected to the reader.**

- The existing *PAPTSAK radio frequency smart particle detection software package* (see Appendix for manual) was enhanced to interrogate automatically multiple transponders in the vicinity of the scour hole using the three antennas connected to the reader supplemented with a multiplexer. The software has a built-in timer that triggers measurements of individual transponders with each antenna consecutively at user-specified time intervals, enabling continuous measurements. The software was equipped with the necessary algorithms to quantify the RSSI-determined depth and triangulate the positioning of the transponders. The software also permits remote connection and control, allowing for scour measurements and the 3D geospatial mapping of scour holes to be performed remotely.

1.2 POTENTIAL IMPACTS OF THE RSDS

At present, conventional scour monitoring is cumbersome. Current approaches require considerable skills in installing, collecting, transferring and interpreting the data. They are also subjective and time consuming. Methods, such as tethered sounding weights and long poles, provide point measurements and limited 3D information about the scour hole geometry. They do not provide continuous information on scour depth and volume, or work during floods. Other, more advanced methods using side-scan sonars or time-domain reflectometers can be extremely expensive. The RSDS will address these limitations by providing cost-effective, autonomous, continuous, and remote measurements of the 3D scour hole geometry.

In addition, the RSDS can increase safety for DOT maintenance/monitoring crews and improve manager insight and decision-making by facilitating an organizational paradigm shift to condition-based management that offers a substantial cost reduction in bridge scour monitoring through timely recognition of scour related problems and a reduction in the required man hours for physical monitoring. Further benefits of the RSDS are also demonstrated in Section 3.6 below.

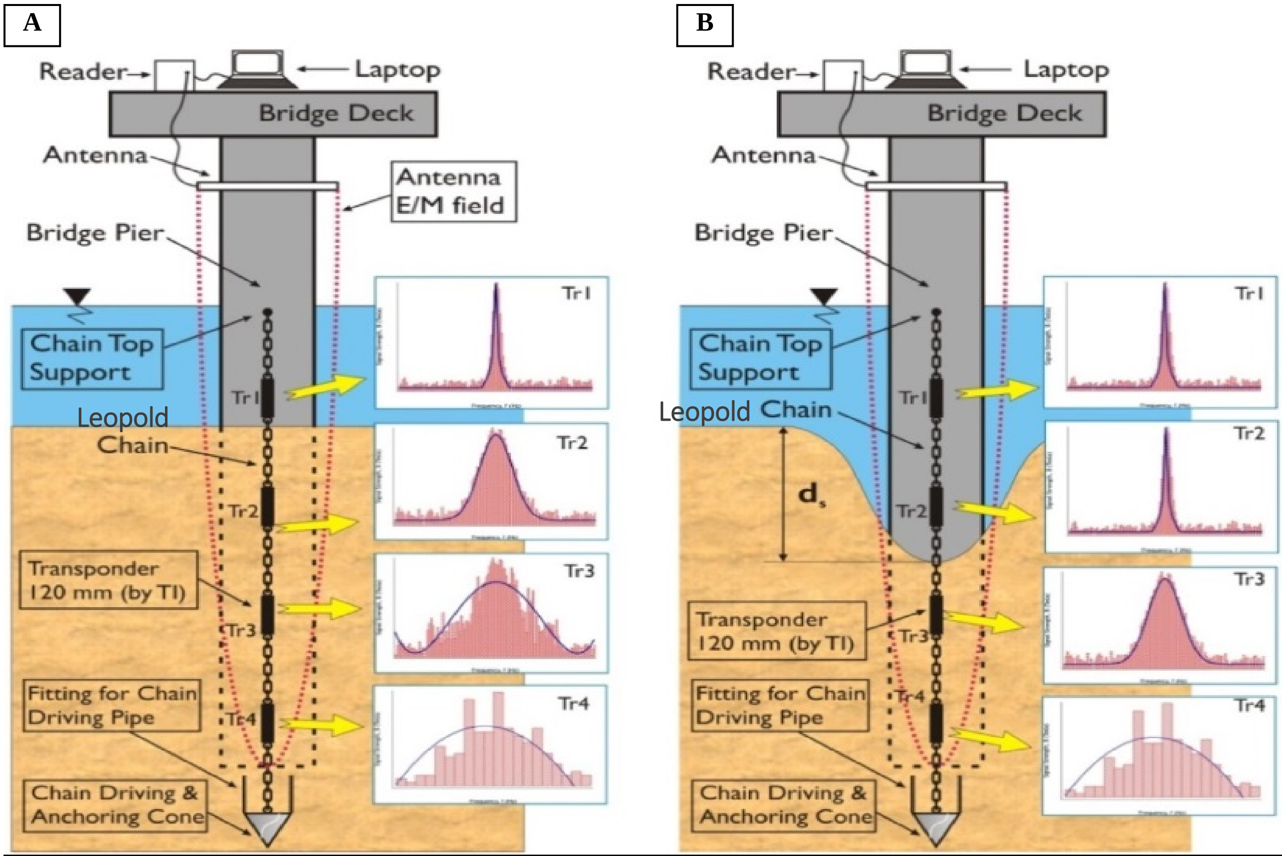


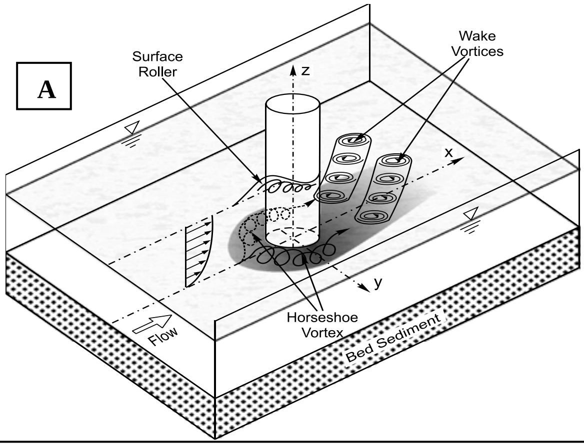
FIGURE 2 Detecting scour depth with a Leopold Chain and the RSSI concept. The spread of the PDF identifies if the transponders were buried or exposed under (A) no scour and (B) scour conditions. In the figure, Tr1, Tr2, Tr3, Tr4 refer to Transponders 1, 2, 3, and 4, respectively, d_s is the maximum scour depth, and E/M stands for electromagnetic field.

2 CONCEPT AND INNOVATION

2.1 PROBLEM STATEMENT

The FHWA has identified more than 150,000 bridges in the U.S. that are "vulnerable to scour" or have "undetermined foundation conditions" (*5*). The scour near the piers and abutments of these bridges results from complex interactions (Figure 3A) between the bridge structure and the approaching stream flow (*6* - *8*). Excessive scour can expose the bridges' foundations and compromise their stability (Figure 3B). Thus, scour can have significant economic impacts and potentially catastrophic consequences on the safety of the traveling public, making it a problem of national importance (*5*).

Although scour monitoring is of prime importance, currently the FHWA requires assessments of a bridge's scour condition only on a biannual basis due to financial and labor constraints. The inspections are typically performed by physically probing the scour hole. This physical probing is a time- and resource-intensive process with low accuracy and limited applicability during high and debris-laden flows, as well as under icy conditions (*10*). New instruments, including side-scan sonars, time-domain reflectometers, fathometers, acoustic depth sounders, ground penetrating radar, and fiber bragg grating sensors have significant advantages over physical probing, but they are costly and may also provide questionable measurements during highly turbulent conditions (*11* - *15*). All of these scour monitoring methods require personnel to be physically present at the bridge site during the measurements, which puts them at risk during flood conditions. Additionally, these methods can be time consuming, and may require traffic control or bridge closings, which is undesirable when there are high volumes of traffic.



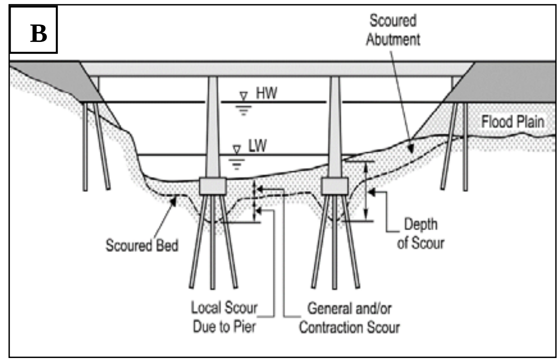


FIGURE 3 (A) Complex flow interactions between the flowing water, bed sediment, and bridge pier causes scour. (B) The scour exposes the foundations of abutments or piers, compromising their integrity (*9*).

The relatively new RFID technology automates the collection and transmission of scour data, thereby avoiding the need for maintenance personnel to be present at the bridge sites, thus minimizing the risks. Furthermore, the RFID technology is relatively more cost-efficient (see section 4.3 of this report for the cost estimates). An RFID system when equipped with data telemetry allows for remote monitoring of scour, even from one's own office, and provides an early warning of impending bridge failure as a result of scouring. Additional benefits of remote monitoring include the potential reduction in the labor costs to perform monitoring. This evolving technology, once established, accommodates the acquisition of real-time data to calibrate scour prediction equations and enhance the state of knowledge about the scour process through field monitoring in large rivers (e.g., the Missouri River). These unique data offer a deeper understanding of the Lagrangian motion of individual particles, dynamic particle trajectories, and displacement speeds near structures for the development of more improved methods of scour protection at hydraulic structures (*16*, *17*).

2.2 RFID CONCEPT

2.2.1 Background

The RFID technology is a wireless, identification technology that uses/transmits radio waves to transfer information between a reader and a transponder through an excitation antenna. The technology has advanced the study of sediment transport from the Lagrangian perspective (*18 - 21*). Compared to other sediment tracking techniques, RFID technology has high recovery rates of around 90% (*22*), allowing researchers to investigate reliably the motion of individual particles.

The majority of past studies (*4*, *23 - 25*) have explored the incorporation of transponders into sediment particles to detect the onset of sediment motion atop channel beds, but the RFID systems used in these studies were only applicable to sediment detection atop the bed surface. *They did not have the capability to provide the geospatial location of the particles in space and over time, especially when the particles were buried. As such, these studies have been limited in terms of monitoring sediment movement and measuring scour reliably.* Additionally, existing RFID systems are unable to detect nearby transponders at the same time due to the radio signal collision effects (i.e., only a single transponder can be detected within the range of the antenna), further limiting their applicability for scour measurements.

Background and Overview

- **Low frequency radio waves can pass through water columns and saturated sediment, making them well-suited for stream scour studies.**
- **This study enhances a passive, low frequency RFID system to provide autonomous 3D monitoring of scour hole evolution at hydraulic structures.**
- **Development of the *RSSI* relationship with distance to detect transponders buried in the sediments has made autonomous scour monitoring with RFIDs feasible.**

By addressing the limitations of existing RFID systems, the RSDS is well-suited for monitoring the changes in scour hole depth and volume. RSDS incorporates the RSSI concept and transponders with inclinometers, as well as anti-collision and triangulation features for detecting buried transponders and providing 3D geospatial measurements that translate to reliable predictions of scour hole development (i.e., depth and extent) and accurate assessments of the stability and integrity of hydraulic structures.

2.2.2 System Overview

A standard RFID system (Figure 1) requires 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 with a unique ID embedded in its memory; and (iii) the excitation antenna, which ensures the two-way communication between the reader and a transponder (*26 - 28*). 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.

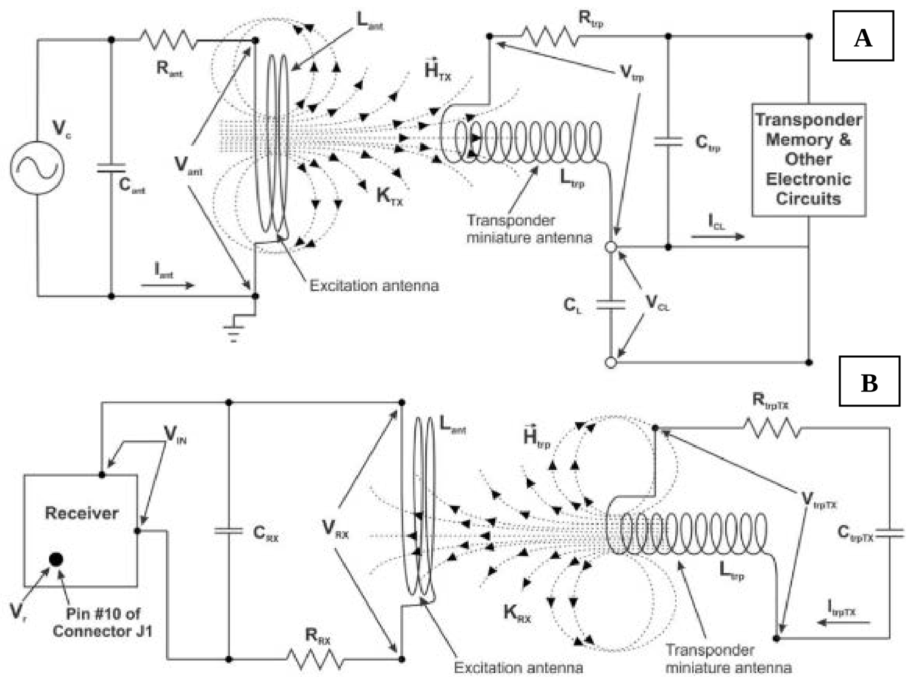


FIGURE 4 Illustration of the active communication between the transponder and the reader (A) Phase I – charge/ transmit; (B) Phase II – receive/ listen. In the figure, *V* represents voltage, *L* represents inductance, *C* represents capacitance, *I* represents current, *H* represents the magnetic field and *K* is a factor that reflects the degree of inductive coupling.

