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SIMPLE COST-EFFECTIVE SCOUR SENSOR

Prepared By
Farhad Ansari
University of Illinois at Chicago

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A report of the findings of
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Simple Cost-Effective Scour Sensor

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16. Abstract

Local bridge scour is caused by the interference of bridge piers with the flow of water and is characterized by the formation of scour holes. Local scour occurs at a bridge pier when the local flow field is strong enough to remove bed materials. Several variables affect the scour depth including the flow intensity, the relative flow depth, the pier-width, and the properties of the river bed materials.

This study developed a fiber optic scour sensor capable of monitoring and providing quantitative characteristics of both scour depth and flow processes, i.e. rate. The proposed fiber optic scour sensor will include a single Fiber Optic Bragg Grating (FBG) sensor embedded inside a rod cantilevered into the river bed. The sensor will allow for better monitoring of scour and therefore better bridge maintenance.

Research results proved that the simple concept for the development of a very low cost sensor with only one sensing element is sound. The simplicity of the sensor allows for widespread implementation in myriads of scour critical bridges. Field experimentations have been limited to few tests; however, and the system has not been thoroughly tested under flood situations. Further experiments are necessary to accurately determine the sensor resolution and repeatability under field conditions and to further establish the software for more sophisticated and user-friendly remote monitoring applications.

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Members of the Technical Review Panel are the following:

Dave Copenbarger, IDOT (Chair)
Patricia Broers, IDOT
Sarah Wilson, IDOT
Matthew O'Connor, IDOT
William Shaw, IDOT
Mark Gawedzinski, IDOT

EXECUTIVE SUMMARY

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BACKGROUND

Scour is considered one of the major causes of highway bridge failures in the United States. It is especially prevalent during floods and periods of rapid river flow activities. During floods, erosion of the foundation materials below the bridge piers causes structural instability. This process is dynamic, where erosion takes place near the peak flow rates, and deposition of sediments occur during the descending stages of the flood. If local scour is not identified in time, the structural integrity of the foundation progressively deteriorates and leads to severe damage and collapse of the bridge. According to the data from the National Bridge Inventory (NBI), 484,546 highway bridges out of an inventory of 590,000 in the United States cross over waterways. Sixty percent of these bridges have been declared scour critical (Hunt and Price 2003; Gee 2003). The 1987 catastrophic collapse of the Schoharie Creek Bridge in New York state due to scour was one of the most severe bridge failures in the United States. Considering the consequences of scour damage, the Federal Highway Administration (FHWA) issued a Technical Advisory in 1988 revising the National Bridge Inspection Standards (NBIS) to require evaluation of all bridges for susceptibility to damage resulting from scour. This issue is not only confined to the U.S. boundaries, and local scour was identified as high-priority research needed for infrastructure by the North American Euro Pacific Workshop for Sensing Issues in Civil Structural Health Monitoring (Ansari 2004). Participants of this workshop included government highway agency engineers as well as researchers from academia and industry from the U.S. and other countries. Development of a simple, reliable, and cost-effective scour monitoring system that is easily mass produced will have a tremendous impact on the state of health of our bridges. Mass production and cost efficiency paves the way for rapid distribution to highway agencies and ensures safety. Furthermore, it assists the highway officials in scheduling periodical maintenance programs and circumvents costly repairs and bridge replacements as well as emergency road closures.

Local scour is caused by the interference of bridge piers with the flow and is characterized by the formation of scour holes resulting from clear-water scour or live-bed scour. Clear-water scour occurs when the bed materials upstream of the scour area are at rest. The maximum local scour depth is reached when the flow can no longer remove bed material from the scour area. Live-bed scour occurs when the river transports general sediment.

A review of the state-of-the-art reveals that a great amount of effort has been expended for the research and development of scour monitoring sensors and systems. Applicability of the existing methodologies, however, has been limited considering issues pertaining to the complexity and cost effectiveness, resolution, capability for providing repeated and reliable information, installation, and rigor in data retrieval and processing. A wide array of methodologies have been used in attempts to develop scour monitoring sensors including sonar (Mason et al. 1994; Hays et al. 1995), time domain reflectometry or TDR (Dowding et al. 1994; Yankielun et al. 1999), sliding collar (Lagasse et al. 1997; Richardson et al. 1994), radar (Gorin et al. 1989), piezoelectric (Lagasse et al. 1997), and the seismic transducer techniques (Zabilansky 1996).

Radar and sonar-based techniques have been successful in monitoring the scour depth after a flood event. However, their applicability for monitoring the scour event in real time has been limited, and both techniques involve rigorous data processing and interpretation schemes. The information provided by battery operated devices including those based on neutral buoyancy of seismic transducers are crude, and in general, these devices have limited active lives. Buried mechanical devices such as magnetic collars are comparatively inexpensive. However, it is not possible to reset these devices for reuse, and issues pertaining to binding and installations have hindered their usage. Techniques based on TDR either use sacrificial sensors that break off during scouring events or solely depend on the impedance mismatch and are not practical for real applications involving various types of sedimentations. Attenuation and pulse dispersion errors due to the length of electrical cables as well as probe length limitations are amongst other deficiencies of these systems. Sensors based on spatial positioning of PZT or fiber optic sensors (Bin et al. 2006) on a rod that can be driven into the sediment provide only incremental resolution. Moreover, these multi-sensor arrangements are expensive since they require sophisticated multi-channel data acquisition and interpretation techniques. None of the currently available scour monitoring techniques possesses the necessary attributes for widespread deployment in scour critical bridges. The desired device must be:

- accurate
- simple in principle
- easy to install and operate
- simple to calibrate
- cost effective
- reliable

In addition, the sensor has to survive many floods and operate maintenance-free over a long period of time. These attributes provide the authorities with the necessary tools to make decisive actions for maintenance as well as secure the safety of the traveling public. The payoffs are significant in terms of tremendous cost savings for the federal and state highway agencies considering the current annual levels of scour damage and bridge failure related expenditures.

