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YANTU LIXUE YU GONGCHENG XINJINZHAN

主 编　胡黎明　梅国雄　吴志斌　罗嗣海

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目　录

Develop and Field Evaluation of a Real-time TDR Bridge Scour Monitoring System

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Abstract Bridge scour is the biggest cause of bridge failures. Erosion of soil around the bridge foundation could lead to problems from instability of substructure to complete bridge failures. An effective scour risk countermeasure is to deploy bridge scour monitoring system. Besides preventing the risks of catastrophic failures, field scour data can also be used to calibrate and refine the existing bridge scour simulation models. This paper describes the development and field evaluation of a TDR(Time Domain Reflectometry) based on bridge scour monitoring system. TDR is a guided electromagnetic wave that determining the interface between materials layers based on the contrast in the dielectric properties. It is capable of determining the interface between water and sediment, from which the extent of erosion can be determined. This paper discusses the technical basis, the sensor fabrication, the procedures for field installation, and TDR scour sensor performance in a long term bridge scour monitoring program.

Key words TDR, Bridge Scour; Risk Management; Structural Health Monitoring

1 Introduction

Bridge scour has been identified as the major cause of bridge failures in the United States for a long time and it remains a stubborn adversary to engineers. The erosion of soil around the bridge foundations may leave the superstructures without enough support and could eventually lead to complete collapse of the bridge. A recent National Cooperative Highway Research Program (NCHRP) report revealed that during the time span of 1966-2005, 58% of the reported bridge failures (1,502 in total) were ascribed to scour[1]. The consequences are self-evident: disruption of the transportation network, direct costs for replacing and restoring of the structure, indirect costs suffered by the general public, and the worst situation, loss of lives. Prominent examples of catastrophic collapse of bridges due to scour include the Schoharie Creek Bridge in the state of New York (1987), the Walker Bridge over Hatchie River near Memphis, Tennessee (1989) and the I-5 over Los Gatos Creek in California (1995)[2]. During the past several decades, a lot of research has been conducted to advance the design, evaluation and inspection of bridge scour and the Federal Highway Administration's Hydraulic Engineering Circular No. 18 (HEC 18: Evaluating Scour at Bridges) has been updated to the fifth edition. The seriousness of the scour also results in mandatory regulations for evaluation and inspection for every overwaterway bridge[3]. Therefore, an accurate, cost effective, and easy-to-install scour sensor is in high demand.

In addition, scour will be most severe in flood events and bridges will be at high risk of failure during flood events. Hence, real-time scour information is critical for officials to predict the potential evolution of the scour hole and to take immediate action to close the bridges prior to the failure. On the other hand, the flood also threatens the security of the scour sensor itself since it always means extra hydrodynamic loads and huge amount of debris, which may damage the sensors easily. Also, during the flood recession, sediments would probably refill the scoured hole and this sedimentation process should also be identified. Therefore, the ideal field scour sensor should also provide real-time scour information and have to be durable and robust.

Whereas field monitoring is essential for bridge risk management, and the field scour data is also particularly useful for calibrating and updating the existing scour prediction models. Scour prediction formulas are usually functions of characteristics of the bed material, bed form, flow and pier configuration. Numerous equations are available for local pier scour and most of them are based on the laboratory experiments, where all the above-mentioned characteristics are simplified or idealized. For previous editions of HEC-18, the pier scour equation based on the CSU equation is recommended for scour prediction. However, comparisons with field data revealed that the existing equations (including the HEC-18 equation) frequently over predicted the scour depth. In the latest version of HEC-18, another methodology is recommended as an alternative method to the CUS based equation. This methodology is the Florida DOT pier scour methodology based on the NCHRP equation (or the Sheppard and Miller (2006) equation)[4], which is proved to perform better for both laboratory and field data. However, field scour data is still far from sufficient. Real-time and continuous monitoring of scour at bridges would provide valuable information to improve the prediction models as well as to unveil the underlying mechanism of bridge scour.

