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16. Abstract

This State Study 229 was proposed as the Phase I study for implementing sensing technologies and computational analysis to assess bridge conditions and support decision-making for bridge maintenance in Mississippi. The objectives of the study are to: (1) prioritize the major detrimental bridge substructure deterioration in Mississippi waterway and their measurable parameters; (2) identify instrumentation technology for wirelessly in-situ monitoring of these parameters; (3) develop computational framework that can correlate the identified bridge substructure deterioration with the structure performance; (4) integrate research findings into education and professional preparation for students and professionals; and (5) prepare the field implementation for the next phase study and identify further needed research in above areas.

This finial report synthesizes the available findings from existing research and presents the major outcomes obtained from this State Study, which are summarized as follows. The bridge scour is determined as the major detrimental deterioration for bridges in Mississippi waterway by the project TAC members of MDOT and the project team. The fixed monitoring sensor for detecting scour at the bridge substructure has been identified as suitable means to ensure the bridge safety against scour. Literature reviews along with technical seminars on various scour monitoring devices, including Sonar, Magnetic sliding collars, Float-out devices, Tilt-sensor, and Time Domain Reflectometer (TDR), have been conducted and delivered to the inspectors and engineers at the MDOT Bridge Division. The TDR scour-monitoring sensor with wireless data transmission system was selected and evaluated for the field implementation of scour monitoring in the next phase study. A bridge in service has been chosen for implementing the field test of the selected scour monitoring system for the phase II study. The field installation plan and design was completed for the implementation of the selected sensor for the next phase II project.

The computational model of the scoured bridge and probabilistic inference are proposed and examined for assessing the bridge performance and its associated uncertainties for given scour conditions based on dynamic measurements. The method for predicting the reliability of the performance scoured bridge based on quantified uncertainties associated with the bridge damage models and scour damage is presented. The acceptable performance reliability or predicted probability of failure of scoured bridge has been identified. The application and effectiveness of proposed assessment approach are illustrated and examined through a numerical simulation of a selected prototype bridge. The future research needs for field verification of the selected scour monitoring system and the proposed computational framework are discussed.

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Instrumentation and Computational Modeling for Evaluation of Bridge Substructures across Waterways

Final Report for State Study-229

Department of Civil and Environmental Engineering

Jackson State University

December 2013

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EXECUTIVE SUMMARY

This State Study 229 was proposed as the Phase I study for implementing sensing technologies and computational analysis to assess bridge conditions and support decision-making for bridge maintenance in Mississippi. The objectives of the study are to: (1) prioritize the major detrimental bridge substructure deterioration in Mississippi waterways and their measurable parameters; (2) identify instrumentation technology for wireless in-situ monitoring of these parameters; (3) develop computational framework that can correlate the identified bridge substructure deterioration with the structure performance; (4) integrate research findings into education and professional preparation for students and professionals; and (5) prepare the field implementation for the next phase study and identify further needed research in above areas.

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The subsequent report is organized as follows.

Chapter 1 provides an introduction of the bridge failure due to scour, scour monitoring, assessment of scoured bridge, and the objectives and scope of the presented State Study.

Chapter 2 presents a general literature review on fixed scour monitoring instrumentation.

Chapter 3 outlines the collection, processing, and analysis of sensor measurement data.

Chapter 4 presents characteristics of selected TDR and its installation method.

Chapter 5 delivers the plan and design of the field implementation of the selected scour monitoring system for the phase II project in the future.

Chapter 6 introduces the computational framework for modeling scoured bridges and assessing uncertainties associated with structural models and detected scour.

Chapter 7 illustrates and examines the proposed computational framework through numerical simulation of monitoring a scoured bridge.

Chapter 8 provides the summary and future research needs.

CHAPTER 1 INTRODUCTION

1.1 Scour at Bridge Substructure and Its Impacts

Bridge substructures include piers, abutments, and foundations, which are critical components for bridges' safety operation. In addition to long-term environmental deterioration, the bridge substructures across major waterways in Mississippi are also frequently subject to scour due to flood and collision from barge or ship. Bridge scour refers to the removal of sediment such as soil, sand, and rocks from around bridge piers or abutments by swiftly moving flood current. It can scoop out scour holes around bridge piers or abutments. As scour occurs progressively, supporting material of bridge foundations is removed and replaced with material that has little or no bearing capacity. Thus, scour can quickly reduce the load capacities of bridge foundations and is most common cause of bridge failure from floods.

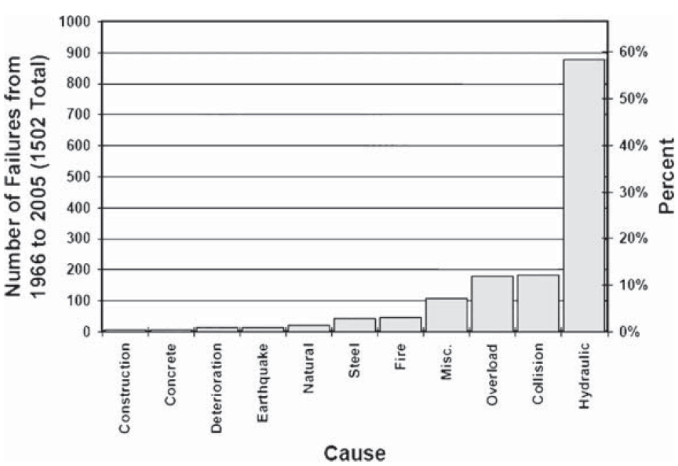


Figure1.1 Causes of bridge failures in the United States (Hunter 2009)

Scour at the foundation of bridges is the primary cause of bridge failures in the United States. Among bridge failures in the United States, 60% of them are due to scour. Figure 1 .1 shows statistics compiled by the Structures Division of the New York State Department of Transportation (DOT) and calculated using the National Bridge Failure Database. From 1966 to 2005, there have been at least 1,502 documented bridge failures. Of those bridge failures, 58% were the result of hydraulic conditions. Second on the list, but substantially behind, were collisions by ships, trucks, or trains, and overload. Earthquakes were a distant eighth on the list. A bridge is considered scour critical when its foundations have been determined to be unstable for the calculated or observed scour condition.