DEVELOPMENT OF SCOUR SENSOR

GENERAL DESCRIPTION OF THE PROPOSED SCOUR SENSOR

The work described here pertains to the development of a scour sensor capable of monitoring the scour depth. The system includes a single sensor element based on any of the sensing mechanisms including but not limited to: fiber optics, electrical strain gages, accelerometers, PZT sensors, wireless sensors, etc. The sensor element is attached to a rod cantilevered into the river bed. As the scour initiates and develops, it changes the dynamic characteristics of the rod, which is measured from the sensor attached to the rod. The dynamic characteristics of the rod are independent of the flow rate, and it is directly related to the scour depth.

This report begins by describing the dynamic characteristics of a rod or a pile when submerged in a fluid and embedded in soil. Then, the calibration process is described including finite element modeling, followed by preliminary proof of concept experiments and results and field tests.

SENSOR CALIBRATION PROCEDURE

The natural frequency of a submerged rod driven into the river bed soil results from interaction of river water, river-bed soil, and the rod. If the effect of water and soil is ignored, the natural frequency of a cantilevered rod with a circular section and uniform distributed mass is calculated through the following formula:

$$\mathrm{f} = 0.14\frac{\mathrm{d}}{\mathrm{L}^2}\sqrt{\frac{\mathrm{E}}{\rho}} \qquad (1)$$

In which d and L are the rod diameter and length, E is the rod material modulus of elasticity, and ρ is the rod density. When the effect of water as an interacting fluid comes to the picture, the natural frequency of a cantilevered rod submerged in a fluid with ρ_w density becomes:

$$\mathrm{f} = 0.14\frac{\mathrm{d}}{\mathrm{L}^2}\sqrt{\frac{\mathrm{E}}{\rho + \rho_w}} \qquad (2)$$

The primary effect of the surrounding fluid on the natural frequency of a symmetric structure in the fluid is simply to increase the effective mass.

In reality, a rod driven inside the soil does not act as a perfectly fixed cantilever. Therefore, the flexibility of the rod and the surrounding soil should be modeled properly in the modal analysis. The winkler reaction spring system for lateral support by the surrounding soil can be assumed for this purpose (Figure 1). Discrete soil spring stiffness $\mathrm{K_i}$ at depth $\mathrm{z_i}$, as shown in Figure 1,can be determined for a given tributary length $\mathrm{B_i}$ of the rod:

$$\mathrm{K_i} = \mathrm{k^* z_i B_i} \qquad (3)$$

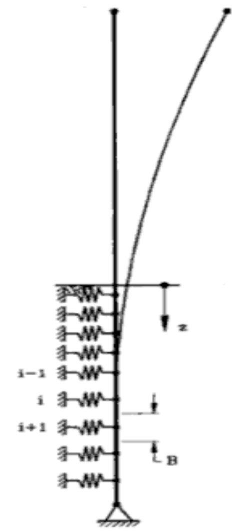

Figure 1. Sensor rod and the idealization of the soil subgrade modulus with winkler reaction spring system.

Values for k^* can be obtained from the geotechnical literature in relationship to Young’s modulus or subgrade modulus of the soil, which in turn can be found (although with significant variability) from standard penetration tests, shear wave velocity measurements, or direct bearing tests carried out by an experienced geotechnical engineer. The natural frequency of a rod with above conditions as well as the sensor calibration factor is considerably sensitive to the value of k^*. For this reason, practical implementation of the scour sensor requires accurate determination of k^*. The investigators developed a field calibration procedure based on finite element modeling of the soil which eliminates the need for prior knowledge of k^*.

B SENSOR CALIBRATION METHODOLOGY

Field calibration of the scour sensor by physical means is an impractical proposition. The procedure would involve embedment of the sensor rod in the river bed soil and removal of predetermined levels of soil. The calibration curve determined in this manner may be represented by a sensor frequency change for various levels of scour depth. To eliminate the issues involved in the calibration procedure in removal of river bed soil under moving water, the proposed calibration method takes advantage of numerical modeling through a hybrid approach. The method involves finite element modeling as well as a benchmark measurement of the sensor dynamics at the time of installation and/or first embedment of the sensor rod in the river bed.

Thus, the finite element model of the submerged rod where half of its length is embedded inside the soil was constructed using commercial software (ANSYS). For given sensor rod design parameters, i.e. material, diameter, embedded length in the river bed, total length, etc., it is possible to perform modal analysis. Modal analysis provides the dynamic characteristics of the submerged vibrating rod such as the natural frequency of the rod under submerged conditions, and the modal shapes of the rod. As discussed earlier, modeling of the river bed soil required measurement of k^*. The analysis instead was performed for a range of k^* values from 5 to 400 lb/in^3. The calibration factors for all the soils modeled in the finite element program are shown in Table 1. The variation of the calibration factors against the base (reference) frequencies corresponding to the undisturbed state of the sensor rod represents the effect of the soil subgrade modulus on the calibration factor. A typical curve indicating the variation of the calibration factor as a function of the subgrade modulus is shown in Figure 3. This numerically computed curve represents the variation in the calibration factor due to the subgrade modulus for a 6-feet-long sensor with 0.5 in diameter and an embedded length of 3 ft.

The sensor calibration procedure involves determination of the calibration curve according to the sensor dimensions and material properties (Figure 3). Once the sensor is embedded, the fundamental frequency of the submerged sensor is measured where it represents the base or reference frequency for the original length of the sensor rod. The calibration curve in Figure 3 is then employed to convert the base frequency into the calibration factor which automatically incorporates the effect of the river bed subgrade modulus. This value is recorded as the calibration factor, and it is used for estimating the scour depth based on the changes in the base frequency during floods.

