# Multi-Level Adaptive Remote Sensing Package for Bridge Scour Health Management

**(RITARS-12-H-ASU)**

**Office of the Assistant Secretary for Research and Transportation (OST-R)**

**Program Manager: Mr. Caesar Singh**

**Final Report**


**PI: Aditi Chattopadhyay**

**Co-PIs: Masoud Yekani Fard, Sandeep Gupta, Georgios Varsamopolous (ASU)**

**and**

**Thanos Papanicolaou (UIowa)**


**December, 2014**

**Table of Content**

## Executive Summary:

In this project for the U.S. Department of Transportation (DOT), our overarching objective was to develop an integrated means for reliable monitoring, inspection, detection and prediction of local scour for bridge structures. Our Multi-level, Adaptive, Remote Sensing System (MARSS) integrates remote sensing and wireless technology with an adaptive, information processing, prognosis, and decision support system to assess different modes of scour (i.e., clear-water vs. live-bed scour), as well as their extent in terms of depth and volume near bridge structures.

## Introduction:

Over the past few decades, various fixed scour monitoring instruments have been installed on bridge structures for measuring bridge scour depth. They include sonar, Manual Sliding Collar, tilt sensors, float-out-device, sounding rods, and Time Domain Reflect meters (Hunt 2009). Typical issues reported of unmanned detection techniques are either vulnerability or survivability of the device under harsh conditions. New sensing technologies to measure critical scour depth have been suggested such as Fiber Bragg Grating (FBG) (Xiong et al. 2012; Zarafshan et al. 2012), Smart Rocks (Radchenko et al. 2013), and RFID systems. These efforts have shown good potential to overcome the disadvantages of traditional scour monitoring instruments for real-time scour monitoring; however, the fidelity of these technologies have yet to be proved in real bridge scour events. This final summary report details the efforts of the research team for online detection and prediction of scour using RFID technology and it is outlined per task below.

1. **Task 1: Integrated Sensing Technology for Scour Monitoring.**

The main objectives of this task were as follows:

a) To develop and use RFID technology to determine local scour around bridge piers during scour critical events.

b) To install RFID system in 2 bridges in Iowa and Arizona

c) To integrate RFID system into MARSS.

*1.a*) A 3.05 m x 2.13 m, custom-made antenna (Figure 1) was designed and constructed for detecting Radio Frequency ID (RFID) transponders at a distance up to 12 m with success of detection around 50%, when buried in a mixed water-sediment column. In order to achieve this goal, the number of loops and the loop spacing, as well as the inductance and efficiency factors, for the custom-made antenna were adjusted based on the RFID system specifications (e.g., radio signal frequency, reader transmitting energy, maximum allowable antenna inductance by the reader).

A Campbell Scientific Geostationary Operational Environmental Satellites (GOES) data collection platform was prepared to relay data from our RFID transponders through an orbiting satellite to a ground station. We can access the ground station via the internet to retrieve the data with our desktop computers. The collection platform is a packaged instrument, so that we only need to ensure the data from our RFID readers are in a suitable format for the data loggers. The data logger is enclosed in a weather-resistant enclosure that is 40.6 cm wide and 45.7 cm tall.

A key component of the RFID system is the reader. The reader not only emits the initial radio signal to activate the RFID transponders, but also receives and processes the return signal from the transponders. Three readers for the RFID systems were constructed by assembling the various electronic components, which included the circuit boards, attached wires, and connection ports for the computer and RFID antenna. The circuit boards were placed in a water-resistant assembly box. The necessary wires were soldered to circuit board and various switches and connection ports. The components were tested for functionality. Several of the programming steps have been developed from past funded research and will be treated here as a “black box” (i.e., no details of how these steps were developed will be provided as this is not the purpose of this project). The custom-made RFID antenna (Figure 1) was designed and constructed with the following specifications. The antenna uses 12-gauge wire in 2 loops that are spaced 3.38 cm apart. The RFID antenna inductance, which is a measure of the energy storage capacity of the antenna in its electromagnetic field, is 45 μH. Based on the RFID reader specifications, the RFID antenna inductance should not exceed 80 μH. The efficiency factor of the RFID antenna is 356.1 and quantifies the bandwidth of the RF signal. Three RFID readers capable of determining transponder vertical location within the sediment bed by measuring the Return Signal Strength Intensity (RSSI) of the transponders were assembled. The reader communication firmware was updated to allow the user to implant a unique “wake-up” pattern in the memory of each transponder, so that they transmit their return signal in a sequential pattern. Additionally, the reader firmware automatically performs measurements of the RSSI. This update improved the efficiency of the measurement procedure for the RSSI, which is related to the scour depth in this project.

Figure 1. (left) custom-made antenna (right) Leopold chain with two encased transponders in a fishing net and secured with paracord

*1.b*) Folding chain is one of the main components in installation of the RFID system. To construct the folding Leopold chain (Figure 1), 120-mm long RFID transponders with a 25-mm diameter were each assigned their own identification number, so that they could be distinguished from one another. The RFID transponders were encased in PVC tubes that were slightly larger (125 mm long x 25.4 mm diameter) than the transponders. The tubes were capped and sealed with PVC glue to ensure that the casings were water-tight. The encased transponders were placed into a small fishing net and attached to a plastic chain using plastic screws. It is important that there is no nearby metal to the transponders, which will interfere with the radio signal. The fishing net was also secured to the chain using paracord. A geodetic survey was conducted using a Total Station of a 350-m long reach of Clear Creek (Figure 2) near Camp Cardinal in Johnson County, IA where the RFIDs were installed. The approach flow is a key parameter needed for developing a scour formula at the site. Therefore, a pressure transducer, or water level logger, was installed well upstream of the bridge to measure the water depth of the approach flow. These water level loggers are vented pressure transducers from Global Water Instrumentation (Model # WL-16U; Figure 2). . The transducer was positioned 10 cm above the bed. A stilling well consisting of a slotted pipe was placed around the T-post to minimize the effects of waves. Four additional T-posts were placed in front of the stilling well to capture debris flowing downstream thereby protecting the pressure transducer. These measurements can be used in established formulas for determining scour, as well as the prognosis algorithm.

The installation process into the stream bed for the RFID transponders along a Leopold chain using a vibracore drill was described in a printed manual (Appendix A). The manual include all necessary steps prior to and after the RFID transponder installation in the field. Proper installation of the RFID transponders is of primary importance for the successful monitoring of scour within a river channel as the orientation of the transponders dictates the decay signal strength from the transponders; therefore, much attention is required. It is important to note that each site where the transponders will be installed has specific characteristics that may alter the installation process, thus the installation process described in the manual may need modification to meet these site differences. The classical Leopold folded erosion chain to measure scour was modified to incorporate the use of the RFIDs. New materials (e.g., aviation electronics grade silicon, silicon grease, epoxy or urethane) were tested during this project to protect the transponder circuit boards while they are submerged in the river bed. These new materials not only ensured that the transponders are waterproof, but also minimized the buildup moisture within the external encasing, vibrations due to near bed turbulence, and temperature gradients. To develop a baseline condition for continuous testing of the RFIDs, a bathymetric map of the stream reach near the monitoring site on Clear Creek was developed using a combination of the geodetic surveys and sonar measurements. Figure 2 shows the measuring locations in the reach. The stream channel at this site is approximately 25 m wide and has a bank height around 3.5 m. These data were input into the Finite-Element Surface-Water Modeling System (FESWMS) 2-D hydrodynamic model. FESWMS is a modular set of computer programs that simulates two-dimensional, depth-integrated, surface-water flows and was used to develop a velocity flow field for the Clear Creek site. Figure 2 shows the representative flow field the Clear Creek reach and reveals areas of accelerating flow (i.e., blues areas) and decelerating flow (i.e., red areas). A series of four RFID transponders were placed at 2, 4, 8, and 12 ft. depths below the bed surface at the Clear Creek site. They were secured to a chain that ran along the stream bed and up the bank to a ground anchor. Transponders that were programmed with a unique wake-up pattern, along with unique identification or Serial Numbers (S/N) were used. The scour depth at the Clear Creek site on 04/05/2013 measured 0.085 m, while the scour depth measured 0.80 m on 06/07/2013, which followed three large flood events. These measured scour depths were compared to the predicted maximum scour depths using the established scour formulae by Jain and Fischer (1979), which predicted a maximum scour depth of 3.80 m, and CSU (1975), which calculated a scour depth of 1.94 m. These differences highlight the need to develop site-specific scour formula. The January and February 2014 measurements were conducted under low flow conditions and no scour was observed. However, the March measurements, which followed a snowmelt-driven runoff event, produced limited scour of a few inches. Figure 3 shows the processed RF signal strength decay curves corresponding to select measurement dates. The decay curve for the transponders on 04/05/2013 follows the expected linear pattern indicating little to no scour. Conversely, the decay curve for the transponders on 06/07/2013 shows that the transponder buried initially 2 ft. below the stream bed (marked with the red circle) significantly deviates from the linear trend indicating an abrupt change in transponder orientation resulting from its exposure due to scour. The 4-ft transponder during the March 2014 measurements shows a little more deviation, suggesting some slightly more scour. This was confirmed visually with a point gauge.