The scour erosion degradation had been attributed to the collapse of several bridges in Mississippi in the past. Examples include both the State Highway 33 Bridge and the Illinois Central Railroad Bridge at Rosetta, which were washed out during the flood of 1974. The MDOT set up its first statewide underwater bridge inspection program in 1988. Serious damage was found on bridge substructures across waterways during these inspections. At two parallel bridges on I-10 near Biloxi, for example, significant scour had occurred, exposing the steel piling. These piles had suffered from severe corrosion with cross sections reduced by 50%. Because of the reduced cross section, the web and flanges of the piles had buckled locally. This damage was exacerbated by collisions associated with barge traffic on the waterway. These combined effects had reduced the estimated margin of safety against collapse of the two bridges to near zero, even though the two bridges were built in 1967. Two alternatives had to be used to repair the above bridge substructure. The piles with more seriously damaged were encased in concrete, and the ones with less serious damages were dewatered and a concrete seal was placed around the piles. After 10 years, the piers with pile encasements showed no additional scour effects. However, the piers with the large concrete seals had scoured by as much as 10 ft.

1.2 Detecting and Monitoring Scour

Since the majority of bridges in Mississippi are across major waterways, MDOT faces the challenges to determine if these bridges can continue to operate safely or if they need to be repaired or replaced particularly aftermath flood or collision events. Primary inspection of bridge substructures underwater portions is usually conducted by sending Engineer-divers to inspect the substructures visually, even in cases where visibility is extraordinarily low. These inspections are dependent on personnel making on-site scour depth measurements at one instant in time, while the maximum scour depth could have already occurred or will occur after the scour measurement has been taken. Beyond the infrequency of inspection, these types of personnel-intensive inspections are subjective by their nature and cannot detect hidden deterioration or damage. Moreover, the underwater inspection during high flow situations poses a risk to inspection personnel.

In according to the study by Hunt (2009), several methods of monitoring bridge scour have been developed in the past 20 years, spanning a range of measurement approaches, complexities, costs, robustness, and measurement resolutions. With the successful completion of NCHRP Project 21-03, Instrumentation for Measuring Scour at Bridge Piers and Abutments, more than 120 of bridges were instrumented for monitoring scour. These bridges are instrumented because the scour estimates appear overly conservative and it is prudent to observe scour activity during flood events before spending resources on other types of countermeasures. Other bridges are scheduled to be replaced, and monitoring is an alternative measure to help ensure the safety of the traveling public until the new bridge is completed.

Scour monitoring allows for action to be taken before the safety of the public is threatened by the potential failure of a bridge due to scour. Among three types of means for monitoring bridge scour, i.e., visual monitoring, portable instruments and fixed instruments, fixed instrumentation describes monitoring devices which are attached to the bridge structure to detect scour at a particular location. Typically, fixed monitors are located at piers and abutments. The number and location of for installing the fixed monitors should be properly considered, as it may be impractical to place a fixed instrument at every pier and abutment on a bridge. Instruments such as sonar monitors can be used to provide a timeline of scour, whereas instruments such as magnetic sliding collars can only be used to monitor the maximum scour depth. Data from fixed instruments can be downloaded manually on site or it can be tele-transmitted to another location. Scour monitoring is an efficient, cost-effective countermeasure alternative.

On the other hand, full-scale bridge dynamic tests have revealed that dynamic characteristics of bridges can be identified based on measurements of structural dynamic response caused by traffic and wind loads (Salane et al. 1981; Manning 1985; Gregory et al. 1985; Dewolf et al. 1992; Huston et al. 1993). Decreases in bridge modal frequencies were found to be related to the member damage in terms of reduced coefficients of computed stiffness of corresponding members of bridge superstructures. Furthermore, Samizo et al. (2007) had revealed that modal frequencies of piers decreased as soil level around foundations decreased based on the measured ambient vibration of bridge piers. Olson et al. (2005) had conducted field dynamic tests on real bridges with scours simulated by gradually removing the soil around piles, and reported that obvious decreases in fundamental modal frequencies measured at the top of piers as scour damage increases. Besides, they found that the deterministic approach of system identification cannot be used to correctly identify the intact, excavated, or broken piles, and may be not suitable for bridge substructures' damage detection.

However, many field tests have revealed that the change of the vibration characteristics of bridges may be caused by environmental variations, such as the change of temperature or humidity, which may alter structural material's Young's modulus and mass density and also induce the internal thermal stress and boundary condition change (Kim et al. 2003; Clinton et al. 2006; Catbas et al. 2008). For examples, Farrar et al. (1994) found that environmental variations could produce changes in modal frequencies of a bridge, which were large enough to mask the change in modal frequencies caused by actual damages. Peeters et al. (2001) also reported that the modal frequencies could fluctuate up to 18% due to temperature fluctuation based on field measurements of a bridge in Switzerland.

Different approaches have been proposed to deal with environmental impacts on vibration-based SHM, including: (i) measuring environmental parameters directly, and conducting regression analyses to relate the change of vibration measurements to the structural damage and environmental variations respectively (Peeters and De Roeck 2000; Fritzen et al. 2003; Nandan and Singh 2011); (ii) constructing damage-sensitive features extracted from measured data that is sensitive to damages and insensitive to environmental variations without measuring the environmental parameters (Manson 2002; Sohn 2003; Ren 2011; Lin 2011); and (iii) dividing datasets of vibration measurements into subsets, which are dominated by different environmental variations and structural damages separately, and identifying and removing the subsets that are dominated by environmental variations from the selected dynamic features (Sohn and Farrar 2001; Sohn et al. 2001a,b; Deraemaeker et al. 2008). However, those efforts were limited to deterministic approaches. Inevitable uncertainties related to model, feature extraction, and data processing in aforementioned approaches have not been explicitly addressed.

1.3 Assessing Scoured Bridge

The detected scour does not provide any direct indication of the impact of scour on the bridge's structure integrity and performance. The detected scour depth is only a condition data and has to be translated in terms of the remaining capacity of the scoured bridge, which can be meaningful for decision-making. For a scoured bridge, a management decision on its operation, closure, retrofitting, or replacement should be made based on assessing whether it can meet a specific performance level, i.e., Fully Operational, Operational, Life-safe Threaten, or Near Collapse under specific loads or hazards (SEAOC 1995). Such performance level may be only determined based on reliable structural models. In this regard, a computational model could be used to assist assessment of the bridge's capacity with the identified bridge scour.