In summary, bridge scour sensors are in urgent need and the ideal sensors should be accurate, cost effective, easy-to-install as well as durable and robust; it should also provide continuous information of the real-time scour/sedimentation process. A number of scour sensors have been designed over the past two decades. The traditional methods include the sounding rods, sonares, tilt sensors, buried or driven rods (e.g. magnetic sliding collar), and other buried devices such as float-out sensors. Such techniques can meet one or several of the above-mentioned requirements but not all of them. All these methods are discussed and summarized in NCHRP and FHWA reports[1,5]. The strengths and weaknesses of such methods can also be found elsewhere[6]. In addition to the traditional methods, we also found some interesting innovative sensing techniques during recent years. Fiber Bragg grating (FBG) sensors were applied to detect scour phenomenon directly or indirectly. Scour can be monitored directly through strain sensing with distributed FBG sensors mounted on a cantilevered or fixed rod/bar near the bridge piers[7,8]; it can also be detected indirectly by relating the natural frequency of vibration of an embedded rod in the riverbed to the scour depth and the natural frequency of the rod can be measured using a single FBG sensor. Direct measurements can also be realized by using distributed pressure MEMS sensors[9] or piezoelectric films[10]; attempt to relate the fundamental frequency of the bridge itself with the scour depth has also been made by using motion sensors[11]. Imaging techniques has also been introduced to monitor real-time scour processes. Chang et al. (2012)[12] developed a multi-lens system which can track scour images and retrieve the scour information through image recognition processes. Extending single point measurement to 3-dimensional profiling of the bed form around bridge piers has also been attempted by using rotatable sonar profiler[13].

All of these innovative techniques are encouraging. However, each of the techniques has its own drawbacks. For example, the accuracy of the direct FBG sensor depends on the number of FBG elements in the sensor and the measured scour depth is in a discrete incremental fashion; the main drawback of the indirect methods is the efforts should be made to differentiate scour effects from other possible reasons (e. g. ambient perturbations, and traffic) for natural frequency shift of measured structures; turbidity of the flow, especially in flood periods, will definitely present challenges for camera or sonar based on techniques.

In this paper, we present an innovative scour sensor which provides both reliable (direct measurement) and continuous (real-time) scour information, with little to no affects from the turbid flow. This sensor is a Time Domain Reflectometer (TDR), which is specifically designed for field applications. TDR is based on the guided electromagnetic wave technology; it is super accurate for detection of interface where the dielectric properties mismatch. Scour is a particular interface problem in that the interface between water and sediment defines the scour profile; and the dielectric properties of sediment and water differ from each other significantly. Therefore, it is straightforward to apply TDR technique to detect the scour process. Dowding and Pierce (1994)[14] proposed to measure scour by detecting the shearing of a coaxial cable by the stream flow and apparently this system is not reusable. Yankielun and Zabilansky (1999)[15] first introduced a TDR probe to identify the sediment/water interface for scour monitoring. While it was proved rugged enough to resist flood/icing damage, the intrinsic design of the probe made it difficult to install in the field, difficult to interpret the signals and limited to a relatively short sensing range. Efforts are made to develop a robust algorithm for scour measurements using the TDR signals[16-20]; a more reliable design of the TDR sensor has also been proposed to address the practical issues such as cost, sensitivity, durability and easiness to install[21-23]. All these studies paved the way for field application of the innovative TDR sensor for real-time scour monitoring.

This paper presents our latest progress on the in-situ application of the innovative TDR sensor to advance the state of practice of field scour monitoring. The design and fabrication of this TDR sensor is will be first presented briefly, followed by a description of technical basis of the TDR scour sensor; the field deployment of the sensor and its long term performance will be emphasized; successes and pitfalls are then discussed; the sensor will be improved in the future to strengthen the weak points in the whole sensing system and will be deployed on more bridges across the world.