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. In terms of power source, the transponders are classified as passive or active (*1*, *28 - 30*). Passive transponders are powered by an integrated capacitor, which is charged from the energy of the magnetic field generated by the antenna. In contrast, active transponders are powered by an internal battery. Furthermore, RFID systems can operate in the following three frequency ranges: (i) low frequency, 9 - 195 kHz; (ii) high frequency, 3 - 300 MHz; and (iii) ultra-high frequency, 700 MHz - 3 GHz (e.g., *1*, *29 - 31*). Typically, active RFID systems operate in the high frequency band, while passive systems in the low frequency band.

The effectiveness of the high frequency transponders is limited in saturated sediments and through the water column as the high frequency waves experience significant backscatter, causing signal dilution (*32 - 34*). Low frequency systems have shown better penetration through saturated sediments and water columns compared to high frequency waves (*2*, *32 - 36*). Therefore, low frequency systems provide an invigorating opportunity for application in riverine and sediment environments. Laboratory tests showed an operating resonance frequency of 134.2 kHz was most optimal (*4*). Thus, a low frequency system was employed herein for monitoring scour.

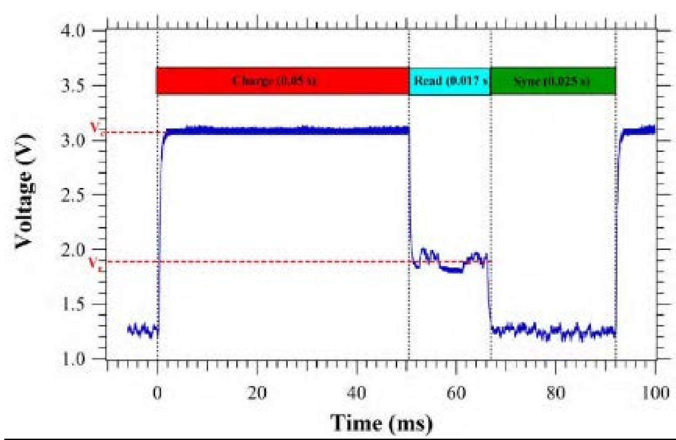


FIGURE 5 The read cycle of the RFID system communication signal. It consists of the charge, receiving, and synchronization phases.

The operational mode of the selected low frequency system, which lasts approximately 0.09 s, consists of two active read cycle phases and one subsequent inactive phase (Figure 4 and 5), namely the following:

- *Phase I* is the charge or transmit phase. It lasts approximately 0.05 s (Figure 5). During Phase I the reader transmits radio waves at the resonant frequency of 134.2 kHz through the antenna, enabling the charge of any transponder within the magnetic field of the antenna. A constant voltage, V_c, of ~3.12 volts is applied at the transmit circuit of the reader to energize the excitation antenna.
- *Phase II* is the receiving or listening phase. It lasts approximately 0.02 s (Figure 5). During the receiving phase, a time-averaged voltage is sampled on the radio module. This voltage can be used to estimate the analog strength of the received signal, which is the Received Signal Strength Indication (RSSI) voltage, V_{RSSI}.
- Phase III is the inactive synchronization period. This phase lasts approximately 0.02s (Figure 5). During the synchronization period, there is no communication between the reader and the transponder, and the reader remains idle and is reinitialized for the following read cycle.

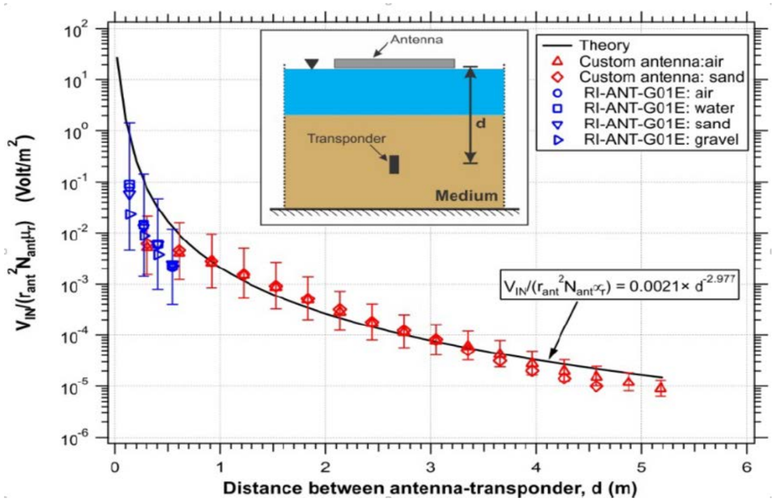


FIGURE 6 Relationship between V_{in} received at the reader and the distance, *d*, between transponder and the antenna. V_{in} is directly related to V_{rssi}. r_{ant} and N_{ant} are the antenna radius and number of antenna wire loops respectively. The red symbols represent data measured with a custom-made antenna and the blue symbols represent data measured with a Texas Instrument RI-ANT-G01E commercial antenna.

An important characteristic of the receiving phases is the way that the “transferring” of information (radio waves 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). Taking the functionality of the low frequency system into consideration, this project team has developed a relationship between the V_{RSSI} and the distance from the antenna to a transponder that may be submerged or buried in saturated sediment under different orientations (Figure 6). This advancement has now made it feasible to utilize the Leopold Chain concept and Lagrangian tracking of individual particles to evaluate scour hole geometry (i.e., scour depth and volume) evolution, following further key improvements to the system that have been implemented as part of this study and are described below.

2.3 INNOVATION

The innovation of this IDEA project is the development of an RFID Scour Detection System, or RSDS, to monitor scour hole evolution autonomously, continuously, and remotely near bridge piers and abutments. The RSDS is capable of providing repeatable and reliable measurements of scour depth and volume. It is an enhancement of an existing low frequency passive RFID technology, that continuously monitors scour depth and volume at a bridge site. Not only does the RSDS provide real-time assessments of the scour condition, for threatened sites, but also it provides unique continuous measurements, even during high flow events, that can improve existing scour equation through the development of decay functions that reflect the changes in the shear force applied by the flow as the scour hole develops.

The RSDS

- **A novel RFID Scour Detection System (RSDS) is developed that facilitates remote wireless technology to measure scour continuously and in real-time for different flows, including floods.**
- **The automated system is based on low frequency passive RFID technology and provides unique continuous measurements over a range of flows to develop enhanced predictive ability of scour evolution.**

The RSDS (Figure 1) uses, *for the first time*, the RSSI concept that relates the strength of the returned signal from a transponder to its corresponding antenna- reader) to the distance between the transponder and the antenna-reader. By doing so, the accuracy of the distance measurements has improved considerably. It has been shown that the RSSI of a transponder buried in gravel or sand can be smaller compared to transponders that are not buried (*4*). This is because gravel amplifies detuning of the transponder antenna for short distances and sand absorbs the radio signal. By accounting for the magnetic permeability of the bed media, the RSDS is able to quantify the effect of the media on the RSSI of buried transponders and, as a result, accurately estimate the depth of scour.

Additionally, the transponders of the RSDS have been upgraded to include an inclinometer to measure the angle of the transponder relative to the antenna plane. The incorporation of the inclinometer allows the distance from a transponder to an antenna to be estimated more accurately, within ~5 cm, by accounting for the transponder's orientation. This is crucial since the magnitude of the RSSI can drop by as much as 80% when the transponder inclination relative to the antenna shifts from perpendicular to parallel; see section 3.2). This improvement allows for the incorporation of the RFID technology into the Leopold Chain method of monitoring scour (*3*).

Enhancements to the reader firmware have helped overcome the communication breakdown of other RFID-based systems when they try to detect multiple transponders with the magnetic field generated by the antenna. The anti-collision feature allows for the detection of multiple return signals from all transponders at the same time.

Moreover, by incorporating a triangulation functionality into the system, the *x*, *y* and *z* coordinates of each transponder can be tracked over time. Thus, 3D-mapping of a scour hole or the displacement of a hydraulic countermeasure is possible with the RSDS. The accurate signal strength concept when used in concert with the anti-collision system and triangulation feature facilitates the basis for the Lagrangian geospatial approach through the use of multiple transponders to map the size of the scour hole and develop a 3D contour map of its volumetric evolution and/or be used for evaluating riprap failure (Figure 7). The signal strength of each transponder is used to estimate reliably the distance between that transponder and the antenna.

The specific enhancements made in this study are discussed below in the section 3.1 for the main components of the RFID system, i.e., transponder enhancement and reader enhancements. Also described are the upgrades made to the existing system's PAPTSAK software to accommodate the new system enhancements.

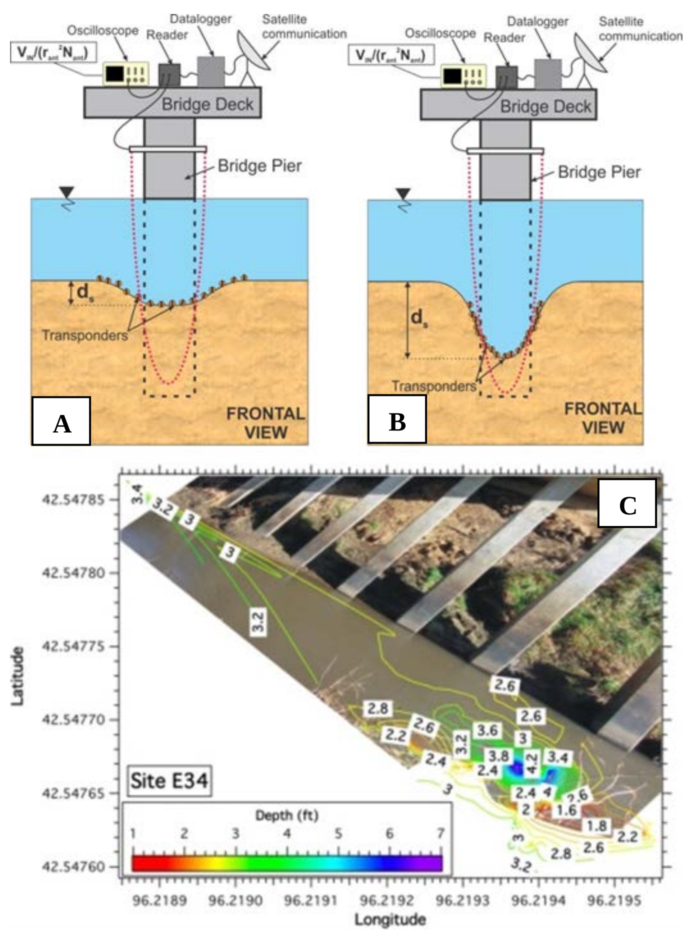


FIGURE 7 Lagrangian geospatial approach. (A) Multiple transponders are placed around a bridge pier. (B) As the scour hole develops the transponders conform to the shape of the hole. (C) Survey of a scour hole in Iowa developed using a series of transponders.

3 INVESTIGATION

This section describes the tasks that were undertaken to develop the RSDS. This project was organized into two successive stages. Stage 1 involved enhancing the main components of the RSDS system (i.e. the transponder, reader, and software) and testing of their functionality with analyses performed to evaluate uncertainty related to the scour estimates. Stage 2 involved verifying the RSDS through applications in the laboratory and the field. This section provides a succinct description of each task.

3.1 STAGE 1: ENHANCEMENTS TO LOW FREQUENCY PASSIVE RFID SYSTEM

3.1.1 Transponder Enhancements

Existing low frequency transponders from Texas Instruments (TI) were enhanced for incorporation in the RSDS. The original off-the-shelf transponders consisted of a TI LF-LF Dual Antenna Passive GO board with an integrated TMS-37F128 transponder circuit and an MSP430-F1232 microcontroller, a 2.5 mH transmit antenna, a 4.7 mH receive antenna, and an on-board 2023 battery. The TMS-37F128 circuit is the component of the transponder responsible for the radio frequency communication with the reader. The firmware for the MSP430-F1232 microcontroller was uploaded via a JTAG interface and MSP430-FET box. Images of the setup and tool are provided in Figure 8. These existing transponders were enhanced by incorporating four additional functionalities, namely (i) an automated function for RSSI measurements; (ii) an inclinometer; (iii) a "wake-up" function; and (iv) waterproof encapsulation for the transponder electronic circuits. These enhancements are describe briefly below.