The scour impacts on bridge's pile reliability have been investigated by Diamantidis and Arnesen (1986). They concluded that the pile reliability decreases almost proportionally with the scour depth. Bennett (2009) and Daniels et al. (2007) studied the capacity of typical bridge pile groups and pile bents with various configurations under different extent of scour. They found that the scour occurring around any pile group and pile bent significantly reduces their flood load resistance. Federico et al. (2003) proposed a simple procedure to assess the vulnerability of bridge piers in rivers, and suggested that its further improvement could be achieved by: (i) examining the geotechnical limit states of the foundation subsystem, (ii) analyzing the time evolution of scour phenomena, and (iii) comparing between theoretical results and in-situ experimental measurements.

A risk-based model for assessing scour threat to bridge foundations was developed by Stein et al. (1999). In their model, the probability of scour failure is estimated based on waterway adequacy, substructure condition, and channel protection. This conceptual model empirically considered average daily traffic, types of foundation, condition ratings, and field scour evaluations. This model can be used to calculate annual risks associated with scour failures for managing a pool of bridges and prioritizing efforts. Yanmaz (2002) presented a model for assessing the reliability of cylindrical pier with local scour for decision-making. However, this model is based on a simplified assumption that a bridge fails when the maximum depth of scour around bridge pier reaches or exceeds the depth of pier footing.

It is usually difficult to accurately determine the extent of bridge scour and the other properties for the structural model. With those uncertainties, scoured bridges may be better assessed by using probabilistic framework in terms of the probability of failure in meeting the expected performance level. With advance in computational capacities and statistical sampling techniques, the Bayesian probabilistic framework could provide a new perspective for rigorously quantifying uncertainties encountered in monitoring and assessment of the scoured bridges. Within this framework, uncertain parameters of damages or other structural properties can be represented in terms of their probability density functions (PDFs), while uncertain models of the bridge system or impacts of environmental variations can be represented in terms of the relative probabilities of several competing models. Once in-situ measurements become available, those probability distributions can be updated through Bayes' Theorem. With those quantified uncertainties, the bridge performance reliability can be determined.

1.4 Objectives and Scope of State Study 229

This State Study 229 was proposed as the Phase I study on implementing sensing technologies and computational analysis to assess bridge conditions and support decision-making for bridge maintenance in Mississippi. The goal of this phase I study is to synergize the efforts of research and education to develop and transfer wireless instrumentation and analytical modeling for bridge substructures in waterways into Mississippi bridge maintenance practice.

The objectives of the study are to: (1) identify and prioritize the detrimental bridge substructures deteriorations and damages in Mississippi waterways and their measurable parameters; (2) identify instrumentation technology for in-suit wireless monitoring of these parameters; (3) develop multi-scale bridge analytical model that can correlate the identified bridge substructures deteriorations with the structure health conditions; (4) integrate research findings into education and professional preparation for diverse students and professionals; and (5) prepare the field implementation for the next phase project and identify further needed research in above area.

Expected outcomes of the phase I study are: (a) to develop suitable pilot instrumentation and modeling that can monitor, simulate, and evaluate bridge substructure damage caused by scour to supplement current bridge underwater inspection practice; (b) to establish collaboration among faculty, professionals, and students and engage more people into research and education on development and implementation of emerging technologies for bridge maintenance practice; and (c) to lay out technical foundation and professional preparation for implementation of in-suit instrumentation to improve current bridge inspection and enhance transportation safety in Mississippi.

To archive the above objectives and outcomes, several major tasks have been proposed for this Phase I project and are outlined as follows. The subsequent chapters in this finial report present major outcomes from those tasks.

Task 1: To examine the bridge scour records and site conditions of Mississippi bridges, and determine the candidate bridges, which are used for the field test of scour monitoring system in the next Phase II project after completing the current Phase I project.

Task 2: To conduct literature review on the current practice on application of wireless sensor instrumentation technology into bridges, with particular emphasis on available advanced instrumentation technologies those are suitable for monitoring scour at the specific site condition, and outline the inventory of suitable sensor candidates for monitoring scour for the designated Mississippi bridges.

Task 3: To develop pilot instrumentation and lab test for a wireless scour monitoring system that can be implemented on the designated prototype bridge site, including the design and fabrication of the scour sensor, and purchase and assemble of suitable off-shelf instrumentation component or system that are durable and easily installed, and can reliably provide data on the scour measurement.

Task 4: To provide instrumentation recommendation to MDOT TAC, and select final instrumentation from the “short list”, and develop implementation plan for field test of instrumentation at selected bridge sites for phase II project.

Task 5: To develop educational materials, hold a workshop, and provide in-house seminars for MDOT bridge inspectors, designers, and managers, as well as researchers and consultants.

CHAPTER 2 FIXED SCOUR MONITORING INSTRUMENTATION

This chapter outlines the inventory of available fixed scour monitoring device and their characteristics based on literature review of available sensors and advanced instrumentation technologies that are suitable for monitoring scour at the specific site condition. Particular attention will be paid to the available instrumentation that can be integrated with each other and monitor scour from multiple perspectives.

Table 2.1 Type of fixed scour monitoring instrumentation

Fixed Instrument	Mechanism
Sonar (fathometer)	A transducer provides streambed elevations
Magnetic Sliding Collar	A driven rod with sensors on a vertical support with a sliding collar placed at the streambed level
Float-Out Device	Buried transmitter that will float to the surface if scour exposes it
Tilt or Vibration Sensor	Record movements of the bridge
Sounding Rod	Manual or mechanical device (rod) to probe streambed
Time Domain Reflectometer	The round-trip travel time of an electromagnetic pulse in two buried parallel pipes provides information on changes in streambed elevation

2.1 Fixed Instrumentation and Scour Monitoring

According to the FHWA guidelines, existing bridges found to be vulnerable to scour should be monitored and/or have scour countermeasures installed. The fixed instrumentation, such as sonic fathometers (depth finders), was recommended as scour monitoring countermeasures in the FHWA's HEC-18 by Richardson and Davis (2001 and 2003). Such fixed scour monitoring instrument was also recommended in *Instrumentation for Measuring Scour at Bridge Piers and Abutments* by Lagasse et al. (1997). Both researches had developed, tested, and evaluated the instrumentation in the laboratory and in the field. Other types of fixed scour monitoring systems were also tested in those researches, including sounding rods and other buried devices. Subsequent to this research, two additional fixed monitors were developed and installed—float-out devices and tilt sensors, both of which are now being used extensively. Table 2.1 summarizes the types of fixed scour monitor instrumentation that are being used in the United States.