2 Sensor design and fabrication

TDR is a guided electromagnetic wave technology that measures material properties based on the speed and attenuation of electromagnetic waves. It was originally used by electrical engineers to locate discontinuities in electrical cables; it has been increasingly adopted by civil and environmental engineering communities for characterization of geomaterials[24-25]. The traditional and most commercial TDR probes include two or three bare metal rods. TDR encounters challenges in application to highly conductive materials due to the significant attenuation of the electromagnetic waves in such materials. This drawback can be compensated by either shortening or coating the TDR probes[26]. The latter approach is adopted in this study. Efforts are also made to design the TDR probe to be ready for various field applications. This means the TDR probes should be durable, economic, easy to transport and install as well as accurate and sensitive.

Different from traditional TDR probes which usually consist of separated cylindrical rods, the proposed sensor is a composite design. It mainly includes: (1) three flat metal bars as the wave guide; (2) tapes and adhesive coating to improve its performance in highly conductive materials; (3) high-strength E-glass U-channel as the structural support [Figure 1(a), (b)].

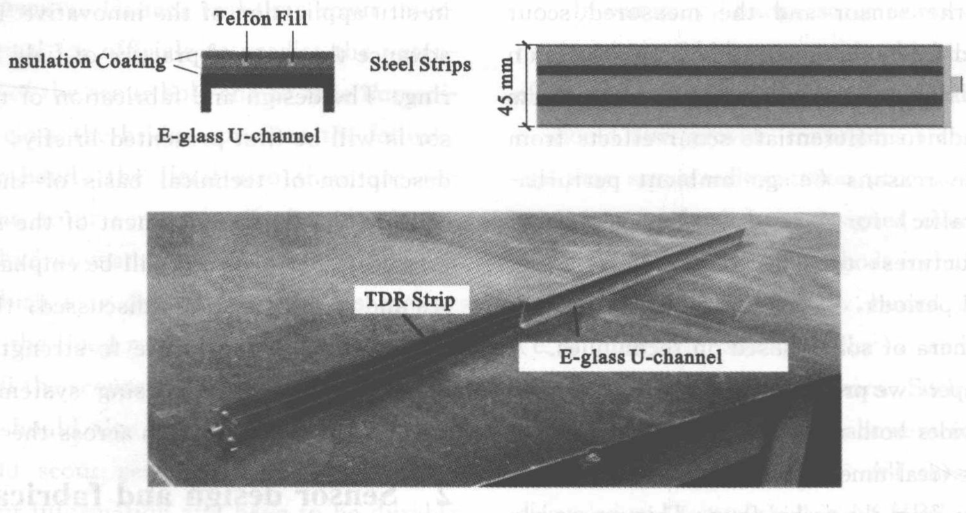


Fig. 1 The newly designed field TDR bridge scour sensor

(a) The schematic drawing of the cross-section of the sensor; (b) The longitudinal view of the sensor;
(c) The photo of the fabricated bridge scour sensor (one portikon of the E-glass U-channel is cut to expose the TDR strip)

All the materials are cost effective, and the fabrication process also saves time and efforts. Three high-carbon stainless steel strips (12. 5 mm ×2. 54 mm) were first aligned parallel to each other with spacing of 2mm; the gaps were then filled with Polytetrafuoroethene (PTFE) Teflon; the top and bottom surfaces were covered with tape and a thin layer of adhesive coating; the integrated strip wave guide were then completely mounted on the E-glass U-Channel (50. 8 mm × 14. 3 mm × 3. 2 mm). The geometry of the strip sensor makes it close to 50 ohm impedance when exposed to air; this ensures the impedance match to the coaxial cables. The fabricated sensor is shown in Figure 1c and a portion of E-glass is cut off the expose the strip wave guide. It is worth noting that the total material cost for the sensor of 20ft long is less than MYM100; in addition, the cross-section of the sensor is small enough to fit in a standard geotechnical borehole.