- A new circuit was added to the transponder motherboard to facilitate automatic measurement of the RSSI values and append them to the transponder information sent to the reader. Previously, the RSSI values were obtained by connecting an oscilloscope to the reader (*4*, *37*). In the RSDS, the integrated microcontroller, when interrogated, performs an RSSI measurement from the radio frequency signal strength, combines the RSSI measurement information with the transponder unique serial number, and then transmits this information back to the reader.
- The transponders were furnished with Micro Electro Mechanical Sensor inclinometers to provide accurate measurements of the transponder orientation relative to the antenna. By accounting for the angle that the returned radio waves intersect with the antenna plane, the ability to detect the transponders improved dramatically. Transponder orientation was found to have a strong influence on the detection likelihood and the RSSI (*4*).
- A wake-up function was programmed into the transponders with integrated TMS-37F128 circuits to circumvent the communication breakdown between the reader and multiple transponders found within the magnetic field generated by the antenna. By programming a unique wake-up pattern in the memory of each transponder, the user can wake up and interrogate only the desired transponder. If more transponders are within the field of the reader antenna, these (i.e., their microcontrollers) do not wake-up and hence do not transmit any information back to the reader preventing collision between signals of multiple transponders. Thus, the circuits and wake-up function allow the sequential interrogation of multiple transponders by prioritizing the communication with each transponder (Figure 9).
- To minimize the likelihood of destructive impacts and improve the durability of the RSDS, the transponders were encased in a potting compound (i.e., a resin; see Figure 10) to prevent potential moisture buildup, excessive vibrations, and temperature gradients that would compromise the operation of the enhanced transponders. Various "filling" materials (i.e., aviation electronics grade silicon, silicon grease & epoxy) were tested before the potting compound was selected. Previously, the transponders were encased only in an external PVC tube (*37*), which was "transparent" to the radio waves but allowed for moisture build-up and temperature gradients.

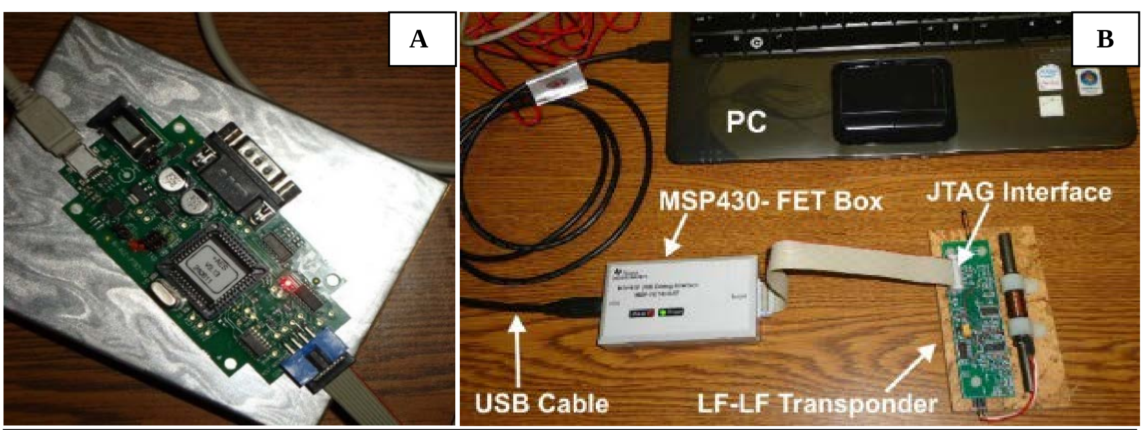


FIGURE 8 (A) TMS-37F128 transponder programmer board. (B) Connection of the transponder to PC via JTAG interface for uploading the MSP430 firmware.

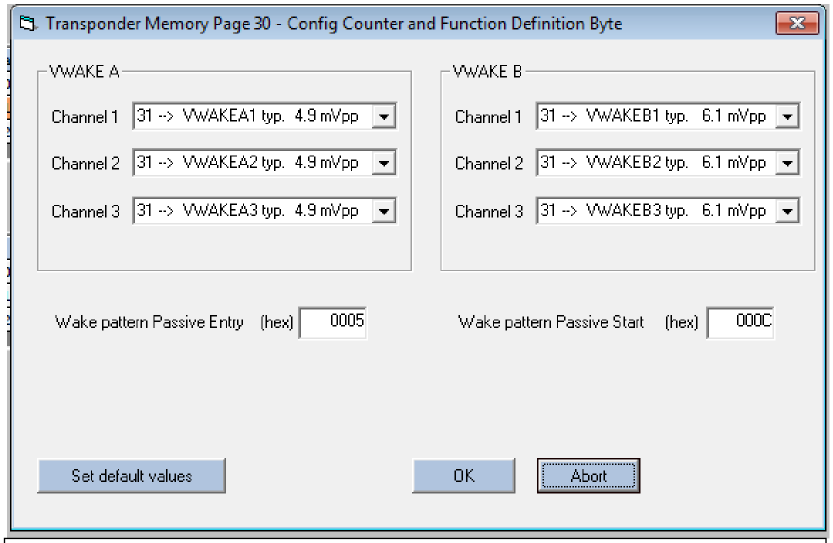


FIGURE 9 Window for configuring the wake pattern for the TMS-37F128 transponder.

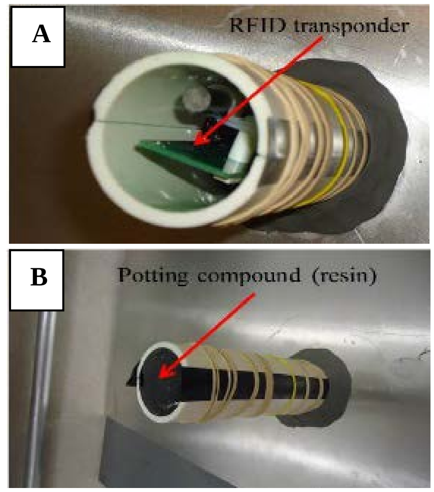


FIGURE 10 Encapsulating the transponder. (A) Transponder placed in a mold. (B) Transponder encased in potting compound.

3.1.2 Reader Enhancements

The transponders are designed for use with a TI-manufactured reader consisting of a RI-ACC-ADR2-10 control module and a RI-RFM-008B radio module. Firmware enhancements were made to the RSDS reader to incorporate a multiplexer for connecting three antennas to the same reader.

- A multiplexer was incorporated in the reader to coordinate the sequential measurements of the transponders from three separate antennas. The three antennas were needed for obtaining the transponder x-, y- and z- coordinates via a triangulation algorithm (see Software Improvements below). In addition, the reader was enhanced with networking capability, including Ethernet connectivity and network circuit boards, to allow the connection and synchronization of an array of RSDSs for monitoring multiple structures or scour locations.

3.1.3 Software Improvements

Enhancements have been made to the existing PAPTSAK radio frequency smart particle detection software package (*4, 37*) to detect transponders by recording the transponder ID number and the detection timestamp. The upgraded software has the following capabilities.

- The software package has been upgraded to accommodate the additional information of the RSSI measurement and transponder inclination from the enhanced transponders, as well as information from the multiple antennas connected through the multiplexer.
- A triangulation algorithm has been implemented to determine the x-, y-, and z-coordinates of installed transponders. The algorithm receives inputs from the three antennas, and then applies the circumcircle triangle theory.
- Upgrades have been made to the software to enable remote interaction and execution of commands for interrogating and detecting transponders via a network.

Transponder Enhancements

- **Integrated circuit to collect RSSI measurements.**
- **Micro Electro Mechanical Sensor inclinometer to measure transponder orientation.**
- **Wake-up function to provide anti-collision features.**
- **Triangulation functionality to identify the x-, y- and z-coordinates.**
- **Potting compound to prevent moisture build-up and temperature gradients.**

Reader Enhancements

- **Multiplexers to link to three antennas for triangulation.**

Software Improvements

- **Accommodate RSSI and inclination measurements.**
- **Perform triangulation algorithm.**

3.2 TESTING OF THE ENHANCEMENT IN THE RSDS

3.2.1 Testing of Encased Transponders and Inclinometers

Testing of the enhanced transponders was conducted at the Hydraulics and Sedimentation Laboratory at the University of Tennessee. Initially, tests were performed to evaluate both the ability of the potting compound to protect the transponder from moisture and temperature gradients and the influence of the potting compound on the RSSI-determined distances between the excitation antenna and the transponders. These tests were to confirm that the potting compound was truly transparent.

Three sets of distance measurements were conducted with the enhanced transponders. The first set of measurements was conducted before the transponders were encased. A second set was conducted right after encapsulation. A final set was conducted after the encased transponders had sat in a pressurized water tank for 10 days. Results from the tests immediately after encapsulation revealed no changes in the signal strength and estimated distances compared well with the first set using the “naked” transponders. These tests confirmed that *the potting compound was essentially “transparent” and did not inhibit the radio waves*. Results from the tests of transponders after sitting 10 days in the water-pressurized tests were also similar as the initial tests, showing no loss in the signal strength and detection distances, suggesting the potting compound prevents moisture build-up.

The experiments also examined the influence of the potting compound on the inclination readings provided by the inclinometers. The inclination tests showed that the potting compound was still “transparent” to the radio waves regardless of the transponder orientation. Figure 11 shows the changes in RSSI with the transponder orientation for different antenna-transponder distances. The RSSI values were approximately the same for the transponders with and without the potting compound. Furthermore, the RSSI changed with transponder orientation. The changing RSSI with orientation highlight the importance of accounting for the transponder orientation for distance measurements in the RSDS.

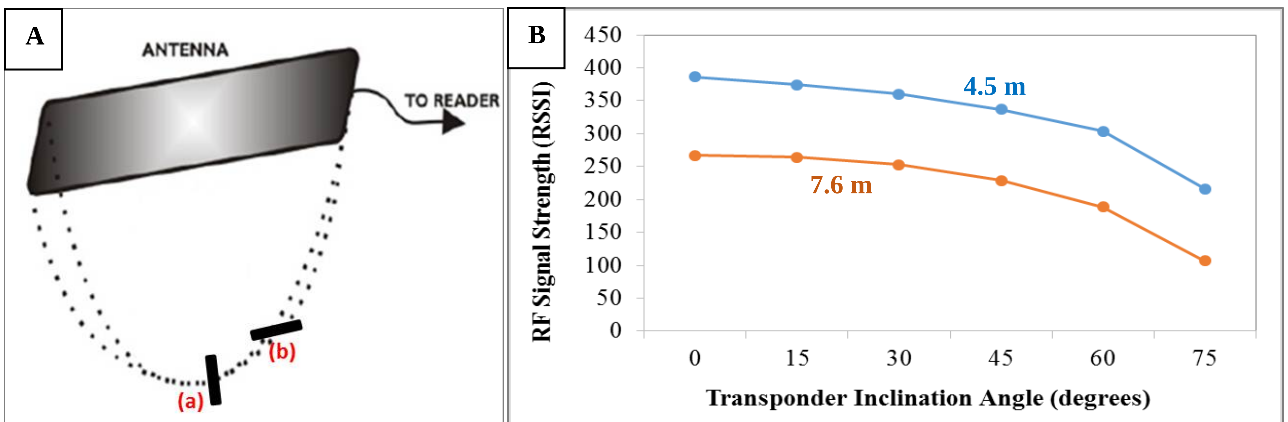


FIGURE 11 (A) Illustration of transponder’s orientations with respect to the excitation antenna plane. (B) Observed relationship between the RSSI and inclination angle of transponder from antenna plane at transponder-antenna distances of 4.5 m (blue) and 7.6 m (orange).

3.2.2 Wake-up Functionality Tests with Multiple Transponders

The Leopold Chain (*3*) concept was used to test the wake-up functionality programmed into the transponders. Multiple transponders were placed along a Leopold Chain (Figure 12A), which was then installed into a simulated scour hole in the laboratory using procedures developed by (*41*). The experimental setup included a 1-m long, 0.6-m wide acrylic tank to accommodate the Leopold chain method scour experiments (Figure 12B). A chain was attached to each other through strings. A model bridge pier was replicated with a 0.127-m diameter PVC pipe that was fixed into the bottom of the experimental tank and covered with sand (d_{50} = 1.9 mm). The chain was buried vertically into the sand column, in front of the upstream face of the model bridge pier, in the location where the maximum scour was expected to occur. The transponders were placed on the chain in such a way that their long axis orientation to be favorable (perpendicular) to the excitation antenna plane.