In according to the study by Hunt (2009), those various devices are either mounted on the bridge or installed in the streambed or on the banks in the vicinity of the bridge. Those scour monitoring devices transmit measurement data to a data logger at its remote unit. The data from any of these fixed instruments can be downloaded manually at the site or it can be telemetered to another remote location. The early scour monitoring devices measured streambed elevations using simple units mounted on-site and read manually. Almost all of the more recent installations use remote data transmission technology. Each bridge can have one or more remote sensor units that transmit data to a master unit on or near the bridge (Figure 2.1). The scour monitoring data are then transmitted from the master unit to a central office and/or posted on the Internet. The different types of fixed scour monitoring instruments and their characteristics are summarized in the following sections based on findings by Hunt (2005).

Figure2.1. Master station with data logger (Hunter 2009)

2.1.1 Sonars

Sonar scour monitors are mounted onto the pier or abutment face (Figures 2.2–2.5) to take streambed measurements, and each is connected to a data logger (Figure 2.1). The sonar instrument measures the distance from the sonar head to the riverbed and back based on the travel time of a sound wave through water. The data logger controls the sonar system operation and data collection functions. The data logger is programmed to take measurements at prescribed intervals. Sonar sensors normally take a rapid series of measurements and use an averaging scheme to determine the distance from the sonar transducer to the streambed. These instruments can track both the scour and refill (deposition) processes. The early sonar monitors used existing fish finders. Currently, new sonar monitors range from the fish finders to smart sonar transducers, both of which are commercially available.

Figure2.2. Scour monitoring system mounted on a pier on the Robert Moses Causeway over Fire Island Inlet, New York (circled) (Copyright: Raimondo di Egidio 2002,cited by Hunter 2009)).

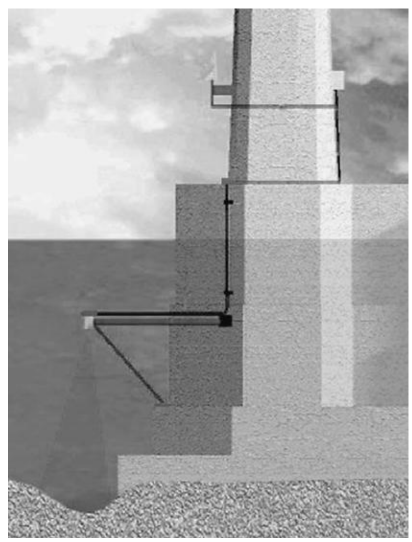


Figure2.3. Schematic of a sonar scour monitoring system (see Figure 2.2) (Courtesy: Hardesty & Hanover, LLP, cited by Hunter 2009).

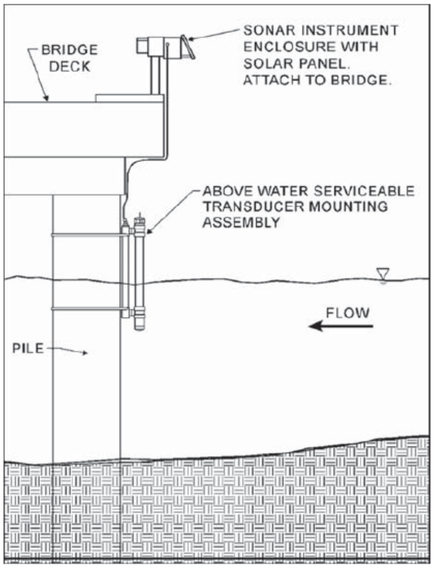


Figure2.4. Schematic of sonar scour monitoring system (Lagasse et al. 2001a, cited by Hunter 2009).

Figure2.5. Detail of conduit to underwater sonar monitor (Copyright: Raimondo di Egidio 2002, cited by Hunter 2009).

This type of monitoring sensor system has a purchase cost of roughly $4,000. Even though this type sensor is able to measure the current level of scour so information on the refilling is collected, its measurement can be affected by the aerated flow and bed load. Besides, this type of sensor device is not structurally robust. However, it may be mounted in a variety of elevations out of the way of debris. This type of sensor requires DC power and the interface with a data logger is wired. It is capable of multiplexing and does contain some self- diagnostic routines. This sensor can be mounted at various angles of inclination without affecting function as long as the bed is perpendicular to the sent “ping”.

2.1.2 Magnetic Sliding Collars

Magnetic sliding collars (Figures 2.6 and 2.7) are rods or masts that are attached to the face of a pier or abutment and driven or augered into the streambed. A collar with magnetic sensors is placed on the streambed around the rod. If the streambed erodes, the collar moves or slides down the rod into the scour hole. The depth of the collar provides information on the scour that has occurred at that particular location.

The early version of the sliding magnetic collar used a battery-operated manual probe that was inserted down from the top and a buzzer sounded when the probe tip sensed the level of the magnetic collar. More recent collars have a series of magnetically activated switches at known distances. Magnets in the steel collar come into proximity with the switches as it slides into the scour hole, the switches close and their position is sensed by the electronics. The data logger reads the level of the collar by means of the auto probe and senses scour activity. Although sonar scour monitors can be used to provide the infill scour process at a bridge, magnetic sliding collars can only be used to monitor the maximum scour depth.

Automated magnetic sliding collars-based scour monitoring has a system cost of roughly $10,000. It is a buried rod device which can measure the lowest level of scour where the sensor is located. It is somewhat robust with regard to debris because its housing shell is made of a structurally rigid metallic pipe and it is not exposed to debris at the water surface. It is a powered sensor with a wired interface to a data logger. It has moving parts, which detracts from its reliability compared to a sonar or float-out device. It directly measures scour, is multiplex capable and does have some diagnostics capability. It requires a pile driver to install and is susceptible to mishandling or vandalism. It is rigidly mounted and must be mounted vertically.