3 Technical basis and procedure of scour monitoring using the innovative TDR sensor

TDR works by generating a small-magnitude and short-time electromagnetic pulse to the probes and "listen" to the echoes from materials. As shown in Figure 2(a), a simple setup of the TDR system typically includes a TDR sensor, a TDR signal generator and a data acquisition system. The electromagnetic wave travels with different speeds in materials with different dielectric spectra. When the sensor is embedded in layered materials, the mismatch of materials will result in reflections, which can be displayed cleared in the time domain signal [Figure 2(b)]. The dielectric constants for air, water and sands are approximately 1, 80 and 3. The huge differences between the dielectric properties of water and sands make it ideal for scour monitoring.

Figure 2 shows the laboratory setup of the scour sensing and corresponding sample signals. In a TDR signal, the time information is displayed by the apparent length L_a. Based on the relationships among apparent length, physical probe length in materials (L), and wave speed in materials, the dielectric constant K_a are related to L and L_a. [Eq. (1), for details, see yu and yu 2006]. To determine L_a, the reflection points can be determined with the commonly used "tangent line" approach.

$$K_a = \left(\frac{L_a}{L}\right)^2 \quad (1)$$

One should note that the measured signals represent the dielectric information of the whole sensor system, and any material in the sensor's effective sensing region contributes to the final signal. In the region (b-d) of the system shown in Figure 2a, the contributive materials include water, soil and non-waveguide materials of the sensor (e. g. PTFE, coating and E-glass).

For the layered water and soil system, the semi-empirical volumetric mixing model [Eq. 2, Birchak et al. 1974] was utilized to estimate the apparent dielectric constant of the water/soil mixture [Eq. (3)].

$$(K_{mix})^{\alpha} = \sum_{i=1}^{j} \upsilon_i (K_i)^{\alpha} \quad (2)$$

where K_{mix} is the dielectric constant of a mixture material; υ_i and K_i is the volumetric fraction and dielectric constant of each component of the mixture, respectively.

$$\sqrt{K_{a,mix}} = \frac{L_1}{L}\sqrt{K_{a,w}} + \frac{L_2}{L}\sqrt{K_{a,s}} \quad (3)$$

where $K_{a,mix}$, $K_{a,w}$, and $K_{a,s}$ is the apparent dielectric constant of the layered water/soil system, the water layer and the soil layer, respectively.

After normalization, a linear relationship was found between the normalized mixture dielectric constant and the normalized soil layer thickness [Eq. (4)].

$$\frac{\sqrt{K_{a,mix}}}{\sqrt{K_{a,w}}} = \frac{x}{L}\left(\frac{\sqrt{K_{a,s}}}{\sqrt{K_{a,w}}} - 1\right) + 1 = ax_r + b \quad (4)$$

where x and x_r denote the thickness and the normalized thickness of the soil layer, respectively. a and b are constants which can be obtained using linear fitting of the measured data.

Through a series of laboratory experiments with different types of sands and water, Yu and Yu (2006) established a general form for Eq. (4) [(Eq. (5)].

$$\frac{\sqrt{K_{a,mix}}}{\sqrt{K_{a,w}}} = -0.43x_r + 1 \quad (5)$$

From Eq. (5), it is apparent that once the dielectric constant of the soil/water mixture ($K_{a,mix}$) is determined, it is easy to find the thickness of the soil layer. For example, in Figure 2(b), when the thickness changed (from 70 cm to 5cm), the apparent length also altered (from L_a to L_a').

As mentioned earlier, the materials of the sensor also contribute to the measured dielectric constant. To obtain the dielectric constant of the soil/water mixture ($K_{a,mix}$) from the matured overall dielectric constant (K_a), Yu and Yu (2013) has established a calibration equation for this particular TDR sensor through experiments [Eq. (6)].

$$\sqrt{K_{a,mix}} = -0.12K_a^2 + 7.93K_a - 59.50 \quad (6)$$

In summary, the complete procedure to detect scour using the proposed TDR sensor is shown in Figure 2.