*1.c*) To facilitate the development of MARSS, two versions of the PAPTSAK RFID software were provided, one of them being a command line version, which was not initially proposed. A socket was developed to allow the use of the PAPTSAK from the DOS command line. All of the above was needed for the integration of the RFID system into the MARSS package. The PAPTSAK RFID software was also modified to include the transponder inclination angle function that returns the transponder orientation angle with respect to the excitation antenna. The PAPTSAK RFID software and the inclination function were also tested at the Willow Creek Park, IA. Measurements of the transponder RSSI values and different inclination angles were recorded (Table 1) to ensure that the software return angle was accurate. We were able to get 24 ft. with at least 50% success rate or higher and 32 ft. with 37% success rate.

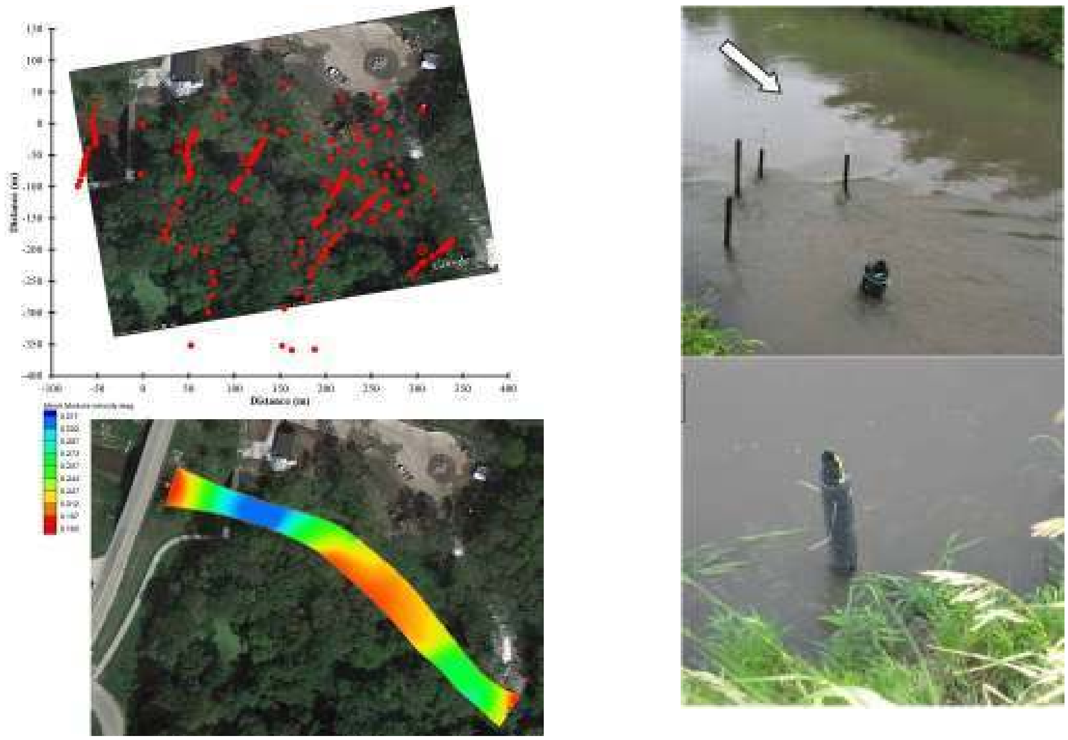

Figure 2. (left) Survey points and the velocity flow field of Clear Creek (right) pressure transducer Installed in a stilling well.

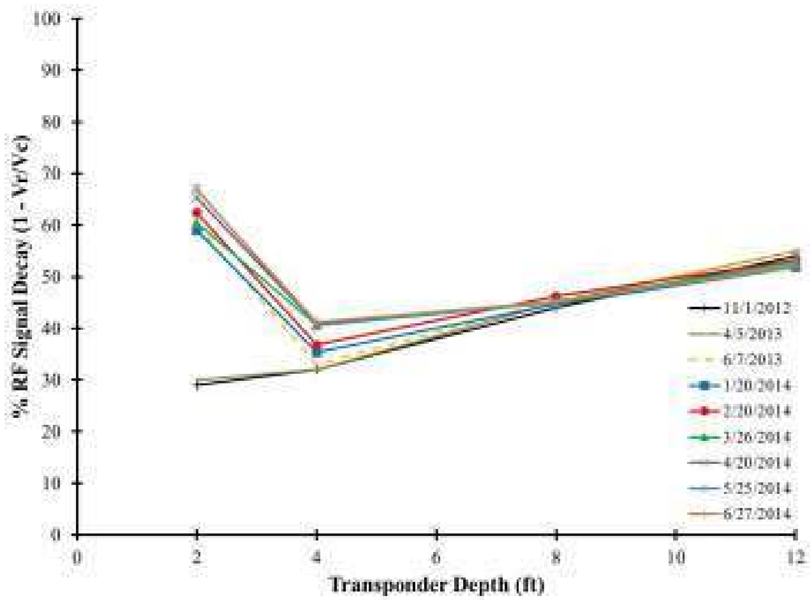

Figure 3. Processed RF signal strength decay curves at the Clear Creek site.

Table 1. Field test data sheet for transponder RSSI (Received Signal Strength Indicator) values and different inclination angles.

| Distance (ft) | Angle (deg.) | Converted Avg. RSSI | Success rate (%) |
|---|---|---|---|
| 18 | 0 | N.A. | 20 to 60% |
| 15 | 0 | 266.8 | 100% |
| | 15 | 263.5 | 100% |
| | 30 | 253.2 | 100% |
| | 45 | 229 | 80% |
| | 60 | 188.7 | 70% |
| | 75 | 106.5 | 20% |
| | 90 | N.A. | 0% |
| 10 | 0 | 385.6 | 100% |
| | 15 | 374 | 100% |
| | 30 | 359.5 | 100% |
| | 45 | 336.9 | 100% |
| | 60 | 303.8 | 100% |
| | 75 | 215.75 | 40% |
| | 90 | N.A. | 0% |
| 9 | 0 | 431.1 | 100% |
| 5 | 0 | 677.1 | 100% |
| | 90 | 227.25 | 40% |

## 2. <u>Task 2: Data Processing.</u>

The main objectives of this task were as follows:

a) To process RFID data to determine scour hole depth and volume.

b) To implement the detection algorithm into MARSS

c) To test and demonstrate the MARSS software in a real setting

*2.a*) The verification of the PAPTSAK RFID software was performed by measuring the RSSI of the transponder under various environmental conditions and orientations of the transponders with respect to the excitation antenna. Key parameters for developing a scour formula were identified based on existing scour formulae. A thorough literature review of widely used scour formulas was conducted. These parameters include flow depth, intensity of the approach flow, and the Froude number, as well as the bed sediment particle size distribution and the channel geometry. Additionally, information is required regarding the bridge pier shape and its alignment with respect to the approach flow. An RSSI vs. distance calibration curve (Figure 4) has been developed for this project. The PAPTSAK RFID software now includes an input box where users can manually enter the relative magnetic permeability (μr) of the surrounding medium (e.g., water, sand, gravel). Magnetic permeability is the ability of a specific medium to support the formation of a magnetic field within itself and affects the decay of the RF signals between the antenna and transponders. The relative magnetic permeability is the ratio of the magnetic permeability of the specific medium to the permeability of air. The new command line version of the PAPTSAK RFID software is able to operate in two modes. The first mode allows the user to manually interact with the program through the command prompt. The second mode allows other applications to interact with the program through a TCP socket. The program (server) will accept the same set of commands through the socket and return the output to the client.