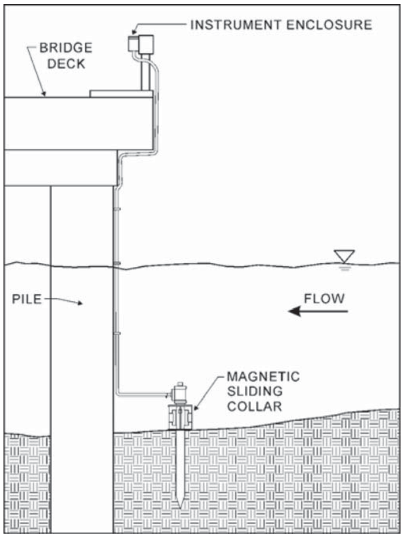


Figure2.6. Schematic of a magnetic sliding collar (Lagasse et al. 2001a, cited by Hunter 2009).

Figure2.7. Magnetic sliding collar installation (Hunter 2009)

2.1.3 Float-Out Devices

Buried devices can be active or inert buried sensors or transmitters. Float-out devices (Figures 9 and 10) are buried transmitters. This device consists of a radio transmitter buried in the channel bed at pre-determined depth(s). If the scour reaches that particular depth, the float-out device floats to the stream surface and an onboard transmitter is activated. It transmits the float-out device's digital identification number with a radio signal. The signal is detected by a receiver in an instrument shelter on or near the bridge. The receiver listens continuously for signals emitted by an activated float-out device. A decoded interface decodes the activated float-out device's unique digital identification number that will determine where the scour has occurred. A data logger controls and logs all activity of the scour monitor. These are particularly easy to install in dry riverbeds, during the installation of an armoring countermeasure such as riprap, and during the construction of a new bridge. The float-out sensor is a small low powered digital electronics position sensor and transmitter. The electronics draws zero current from a lithium battery, which, according to the manufacturer, provides a 9-year life expectancy when in the inactive state buried in the streambed.

Float-out scour monitoring systems have a system cost of roughly $3,500. They only provide a measurement if the scour has progressed past a datum. There is a power requirement, but which is minimal. However, the device cannot be checked to verify operational capability and the on-board power must be reliable for long periods without use. The interface with a datalogger is wireless.

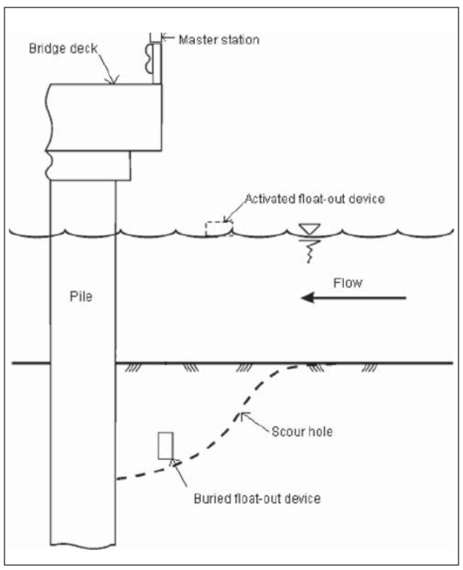


Figure2.8.Schematic of a float-out device (Texas Transportation Institute, cited by Hunter 2009).

Figure2.9. Float-out devices color coded and numbered for identification (Texas Transportation Institute, cited by Hunter 2009)..

2.1.4 Tilt Sensors

Tilt sensors (Figures 2.10 and 2.11) measure movement of the bridge itself. A pair of tilt sensors or clinometers will monitor the position of the bridge. One (*X*) monitors bridge position parallel to the direction of the traffic (longitudinal direction of the bridge), and the second (*Y*) monitors the position perpendicular to traffic (usually parallel with the stream flow). Should the bridge be subject to scour causing one of the support piers to settle, one or both of the tilt sensors would detect a change in position. Should the change as detected by the *X, Y* tilt sensor in bridge position exceed a programmable limit, the data system would send out an alert status message.

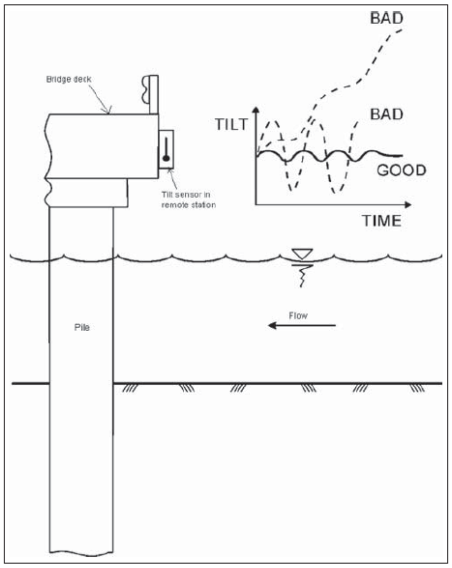


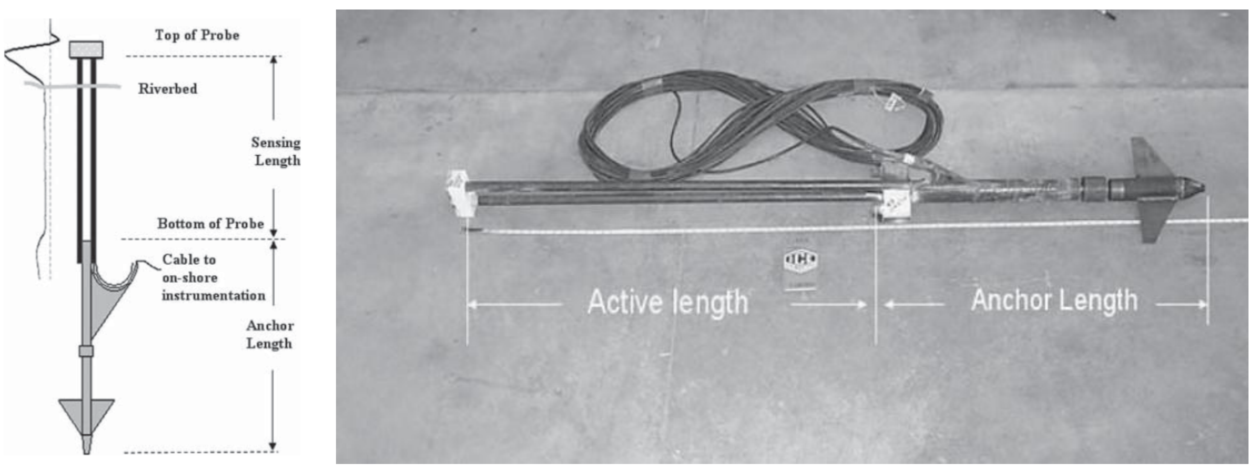
Figure2.10. Schematic of tilt sensor device (Texas Transportation Institute, cited by Hunter 2009).