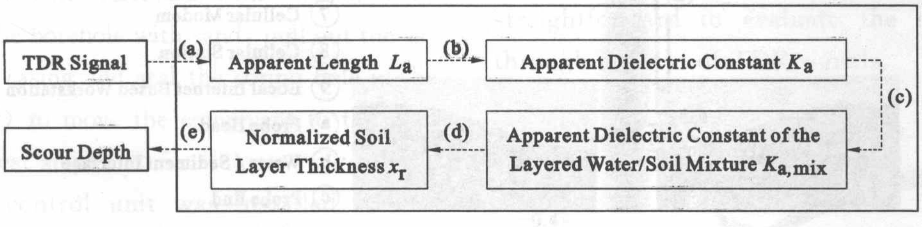


Fig. 2 The procedure to determine the scour depth through the TDR signals

(a) The apparent length can be obtained from the reflection points in the TDR signal, which represents the head and the end of the TDR probes;
(b) K_a is calculated using Eq. (1); (c) $K_{a,mix}$ is a function of K_a[Eq. (6)]; (d) x_r is calculated using $K_{a,mix}$[Eq. (5)];
(e) the relative scour depth can be obtained given sediment layer thicknesses at two times

4 Field deployment of the TDR scour monitoring system

4.1 System design

As discussed in the introduction section, an ideal field scour monitoring system should provide real-time scour information. Figure 3 illustrates the proposed field scour monitoring system using the newly designed TDR strip sensor. The TDR sensors are designed to be partially imbedded in the river bed (Figure 3①); thanks to the sensor's capability for serial multiplexing, several TDR strip sensors can be installed at different locations in vicinity of bridge abutments or piers at the same time. The sensors are connected with the field control unit via coaxial cables (Figure 3②). The control unit includes a TDR signal generator (Campbell Scientific? TDR 100) with a multiplexer (Campbell Scientific? SDMX50) (Figure 3③), a data logger (Campbell Scientific? CR1000, Figure 3④), a rechargeable battery (NP12-12T, Figure 3⑤) with a solar panel (Figure 3⑥) and a cellular modem (Figure 3⑦). The control unit sends electromagnetic waves to the TDR sensor with the signal generator; it collects the data from the sensors with the data logger and sends them to the internet server via the cellular modem; the data logger can be programed to read TDR data at preset time intervals (e.g. 1 hour). Researchers or officials can visit the corresponding website to check the data with any internet accessible terminals (e.g. PCs, Smart phones and etc.).

The sensors are installed with routine geotechnical investigation equipment and procedures and this will be discussed in detail in the following section; the whole system is powered by the rechargeable battery with energy from the solar panel and the battery and power consumption data can also be monitored in addition to the TDR data; the components of the control unit are integrated in a compact box, which is fixed on the bridge deck. All of these features ensure the proposed monitoring system economic, efficient and easy for installation and management.

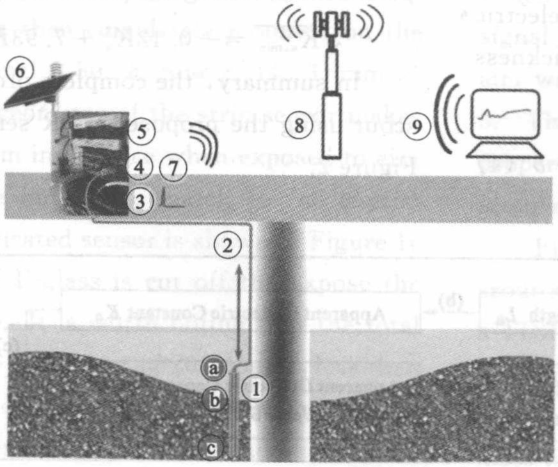


Fig. 3 Schematic diagram of the real-time TDR field bridge scour monitoring system. Components ③～⑦ constitute the control unit, which collects and sends TDR data wirelessly, as well as provides power to the system

4.2 Field deployment

The bridge under monitoring is the seven-span BUT-122-0606 Bridge on State Route 122 over the Great Miami River in Butler County, OH. According to USGS stream flow statistics, the annual average discharge at this location is about 6209 ft^3/s[27] (USGS website). The riverbed sediments are mainly silty clay with gravels. And during year 2004 and 2008, there were three major flood events with discharge over 50000 ft^3/s. Under-water inspections in 2004 and 2007 indicated a significant increase (around 2ft) of local scour around several piers, due to the flood events. The installation of this pilot monitoring station is expected to further provide real-time scour data, which will assist operational decision making and provide information for countermeasure design.