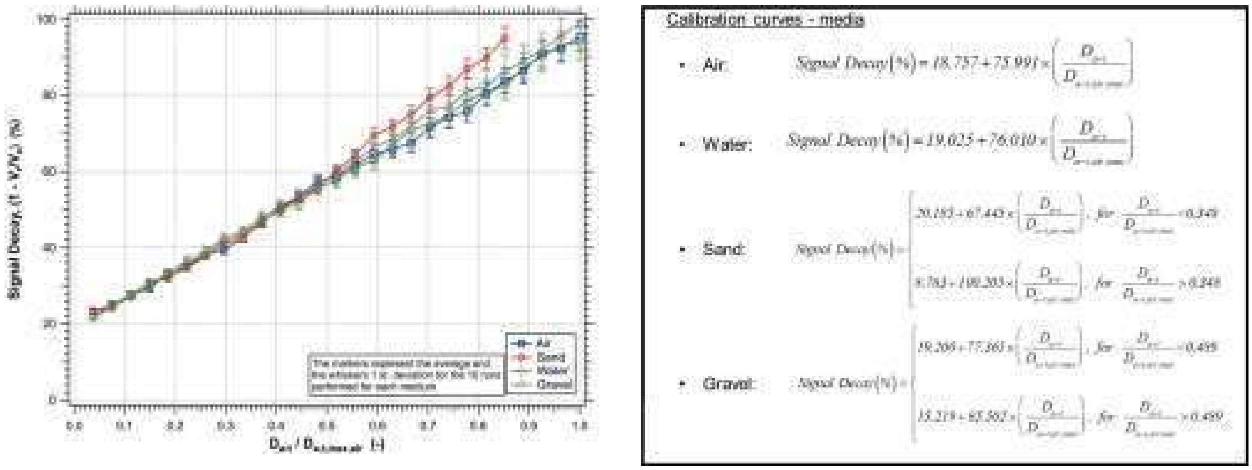


Figure 4. An RSSI vs. distance calibration curve

*2.b*) Detection in MARSS has two components. (i) Detection during data collection: a data examination procedure is added into the data-gathering software of the gateway. If scour is detected then an alert procedure is activated. The alert procedure can perform actions according to the preferences of the operator, e.g. can make an audible signal at the gateway, or initiate more frequent data sampling, or send in a notification to a control room if connectivity to it is available. (ii) During the loading of data from the database, the MARSS software reviews the values and runs a scour detection technique, which in the simplest form is value comparison to a preconfigured threshold. Once scour above threshold is detected, then a message dialog box is popped up and warns the user of the detection (Figure 5).

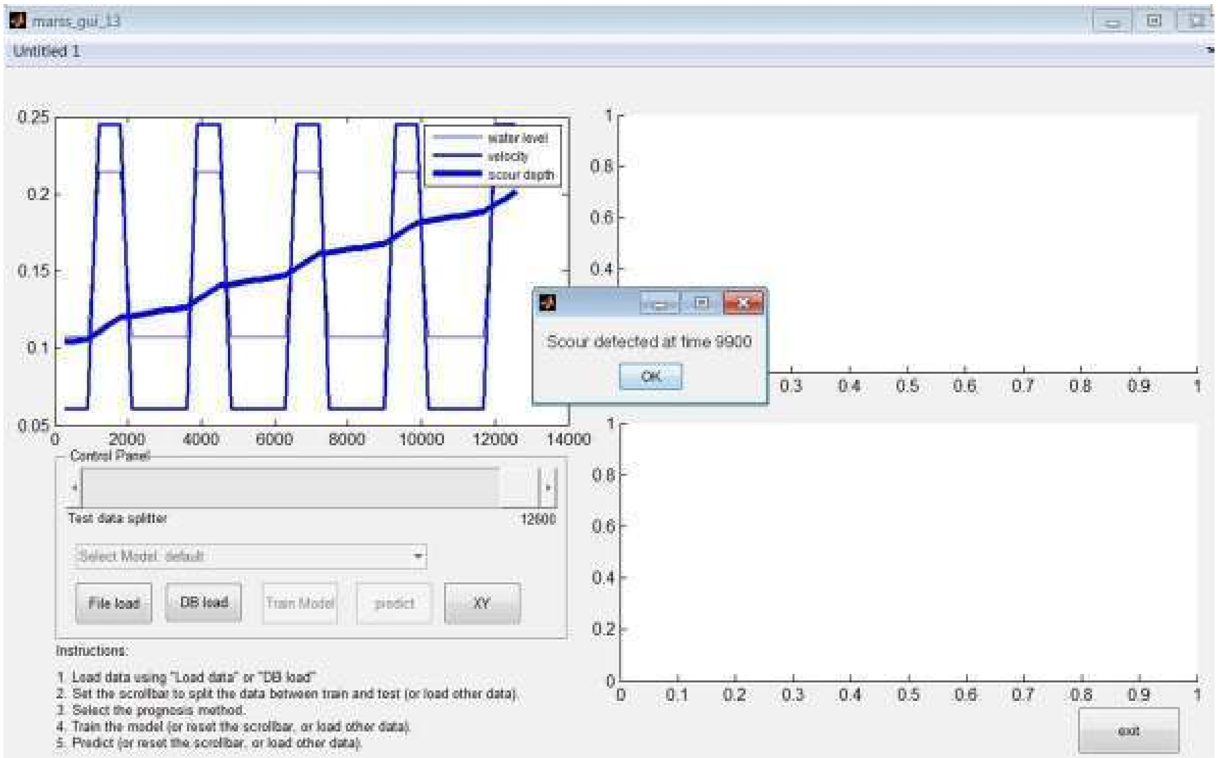


Figure 5. Scour detection screen

*2.c*) A load screen and a dashboard screen were developed for on-site MARSS system. The dashboard screen provides view of all the vital information for the sensor status as well for sensor readings. The load screen is a database selection form. The form does discovery of the database, then contacts the database and populates the information from it. The need to produce field-mode software has forced us in thinking innovative ways to come up with a design that is usable and friendly. The load and dashboard screen consists of three parts: the top part, where bridge catalogue information is displayed (name of the bridge, owner etc), the right part, where information about the piers and their scour is displayed, and then the left part where the controls and selection menu is placed (Figures 6 & 7). The user can track the “Gateway Battery Level” and “FDM Reading” for the bridge and “Node Power” and “Scour Depth” of each pier separately and regularly. Information in the form could be fetched manually by pressing “Refresh” button or select “Auto Refresh” check box to update and fetch form information in a predefined time sequences. User can select any of the piers form the list of piers to access to analysis form and this process will be done when user press the “Select Pier for Analysis” button.

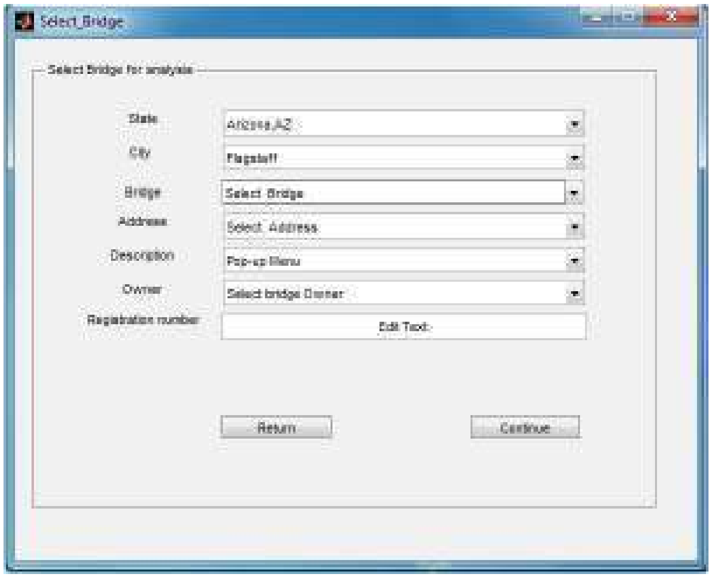


Figure 6.The load screen (it discovers only one bridge in the database and populates the fields automatically.

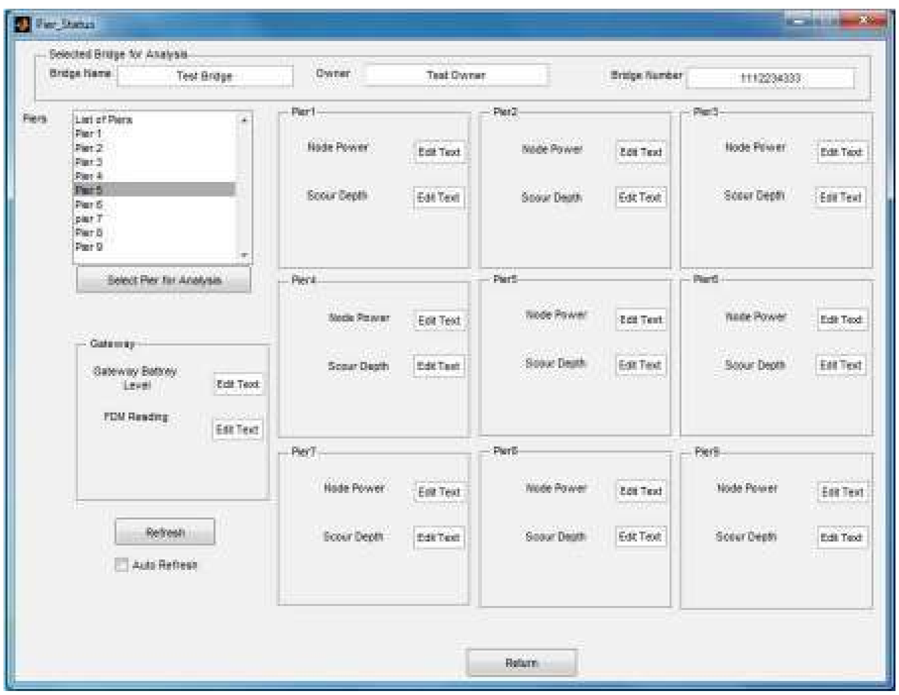


Figure 7. The dashboard form

## 3. Task 3. Diagnosis and Prognosis for Life Estimation

The main objectives of this task were as follows:

3.a) To develop a scour estimation equation as a threshold scour depth for MARSS based on the field data

3.b) To develop a data driven Gaussian process based prognosis model and integrate RFID sensors data to predict scour depth under clear water and live bed conditions.