Figure2.11. Tilt sensor installation with detail of the sensor (cited by Hunter 2009).

The California DOT (Caltrans) (Avila et al. 1999) notes that the tilt sensors monitor the ever-changing position that normally occurs because bridges must be redundant enough to withstand some amount of movement without failure. It is difficult to set the magnitude of the angle at which the bridge is in danger. Bridges are not rigid structures and movement can be induced by traffic, temperature, wind, hydraulic, and earthquake loads. It is necessary to observe the "normal" movement of the bridge and then determine the "alarm" angle that would provide sufficient time for crews to travel to the bridge to inspect and close the bridge to traffic, if necessary. Caltrans has accomplished this by installing the tilt sensors and monitoring normal changes in bridge position for several months and setting the "alarm" angle based on the unique signature of each pier monitored on any given bridge.

2.1.5 Time Domain Reflectometers

In Time Domain Reflectometry an electromagnetic pulse is sent down one pipe and returns through a parallel pipe, both of which are buried vertically in the streambed (see Figures 13a and b). When the pulse encounters a change in the boundary conditions (i.e., the soil–water interface), a portion of the pulse's energy is reflected back to the source from the boundary. The remainder of the pulse's energy propagates through the boundary until another boundary condition (or the end of the probe) causes part or all of the energy to be reflected back to the source. By monitoring the round-trip travel time of a pulse in real time, the distance to the respective boundaries can be calculated and this provides information on any changes in streambed elevation. Monitoring travel time in real time allows the processes affecting sediment transport to be correlated with the change in bed elevation. Using this procedure, the effects of hydraulic and ice conditions on the erosion of the riverbed can be documented.



(a) (b)

Figure2.12. (a) Schematic of time domain reflectometer; (b) Time domain reflectometry probe (Courtesy: U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory).

The instrument has the most complicated signal analysis of the instruments in this document. Campbell Scientific sells a device to produce the pulse and analyze the return signal.

2.1.6 Sounding Rods - BRISCO™ Monitors

Sounding-rod or falling-rod instruments are manual or mechanical (automated) gravity-based physical probes. As the streambed scours, the rod, with its foot resting on the streambed, drops following the streambed, causing the system counter to record the change. The foot must be of sufficient size to prevent penetration of the streambed caused by the weight of the rod and the vibration of the rod from flowing water. These were susceptible to streambed surface penetration in sand bed channels. This influences their accuracy.

The BRISCO™ Monitor is a sounding-rod instrument (Figure 2.13). It was among the first types of scour monitors and was installed mostly in colder climates. They were developed by Cayuga Industries in upstate New York shortly after the failure of the New York State Thruway over Schoharie Creek in 1987 as a result of scour. The system consists of a probe resting on the river bottom connected by a cable to a reel. There is an electrical monitor of the movement of this reel that transmits to a digital readout that is placed on the pier.

Figure2.13. Sounding rods installed to monitor riprap in New York (Hunter 2009).

The NCHRP Project 21-3 on fixed instrumentation (Lagasse et al. 1997) noted that BRISCO™ Monitors were available, but had not been tested extensively in the field. The project included some preliminary lab and field testing of the BRISCO™ Monitor; hereafter known as a sounding rod instrument; however, the sonar monitors and magnetic sliding collar showed better results and were the focus of the final part of the project. It has been documented that Cayuga Industries is no longer producing these devices.

If a series of streambed elevations over time are of interest, sonars, magnetic sliding collars, and sounding rod monitors can be used. If a bridge owner is interested only when a certain streambed elevation is reached, float-outs can be employed. For specific information on a pier or abutment, tilt sensors measure the movement of the structure. Survey respondents also used fixed instrumentation to gather information on water elevations, water velocities, and temperature readings.

Data from any of these fixed instruments can be downloaded manually at the site or can be telemetered to another location. A scour monitoring system at a bridge can use one of these devices or include a combination of two or more of these fixed instruments, all transmitting data to a central control center. These types of scour monitors are being used in a wide variety of climates and temperatures, and in a host of bridge and channel types throughout the United States.

2.2 Summary of Fixed Scour Monitoring Installations

Fixed monitors are typically located at piers and abutments. The mostly used monitoring sensors include sonars, magnetic sliding collars, float-out devices, sounding rods, tilt sensors, and time domain reflectometers (TDRs). The type of fixed scour monitoring system employed depends on what kind of information is desired.

Sonar: The sonar instrument measures the distance from the sonar head to the riverbed and back based on the travel time of a sound wave through water. Sonar sensors normally take a rapid series of measurements and use an averaging scheme to determine the distance from the sonar transducer to the streambed. These instruments can track both the scour and refill (deposition) processes. However, this type of sensor device is not structurally robust, but the device may be mounted in a variety of elevations out of the way of debris. The sensor requires DC power and the interface with a data logger is wired. It is affected by aerated flow and bed load.