Five TDR sensors were installed at different piers. The sensors are located approximately 1ft from the corresponding piers and 6ft from the side walk (Figure 4); these locations are selected considering the maximum shear stress location and the easiness to install. The locations of the TDR sensors are shown in Figure 5.

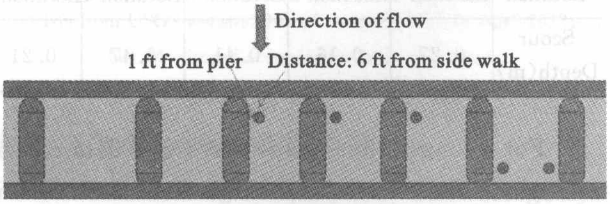
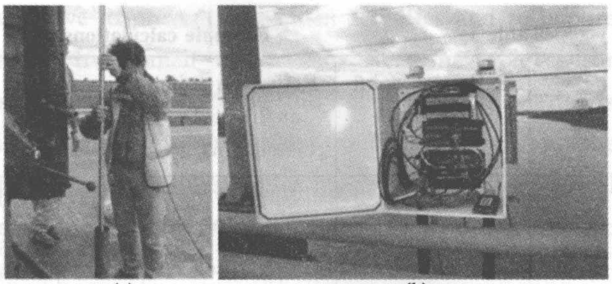


Fig. 4 The locations of the installed TDR sensors at the BUT-122-0606 bridge on state route 122 over the great miami river

The TDR sensors are installed through routine geotechnical site investigation equipment and procedures [Figure 5(a)]. The procedure can be summarized as: (1) to locate the equipment at the designed location on the bridge deck; (2) to core through the bridge deck; (3) to drill in the river bed to the design depth; (4) to lower the TDR sensor into the borehole; (5) to backfill the borehole with sand, pull out the assisting borehole casing and seal the coring hole in the bridge deck; (6) to move the equipment to the next location and repeat steps 2 to 5.

The field control unit was installed on the bridge near Location 4 shown in Figure 5. All the sensors are connected to the control unit via protected coaxial cables. A pair of steel pipes were fixed on the bridge to host the housing box [Figure 5(b)]. The field monitoring station is proved to be easy to access as well as protective to the control units.



(a) (b)

Fig. 5

(a) Installation of the field TDR sensor using traditional geotechnical equipment and procedures;

(b) The installed field control unit

5 Long-term performance of the system

The field TDR bridge scour monitoring system was installed in September, 2009. Since then, the system has continuously served with encouraging performance. Routine maintenance has been conducted; it is found there are several challenges on the protection of the system. These challenges need to be addressed in order to improve the longevity of the system.

5.1 Preliminary Data Analysis

Figure 6 shows a typical signal from the field sensor. The reflections of the electromagnetic wave at the probe head, water/sediment interface and the probe end are clear. Following the algorithm and procedures elaborated in Figure 3, it is straightforward to evaluate the scour evolution through a series of TDR signals.