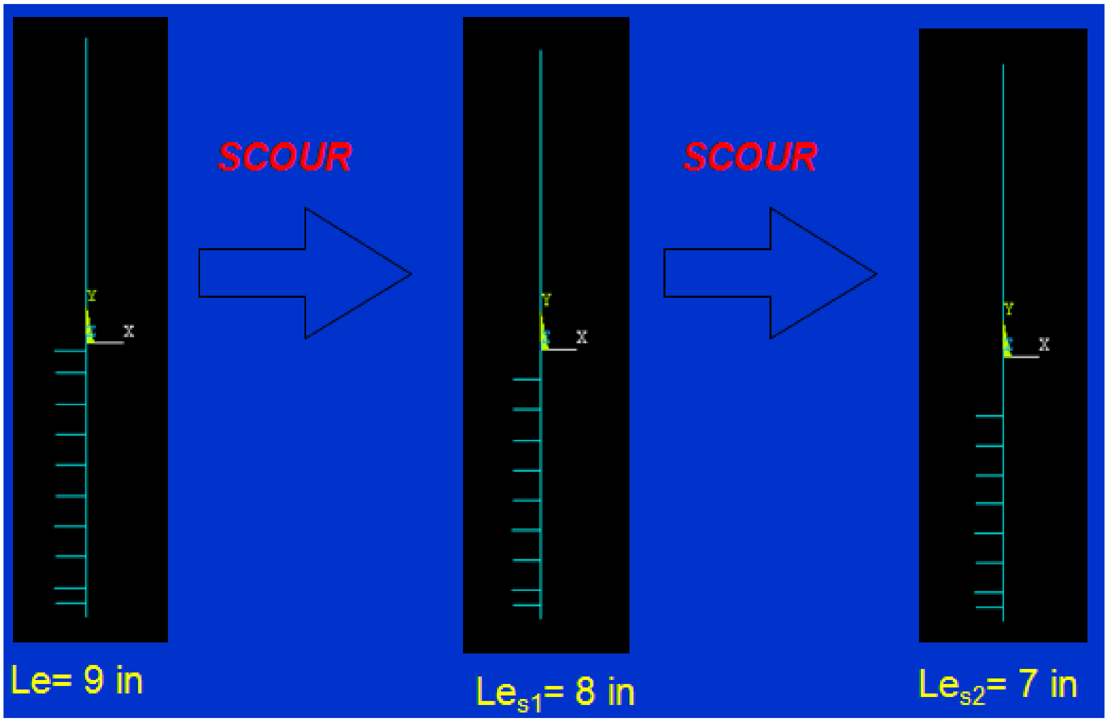

Figure 2. Finite element model of the sensor rod with the reference coordinates and the spring series idealization of the subgrade modulus for the river bed soil.

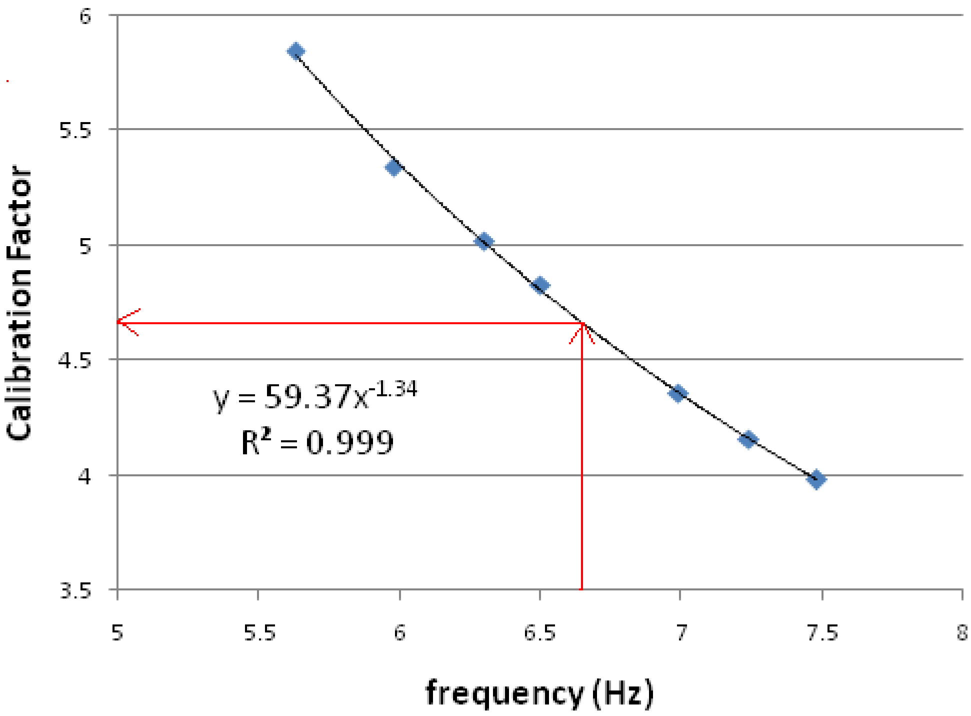

Figure 3. Field calibration curve.

DEVELOPMENT OF PRELIMINARY REAL-TIME MONITORING SOFTWARE

The designed sensor is based on an instrumented rod driven into the river bed. The rod is instrumented solely with one sensing element; in this case the Fiber Optic Bragg Grating Sensor (FBG) is mounted on the rod surface. The FBG sensor provides the time-domain signal of wavelength which is proportional to the mechanical strain of the rod. The Fast Fourier Transform (FFT) on arbitrarily selected sets of signal points presents the frequency content of the signal in that time interval. The dominant fundamental frequency (the frequency with the maximum power) can be extracted from the FFT power spectrum of each data set. This frequency varies linearly with the change of the scour depth. As discussed earlier, this concept constructs the principal idea of the proposed sensor for measuring the scour depth near the bridge piers.

A computer program was developed using the Lab-View software to perform FFT and for the computation of the fundamental frequency for the time domain data points in real time. A calibration curve similar to the one shown in Figure 3 can be programmed into the software knowing that this curve is for a particular sensor design. The software has capability for real-time acquisition of data and conversion of the raw data to scour depth in graphical format. It also has a user-interface platform for setting parameters, changing calibration and sensor length data, etc. This software was used for the proof of concept tests and later refined for field tests.