3.a) Two groups of field datasets from the literature were selected: (i) 508 sets of field data from the bridge scour data management system (BSDMS) by Landers and Mueller (1996), and (ii) 110sets of field data from the FHWA documentation by USGS (2012). Data preparation included 2 main steps: 1) sorting usable data on 508 sets of BSDMS field data, and 2) fusing 110 sets of FHWA field data, that do not indicate the location of data collection as a parameter. The common parameters between BSDMS and FHWA are effective pier width, approaching flow depth, approaching velocity, median grain size, sediment gradation coefficient, and scour depth. These five parameters were selected as features for SVM (Support Vector Machine) classifiers. Using SVM unknown parameters are identified with data merging technique, and after data cleansing process, four hundred and three (403) sets of upstream samples and 61sets of downstream samples remained. Bridge scour model comparisons are made using a model performance plot (Figure 8). The 45° line is the ideal fit between predicted scour depth and the observed scour depth. The points above the ideal fitting line are allowable but they represent conservative scour predictions. The points below the ideal fitting line should be avoided because they imply that the model will fail to predict the actual scour level. The mathematical formula of conservative and failure rates is expressed by measuring the distance between an arbitrary point and an orthogonal projection point onto the ideal fitting line. Multi-objective optimization using genetic algorithm (MOGA) was used to minimize both conservative rates and the failure rates. Scour depth estimation formulation is shown in equation (1). The formulation was intentionally selected having power terms to make shape similar with existing empirical models.

$$\frac{y_s}{y_1} = 0.69 \times \left(\frac{a}{y_1}\right)^{0.35} \times \left(\frac{D_{50}}{y_1}\right)^{-0.10} \times \sigma^{0.39} \times Fr^{0.56} \tag{1}$$

where $y_s$ is the estimated scour depth, $a$ is the pier width, $y_1$is the approaching flow depth, $D_{50}$ is the diameter of bed material, $\sigma$ is the sediment gradation coefficient and $Fr$ is the Froude number. More detailed formulating procedure can be found in (I.Kim et al. 2014 and I.Kim et al. 2013). The new scour depth prediction model is compared with Froehlic model (Froelich 1988), HEC-18 equation (Arnesen et al. 2012) and the data driven Gene Expression Programming (GEP) (Khan et al. 2012) as shown in Figure 8.

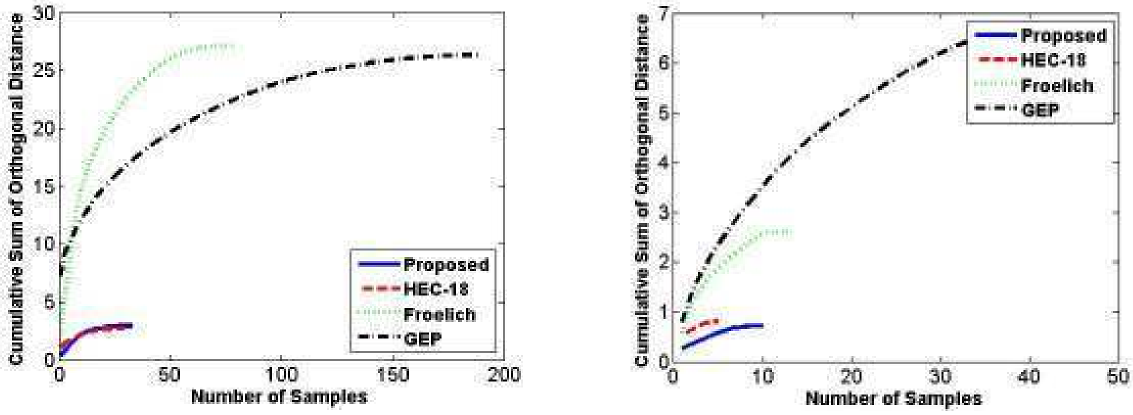


Figure 8. (left) The failure rate of upstream data, (right) The failure rate of downstream data

*3b*) The evolution of scour is highly stochastic in nature. In order to capture this uncertainty, probabilistic prognostic methods were developed to predict scour depth. First, a Gaussian process based prognosis model is developed to predict temporal scour using laboratory and field data sets from literature (Melville and Chiew, 1999; Mueller and Wagner, 2005). Then, a stochastic filtering approach (particle-filtering) was developed and integrated with the Gaussian process prognosis model to i) include the uncertainty in measurement data from RFID sensors and ii) to predict the scour depth using irrelevant training data. It is to be noted that the input parameters; current scour depth, flow depth and velocity are obtained through the RFID system and pressure transducer. A Gaussian Process (GP) model, which includes Bayesian uncertainty, is used for the prediction of the time-dependent scour depth. The GP is a collection of random variables, any finite number of which has a joint Gaussian distribution. GP makes predictions by projecting the input space to the output space, through inferring their underlying non-linear relationship. Once the algorithm is trained with the input and output parameters, it can predict the output parameter for unknown or new sets of input parameters. Figure 9 shows the prediction using laboratory and field data (Neerukatti et al., 2014). Multiple predictions were made using different combinations of the data. A coefficient of determination of 0.9016 was achieved for the laboratory data and 0.9018 was achieved for the field data.

An important aspect in predicting the scour depth is accounting for the uncertainties in both measured and predicted values. This is often the case in field applications, where the scour depth can be measured using RFID sensors. Therefore, it is necessary to account for this variability in measurement, and update both measured and predicted scour depth optimally at each time step. In this integrated methodology, the scour rate is predicted instead of the scour depth under varying flow conditions. This scour rate is then explicitly integrated over time to predict the temporal evolution of scour. In field conditions, it is often not possible to have the correct scour data to make real-time predictions. Therefore, the model has been modified to incorporate irrelevant scour data and make accurate predictions. Scour depth updates are used to calculate the error in the irrelevant training data, and correct for the error in making predictions (Neerukatti et al., Under Review). The results of prediction using both correct and irrelevant training data are shown in Figure 10. The legend “Adaptive Long Term Estimate” shows the prediction using the corrected scour rate. The scour rate is over-predicted by approximately 10%, which is a fail-safe prediction.

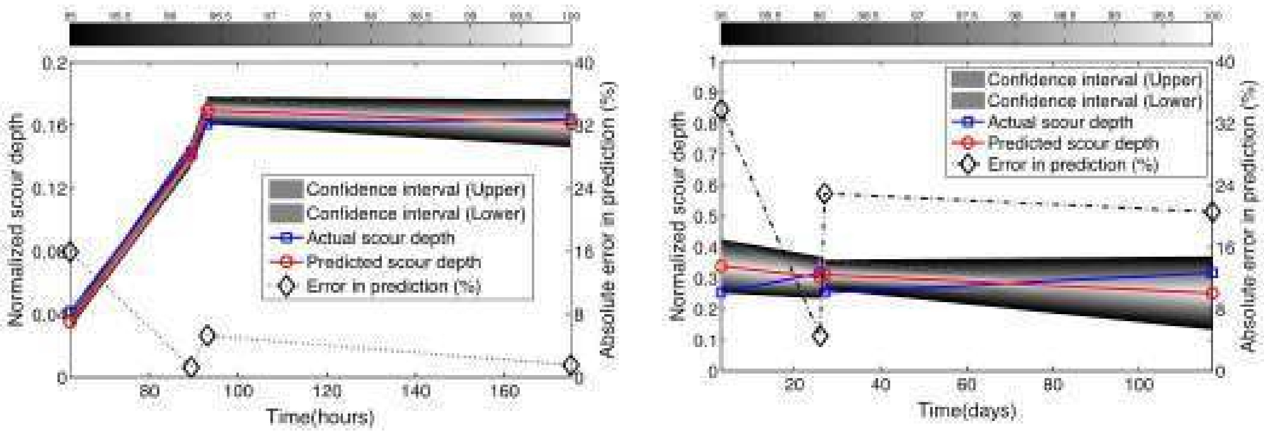


Figure 9. Prediction using Gaussian process prognosis model (left) laboratory data (right) field data