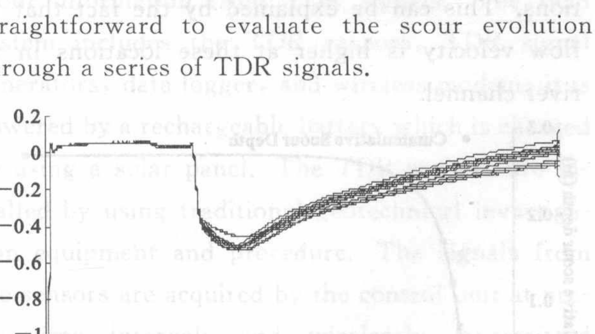


Fig. 6 Sample signals of the field TDR sensor. The reflection points and the change of the probe end reflection are clear

Table 1 **Example calculations using the algorithm elaborated in Figure 3**

Day	Reflection point at the probe head(m)	Reflection point at the probe end(m)	L_a (m)	K_a	$K_{a,mix}$	x_r	x(m)	Incremental scour depth(m)	Total cumulative scout depth(m)
1	26.29	32.2	5.91	15.04	32.42	0.85	1.30	0.00	0.00
2	26.29	32.3	60.1	15.55	34.60	0.81	1.23	0.07	0.07
3	26.29	32.36	6.07	15.86	35.90	0.78	1.18	0.04	0.12
4	26.29	32.43	6.14	16.23	37.40	0.75	1.14	0.05	0.17
58	26.29	32.03	6.29	17.03	40.56	0.68	1.04	0.10	0.27

An example of the implication of the TDR scour algorithm is shown in Table 1. The data is sampled at location 1 (Figure 4) in the two months after installation.

The cumulative scour depth is also illustrated in Figure 7. It is interesting to observe that the scour developed fast in the first several days after installation and it tended to be stable in long time. The fast growing scour depth in the initial stage is probably due to the disturbance of the local sediments during scour sensor installation; after most of the weak soils were eroded, the scour evolves gradually. The scour depths for all the five monitoring locations for 2 months after of installation (as shown in Table 2) revealed that the scour depths in the middle spans (i.e. Location 3 and 4) are slightly larger than those at the other locations. This can be explained by the fact that the flow velocity is higher at these locations in the river channel.

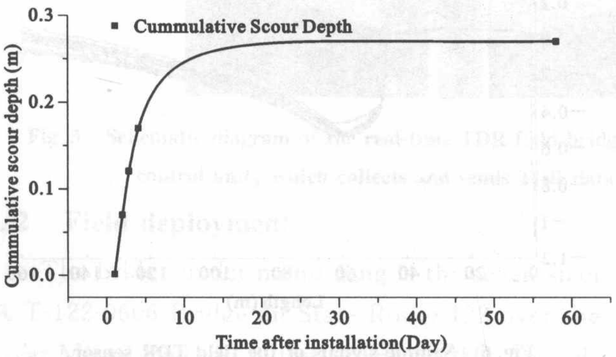
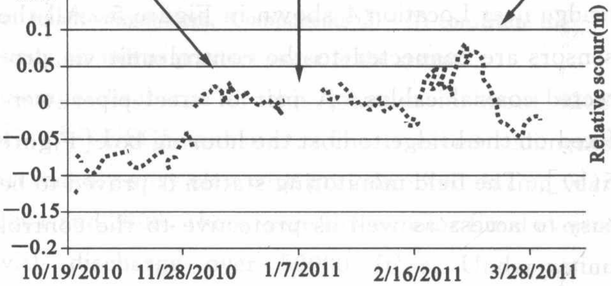


Fig. 7 Scour evolution at Location 1 during the first two months.

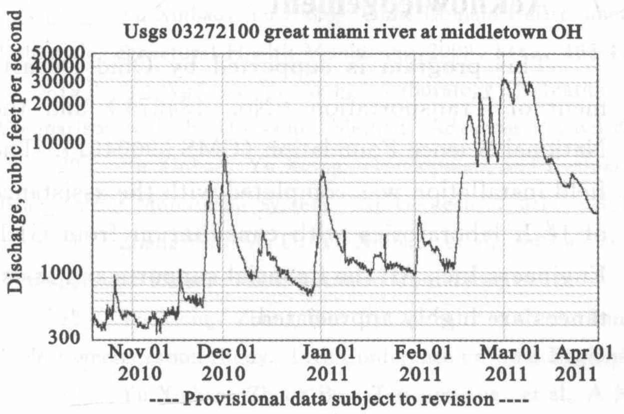
Table 2 **The cumulative scour depths at the five locations 2 months after installation**