PROOF OF CONCEPT TESTS

The experimental setup shown in Figure 4 was used for the proof of concept tests, using the hydraulic pump setup and the discharge unit to create a closed-loop flow through the tank. No efforts were made to create any river flow simulations. The idea was to examine the viability of the concept and to correlate the frequency response to scour depth. The scour sensor was installed in the vicinity of the concrete cylinder where the local scour has taken place. The first series of tests were run by removing the soil materials and observing the frequency response. Once it was ascertained that the theory was sound, careful calibration experiments were performed by embedding a graduated ruler inside the sand and through manual removal as well as re-deposition of sand to simulate scour. The physical measurements by the ruler were calibrated against the frequency changes. The software was loaded in a laptop computer and attached to the fiber optic interrogation unit, and the sensor was attached to the interrogation unit for reading the fiber optic sensor signals.

Figure 4. Overall photo of the experimental setup.

PRELIMINARY RESULTS

The removal/deposition calibration results (raw data) are shown in Figure 5. Figure 5 is the measured fundamental frequency of the sensor rod against the carefully measured scour depth by the graduated ruler. The linear regression lines for the removal and the deposition relationships were computed separately as shown in Figure 5. As noticed, there is an outlier data point, which only occurred once, and it is considered a noise-related error, but it was not removed in this calibration. Despite the individual outlier, the R-squared correlations are 0.89 and 0.96 for the removal and the deposition curves, respectively. However, if the single outlier as shown in Figure 6 is removed, the data for the removal will be greatly enhanced, and an R-squared value of 0.96, which is similar to the deposition correlation relationship, will be achieved.

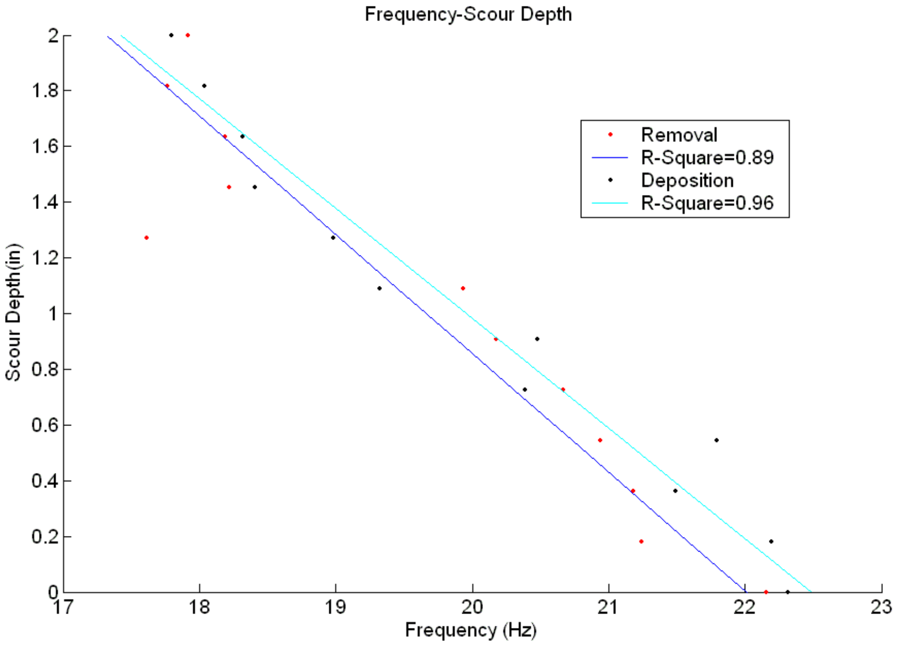

Figure 5. Sediment removal/deposition results.

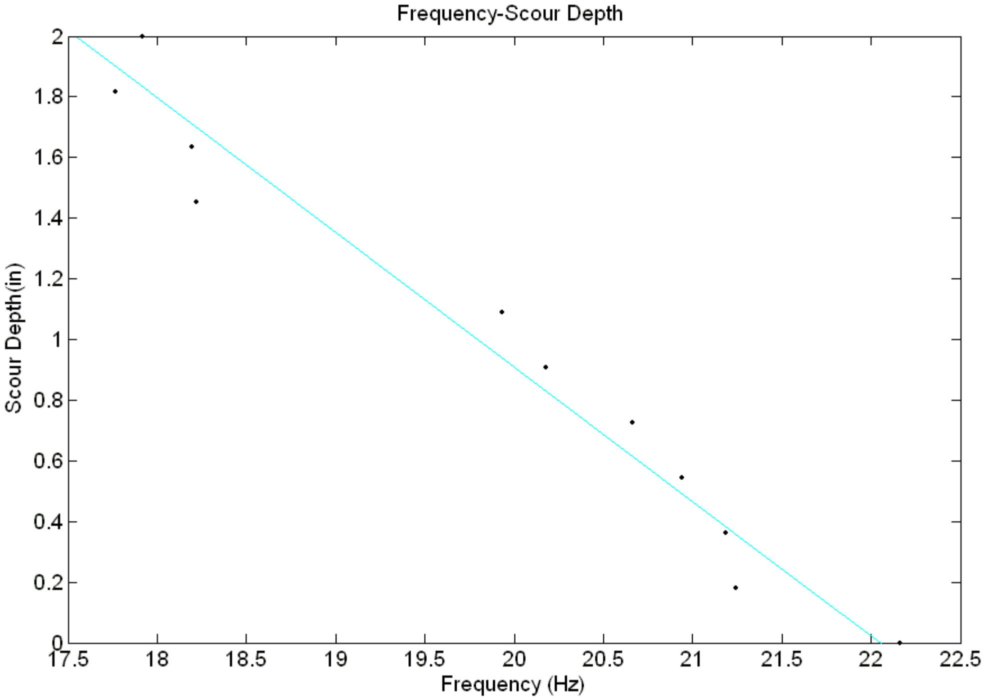

Figure 6. Sediment removal results without the outlier.

SENSOR DESIGN AND FABRICATION

The field sensor design and dimensions were based on the prevaling flow rate loading on the sensor at the particular bridge site. The site for the field tests was selected following consultations with the IDOT personnel in district 1, Ms. Sarah Wilson, and visits to several sites with scour critical bridges. The bridge on Toughy Ave. over the north branch of the Chicago River was selected for the primary field experiments. The real time data summary of the USGS (United States Geological Survey) website was employed for determination of the maximum river flow rate at the selected bridge. The design flow rate was selected for the period between May 1and July 1, 2007. The prevailing flow rate during this period was around 700 cubic feet per second (Figure 7). This flow rate was employed in the design of the sensor. Considering the behavior of a rod driven inside the river bed, the sensor was designed as a friction pile in order to evaluate the response and the stability of the sensor. AASHTO specifications were used for the sensor design.