Magnetic sliding collars: Magnetic sliding collars are rods or masts that are attached to the face of a pier or abutment and driven or augered into the streambed. A collar with magnetic sensors is placed on the streambed around the rod. If the streambed erodes, the collar moves or slides down the rod into the scour hole. The depth of the collar provides information on the scour that has occurred at that particular location. It is somewhat robust with regard to debris because its housing shell is made of a structurally rigid metallic pipe and it is not exposed to debris at the water surface. Although sonar scour monitors can be used to provide the infill scour process at a bridge, magnetic sliding collars can only be used to monitor the maximum scour depth. If the scour hole refills, the collar becomes buried. It is a powered sensor with a wired interface to a data logger. It has moving parts, which detracts from its reliability compared to a sonar or float-out device.

Float-out devices: Float-out devices are buried transmitters. This device consists of a radio transmitter buried in the channel bed at pre-determined depth(s). If the scour reaches that particular depth, the float-out device floats to the stream surface and an onboard transmitter is activated. It transmits the float-out device's digital identification number with a radio signal. The signal is detected by a receiver in an instrument shelter on or near the bridge. These are particularly easy to install in dry riverbeds, during the installation of an armoring countermeasure such as riprap, and during the construction of a new bridge. The float-out sensor is a small low powered digital electronics position sensor and transmitter. They only provide a measurement if the scour has progressed past a datum. There is a power requirement, but it is minimal. However, the device cannot be checked to verify operational capability and the on-board power must be reliable for long periods without use.

Tilt-sensor: Tilt sensors measure movement of the bridge itself. A pair of tilt sensors or clinometers will monitor the position of the bridge. Tilt sensors are relatively cheap and convenient to install and use. However, it is difficult to set the magnitude of the angle at which the bridge is in danger. Bridges are not rigid structures and movement can be induced by traffic, temperature, wind, hydraulic, and earthquake loads. It is necessary to observe the "normal" movement of the bridge and then determine the "alarm" angle that would provide sufficient time for crews to travel to the bridge to inspect and close the bridge to traffic, if necessary.

Time Domain Reflectometry: In Time Domain Reflectometry an electromagnetic pulse is sent down one pipe and returns through a parallel pipe, both of which are buried vertically in the streambed. When the pulse encounters a change in the boundary conditions (i.e., the soil–water interface), a portion of the pulse's energy is reflected back to the source from the boundary. Monitoring travel time in real time allows the processes affecting sediment transport to be correlated with the change in bed elevation. However, the instrument has the most complicated signal analysis of the instruments.

Sounding-rod: Sounding-rod or falling-rod instruments are manual or mechanical (automated) gravity-based physical probes. As the streambed scours, the rod, with its foot resting on the streambed, drops following the streambed, causes the system counter to record the change. The foot must be of sufficient size to prevent penetration of the streambed caused by the weight of the rod and the vibration of the rod from flowing water. These were susceptible to streambed surface penetration in sand bed channels. This influences their accuracy.

The best scour monitoring design should be the combination of various type sensors to obtain more useful information on scour depth through direct monitoring and changes of structural property, such as using sonar and tilt sensor, sonar and vibration sensor, etc. Accordingly, decision-makers will reap great benefit from the obtained information.

CHAPTER 3 DATA COLLECTION AND ANAYLISYS

3.1 Data Collection

3.1.1 Frequency of Data Collection

Based on the survey of NCHRP, the data collection procedures for the fixed scour monitoring systems varied among the respondents. The survey asked the owners about the protocol for several items regarding the data collection. This included the frequency with which the fixed monitors record data and how often the data are collected and reviewed under normal procedures and during emergency situations.

The fixed scour monitor instruments that take periodic readings can be programmed for any desired interval. The respondents reported that the intervals for their readings ranged from every 15 minutes to one time per month. Most of the monitors were programmed to take readings one to two times per hour.

The streambed elevation data are typically stored in a data logger and can be collected and reviewed by the owner or his/her designee at any desired interval. These data can be downloaded at the bridge site or from a remote site by means of telemetry. The respondents to the survey indicated that the interval at which their data are collected and reviewed under normal circumstances could be daily, weekly, or monthly. About half of the responses checked the category "other" and noted that this was done during floods or as needed.

During emergency situations, the frequency with which data were collected also varied. It included every 15 minutes, hourly, twice daily, daily, and bi-weekly.

3.1.2 Method of Data Collection

The data can be downloaded and retrieved automatically by means of telemetry or at the bridge site. The telemetry can be set up using a landline telephone, cellular telephone, or through a satellite connection. The respondents used one of the three systems. The majority of the respondents used telemetry to retrieve the bridge scour monitoring data. The automatic system can be conducted to a base computer or to a network for retrieval through an Internet connection. The Internet was the most common system used by 61% of the survey respondents. The second most-used method, used by 28%, was telemetry to a base computer. The remaining 11% downloaded the data at the bridge site. Earlier installations most often involved manual downloading of the data at the bridge sites.

Multiple modes for downloading the data at a particular bridge have been used. Satellite and local retrieval at the bridge site were the most frequently reported modes. These were followed by the landline telephone. The cellular telephone was not as common and was usually used when the landline telephone was not available. The sketch of data collection and transmission is shown in the Figure 3.1 below.