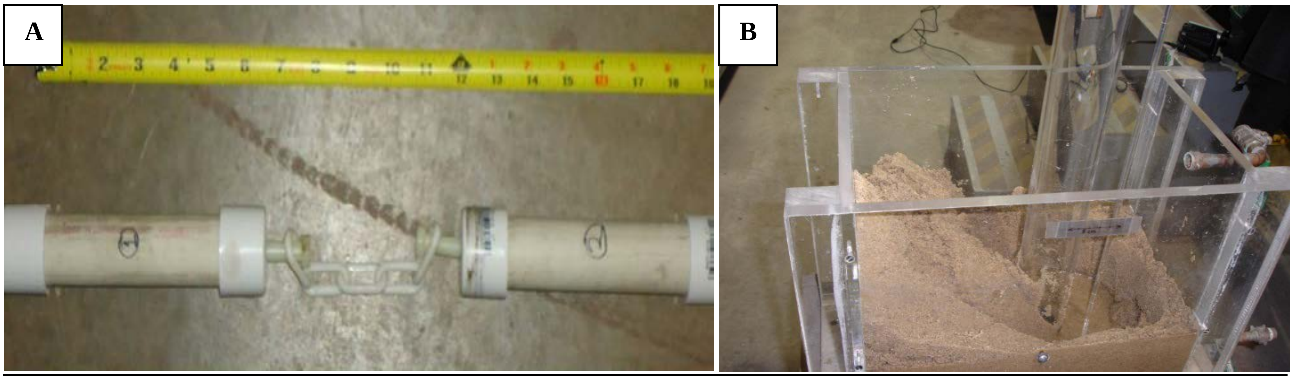


FIGURE 12 (A) A close-up image of the Leopold chain with two encased transponders and a plastic chain to minimize interference. (B) Pier setup used to test the wake-up function.

Water was recirculated into the experimental tank 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 had a 0.004-m diameter and was pointed towards the bridge pier, where the buried chain located to create scour around the pier. Two, 0.05-m x 0.15-m acrylic plates were inserted vertically into the sand bed on each side of the pier, forming a funnel with an angle of 60º, to prevent the surrounding sand material from infiltrating the developing scour hole. *The RSDS was able to successfully detect all the transponders in the Leopold chain, all of which were in the field of the excitation antenna*. Furthermore, the method was able to successfully detect scour hole formation around the bridge pier model. The orientation of the highest transponder changed as the scour hole evolved. When this happened the *RSSI* reduced, indicating the onset of scour.

3.2.3 Triangulation Tests for Locating the Buried, Encased Transponders in the 3D Domain

Experiments were performed in the Hydraulics and Sedimentation Laboratory to test the triangulation routine that was developed for the PAPTSAK software. Antennas placed at three different locations were used to test the code (Figure 13A). The geospatial coordinates of the locations were noted and then fed into the PAPTSAK software. The software calculated the distance from the antenna to the transponder from each location using the RSSI, and then used the circumcircle theory to determine the x-, y-, z-coordinates of the transponder. Eight experimental runs were conducted. In each case the computed coordinates were verified manually (with calculations by hand) using the circumcircle theory, and with a global positioning sensor device placed right at the location of the encased transponder. Figure 13B illustrates a command prompt version of the PAPTSAK software performing the triangulation of the center coordinates of a transponder.

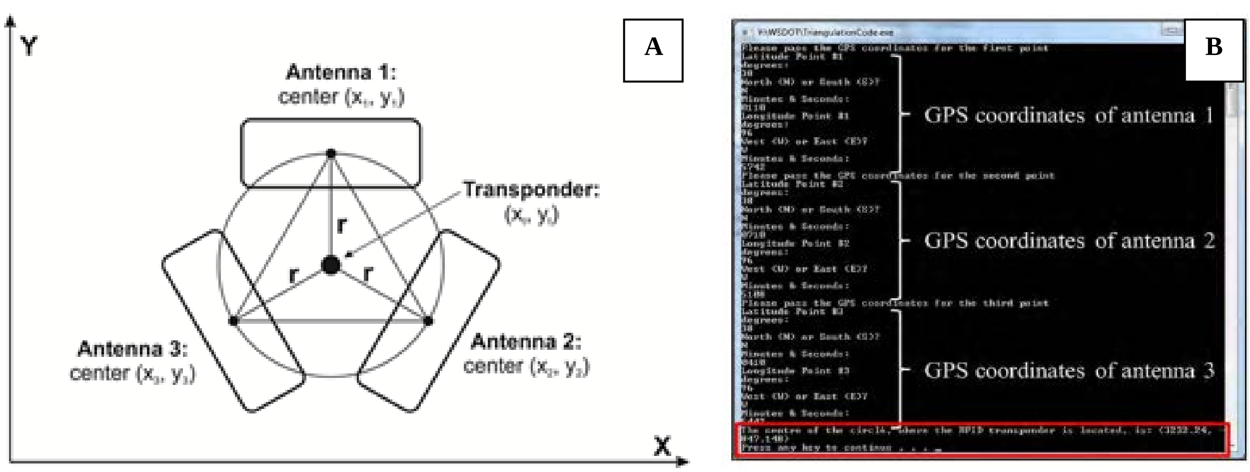


FIGURE 13 Test of triangulation routine

The accuracy of the experiments were affected by the accuracy of the geospatial tracking device and the accuracy of placing the excitation antenna at the same location for each run. *After the eight repeated runs and by comparing the triangulation algorithm outputs with the actual transponder's location in the 3D domain, the average deviation of the calculated coordinates was ~5 cm.*

3.3 UNCERTAINTY ANALYSIS

We performed an uncertainty analysis to determine the quality of the data provided by the RSDS using the relationship between the RSSI and distance. The voltages corresponding to the signal strength (Figure 11) and distances determined with tape measures were used in the analysis. The analysis was based on the Guide to Expression of Uncertainty in Measurements (*38*) and provided an estimate of the combined uncertainties from all potential sources of error that contributed to distance measurements with signal strength decay. The main sources of uncertainty considered were due to hardware accuracy and environmental factors. The uncertainty analysis (*38*) we followed was divided into five steps:

- Step 1 – the development of the "reduction" equation (Eq. 1), which is a mathematical expression that relates the variable of interest (measured) with the input quantities. In this case the transponder RSSI is the variable of interest, while the mean voltage values of the "charging" (V_c) and "step" (V_r) parts of the signal are the input quantities (see Figure 10).

$$RSSI = \left(1 - \frac{V_r}{V_c}\right) \times 100 \tag{1}$$

- Step 2 – the evaluation of the standard uncertainty of each input quantity (i.e., V_c and V_r). For each measurement point, ten independent repeated voltage values determined with a digital oscilloscope were used to compute the mean and standard deviation (*std*) for each input quantity. In this step, the digital oscilloscope accuracy (*doa*) (0.01%) and resolution (*dor*) (8- bit-type) were computed based on the information provided by the manufacturer (*39*), along with the measuring tape accuracy (*mta*) (0.0007935 m). The assumptions made here were that since the digital oscilloscope and the measuring tape evaluation were carried out by means other than the statistical analysis of a series of observations, their distributions follow the rectangular one (*38*), where the standard uncertainty, *u*, of a value x_i is given by Eq. 2:

$$u(x_i) = \frac{\alpha_i}{\sqrt{3}} \tag{2}$$

  where α is the estimated semi-range of the uncertainty.

- Step 3 – the determination of the operational condition uncertainties for each input quantity, based on the ten independent repeated measurements. The operational condition uncertainties are the summation of the uncertainty components of each input quantity (Eq. 3 & Eq. 4).

$$u(V_c)_i = \sqrt{(std(V_c)_i)^2 + (doa)^2 + (dor)^2 + (mta)^2} \tag{3}$$

$$u(V_r)_i = \sqrt{(std(V_r)_i)^2 + (doa)^2 + (dor)^2 + (mta)^2} \tag{4}$$

  where $u(V_c)_i$ is the operational condition uncertainty for the i^th measurement point of the input quantity V_c; and $u(V_r)_i$ is the operational condition uncertainty for the i^th measurement point of the input quantity V_r.

- Step 4 – the calculation of the combined standard uncertainty, $u_c(RSSI)$, for each measurement point (Eq. 5). Here, the operational condition uncertainties are multiplied with the sensitivity coefficients. The sensitivity coefficients are the partial derivatives of the reduction equation with respect to each input quantity (Eq. 6 & Eq. 7) and according to (*38*), these partial derivatives are a measure of the variation in the values of the output estimates due to small changes in the value of the input estimates.

$$u_c(RSSI)_i = \sqrt{(u(V_c)_i)^2 \times \left(\frac{\partial RSSI}{\partial V_{ci}}\right)^2 + (u(V_r)_i)^2 \times \left(\frac{\partial RSSI}{\partial V_{ri}}\right)^2} \tag{5}$$

$$\frac{\partial RSSI}{\partial V_c} = \frac{100 \times V_r}{{V_c}^2} \tag{6}$$

$$\frac{\partial RSSI}{\partial V_r} = -\frac{100}{V_c} \tag{7}$$

- Step 5 – the calculation of the expanded uncertainty, u, (Eq. 8) for each measurement point, based on the 10 independent repeated measurements. Typically, the expanded uncertainty is expressed as a 95% confidence interval, at which the sample mean $(\bar{x})$ and the population mean (μ) are within two standard deviations of each other.

$$u = ku_c(RSSI)_i \tag{8}$$

where k is the coverage factor. Typically, for a 95% confidence interval, the value of k is 2 (*38*).

Figure 14 shows the 95% confidence intervals of the transponder RSSI decay (%) for the RSDS with the custom-made excitation antenna. As expected, a closer distance between the transponder and the excitation antenna, until approximately 60% of D_{max} (i.e., the maximum detection distance of 5.2 m used in the uncertainty analysis), translates to a lower level of uncertainty in the RSSI. After that point (60% of D_{max}), the uncertainty in the measurements dramatically increases, indicating that there is a significant deviation from the average measured RSSI. This abrupt change in the confidence interval limits can be attributed to the fact that the signal attenuates with the square of the distance traveled and that attenuation can be affected by environmental factors. The highest levels of uncertainty were observed for the measurement points located at 80 and 100% of D_{max}, respectively. Although one would expect that the uncertainty would be higher for the measurement point located at D_{max}, this irregularity is most likely related to the effects of the environmental factors on the radio frequency signal propagation and attenuation. The results of the uncertainty analysis point towards the reliability of the developed RSDS system, given the consistency with which distance measurement relate to the signal strength.

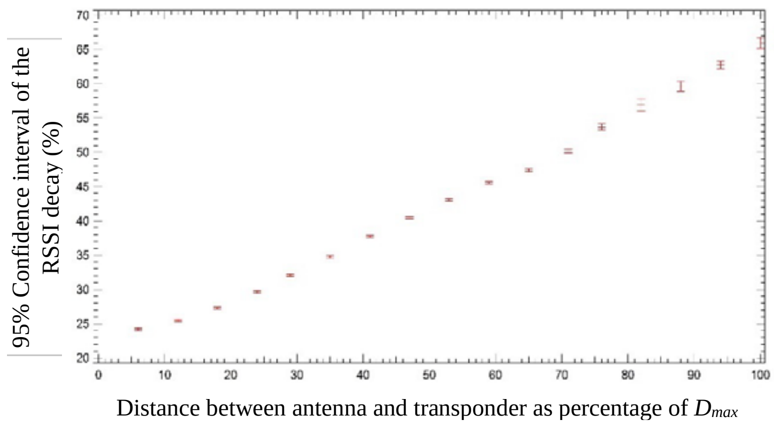


FIGURE 14 Uncertainty analysis plot for the transponder RSSI decay using (*38*) for the system with a custom excitation antenna.

It has been shown (*4*) that the RSSI of a transponder buried in gravel or sand can be smaller compared to transponders that are not buried. This is because gravel amplifies detuning of the transponder antenna for short detection distances and sand absorbs the radio signal, introducing some uncertainty in measurements. Sand is found to have the most effect, affecting the RSSI by as much as 37% in some cases. The RSSI in gravel, however, is not affected for longer detection distances.

3.4 SOFTWARE UPDATES AND DOCUMENTATION

The PAPTSAK software is an object-oriented software written in C++. The new functionalities for estimating the transponder orientation, distance, and triangulation were incorporated into the software as classes. These classes were verified and validated during the experiments described in Section 3.2. The manual for the PAPTSAK software was updated following the upgrades to it. Sections of the updated manual has been added to this report as an appendix. A portion of the manual also illustrates remote control of the software for transponder detection using a command prompt. A snapshot of the graphical user interface component of the software is provided in Figure 15, showing a form that is used to calculate the distance of a transponder from an antenna based on the *RSSI*.