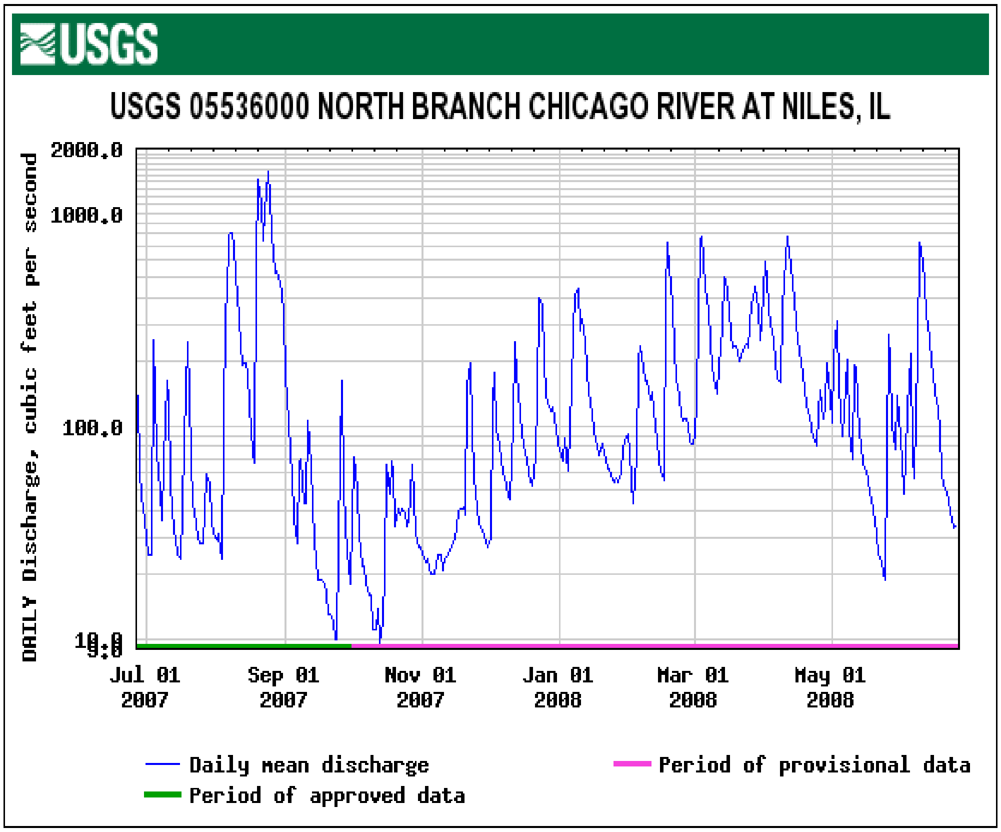

Figure 7. USGS plot of daily discharge for the Toughy Ave. bridge.

The scour sensor idea is valid solely when the sensor is completely submerged inside the river water. In such a case, it is possible to establish a reference calibration factor based on the fully submerged state of the sensor. It is also believed that during flooding, the sensor will remain under the water level. For the first trial, a 6 ft aluminum rod with 0.5 in diameter was considered. The sensor rod was embedded within the river-bed soil with an embedment of length of 3 ft. A schematic sketch of the sensor components is shown in Figure 8.

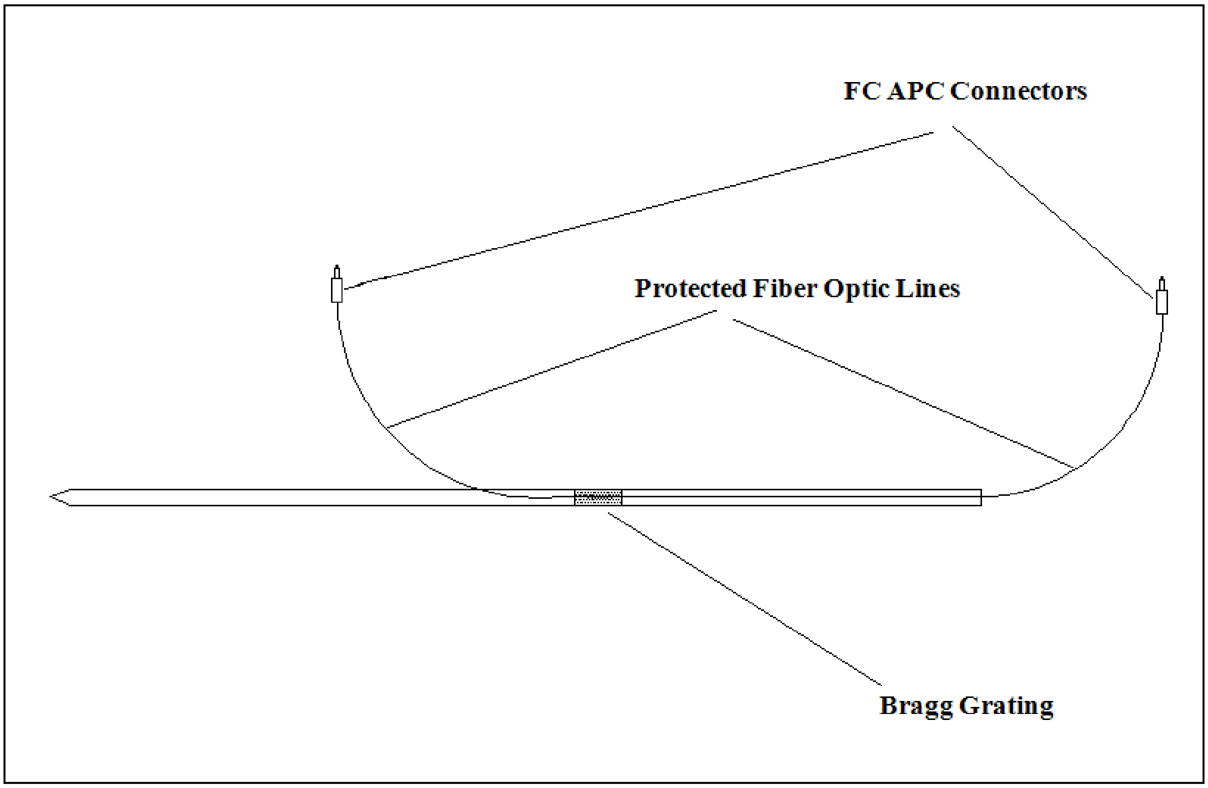

Figure 8. Schematics of the simple scour sensor.