Location	Location 1	Location 2	Location 3	Location 4	Location 5
Scour Depth(m)	0.27	0.16	0.41	0.47	0.21

For a longer time span, the scour data can be related to the stream discharge data and this is beneficial for future scour prediction. For example, during the winter season in 2010 and the spring season in 2011, the stream discharge record [USGS data, Figure 8(a)] at the bridge showed periodic flood events approximately at one month intervals. The discharge reached its peak in March, 2011. Correspondingly, the scour depths at bridge piers also demonstrated periodic peaks during these three flood events [Figure 8(b)]. The scour was also most severe in the March flood period. It is worth noting that the sedimentation (backfilling) process during the flood recessions is also indicative in the TDR data plot.



(a)



(b)

Fig. 8

(a) The stream discharge record of the river at the bridge (data from USGS website) from November 2010 to April 2012; (b) Monitored scour/sedimentation process during the same time-span.

5.2 Challenges and Pitfalls

The success of the proposed TDR bridge system shows that it is a promising countermeasure to scour critical bridges. However, we also encountered some challenges and pitfalls in terms of protection and the long-term performance of the proposed system. These includes: (1) it was found that the coaxial cable and the cable/sensor connector are the weak spots of the whole field sensing system. During the field monitoring period, exposed cables were found to be cut, possibly by vandalism activities. This caused the loss of two scour monitoring sensors. (2) Impact of debris, such as floating wood trunks, possesses a major challenge for the system to survive. Although the TDR probe itself is strong enough to survive the harsh environment, the debris and high flow velocity often shear the coaxial cables. (3) Occasionally, there are some erratic signals, which is different vastly from the normal signals. These may be caused by electromagnetic interference due to lightening or other sources or other sources. But this is relatively a minor issue considering that it is rare.

To protect the coaxial cable, conduits were used to lead the cables to the control unit. It was found effective to prevent vandalism activities and to endure attack from small debris. However, the cable/sensor section and the cable are still vulnerable to huge debris in flood events. According to NCHRP survey, the protection of cables was a major concern for several states (Hunt, 2009). Barrier rods were used to protect a FBG based scour sensor in the field (zafafshan et al. 2012) and were effective preventing impact from tree trunks. But the installation of the barriers into the riverbed may cause extra cost; and big and wide barriers may alter the flow around the sensors and result in inaccuracy for capturing the real scour situation; small and narrow barriers, on the other hand, may provide little protection of the sensor. The protection of the field bridge scour sensing system still needs to be addressed creatively in the future.

6 Summary and conclusions

Bridge scour is a major threat to the health of the bridge and it evolves fast in flood events. Field bridge scour sensors are expected to provide real-time scour information as well as to be accurate, cost effective, easy-to-install and durable. A remote bridge scour sensing system with a newly designed TDR probe is designed and implemented in the field. The TDR sensor is a composite sensor which is made of durable and inexpensive materials; a robust algorithm is developed to retrieve scour information from TDR signals. The field system includes the TDR sensors, TDR signal generators, data logger, and wireless modem; it is powered by a rechargeable battery which is charged by using a solar panel. The TDR sensors are installed by using traditional geotechnical investigation equipment and procedure. The signals from the sensors are acquired by the control unit at preset time intervals and wirelessly transmitted through cellular data service. It was proved that the field TDR sensor system and the proposed algorithm are capable to provide real-time scour and sedimentation information. Challenges also exist in terms of improving the longevity of the system. While the TDR sensors are robust enough to survive the harsh field environment, the cables are found to be the weak spot in the whole system. Efforts are needed to provide enough protection to the cables in the future. It is Also worth exploring to incorporate the field sensing data to a risk-based bridge management as well as to improve the existing scour prediction formulae, which are mostly developed based on laboratory data.

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