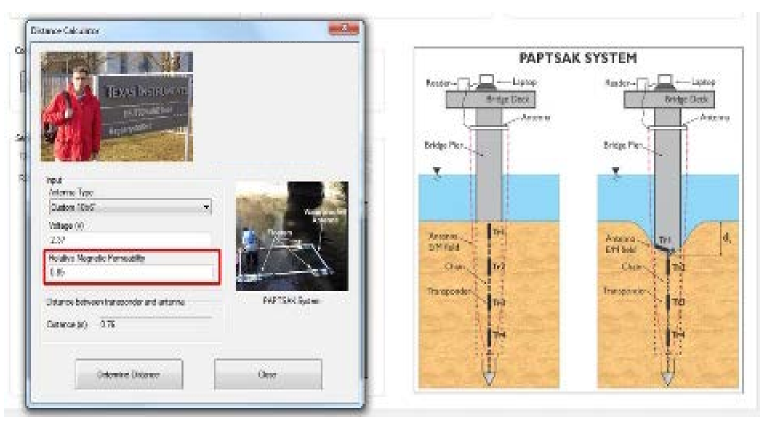


FIGURE 15 Screenshot of the PAPTSAK RFID software "Distance Calculator".

3.5 STAGE 2: VERIFICATION OF THE RSDS THROUGH APPLICATIONS IN THE LABORATORY AND THE FIELD

3.5.1 Testing of the RSDS in the Field

To field test the RSDS, two locations were explored. The Clear Creek, IA site is a sand bed river draining 270 km^2 of mostly agricultural land-use. The Third Creek, TN is gravel bed system. Third Creek, which is a smaller system draining only 7.5 km^2 of mostly urban areas. During the study only Clear Creek experienced measureable scour.

At the Clear Creek site, four transponders have been placed along a Leopold Chain at 0.6-m depth intervals below the bed surface by driving a PVC tube into the bed with the transponders attached to a chain and then removing the tube (Figure 16A). The chain runs along the stream bed and up the bank, where it is secured to a ground anchor. The use of a vibracore was also tested for feasibility and proved useful but at times cumbersome. These steps were videotaped and are being compiled into a "YouTube" video geared to the general public.

Each transponder was programmed with a unique identification serial number and a unique wake-up pattern. Ten RSSI measurements of the transponders from Clear Creek were collected for repeatability and additional statistical analysis of the data. The measured signal decay for each transponder was used to develop a curve relating the normalized decay to the depth of the transponder. The measured values were compared with the calibration equations developed during the testing of the RSDS in Stage 1 and matched well (<10%). The RSSI measurements estimated a 7.6-cm scour depth which compared well with physical measurements (Figure 16B). The shift in the line in Figure 16C shows less signal decay for the more recent measurements. This is a result of less sediment above the transponders from scour to block the radio signal.

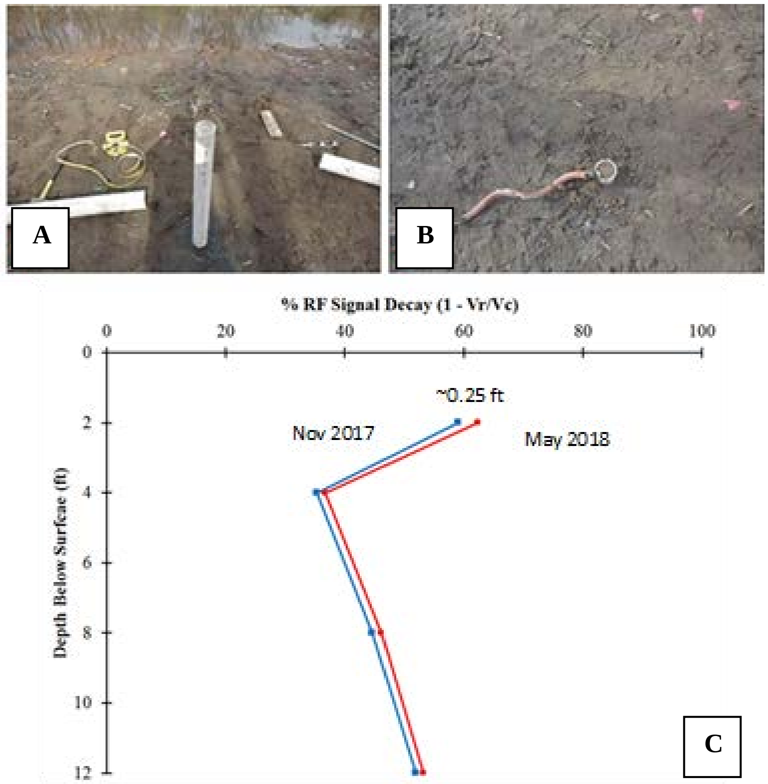


FIGURE 16 RSDS data from Clear Creek. (A) Installation in Clear Creek. Sediment is excavated with a core tube. The Leopold Chain is lowered in the hole and sediment is filled in the tube. (B) The transponders after they are buried. The chain is run back up the bank to secure the transponders. (C) Relationship between the transponder signal decay and its distance from the base station antenna.

3.5.2 Testing of the RSDS in the Lab

The water-recirculating flume in the Hydraulics and Sedimentation Lab at the University of Tennessee used for testing the RSDS has a 0.6-m x 0.5-m cross-section and a useful length of 9.0 m (Figure 17A). Using principles of dimensional analysis and similitude, model hydraulic structures were constructed replicating prototypical Engineered Log Jams (Figure 17B) and placed in the flume. Experiments were conducted for a range of characteristic flow conditions, expected to be encountered by the prototypical structures, including low flow conditions with clear-water scour, bankfull flow conditions, and 25-year floods, which will produce live-bed scour conditions.

Enhanced transponders were inserted in sediment particles which were place in the flume for testing of their potential displacement under different magnitude flows. Two types of spherical particles were tested as potential encasings for 23-mm long transponders. The 25.4-mm spherical particles were made of either glass or concrete coated with tungsten. The density of the encased particles matched the density of quartz. The glass particles were deemed better as they attenuated the RSSI signal less than the concrete-tungsten particles.

Both clear-water and live-bed scour experiments around engineered log jam prototypes were conducted to monitor the 3D evolution of the scour hole geometry. These tests followed the Lagrangian geospatial approach using a number of transponders that were released in the scour holes once scour was detected. A Seatek Multiple Transducer Array ultrasonic ranging system, operating at frequencies 1 Hz – 3 Hz, was used for real time measurement of the scour hole evolution in parallel with the RSDS for verification purposes. The RSDS and the ultrasonic system operate at different frequencies (134.2 kHz vs. 1-3 Hz), and no interference between the two systems was observed, when they were operated simultaneously.

Figure 17C shows the development of the scour hole from three transponders. The changing distances between the antenna and three transponders placed in front the ELJ during a scour experiment. A developed contour map of the scour experiment is in Figure 17D showing good agreement with the transponder depths. The three red circles represent the RFIDs.

This information will be helpful for potential scour monitoring using the RSDS around two ELJs installed by the Washington State DOT on the Skagit River, three miles east of Rockport, WA. A series of transponders along a Leopold Chain will be inserted into the sediment bed around the ELJs. The locations will be based on the expected formation of scour holes using observations from these experiments.

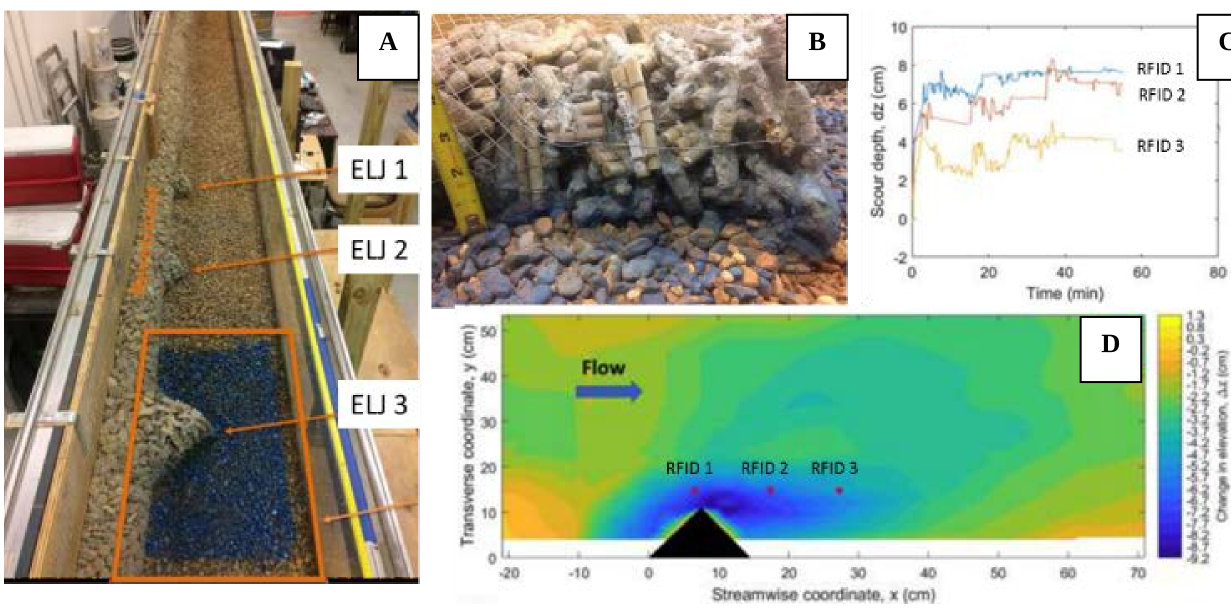


FIGURE 17 RSDS testing in the flume. (A) The flume set-up with the engineered log jams (ELJ). The blue area is the test section where we measure scour. (B) A close up of the ELJ prototype. (C) Changing distance between the base antenna and three RFIDs placed in front the ELJ during a scour experiment. (D) A developed contour map of the scour experiment. The three red circles represent the RFIDs.

3.6 ADDITIONAL APPLICATIONS OF THE RSDS

The following applications further demonstrate the benefits of the RSDS. These case studies at DOT hydraulic structures show the different aspects of the RSDS used for scour monitoring and evaluation purposes.

3.6.1 Application of Camp Cardinal Bridge Protection

On-going scour monitoring at the Camp Cardinal Boulevard bridge in Coralville, Iowa (41º40’35.16” N; 91º35’55.10” W) using a prototype of the RSDS is progressing in collaboration with the Iowa DOT (Figure 18). The Leopold Chain method for monitoring scour development has been implemented at the bridge site in conjunction with flow depth and water quality monitoring. Four transponders have been placed along the Leopold Chain at 0.6-m depth intervals below the bed surface by driving a PVC tube into the bed with the transponders attached to a chain and then removing the tube. The chain runs along the stream bed and up the bank, where it is secured to a ground anchor.

Continued scour measurements are being made at the site (described more in Section 3.5 above) using the RSSI approach mentioned above. Future plans at this site involve the 3D geospatial mapping of the scour hole using multiple transponders scattered within the vicinity of the bridge. The upgraded PAPTSAK software with remote capabilities will also be installed at the site for further testing of the remote component of the RSDS.

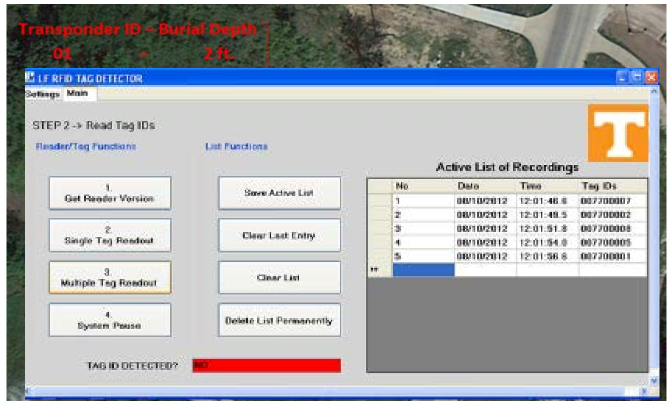


FIGURE 20 Snapshot of PAPTSAK software in the multiple transponder readout mode.

FIGURE 18 Leopold Chain location in Clear Creek near Camp Cardinal Blvd. in Coralville, IA.

3.6.2 Application of Engineered Log Jams

The RSDS is also being considered for monitoring the performance of Engineered Log Jams (ELJs) which are used for bank erosion protection. ELJs have been developed by stream restoration practitioners in partnership with state and federal DOT research initiatives. They are interlocking components of large woody material, root wads, and concrete dolos. Due to their immense weight and arm-like protrusions, the dolos can be easily combined and interlocked with logs, root wads, and cobble ballasts to create a stable structure that provides a complex riparian habitat within the interstitial spacing.