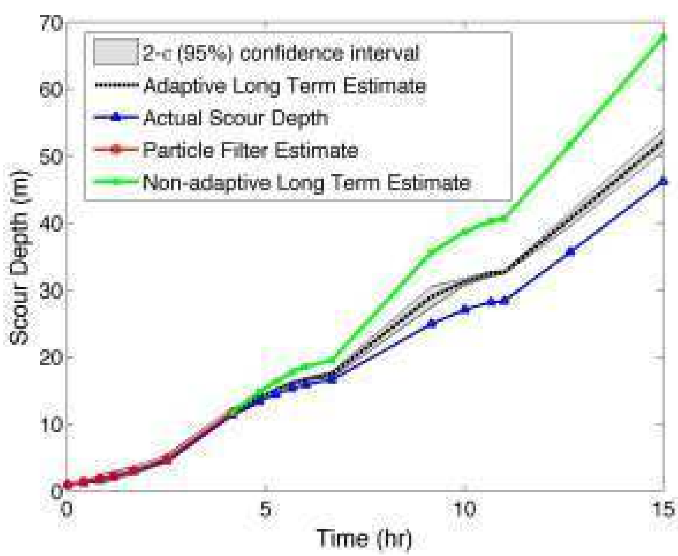


Figure 10. Prediction using the integrated approach with irrelevant data

## 4. Task 4. Decision Support System

The main objectives of this task were as follows:

*4.a*) To Integrate near real-time RFID sensing data with offline sensing data such as data from pressure transducers and other sensors in the prognosis model in MARSS

*4.b*) To develop a GUI based module for MARSS.

*4.a*) The data base was designed to allow for integrated storage of sensor data, so that both real-time data traffic and historical retrieval can be supported. The scalability and usability of the database scheme in servicing both real-time data and historical data was addressed.

*4.b*) The GUI has been designed as an everything-in-one window approach. The window is visually divided into four areas: three graph areas and one control panel, plus a lower area. The control panel is developed with a sequence of steps in mind: load data, set the training point, etc. The main 4 steps in GUI are as follows:
Step 1: Load the data. With the load button, the user is prompted to select the data to use. Once the data is loaded, then they are displayed on the data graph.
Steps 2 and 3: Select the training set and the function. The user slides the scrollbar in order to set the splitting point that defines the training set ("before" values) and testing set ("after" values). Then the user selects the desired function from the roll-down menu.
Step 4: Train and predict. The user presses the "Train" button and then the "predict" button. The other two graphs are populated with the prediction and a comparison with the recorded data.

GUI has been connected to a primary database, designed on MySql. Database is more accurate, reliable and secure than spreadsheets excel files. Especially when the number of records increase, processing the excel file takes time and reduce the response time. DB Load button has been set on GUI to load data from database and from this point user can work with the data. Another new feature in GUI is the XY button. This feature gives user ability to find XY position of any point in both right data graphs of GUI independently. User just needs to click on desire points he/she may interested in to know the position and system will show the XY position as you can see in the Figure 11.

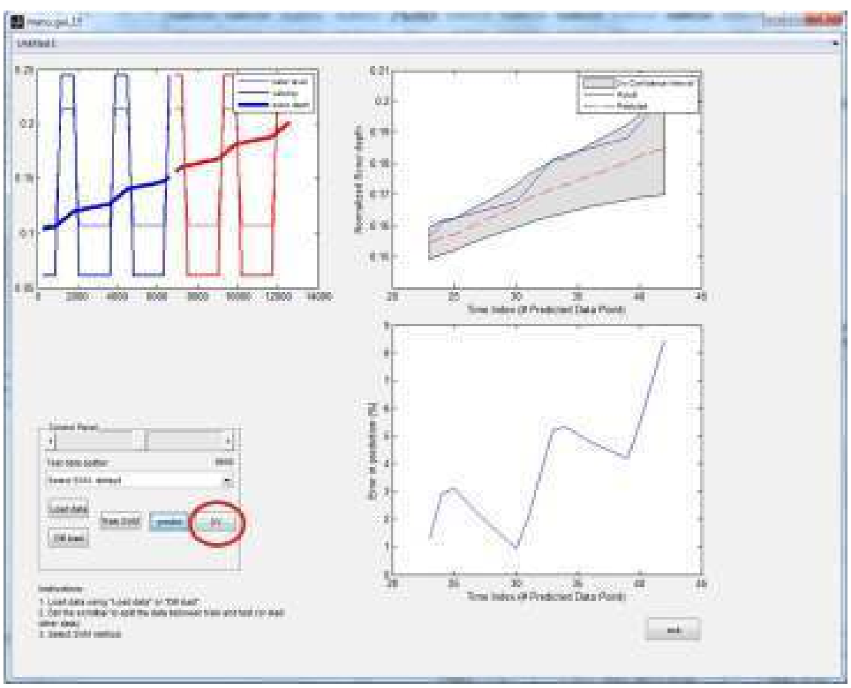

Figure 11. Graphic user interface of MARSS

## 5. Task 5. Cost Benefit Estimation and Outreach Plan

The main objectives of this task were as follows:

5.a) To conduct cost benefit estimation analysis

5.b) To ensure seamless adoption and successful implementation of MARSS

*5.a*) We have systematically collected financial data for quantitative cost benefit estimation analysis. The financial data includes the direct costs of hardware and software systems and hardware/software maintenance and upgrade costs during the life span of the bridge structure. The cost benefit estimation is included in Appendix B.

*5.b*) The advisory board members provided great feedback on the project direction and implementation plans. The frequency of the meetings with the advisory board was once every three months. Particularly we would like to appreciate Drs. Itty P Itty and Anne Elise from ADOT, Dr. Bing Zhao and Mr. Amir Motamedi from FCD, Mr. Casey Kramer from WS DOT, and Dave Claman from IA DOT. Videos of the different installation methods and the measurements in the field were taken during the project. These video were edited and distributed over the internet via "YouTube", as well as the project website (http://aims.engineering.asu.edu/RITA). These videos can be used for potential short courses and later workshops that the project team can provide to DOT personnel who are willing to incorporate the MARSS system at their bridge sites. The following journal papers, conference articles and presentations were submitted.

Kim, I., Yekani Fard, M., and Chattopadhyay, A. (2014). "Investigation of a Bridge Pier Scour Prediction Model for Safe Design and Inspection." J. Bridge Eng.,10.1061/(ASCE)BE.1943-5592.0000677,04014088.

Kim, I., Yekani Fard, M., and Chattopadhyay, A., "Bridge Pier Scour Prediction by Multi-Objective Optimization using the Genetic Algorithm" Proc., 9th International Workshop on Structural Health Monitoring. Stanford, CA September 2013

Neerukatti, R. K., Yekani Fard, M., Kim, I., and Chattopadhyay, A. (2014). "Gaussian process based prognosis model for bridge scour". *International Journal of Engineering Research and Technology* 3(6): 565-573.

Neerukatti, R. K., Yekani Fard, M. and Chattopadhyay, A. (Under Review). "A novel Gaussian process based particle-filtering approach for real-time prediction of scour depth". *Under review.*

Yekani Fard, M., (2014) "Multi-level Adaptive Remote Sensing Package for Bridge Scour Health Management." Transportation Research Board, 93rd Annual Meeting, January 12-16, Washington D.C.

Moustakidis, I.V., A.N. Papanicolaou, and A.G. Tsakiris. 2013. RFID bridge scour monitoring system. 2013 World Environmental and Water Resources Congress, American Society of Civil Engineers (ASCE). May 19-23, 2013. Cincinnati, OH.

Tsakiris, A.G., A.N. Papanicolaou, I.V. Moustakidis, and B. Abban. 2014. Framework for Bridge Scour Measurement Using Radio Frequency IDentification (RFID). 2014 American Society of

Civil Engineers/ World Environmental & Water Resources Congress, American Society of Civil Engineers (ASCE). June 2-5, 2014. Portland, OR.

## Hours/Effort Expended

Labor hours expended for all staff categories are reported in Table 2.

Table 2: Labor hours from 08/01/2012 to 10/31/2014.

| Personnel | Federal | | Cost share | |
|---|---|---|---|---|
| | Plan | Actual | Plan | Actual |
| Aditi Chattopadhyay | 752 | 611 | 857 | 620 |
| Masoud Yekani Fard | 1328 | 1231 | 2085 | 1656 |
| Thanos Papanicolaou | 110 | 101 | 242 | 141 |
| Sandeep Gupta | 60 | 53 | 444 | 394 |
| Georgios Varsamopolous | 699 | 623 | 0 | 0 |
| Graduate Students | 10537 | 10012 | 0 | 0 |

## Acknowledgment

This project is supported by Grant No. RITARS-12-H-ASU from the Office of the Assistant Secretary for Research and Transportation (OST-R), Program Manager Mr. Caesar Singh.