FIELD INSTALLATION – MEASUREMENTS AND RESULTS

The first sensor placement activity took place on June 12, 2008. On this date, the water level was 6 inches above the sensor tip. Therefore, the sensor was completely submerged. The sensor was embedded in the middle of the river width because due to the river flow activity on this date, some contraction scour activity was expected on that section of the river. Due to the small diameter of the sensor rod and the soil conditions in the riverbed, there was no need to use additional instrumentation for driving the sensor rod/pile into the river bed. The sensor was merely driven into the riverbed by few strokes of a hammer (Figure 9). Collected vibration data indicated excellent results in terms of vibration characteristics and prediciton of vibration frequency matching the finite element results. The frequency is obtained through the Fast Fourier Transform (FFT) on the collected sets of time domain signals representing the frequency content of the signal in that time interval. Figure 10 shows a typical signal and its frequency content.

During the day, data was collected in real-time, and seven data sets within the period from 11:51 a.m. to 2:29 p.m. were saved. The first data set was employed to establish calibration and the reference frequency of the sensor. The reference frequency was employed in a manner described in Figure 3 to establish the calibration factor.

Subsequently, this calibration factor was employed to compute the scour depth which is automatically done by the real-time software. The scour depth predicted by this sensor in the period between 11:51 a.m. to 2:29 p.m. is plotted in figure 11. As shown in this figure, the sensor resolution for the scour activity was within an inch. Although, due to rapid river flow, no attempts were made to verify this with a graduated stick.

Figure 9. Sensor installation into the river bed.

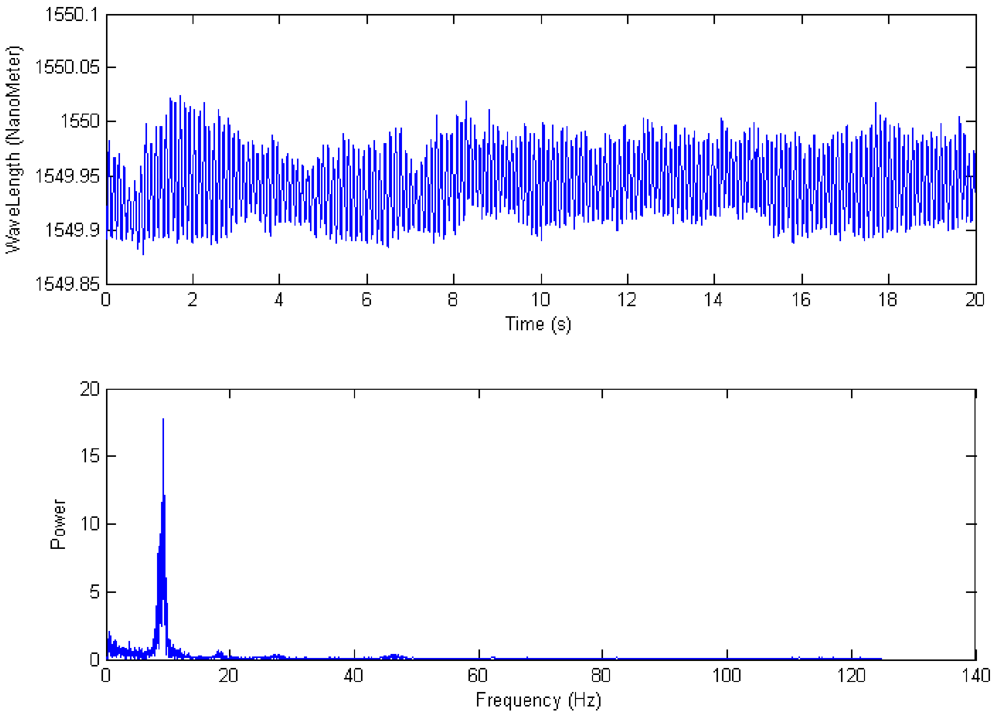

Figure 10. Typical time domain signal and extracted fundamental frequency of the sensor.

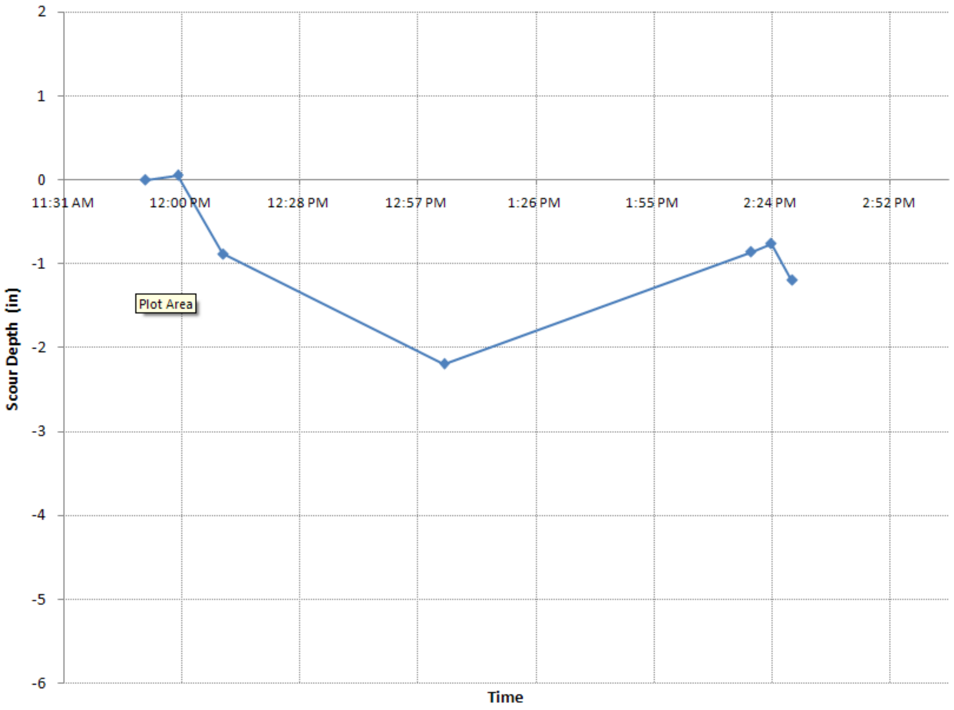

Figure 11. Scour depth in the river as detected by the scour sensor.