Overall dolotimber ELJs provide benefits in terms of multiple design assessment criteria, such as structural stability, ecological benefits, and economic cost. These dolotimber ELJs (Figure 19), unlike riprap and concrete structures, limit negative impacts on fish by decreasing acoustic resonance and are becoming increasingly popular streambank protection design alternatives. This design has been installed by the Washington State DOT, in coordination with several Native American tribes, local governments, and conservation groups, for protecting highways and river crossings. Examples include the installation of ELJs in gravel-bed rivers like the Hoh River bordering US-101 and the Cowlitz River for bank stabilization.

These examples are shedding light on the ELJ's influence on the bed shear stress and how they can induce scour. There are presently very few studies on scour around hydraulic structures like ELJs, especially in gravel-bed rivers. Current formulas for predicting scour around hydraulic structures are mostly applicable to sand bed rivers, and, to a lesser extent, for cohesive sediment beds. These formulas tend to over-predict the volume of the scour hole in gravel-bed rivers since they do not account for the interlocking developed between gravel particles or the effect of the porosity of the hydraulic structure. As such, there is a need for the development of scour formulas specific for gravel-bed rivers that incorporate the decay function of the shear force applied as the scour hole develops (see Section 4.2 for more).

Field monitoring of scour using the RSDS is being discussed at two ELJs installed by the Washington State DOT on the Skagit River, three miles east of Rockport, WA. A series of transponders along a Leopold Chain will be inserted into the sediment bed around the ELJs using a vibracore drill. The locations will be based on the expected formation of scour holes using the observations from experiments (described more in Section 3.5 of this report) performed at the Hydraulics and Sedimentation Laboratory at the University of Tennessee (*40*). Additional transponders will be placed within the ELJ structures in order to monitor their stability.

FIGURE 19 Dolotimber engineered log jams.

3.6.3 Application for the Trinity River Restoration Program

Aspects of the RSDS have been used in collaboration with the Washington State DOT to monitor the Lagrangian movement of sediment particles in the Elwha River under various flow conditions. This project was critical for testing the wake-up, anti-collision features incorporated in the RSDS, as well as the PAPTSAK software (Figure 20). Particle tracking is a critical part of the Trinity River Restoration Program that is designed to help understand coarse sediment movement and how it affects aquatic habitats and infrastructure under peak restoration flows. Randomly placed transponders in "smart particles" representative of the sediment characteristics in the river were monitored. Their locations and pathways were tracked over time to understand general sediment movement. The PAPTSAK software (Figure 20; see Appendix, too) was used with the anti-collision features to provide multiple transponder readouts in areas where several transponders were present. The detected transponders, their positioning coordinates, and the time stamp were recorded with the order of their detection time.

3.6.4 Application of Barb Design for Bridge Waterway Protection

Additional efforts with the Iowa DOT are being discussed to use the RSDS to monitor scour hole evolution and structural integrity for a series of barbs, which are unique hydraulic structures for protecting streambanks and transportation infrastructure. Barbs (Figure 21A) are intended for mild-sloped, gravel-bed streams but can be used in sand-bed streams. They incorporate beneficial geometric attributes of other existing hydraulic structures, which include a trapezoidal shape with inclined sides and a wide-sloped crest.

Its unique shape allows the barb to behave as a partially or a fully submerged weir under various flow conditions. The sloped crest promotes the formation of eddies and sediment deposition on the leeward side of the barb in high flows and also reduces the need for excessive stability measures. During low flow conditions, the sloped-crest barb performs similarly to traditional rectangular-crested hydraulic structures. The barb acts as an unsubmerged constriction that induces a backwater profile in the upstream reach and a drop in the water surface profile at the nose, where 3D flow, high pressure, and shedding vortices induce scour.

FIGURE 21 (A) A barb structure (B) Field monitoring of scour using RFIDs at a barb structure on Raccoon River, IA.

Despite the design advantages of barbs (*41*), their impact on in-stream fluid and sediment redistribution is not well understood because of the lack of detailed laboratory and field data pertaining to the structures. While preliminary measurements (Figure 21B) using RFIDs suggest that barbs decrease shear stress at the nose, and thus decreases relative scour compared with rectangular structures, quantification of scour-hole geometry and maximum scour depth are lacking. Furthermore, little is known about the integrity of the barb structure itself under different flow and scour conditions.

To this end, the RSDS can be used to monitor scour volumes and geometry at the barbs protecting bridges and other road infrastructure crossing waterways. This application involves the use of Leopold Chains to capture the evolution of the scour depth with time, as well as randomly placed transponders in the scour hole that forms near the toe of the barb to provide the 3D geospatial geometry of the hole at a given time using the anti-collision and triangulation features added to RSDS. Future plans are under way for the development and use of "*smart rocks*" (i.e., rocks with transponders inserted into them) that can be placed within the barb structure to monitor its integrity. An expected outcome of the project is a practical manual that helps engineers design and monitor the barb structures for protecting bridge waterways and river restoration project.

3.6.5 Application of Bridge Protection from Knickpoint Migration

The RSDS is planned for developing scour predictive tools associated with knickpoint migration that threatens bridge waterways. Knickpoints (Figure 22A) are upstream-advancing steps in the stream bed. They advance as large volumes of sediment slump from the step face. Currently, there is limited knowledge of migration rates for knickpoints but they have been known to account for more than 60% of the erosion in some streams (*42*). On-going work, in collaboration with the Iowa DOT, continues to monitor knickpoint migration in the Deep Loess region of Western Iowa and evaluate the threats they pose to highway and county road infrastructure due to scour. In these systems, the channel cross-section expands in response to the drop in the bed elevation as the knickpoint advances, which leads to bank instabilities and consequent mass failure. The net result is significant scour that may undermine hydraulic structures. Collectively, knickpoint migration and other channel erosion mechanisms have produced billions of dollars of damage to the infrastructure in the region.

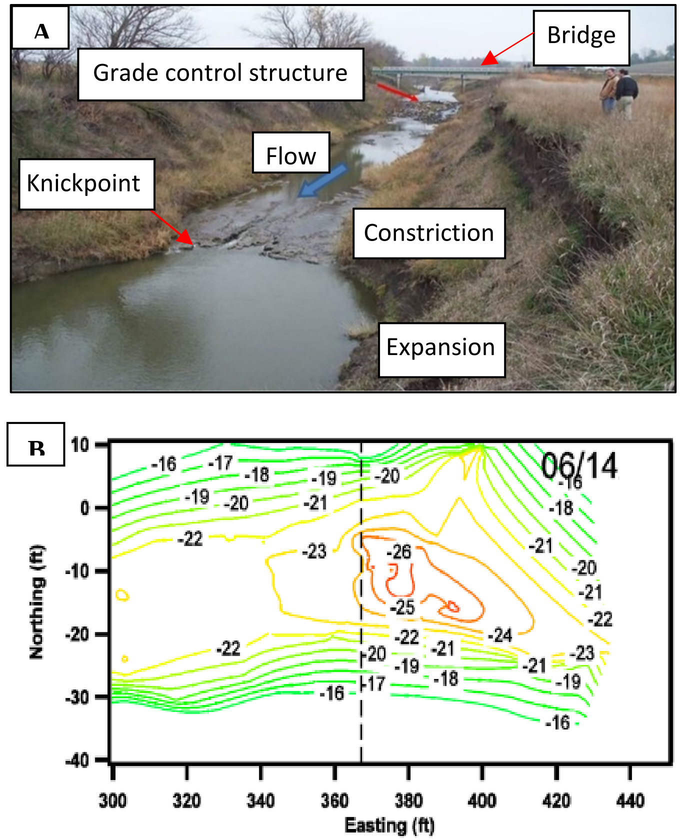


FIGURE 22 (A) An advancing knickpoint threatens an upstream bridge in Iowa. (B) Geometry of knickpoint and scour hole mapped with the RSDS. Contours are in inches.

In the Mud Creek watershed, IA, the RSDS is used to continuously monitor a knickpoint (41°05’51” N; 95°31’00” W) that is about 50 m downstream of a county road bridge (*42*). Leopold Chains at different locations along the river channel and randomly placed transponders are actively monitoring knickpoint migration rates, scour depths, and geometry of the scour hole formed from knickpoint migration. Figure 22B shows a 3D geometry of the Mud Creek knickpoint and scour hole mapped with the RSDS. In addition to scour monitoring, this is expected to lead to protocols for developing mitigation measures at bridges and other hydraulic infrastructure in semi-cohesive stream reaches.

4 PLANS FOR IMPLEMENTATION

A 4-phase plan was developed to promote implementation of the RSDS. This plan for implementation involved both the project team and advisory board members, as well as transportation community users.

The first phase was to build awareness of the RSDS. State DOT engineers Dave Claman (Iowa), Jon Zirkle (Tennessee), and Casey Kramer (Washington State, formerly) provided productive input throughout this project. Interactions with industry were additionally informative and constructive, namely Texas Instruments, Protagd, and Oregon RFID. The provided input was utilized in different steps throughout the project. A website link has been developed on the PI website (http://tpapanicolaou.engr.utk.edu/hydraulic-structures/) which has also been added to the 2-page research results write-up in the appendix.

The second phase was to develop a persuasive argument for the RSDS. The goal was to convince potential users that “*the RSDS offers hydraulic structure managers simple, but robust, user-friendly monitoring and decision-making tools that will enable them to perform meticulous inspection of scour around these hydraulic structures in an automated fashion*.” To make RSDS as transparent as possible to the potential users, a series of user manuals are being developed. The software guide is attached in the Appendix of this report.

The third phase was to develop demonstrations of the RSDS through a series of different applications. These applications were discussed in Section 1.2 of this report. These case study applications show the different aspects of the RSDS used for scour monitoring and evaluation purposes. The applications include the field testing sites (e.g., established in Clear Creek, Iowa). Additionally, in the laboratory flume, clear and live bed scour experiments around ELJ prototypes were conducted and are being discussed for two ELJs installed by the Washington State DOT on the Skagit River. The movement of sediment particles in the Elwha River was monitored under various flow conditions and the PAPTSAK software was used to monitor randomly placed transponders in "smart particles" representative of the sediment characteristics in the river . Finally, applications of the RSDS related to monitoring an advancing knickpoint in Iowa are being discussed as well as to monitor scour volumes and geometry at the barbs protecting bridges and other road infrastructure crossing waterways. These applications involve the use of Leopold Chains to capture the evolution of the scour depth with time, as well as randomly placed transponders in the scour hole that forms to provide the 3D geospatial geometry of the hole at a given time using the anti-collision and triangulation features added to RSDS.

Finally, the fourth phase included dissemination of the information. The following section details the peer-reviewed journal articles, presentations at regional/ national conferences, and proposals that were developed with this project.

Following these products, this report highlights a potential end goal as these applications can lead to an advanced formulation that estimates scour depth and volume at hydraulic structures. The continuous, real-time measurements of the RSDS can capture the modification to bed shear stress as the scour hole evolves and the resultant effect on the growth rate and extent of the scour hole. This results in a decay function, where the shear force applied by the flow decays as the scour hole develops. The maximum depth of scour is reached when the shear force no longer exceeds the erosion resistance of the bed. This formulation has not been examined for a wide range of flow conditions, and thus, existing scour equations do not capture the evolution of the scour hole.

This ultimate application is then followed by a series of costs estimates for the various parts of the RSDS (namely, the antenna, reader, transponders & Leopold Chain, power supply, and communications package). The cost estimates are included for the materials, fabrication, installation and maintenance are as little as $5,777, which is quite cost-effective.

4.1 TECHNOLOGY TRANSFER

4.1.1 Invited Presentations

- CUAHSI Biennial Conference: Hydrologic Connections - Climate, Food, Energy, Environment, and Society. Shepherdstown, WV. July 30 - August 1, 2018.
- 7th International Symposium on Hydraulic Structures. Keynote Address. Aachen Germany. May 15-18, 2018.
- 7th High-level Forum in Hydraulic Engineering and the 2nd International Symposium on Hydraulic Engineering Simulation and Safety. "Lectures on Hydraulics & Sediment Transport". National Key Laboratory at Tianjin University. September 20-22, 2017.
- 8th International Gravel Bed River Workshop. Keynote address: "Boulder effects on turbulence and bedload transport". Kyoto, Japan. September 14, 2015.