"DISCLAIMER: The views, opinions, findings and conclusions reflected in this paper are the responsibilities of the authors only and do not represent the official policy or position of the USDOT/OST-R, or any State or other entity."

### References

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., and Clopper, P. E. (2012). "Evaluating scour at bridges" (No. FHWA-HIF-12-003).

Hunt, B. E. (2009). "Monitoring scour critical bridges" (Vol. 396).Transportation Research Board.

Chattopadhyay, A., Fard, Y, F., Gupta, S., and Papanicolaou, T. (2014). "Multi-level Adaptive Remote Sensing System" USDOT Research and Innovative Technology Administration, <http://aims.engineering.asu.edu/RITA/>

Froelich, D. C. (1988). "Analysis of onsite measurements of scour at piers." Hydraulic Engineering (1988) (pp. 534-539). ASCE.

Guo, J., Suaznabar, O., Shan, H., and Shen, J. (2012). "Pier Scour in Clear-Water Conditions with Non-Uniform Bed Materials" (No. FHWA-HRT-12-022).

Kim, I., Fard, M., and Chattopadhyay, A. (2014)."Investigation of a Bridge Pier Scour Prediction Model for Safe Design and Inspection." J. Bridge Eng.,10.1061/(ASCE)BE.1943-5592.0000677,04014088.

Kim, I., Yekani Fard, M., and Chattopadhyay, A., “Bridge Pier Scour Prediction by Multi-Objective Optimization using the Genetic Algorithm” Proc., 9th International Workshop on Structural Health Monitoring. Stanford, CA September 2013

Khan, M., Azamathulla, H. M., Tufail, M., and AbGhani, A. (2012). "Bridge pier scour prediction by gene expression programming." Proceedings of the ICE-Water Management, 165(9), 481-493.

Landers, M. N. and Mueller, D. S. (1996). "Evaluation of selected pier-scour equations using field data." Transportation Research Record: Journal of the Transportation Research Board, 1523(1), 186-195.

Nassif, H., Ertekin, A. O., and Davis, J. (2002). "Evaluation of Bridge Scour Monitoring Methods." United States Department of Transportation, Federal Highway Administration, Trenton.

Radchenko, A., Pommerenke, D., Chen, G., Maheshwari, P., Shinde, S., Pilla, V., andZheng, Y. R. (2013)"Real time bridge scour monitoring with magneto-inductive field coupling." In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 86922A-86922A).

Xiong, W., Cai, C. S., and Kong, X. (2012). "Instrumentation design for bridge scour monitoring using fiber Bragg grating sensors." Applied optics, 51(5), 547-557.

Zarafshan, A., Iranmanesh, A., and Ansari, F. (2011). "Vibration-based method and sensor for monitoring of bridge scour."Journal of Bridge Engineering, 17(6), 829-838.

# Appendix A

IIHR - HYDROSCIENCE & ENGINEERING

# RFID Transponders Field Installation Manual

PAPANICOLAOU RESEARCH GROUP

**3/1/2013**

# RFID Transponders' Installation Manual

This manual describes the installation process of the 120-mm long, PVC encased, RFID transponders into the stream bed using a vibracore drill. The proper installation of the RFID transponders is of primary importance for the successful monitoring of scour within a river channel; therefore, much attention is required. This manual includes all the necessary steps prior to and after the RFID transponders installation in the field. A demonstration movie was created to accompany this manual, where the setup of the vibracore drill and the RFID transponder installation process are presented.

- **IMPORTANT STEPS PRIOR TO THE RFID TRANSPONDERS INSTALLATION.**

**STEP #1:**

Identify potential scour location(s) in the stream bed along the reach of interest (i.e., possible scour holes around bridge piers). It is important to spot all possible scour locations in your study reach. The best way to accomplish this is by stepping into and walking into the stream, if this is possible, or by using a boat with a sonar device or/and a measuring rod. In all situations, all required safety rules should be followed, including the wearing of life vests.

**STEP #2:**

Once the potential scour location(s) have been identified, a geodetic survey of the study reach should be conducted to determine the exact dimensions of the scour location(s). The geodetic survey can be performed either using a total station or a sonar device (the latter will provide a more detailed depiction of the stream bed topography. This information will be used to select the best location(s) for installing the RFID transponders.

**STEP #3:**

Once the RFID transponders installation location(s) have been confirmed, analysis of the bed particle size material should be performed to develop the bed particle size distribution (i.e., sieve analysis if it is a coarse-grained soil, hydrometer test if it is a fine-grained soil or by image analysis if it is gravel). Sediment cores should be extracted at the vicinity of the installation location(s). This information will be used to estimate the maximum scour depth using existing scour formulas (Jain and Fischer 1979; Froehlich 1988; Melville 1997) for a number of different flow conditions (e.g., channel forming or bankfull discharge with a return period of approximately 2 years, floods, and average annual discharges). This information will be the guide for determining the maximum transponder installation depth. For example, if the maximum predicted scour depth is 5ft., there is little point of installing the transponders below 7ft.

**STEP #4:**

Develop an incipient motion criterion based on the bed particle size distribution to serve as a "warning" system for obtaining RFID measurements. The incipient motion criterion will determine the condition for particle entrainment (threshold of movement). Brownlie (1981) developed an improved Shields diagram for incipient motion (Figure 1). On the y-axis is the dimensionless shear stress ($\tau^*$), while on the x-axis is the particle Reynolds number ($R_p$).

The dimensionless shear stress (or Shields parameter) is defined as the ratio of the bed shear stress ($\tau_o$) exerted by the flow over the submerged specific weight of a particle ($\gamma_s$-$\gamma$) multiplied by the particle characteristic diameter ($d_s$). The bed shear stress ($\tau_o$) is given by the formula: $\tau_o=\gamma*R*S$, where $\gamma$ is the specific weight of water; R the hydraulic radius, defined as the ratio of the channel's cross-sectional area of the flow (A) to its wetted perimeter (P) (the portion of the cross-section's perimeter that is "wet"); and S is the bed slope.

The particle Reynolds number ($R_p$) is defined as the ratio of the friction velocity ($U_*$) multiplied by the particle characteristic diameter ($d_s$) over the kinematic viscosity ($\nu$). The friction velocity ($U_*$) is given by the formula: $U_* = (\tau_o/\rho)^{1/2}$, where $\tau_o$ is the (bed) shear stress exerted by the flow on the stream bed; and $\rho$ is the water density.

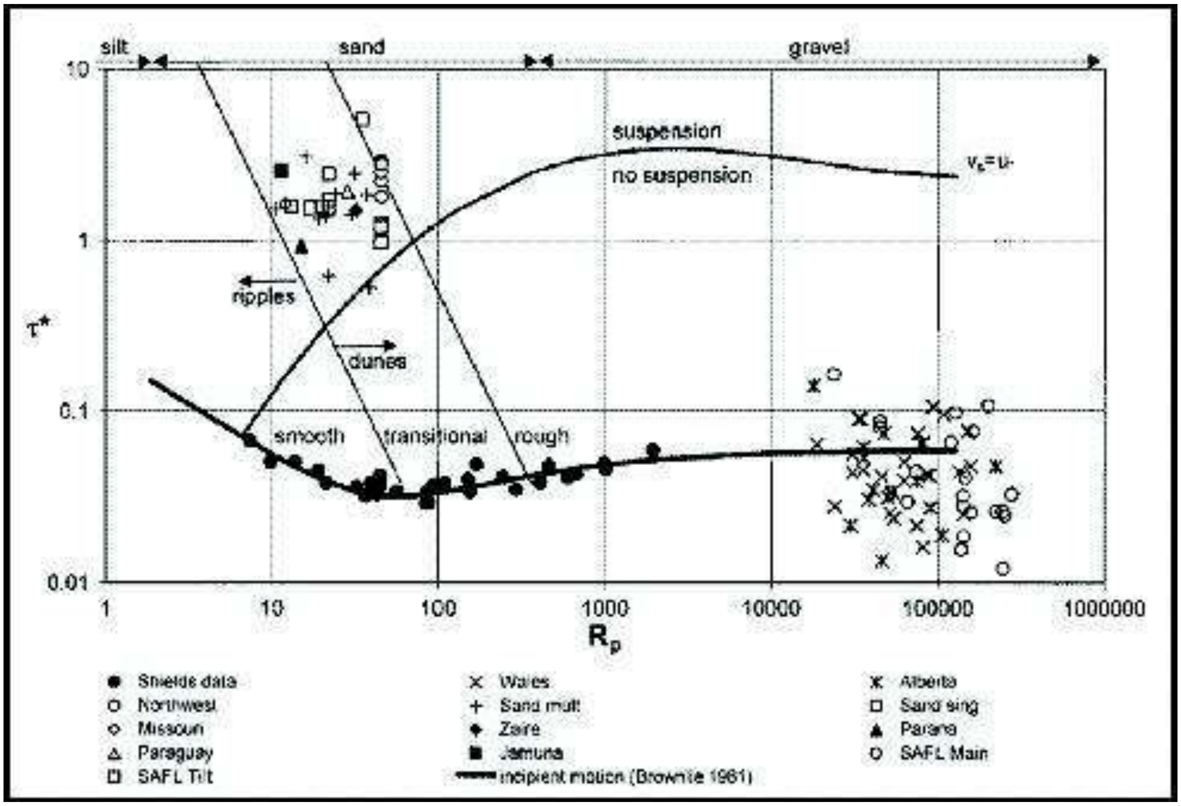


Figure 1. Enhanced Shields diagram for incipient motion according to Brownlie (1981).