Three new sensors with different dimensions were fabricated and installed at the same bridge site on June 23. Table 1 presents the sensors dimensions and the water level with respect to the reference point at the river bed. Two of the sensors were totally submerged (Figure 12). The data collected from all three sensors proved the existence of a constant vibration frequency. In the next data collection activity, the amount of change in the frequency as well as the change in the soil level with respect to the sensor tip was measured for evaluation of the sensor capabilities.

Table 1. Sensor Dimenstions and Their Configurations with Respect to the River Bed and Water Level

Sensor No.	Total Length (in)	Exposed to Water Length (in)	Water Level (in)
1	48	17	20
2	72	36	23
3	48	24	24.5

Figure 12. Three sensors installed on June 23, 2008.

The tests involved sensor calibrations according to the method described earlier and examination of the sensor scour detection capabilities by unearthing the soil around the scour sensor artificially mimicking scour activity. This was possible on this date as the river was relatively calm. IDOT personnel, Mr. Copenbarger, the TAG leader, Ms. Sarah Wilson, and another individual from IDOT were also present during these tests. The sensor was calibrated at the river site by measuring the first fundamental frequency of the sensor and using the calibration curve procedure in a manner similar to the one established in Figure 3 and illustrated in Figure 13 for the particular sensor and the river bed subgrade modulus. Following the calibration process, the earth around the sensor was removed in steps, and each time a graduated long ruler was employed for measuring the scour depth.

Measurements with the graduated ruler were not accurate because it was not possible to see the depth exactly in the murky water. However, the experiments were sufficiently acceptable to prove the field calibration and measurement concept. The frequency change due to scour action as captured by the automated data acquisition system was automatically converted to the scour depth on the computer screen in real time. Tables 2 and 3 show the variation of frequency against artificially created scour for sensors 1 and 3. Tables 4 and 5 as well as Figure 14 provide a comparison between the ruler-measured scours in the field and the amounts predicted by the finite-element-based calibration factors.

Table 3. Frequency Response as a Function of the Scour Depth

Sensor 1	
Frequency (Hz)	Scour Depth (in)
12.13	0
10.93	1.3
10.14	2.7

Table 3. Frequency Response of Sensor as a Function of Scour Depth

Sensor 3	
Frequency (Hz)	Scour Depth (in)
10.2094	0
9.3	1.2
8.35	2.7
8.11	3.7

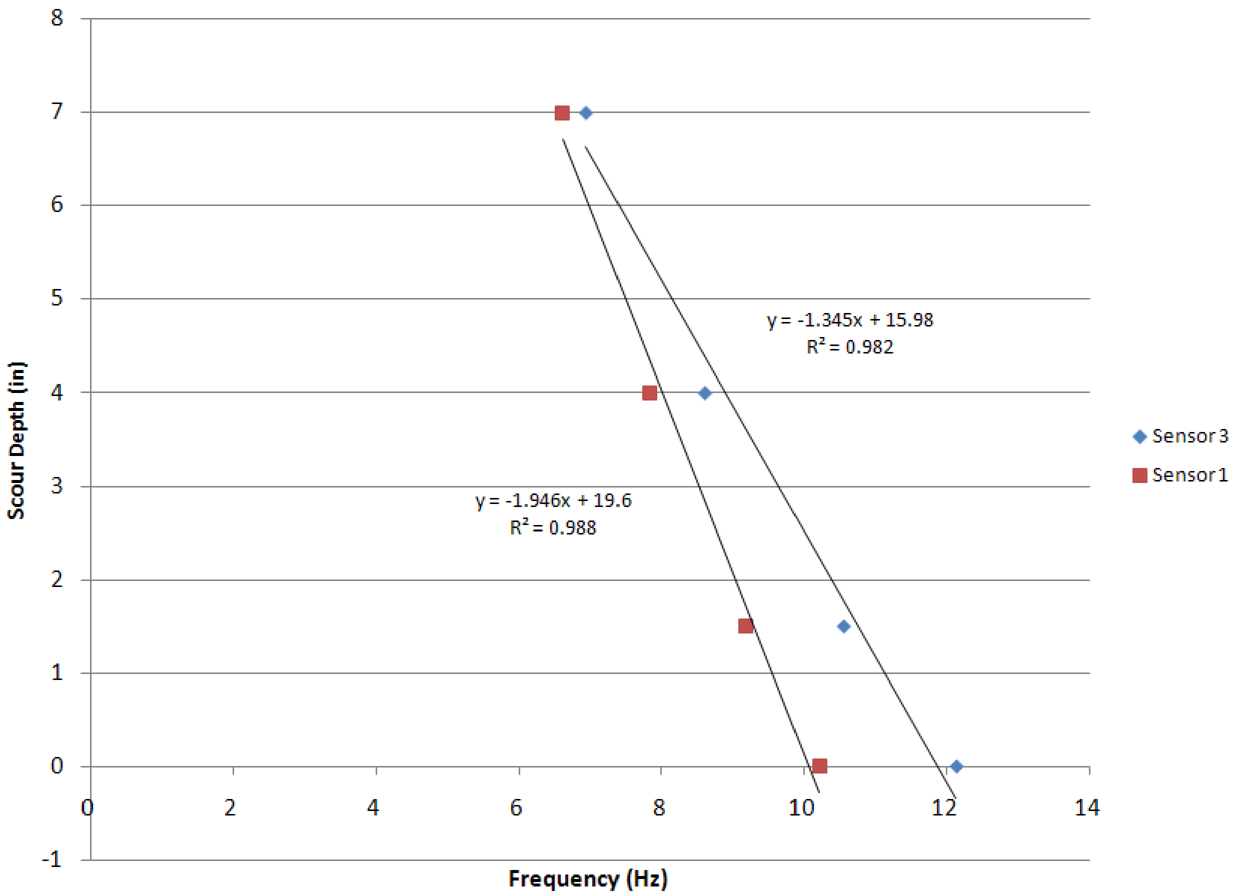

Figure 13. Calibration lines based on the field vibration frequency and the finite element generated results.