4.1.2 Conferences

- Wyssmann, M.A., and A.N. Papanicolaou. 2018. Particle resting times: Modeling the role of turbulence. American Geophysical Union Fall Meeting. December 10-14, 2018. Washington, D.C.
- Wyssmann, M., and A.N Papanicolaou. 2018. Lagrangian modeling of bedload movement in the rolling regime: Estimation of resting and entrainment statistics via the Impulse model. River Flow 2018. September 5-8, 2018. Lyon-Villeubanne, France.
- Elhakeem, M., and A.N. Papanicolaou. 2017. Mitigating river-bank erosion using bendway weir structures. 5th International Conference on Architecture and Civil Engineering, ACE 2017. May 8-9, 2017. Singapore.
- Elhakeem, M., A.N. Papanicolaou, and A.G. Tsakiris. 2017. Monitoring bridge health using smart sensor technology. IEEE Computing Conference 2017. July 18-20, 2017. London, UK.
- Papanicolaou, A.N. 2017. A probabilistic model for sediment entrainment: The role of bed irregularity. 19th European Geosciences Union General Assembly. April 23-28, 2017. Vienna, Austria.
- Papanicolaou, A.N. 2016. Scour monitoring around hydraulic structures with RFIDs. National Hydraulics Engineers Conference. August, 9-12, 2016. Portland, OR.

- Tsakiris, A.G. and A.N. Papanicolaou. 2016. Use of RFIDs for scour monitoring. 95th Annual Meeting of the Transportation Research Board. January, 11-14, 2016. Washington, D.C.
- Tsakiris, A.G., A.N. Papanicolaou, I.V. Moustakidis, and B.K. Abban. 2015. Methodological considerations for particle tracking in riverine applications using Radio Frequency Identification. EWRI-ASCE World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems. May 17-21, 2015. Austin, TX.
- Wyssmann, M.A., A.G. Tsakiris, and A.N. Papanicolaou. 2015. Power spectral density analysis of flow field within a boulder array. EWRI-ASCE World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems. May 17-21, 2015. Austin, TX.

4.1.3 Peer-Reviewed Publications

- Papanicolaou, A.N., F. Bressan, J.F. Fox, C. Kramer, and L. Kjos. 2018. Role of structure submergence on scour evolution in gravel-bed rivers: Application to slope-crested structures. Journal of Hydraulic Engineering. 144(2):03117008.
- Papanicolaou, A.N., A.G., Tsakiris, C.M. Kramer, and M.A. Wyssmann. 2018. Temporal characteristics of bedload conveyance through boulder arrays. Journal of Geophysical Research. Accepted.
- Elhakeem, M., A.N. Papanicolaou, and C.G. Wilson. 2017. Implementing streambank erosion control measures in meandering streams: Design procedure enhanced with numerical modeling. International Journal of River Basin Management. 15(3):317-327.
- Papanicolaou, A.N., and A.G. Tsakiris. 2017. Chapter 2: Boulder effects on turbulence and bedload transport. In: D. Tsutusmi and J.B. Laronne. Gravel-Bed Rivers: Process and Disasters. Wiley-Blackwell. pp. 33-71.

4.1.4 Proposals

- NCHRP 24-48 proposal submission. A Methodology for Determining Scour Depth around Structures in Gravel-bed Rivers. PI: Thanos Papanicolaou. 10/1/19 – 9/30/21. $600,000. Declined.
- NCHRP IDEA Program. Use of synthetic smart rocks for scour countermeasure evaluation around abutments and bridge piers. PI: Thanos Papanicolaou. 10/1/19 – 9/30/21. $150,000. Pending.

4.2 DEVELOPMENT OF SCOUR PREDICTION FORMULA FOR POROUS STRUCTURES AND GRAVEL-BED RIVERS

The 3D geospatial data gathered from the temporal measurements of scour at hydraulic structures, like the barbs and ELJ's described in Section 1.2 above, can lead to the development of new generation scour formula for the design of submerged porous structures and gravel-bed rivers. No such formulas are currently available, and there is uncertainty regarding the use of existing methods for predicting local scour around these structures, especially in gravel-bed rivers.

At present a USGS method for barb design simply states that the maximum scour is about 2.5 times the exposed height of the barb. There is, however, little empirical data to support this number for a wide range of conditions. An approach similar to (*10*) could be adopted, which is a relatively new approach to scour prediction where the local scour around a structure is estimated as an amplification, α, of the contraction scour. The amplification factor reflects the effect of the macro-turbulence induced by the unsteady coherent flow structures (*7*, *43*). This scour formula can be expressed as:

$$d_{sm} = \left[\alpha \left(\frac{\tau_0}{\tau_c}\right)^{\frac{3}{7}} \left(\frac{q_b}{q_0}\right)^{\frac{6}{7}} - 1\right] H \tag{9}$$

where τ_0 and τ_{cr} are the fluid bed shear stress and the sediment critical shear stress, respectively; q_b is the unit flow in proximity of the barb, or the discharge divided by the obstructed width of the channel; q_0 is the approaching unit flow, or the discharge divided by the width of the channel; and H is the approach flow depth. Preliminary laboratory and numerical experiments confirm the suitability of the approach for barbs and suggest α values ranging between 1.8 and 2.2, depending on the submergence of the structure. There are currently no field-based estimates of the α parameter for porous structures. Application of the RSDS is expected to lead to estimates of the values of α, which may then be used for designs.

For gravel-bed river applications, a further consideration is that existing formulas tend to over-predict the volume of the scour hole since they do not account for the interlocking developed between gravel particles or the effect of the porosity of the hydraulic structure on the fluid bed shear stress. For layered gravel beds in which the critical shear stress for particle mobilization increases with depth, the maximum depth of scour is affected by the changing strength of the layers. As such, there is a need for the development of scour formulas for gravel-bed rivers that not only incorporate a decay function that accounts for the change in fluid bed shear stress with evolution of the scour hole, but also a change in the erosion strength. This decay function is illustrated in Figure 23 for layered gravel with increasing erosion resistance with depth. The application of the RSDS to the gravel-bed streams in Washington State will address this need and produce new generation scour formulas for use in the design of hydraulics structures.

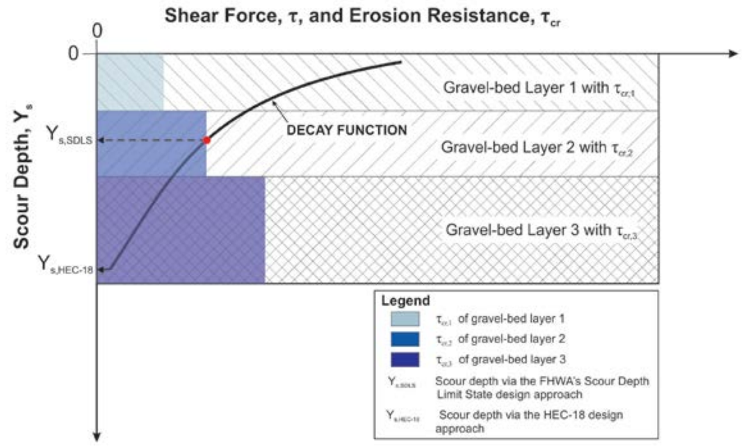


FIGURE 23 Shear decay function concept in a layered gravel bed river (adopted from FHWA). The shear force applied by the flow (black line) decays as the scour hole develops. The depth of scour is reached when the shear force applied by the flow no longer exceeds the erosion resistance of the gravel bed layer (red dot in the figure) (*40*).

4.3 INSTALLATION COST ESTIMATES

As part of our plans for implementation, we have collected financial data and put together cost estimates for installation of the RSDS at a bridge site. Cost estimates were based on the installation of Leopold chains consisting of 5 transponders spaced 0.6 m apart, placed along each pier. Pricing includes the costs for developing the components of the RSDS, labor costs, and installation costs (including labor costs). An overview of the costs is provided below and a more detailed breakdown provided in Appendix B. In total, costs for constructing, installing, and maintaining a RSDS system totals $9,825.

4.3.1 Antennas

The material costs for constructing a three-antenna array are provided in Table B1 in the appendix. A total cost of $3,469 is estimated. The construction of the antenna array will take 2 trained technicians 1.5 days (i.e., 12 hours); which includes the time needed to purchase the necessary parts. For the construction of each subsequent array, it will require the 2 technicians only 8 hours, as the purchasing will already be completed. The installation costs involved in mounting of the antenna will depend on the bridge site accessibility, pier location, water level, and prevailing weather conditions. The following estimates should serve as a guide. A monthly routine check of the installed antenna is recommended. Though minimal inspection is expected, travel time to the site is accounted for. In the event of antenna damage, a new antenna will likely have to be constructed.

4.3.2 Reader

A reader will be attached to three antennas for determining the GPS coordinates of transponders. The assembly of each reader will require a trained technician approximately 4 hours to complete. As detailed in the appendix, a total cost of $1378 is estimated (see Table B2 for breakdown). Note that the installation cost has been considered with the installation of the antenna above and not considered here. The cost for reader maintenance (e.g., tuning) has also been considered with the maintenance for the antenna above.

4.3.3 Transponders

Estimated costs of individual transponders and a Leopold Chain are provided below. The cost estimates are for an installation for monitoring a scour hole that will not exceed a 3-m maximum depth. Five transponders linked with chains approximately 0.6 m apart are thus suitable for this scenario. Costs are provided in Table B3 for our enhanced transponders. It is anticipated that it will take a technician six hours to put a single Leopold Chain together. The anticipated time for installing a single Leopold Chain is 4 hour by two technicians. A total of $1,805 is expected for this component. Note that the cost for transponder monitoring has been considered with the maintenance for the antenna above.

4.3.4 Power Source

An estimated cost of $749 for the power supply is based on the RSDS's ability to run off of a marine battery that is charged by a solar panel (Table B4).

4.3.5 Wireless Data Transfer

Cellular modems may be used to wirelessly transfer data from the RSDS to the maintenance office. A cost of $300 is estimated (Table B5)

4.3.6 Remote Data Transfer

For installations of the RSDS in highly remote areas, an optional GOES satellite may be used to transfer the RSDS data. A cost of $1,922 is anticipated without the satellite. The satellite is expected cost an additional $2,750 (Table B6).

5 CONCLUSIONS

This research offers an innovative RFID Scour Detection System (RSDS) for detecting scour around hydraulic structures and in natural environments. The innovation lies in the utilization of a Low Frequency, passive RFID system to identify the onset of scour and provide remote, autonomous, continuous measurements of the 3D geospatial structure of a scour hole as it evolves. The RFID technology has been around over the last twenty years for detecting object movement and quality of materials. The innovation of this research is not so much found on the development of a new RFID system, but on the introduction of the state-of-the-art methodology of utilizing the concept of the radio frequency signal decay, transponder orientation, and anti-collision between transponders to investigate the problem at hand, scour.

Following that line of thinking, several modifications were made to an existing RFID system using principles of electromagnetic theory, hydraulics, and sediment transport, and transcends the disciplines of electrical engineering, computer engineering, civil and environmental engineering, and sensor engineering. Specifically, (1) a "wake-up" function was programmed into transponders to prevent collision between the signals from multiple transponders placed in the field of an excitation antenna, thus permitting the use of multiple transponders for evaluating the 3D evolution of the scour hole; (2) Inclinometers were installed on transponders to account for the change in signal decay with transponder orientation; (3) a signal strength measurement circuit was installed on transponders; and (4) an appropriate encasing was developed to permit burial of transponders in saturated sediments without impacting their function or communication. Corresponding software upgrades were made to the existing PAPTSAK RFID software to accommodate the enhancements to the RSDS, and to extend its utility to continuously estimate scour depth and scour hole geometry via distances estimated from the RSSI and via triangulation of transponder geospatial coordinates based on the distances from three antennas.

Laboratory experiments and field applications were performed to test each of the enhancements to the system. The RSDS was able to successfully detect all the transponders in a Leopold Chain that was in the field of the excitation antenna. The approach was shown to be able to successfully detect scour hole formation around the bridge pier model using the RSSI-transponder-distance concept. Eight repeated tests on the triangulation algorithm confirmed its capabilities for use with the system in the 3D domain, with an average deviation ~5 cm for estimated transponder coordinates. Results from the encapsulation tests revealed no changes in the signal strength and estimated distances even after 10 days in pressurized water, indicating that the potting compound adopted for the RSDS is essentially “transparent” to the radio waves.

Collaborative efforts with several DOTs are currently underway to apply the developed RSDS to the protection of road infrastructure that cross waterways. The 3D geospatial data gathered from the temporal evolution of scour at scour protection measures around these structures is expected to lead to development of new generation scour formula that can be applied to the design of submerged porous structures, as well as gravel-bed rivers, for which no specific formulas are currently available. The new generation formulas will incorporate a decay function that accounts for the change in fluid bed shear stress with evolution of the scour hole, as well as the effects of particle interlocking on erosional strength in gravel beds and the change in the strength with layering.