## STEP #5:

Once the above tasks have been successfully completed, the RFID transponders can be installed into the stream bed at the specified location(s). The RFID transponders installation will be performed by using a vibracore drill. The vibracore works by having the drill head vibrate at high frequencies to loosen the sediment particle bonds allowing the core tube to penetrate into the soil under the weight of the drill head. The vibracore drill is ideal for use in riverine environments as it easily penetrates saturated sediment. The penetration depth is limited only by the height of the metal structure (tripod) that accommodates the vibracore drill. A vibracore drill system consists of the following components (Figure 2):

(a) The vibracore drill head;

(b) An electrical winch that allows the vibracore to move upwards and downwards;

(c) A power source consisting of 2 heavy duty marine batteries connected in parallel, and resulting in 24 Volts;

(d) An acrylic tube (3 in. inner diameter) attached to the bottom end of the drill head;

(e) A PVC tube (2 in. inner diameter) attached to the bottom end of the acrylic tube. The length of the PVC tube is dictated by the RFID transponder maximum installation depth and the stream flow depth; and

(f) A metal base (i.e., tripod) to support and accommodate for the vibracore. Extension rods can be attached to the tripod legs to facilitate deeper RFID transponder installation depths.

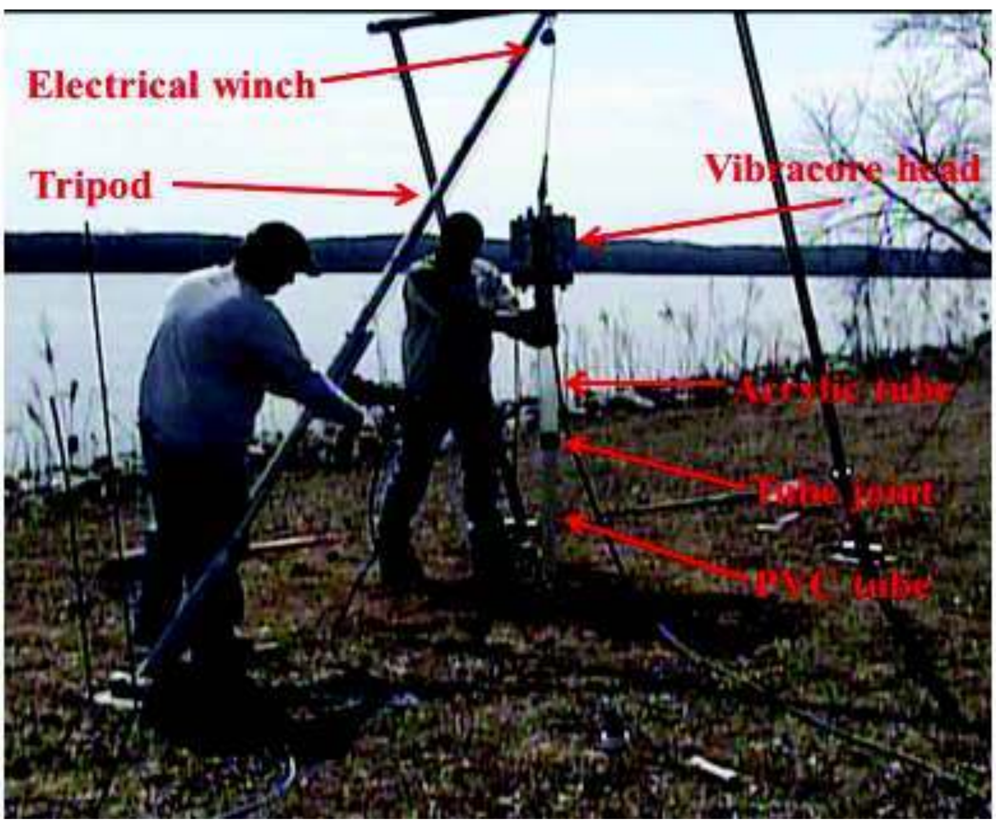


Figure 2. Vibracore drill components and field setup.

## Laboratory preparation for the RFID transponders field installation

Before the vibracore drilling system is used in the field, some preliminary tasks should be conducted in the laboratory to optimize the installation process. These tasks are summarized herein:

1. Assign the RFID transponders with unique identification (ID) numbers. It is better to assign successive ID numbers to RFID transponders if they are attached along a Leopold chain. Always prepare some spare RFID transponders.
2. Encase the RFID transponders in PVC. This is to make them water-tight. Always prepare some spare RFID transponders.
3. Construct a Leopold chain by using a sufficient number of RFID transponders based on the required scour resolution. Always prepare some spare Leopold chains (Figure 3).

Figure 3. Leopold chain constructed with PVC encased RFID transponders.

4. Glue the bottom end of the last RFID transponder on the Leopold chain to a "pointy" PVC cup of 2 in. outer diameter using PVC glue. The "pointy" PVC cup should not be glued on the vibracore PVC tube. The loose "pointy" PVC cup will be used as an anchor for the Leopold chain once the installation depth is reached and the acrylic and the PVC tubes are removed (Figure 4).

Figure 4. PVC "pointy" cup of 2 in outer diameter.

5. Prepare a number of PVC tubes that will be able to account for the following (Figure 5):
    a. The maximum RFID transponder installation depth and
    b. The stream flow depth at the installation location(s).
6. Drill a hole on the upper part of the acrylic tube to pass through and secure the Leopold chain during the installation process, to ensure that the RFID transponders are always oriented perpendicular with respect to the stream bed.

Figure 5. PVC joint connecting the PVC and the acrylic tubes.

## Vibracore system field setup

1. Set up and secure the tripod at the appropriate height to achieve the desirable transponder installation depth.
2. Attach and secure the drill head to the tripod by using the electrical winch. If the vibracore drill needs to be placed higher, then attach the extension rods at the bottom end of the tripod legs.
3. Connect the acrylic and PVC tubes using a PVC joint (Figure 6). If needed wrap the PVC joint with electrical tape to increase the friction between the acrylic and the PVC tubes.
4. Place the Leopold chain built with RFID transponders into the vibracore drilling tubes (acrylic and PVC tubes) (Figure 7). Secure the RFID transponders by passing the chain through the drilled hole (see "Laboratory

preparation for the RFID transponders field installation" tasks 6 for more information) on the upper part of the acrylic tube.

5. Attach the connected acrylic and PVC tubes to the vibracore drilling head by fastening a pair of specially designed screws.

Figure 6. PVC joint wrapped up with electrical tape to increase friction between the acrylic and the PVC tubes.

6. Make sure that the vibracore is always drilling perpendicular with respect to the stream bed. A level can be attached to the vibracore drilling head to ensure that the vibracore is always perpendicular.
7. The vibracore is now ready for use. Once the installation depth has been achieved (Figure 8A), loose the secured chain and slowly pull up the vibracore. As the vibracore tubes coming out of the stream bed, the walls of the drilled hole will collapse and bury the RFID transponders (Figure 8B).
8. Once the Leopold chain has been successfully installed and the vibracore drill has been pulled up, carefully remove the acrylic and PVC tubes, then the vibracore drilling head and finally disassemble the tripod.
9. To install more Leopold chains into the stream bed, follow steps 1-8.