Table 4. Comparison of Measured and Computed Scour

Sensor 3		
Frequency (Hz)	Measured Scour Depth (in)	Computed Scour Depth (in)
10.2094	0	-0.2674924
9.3	1.2	1.5022
8.35	2.7	3.3509
8.11	3.7	3.81794

Table 5. Comparison of Measured and Computed Scour

Sensor 1		
Frequency (Hz)	Measured Scour Depth (in)	Computed Scour Depth (in)
12.13	0	-0.33485
10.93	1.3	1.27915
10.14	2.7	2.3417

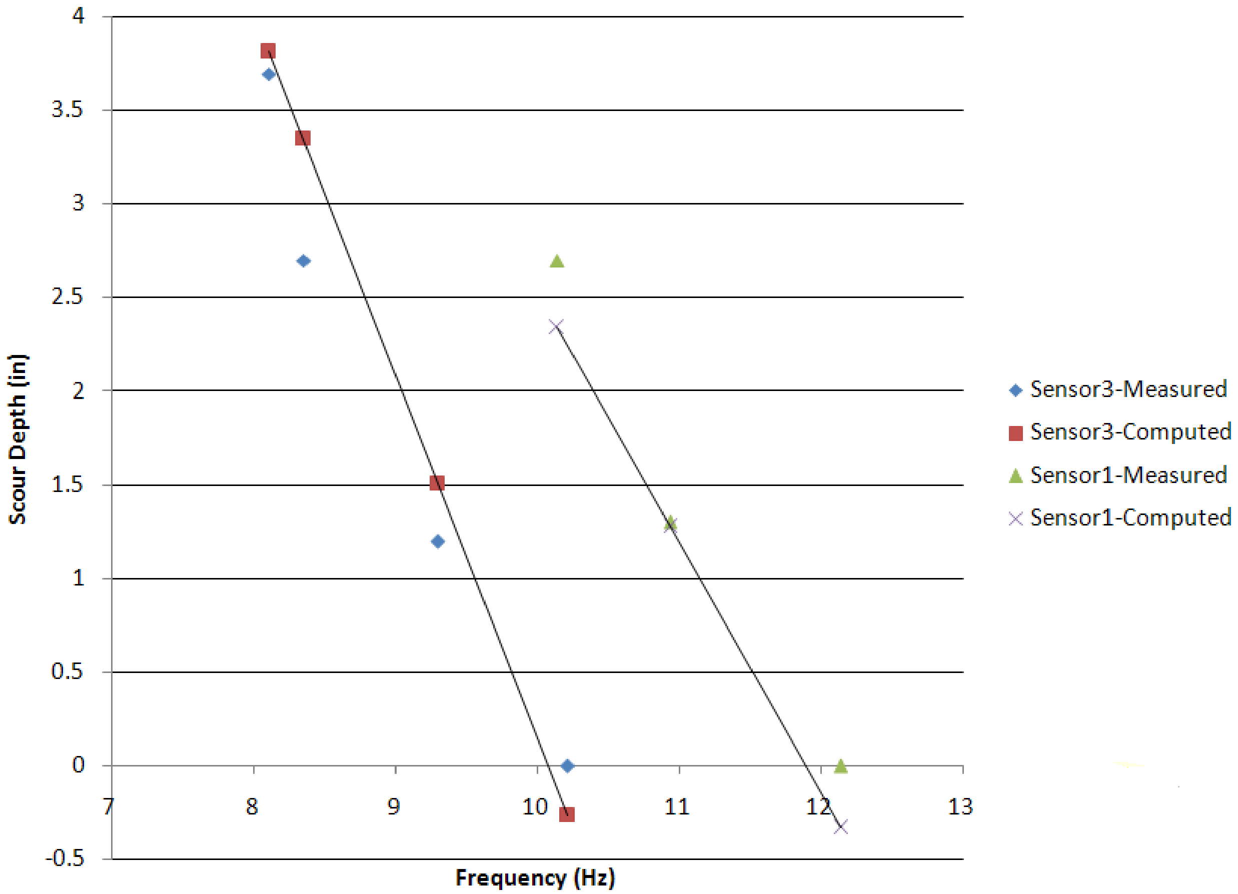

Figure 14. Graphical presentation of the computed and measured scour.

CONCLUSIONS

The work described in this report pertains to the development of a simple and cost-effective scour sensor. The results were the outcome of comprehensive research over a period of 12 months. The work involved proof of concept experiments, establishment of a calibration methodology, finite elements numerical modeling, design and fabrication of a field sensor, as well as implementation of field calibrations and field tests. Research results proved that the simple concept for the development of a very low cost sensor with only one sensing element is sound. The simplicity of the sensor allows for widespread implementation in myriads of scour critical bridges. Field experimentations have been limited to few tests; however, and the system has not been thoroughly tested under flood situations. Further experiments are necessary in order to accurately determine the sensor resolution and repeatability under field conditions and to further establish the software for more sophisticated and user-friendly remote monitoring applications. The current experiments involved use of a fiber sensor. However, many other types of sensor systems could be employed. The advantage in using the fiber optic sensor in this case was that unlike electrical signals, optical signals can safely operate in underwater applications, and they are capable for serial multiplexing. One fiber optic interrogator could handle up to about eight scour sensors at the same time.

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