Future plans are also under way for the development and use of “*smart rocks*” (i.e., rocks with the enhanced transponders inserted into them) that can be placed within hydraulic structures such as barbs to monitor their integrity by continually checking for movement of comprising material and potential modes of failure. An expected outcome of the project is a practical manual that helps engineers design and monitor the barb structures for protecting bridge waterways and river restoration project.

As a next step, we propose organization of webinars and other platforms that further disseminate the outcomes of the study and can lead to community-supported projects that test and further demonstrate the utility of the product in a variety of environments.

6 INVESTIGATORS’ PROFILE

Thanos Papanicolaou is a Professor and the Henry Goodrich Chair of the Department of Civil and Environmental Engineering at the University of Tennessee – Knoxville. He is also the Director of the Hydraulics and Sedimentation Lab (http://hsl.engr.utk.edu) and Chief Editor of the *Journal of Hydraulic Engineering* for the American Society of Civil Engineers. Papanicolaou was the Principal Investigator of this IDEA project and a brief resume can be found on his website (http://tpapanicolaou.engr.utk.edu/).

Papanicolaou has been pioneering the use of RFID technology to measure scour, sediment travel/ residence times, and virtual velocity since 2007. Artificial sediment particles ranging from sand to cobble size have been tagged with transponders for use in various environments. An in-house software (PAPTSAK) has been developed using C++ to control the system and record the particle distances, locations, and inclinations. Papanicolaou has filed for a patent through the UT research and entrepreneurship fund for this new technology.

Papanicolaou has laboratory and numerical expertise in the interaction of turbulent flow and particle movement, including sand-content effects on gravel-bed hydraulics. He has published more than 30 refereed publications in the area of flow - hydraulic structure interactions. A recent publication of his the *Journal of Hydraulic Engineering*, which was part of his Hunter Rouse lecture, focuses on scour around elongated structures like barbs. The barb design that Papanicolaou has developed has been adopted in several states around the country from the Pacific Northwest to the Midwest.

Additionally, Papanicolaou has published more than 60 refereed papers on turbulence and flow-sediment interaction, and about 300 conference papers and presentations on this topic. He has been invited in 3 Gravel Bed River (GBR) conferences where he has been one of the keynote speakers focusing on flow around boulders and secondary currents in gravel-bed rivers. Papanicolaou has also published more than 20 refereed papers in the area of cohesive sediments and bank stabilization near abutments.

He has received funding from several federal agencies including NSF, NAS, NASA, DOE, NOAA, USACE, USDA, USBR, USGS, US Forest Service, FSWS, and the USDOT (through a RITA grant). Over the years, he has received more than 15 million dollars of external funding including funding. He has worked with several DOTs including those from the states of Washington, Iowa, Tennessee, Michigan, Arizona and New York.

Dr. Papanicolaou received the Huber award 2008, was nominated for the Ippen award in 2010, received Hunter Rouse award in 2014, and has received in 2018 the Hans Albert Einstein award. Fellow of ASCE

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APPENDIX A: RESEARCH RESULTS

NCHRP IDEA Program Committee

March 2019

Project Title:

A Radio Frequency IDentification (RFID) Detection System for Assessing Scour Countermeasures and the Stability of Hydraulic Structures

Project Number:
NCHRP_IDEA183

Start Date:
July 6, 2015

Completion Date:
December 31, 2018

Product Category:
Type 2 – Product Application

Principal Investigator:
Thanos Papanicolaou
Professor
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THE UNIVERSITY OF TENNESSEE KNOXVILLE

HYDRAULICS & SEDIMENTATION LAB

Detecting Scour Using an Enhanced RFID System

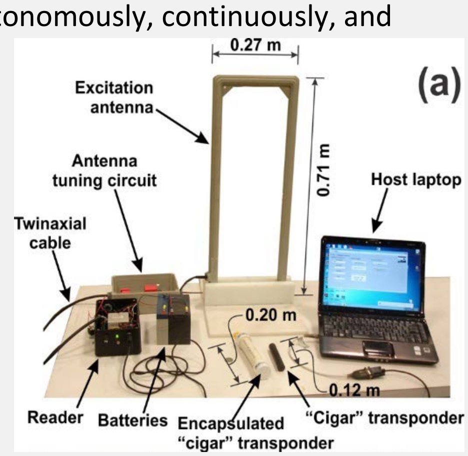
The Radio Frequency IDentification (RFID) Scour Detection System (RSDS) was developed to monitor scour autonomously, continuously, and remotely at bridge piers and abutments.

WHAT WAS THE NEED

The Federal Highway Administration (FHWA) has identified more than 150,000 bridges in the U.S. that are vulnerable to scour. Excessive scour can expose the bridges' foundations and compromise their stability. Although scour monitoring is of national importance, the FHWA requires assessments of a bridge's scour condition only on a biannual basis due to financial and labor constraints.

WHAT WAS OUR GOAL

Our goal was to develop a novel RFID Scour Detection System, the RSDS, for monitoring scour hole evolution autonomously, continuously, and remotely near bridge piers and abutments, thus providing repeatable and reliable 3D scour data for both clear-water and live-bed scour conditions.



WHAT DID WE DO

To improve the applicability of the RFID technology for measuring scour, an existing RFID system was enhanced in this 2-stage project. Stage 1 involved enhancement and testing of the main RSDS components (i.e. the transponder, reader, and software). Stage 2 involved verification of the RSDS through applications in the laboratory and the field.

Enhancements

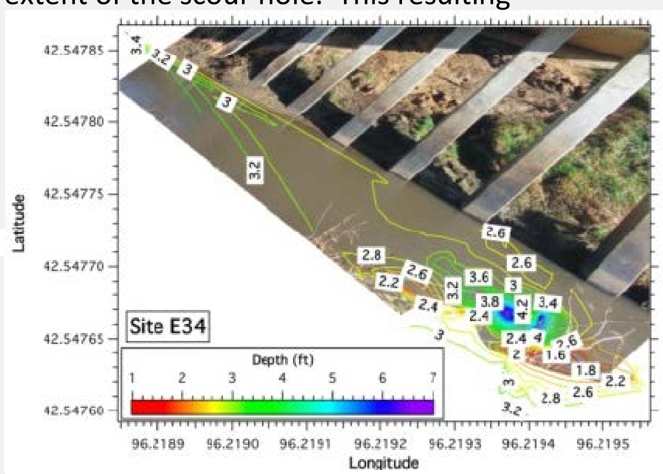
- Integrated circuits and inclinometers added to improve accuracy and detectability when buried.
- Added a wake-up function to provide anti-collision features.
- Developed triangulation functionality to identify the x, y and z coordinates.
- Used potting compound to prevent moisture build-up.
- Enable remote interaction with network capabilities.

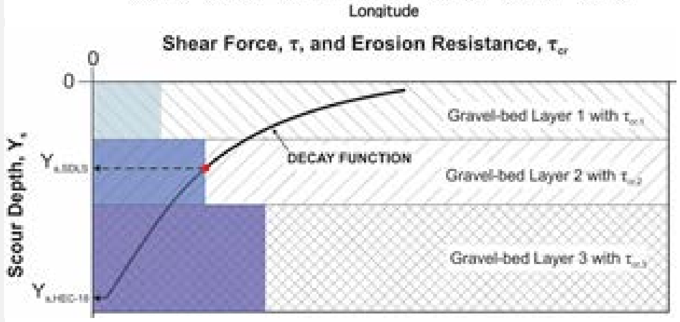
WHAT WAS THE OUTCOME

The continuous, real-time measurements of the RSDS can capture the modification to bed shear stress as the scour hole evolves and the resultant effect on the growth rate and extent of the scour hole. This resulting formulation is a decay function, where the shear force applied by the flow decays as the scour hole develops.

WHAT IS THE BENEFIT

The RSDS automates scour data collection and transmission, eliminating the need for onsite surveys and ensuring personnel safety. It also improves manager insight and decision-making by facilitating a shift to condition-based management that offers a cost reduction through timely recognition.





LEARN MORE
To view the complete report, please visit:
http://tpapanicolaou.engr.utk.edu/hydraulic-structures/

APPENDIX B: INSTALLATION COST BREAKDOWN

TABLE B1 Antenna Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
PVC pipe (2” ID x 10’ L)	4	$6.29	$25.16
PVC pipe (1/2” ID)	16	$1.50	$24.00
PVC 90º-elbows (2” ID)	3	$2.26	$6.78
PVC tau fitting	1	$3.00	$3.00
PVC cup (2” ID)	1	$0.78	$0.78
PVC glue	1	$7.99	$7.99
Clear vinyl tubing (3/8” ID)	1	$29.00	$29.00
Steel rod (1/4” Diameter)	8	$10.00	$80.00
Wooden spacers	16	$1.00	$16.00
12-Gauge stranded wire	1	$62.00	$62.00
Pin connectors (package)	2	$7.50	$15.00
Sub-Total			***$269.71***
Fabrication Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	12	$50	$600.00
Technician 2	12	$50	$600.00
Sub-Total			***$1200.00***
Installation Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	8	$50	$400.00
Technician 2	8	$50	$400.00
Sub-Total			***$800.00***
Maintenance Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	24	$50	$1200.00
Sub-Total			***$1200.00***
Total			***$3469.71***

TABLE B2 Reader Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
Radio module (RI-RFM-008B)	1	$288.25	$288.25
Control module (RI-CTL-MB2B)	1	$352.33	$352.33
Antenna tuning circuits (RI-ACC-008B)	4	$137.90	$551.60
Multiplexer circuit board	1	$24.52	$24.52
Multiplexer wiring harness	1	$102.00	$102.00
Datalogger circuit board	1	$31.95	$31.95
Bluetooth serial adapter	1	$8.85	$8.85
Serial cable	1	$10.05	$10.05
Waterproof enclosure (box)	1	$8.69	$8.69
Sub-Total			***$1378.24***
Fabrication Costs			

Personnel	Hours	Hourly Rate	Total Cost
Technician 1	4	$50	$200.00
Sub-Total			***$200.00***
Total			***$1578.24***

TABLE B3 Transponder & Leopold Chain Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
Transponders (enhanced)	5	$210	$1050
PVC Pipe (1.4” ID)	5	$1.15	$5.75
PVC Cups (1.4” OD)	10	$0.65	$6.50
Plastic Chain	1	$13.00	$13.00
PVC Glue	1	$7.99	$7.99
Heavy Duty Silicone	2	$8.00	$16.00
Plastic Screws	5	$0.40	$2.00
Plastic Nuts	5	$0.20	$1.00
Plastic Washers	60	$0.05	$3.00
Sub-Total			***$1105.24***
Fabrication Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	6	$50	$300.00
Sub-Total			***$300.00***
Installation Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	4	$50	$200.00
Technician 2	4	$50	$200.00
Sub-Total			***$400.00***
Total			***$1805.24***

TABLE B4 Power Supply Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
Marine battery, Size 34M	1	$159.00	$159.00
55 Watt GridMaxx Solar Panel	1	$410.00	$410.00
Xantrex C35 Charge Controller	1	$130.00	$130.00
Ground/Roof Tilt Mount 02	1	$50.00	$50.00
Sub-Total			
Total			***$749.00***

TABLE B5 Wireless Data Transfer Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
Cellular Modem (XT09 1 Watt 900 mHz)	1	$150.00	$150.00
Sub-Total			***$150.00***
Fabrication Costs			

Personnel	Hours	Hourly Rate	Total Cost
Technician 1	2	$50.00	$100.00
Sub-Total			***$100.00***
Installation Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	1	$50.00	$50.00
Sub-Total			***$50.00***
Total			***$300.00***

TABLE B6 Remote Data Transfer Costs

Material Costs			
Item	**Quantity**	**Unit Cost**	**Total Cost**
TX312 GOES Satellite transmitter	1	$2750.00	$2750.00
17992 GPS antenna and 18017-L cable, 7623 Threaded pipe, 1049 NU-RAIL fitting	1	$152.00	$152.00
Datalogger (CR series)	1	$565.00	$565.00
25316 11-dBi Right-Hand Circular Polarized (RHCP) antenna with mounting hardware	1	$560.00	$560.00
COAXNTN-L RG8 antenna cable	1	$50.00	$50.00
ENC16/18 enclosure and 19332 and 19336 antenna accessories to punch holes for the antenna cables	1	$290.00	$290.00
BP24 (24 Ahr) battery back, CH100 regulator and SP20 (20W) solar panel	1	$155.00	$155.00
Sub-Total			***$4522.00***
Fabrication Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	2	$50.00	$100.00
Sub-Total			***$100.00***
Installation Costs			
Personnel	**Hours**	**Hourly Rate**	**Total Cost**
Technician 1	1	$50.00	$50.00
Sub-Total			***$50.00***
Total			***$4672.00***