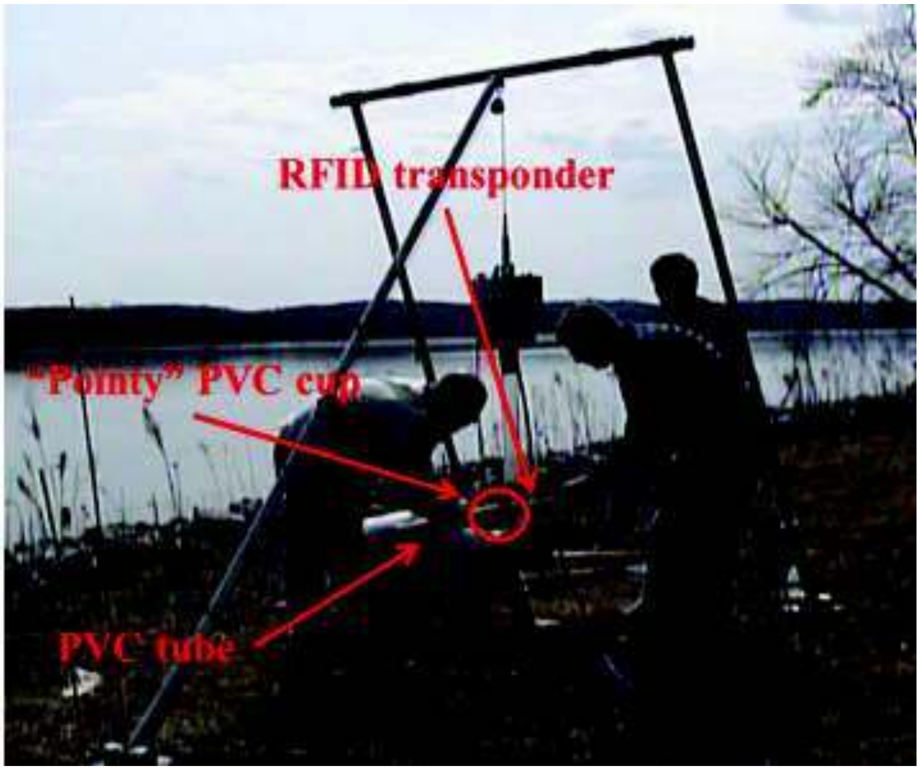


Figure 7. Placing the RFID transponder into the PVC tube and securing it with the "pointy" PVC cup.

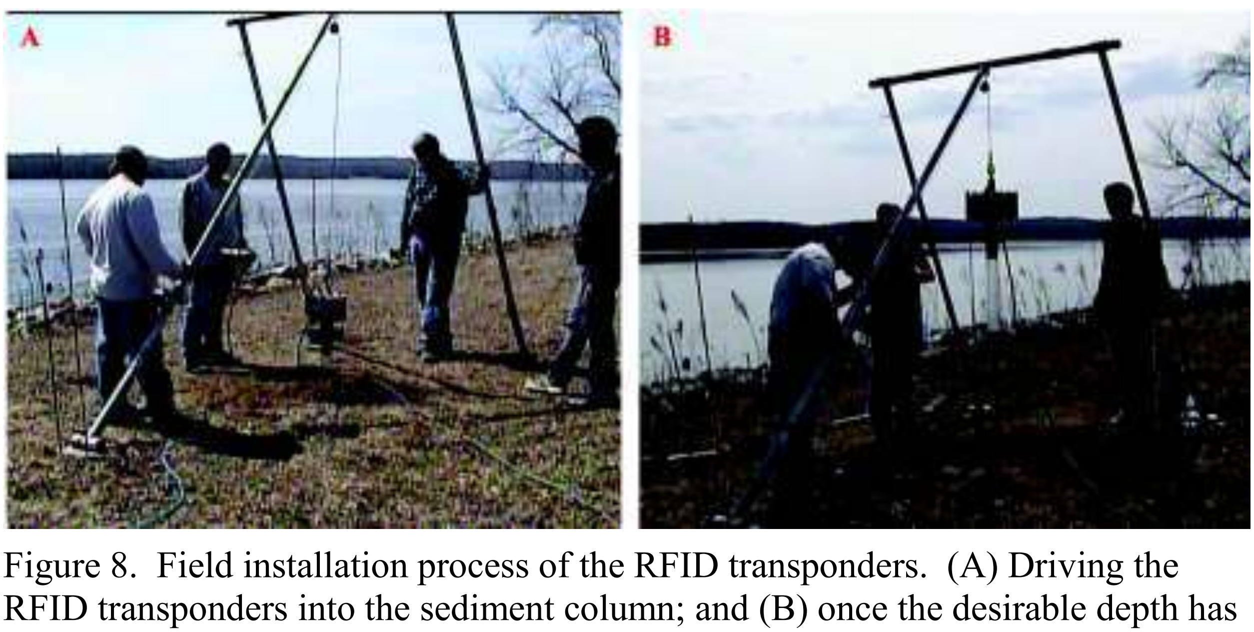


Figure 8. Field installation process of the RFID transponders. (A) Driving the RFID transponders into the sediment column; and (B) once the desirable depth has been reached, the vibracore is pulled up, while the RFID transponders have been buried into the stream bed.

# Appendix B

One of the bridges suggested by the Arizona Department of Transportation (ADOT) was selected as a case study for a cost-benefit analysis of MARSS. However, this analysis will be extended to all the bridges using MARSS. The details for the case-study bridge are as follows:

Bridge name: New River bridge (south bound) over I-17

Structure number: 1291

Number of Piers: 10

For this bridge, the RFID system is designed to detect scour depth up to a distance of 10 ft. We will deploy 5 transponders spaced every 2 ft. along a Leopold chain at the upstream end of each pier and the 2 flanks. Each pier will have one antenna and a reader attached to it, which will detect the RF signal from the transponders. The cost-benefit analysis below contains pricing information for the development of the individual components of MARSS, as well as the labor costs. The hourly wage of the technician was assumed to be $20/ hour, which is the equivalent 2012 base salary for a GS-9 technician. The following tables have been developed for the cost benefit analysis:

1. Antenna
    a. Material cost for one antenna – The table below contains the information needed to construct a 10 ft. x 6 ft. antenna to detect the RFID transponders. These dimensions have been optimized by the Iowa team to maximize the detection distance of the RFIDs. There are no commercially available antennae of this size.

| **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 | $24.00 |
| PVC 90$^o$-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 |
| | | | **$269.71** |

b. Fabrication cost of one antenna – The construction of one antenna will take 2 trained technicians 1.5 days (i.e., 12 hours); however, this includes the time needed to purchase the necessary parts. For the construction of each subsequent antenna, it will require the 2 technicians only 8 hours, as the purchasing will already be completed.

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | Technician | 12 | $20 | $240 |
| 2 | Technician | 12 | $20 | $240 |
| | | | | **$480** |

c. Installation cost for one pier - The mounting of the antennae at the bridge site depends on the accessibility of the bridge, location of the pier, water level of water, and weather conditions.

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | Technician | 8 | $20 | $160 |
| 2 | Technician | 8 | $20 | $160 |
| | | | | **$320** |

d. Maintenance cost for one pier per year - We suggest that DOT personnel should check the antennae installation at least monthly (12 times per year). The actual inspection will be minimal but we have allotted for travel time. Should the antenna be damaged, it will most likely require the construction of a new antenna.

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | **Technician** | **24** | **$20** | **$480** |

2. Reader
   a. Material cost for one reader - One reader will be attached to each antenna.

b. Fabrication cost for one reader – The assembly of each reader will require a trained technician approximately 4 hours to complete.

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | Technician | 4 | $20 | $80 |

c. Installation cost for one pier - It has been considered with the installation of the antenna (item 1c).

d. Maintenance cost for one pier per year (e.g., tuning) - It has been considered with the maintenance for the antenna in 1d.

3. Transponders

a. Material cost for one Leopold chain - We assume a maximum scour depth for this bridge site of 10 ft. with the distance between two transponders on a chain as 2 ft. Therefore, we will need 5 transponders per chain. The commercially available transponders have a detection distance between 7 and 20 ft. depending on the antenna dimensions. The custom (or non-commercial) transponders have a detection distance of about 60 ft.

| Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|
| Transponders (Commercial) | 5 | $25 | $125 |
| Transponders (non-Commercial) | 5 | $210 | $1050 |
| | | | **$125 or $1050** |

b. Material cost for one Leopold chain

| Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|
| 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 |
| | | | **$55.24** |

*This table shows the total cost of the materials required to build a Leopold chain for 5 transponders. The transponders cost is not included.

c. Fabrication cost for Leopold chain

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | Technician | 6 | $20 | $120 |

d. Installation cost for one pier - This is the installation cost for 1 pier.

| Line | Personnel | Hours | Hourly Rate | Total Cost |
|---|---|---|---|---|
| 1 | Technician | 4 | $20 | $80 |
| 2 | Technician | 4 | $20 | $80 |
| | | | | **$160** |

e. Monitoring cost for one pier per year - It has been considered with the maintenance for the antenna in 1d.

f. Replacement cost for one pier per year - The transponders are expected to last five years on moderate use.

4. Power source
   a. A 12 V battery is needed for the reader.

| Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|
| 12 V Battery | 1 | $45.00 | $45.00 |
| Charger | 1 | $40.00 | $40.00 |
| | | | **$85.00** |

b. For data collection we consider laptop with 3 extra batteries for 20 bridges (this is for now)
The approximate price would be $600 for laptop + 3 extra batteries +12 V battery