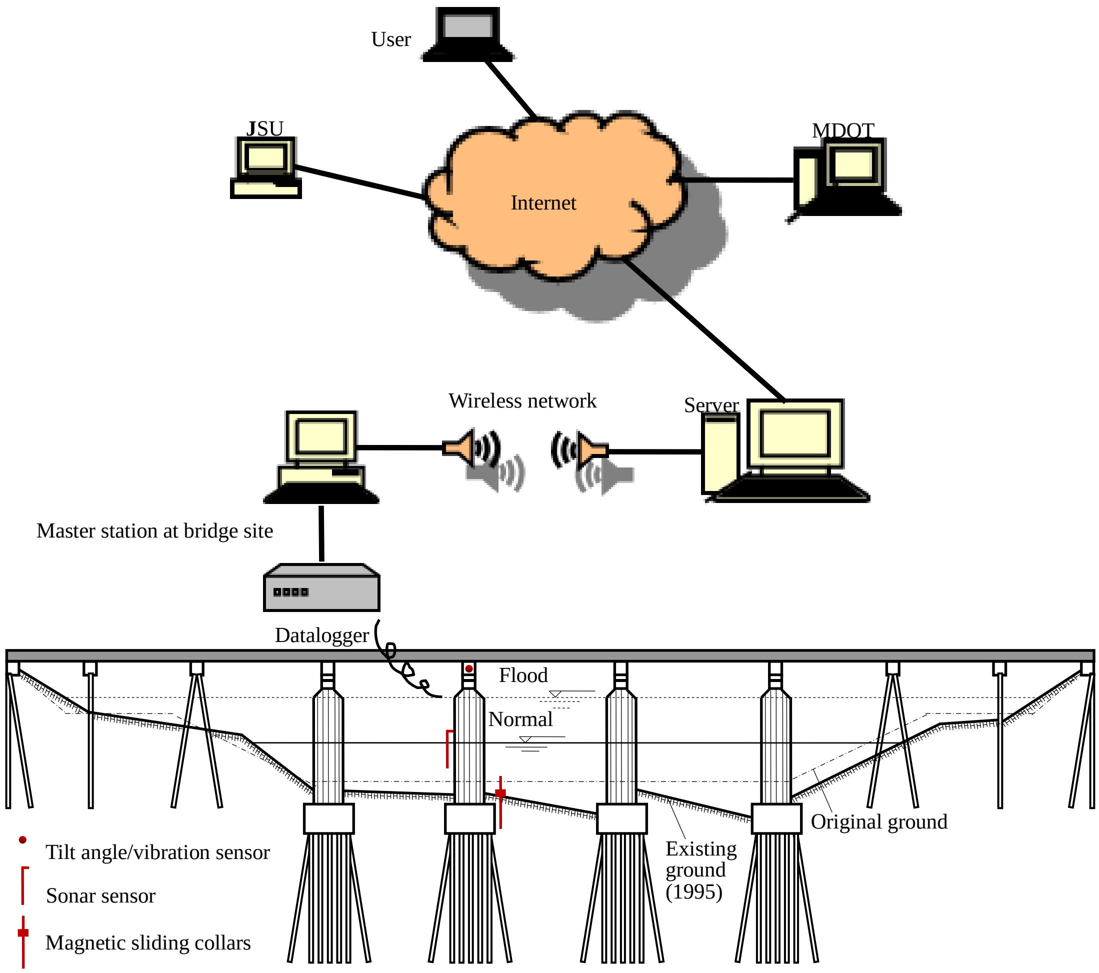


Figure3.1 The sketch of data collection and transmission

3.2 Data Processing and Analysis

The type of fixed scour monitoring system employed depends on what kind of information is desired. If a series of streambed elevations over time are of interest, sonars, magnetic sliding collars, and sounding rod monitors can be used. If a bridge owner is interested only when a certain streambed elevation is reached, float-outs can be employed. For specific information on pier or abutment movements, tilt sensors record changes in the position of the bridge in two directions. Information on water elevations, velocities, and temperature readings are also gathered.

Once the data are gathered, the analysis can be done using a variety of methods. If a scour monitoring system is continuously gathering data over a period of months or years, a large amount of data are generated. Data reduction techniques have been employed to view trends over long periods of time. Based on the monitoring data, the safety of bridge can be calculated and updated.

CHAPTER 4 SELECTED SCOUR MONITORING SENSOR SYSTEM

4.1 Selected Applicable Instrumentation for In-situ Monitoring of Scour

Based on extensive literature review on available monitoring systems, the consultant had made the presentation to the project Technical Advisory Committee (TAC) members on characterizations of each of those devices. The consultant also invited the sensor vendors to provide a further presentation on their products' technical specification and practical application to the TAC members. In brief summary, the magnetic sliding collar has moving parts that detracts from its reliability compared to a sonar or float-out device. The float-out device requires that its on-board power must be reliable for long periods, which make its operational capability is difficult to be verified. The accuracy of radar and sonar devices is affected by aerated flow in rapid floods. The TDR requires the most complicated signal analysis, however, it can provide real-time track on the change in riverbed elevation for capturing scour.

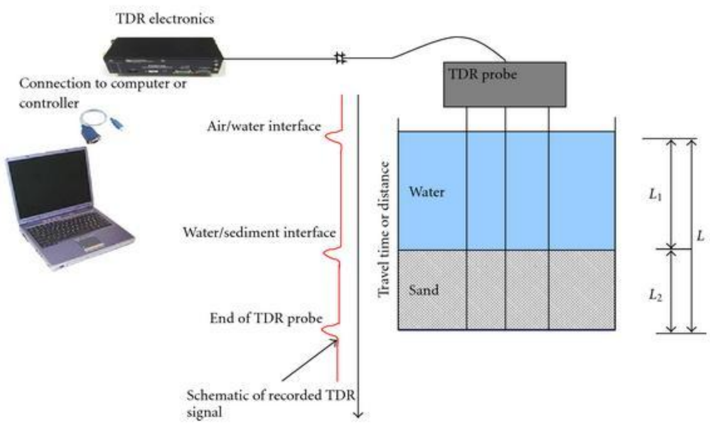
After discussion with TAC members, the TDR (Time domain reflectometers) was selected for the future field implementation and evaluation in the proposed Phase II project. Two available TDR scour sensors were further compared by the consultant and TAC members. One type of TDR sensor is provided by ETI Instrument Systems Inc in Fort Collins of Colorado, a major provider of scour monitoring sensors. This type of TDR sensor is a new product developed based on a prototype TDR sensor originated by the Army Corp. of Engineers. Its scour measuring range is up to 5 ft. This TDR has been used for monitoring the general scour in the streambed, but has not been used for monitoring scour around bridge foundations. The installation of this TDR needs the on-boat operation under bridge decks. An H-shape steel pile must be installed near the bridge piers, and then TDR will be attached to the steel pile.

Another type of TDR sensor is provided by the Case Western Reserve University (CWRU) in

Cleveland of Ohio. It was a product of the research project co-funded by National Science Foundation. This type of TDR sensors can measure the scour depth ranging up to 45 ft. It has been used to monitor scour around piers of a bridge in Ohio State. The installation of this TDR sensor can be operated on the bridge deck. After a series of discussions with TAC members, this TDR sensor was eventually chosen for the field implementation in the proposed Phase II project. This decision was made based on the sensor's capability of measuring a large scour depth, its installation method through operation over the bridge deck, and the vendor's practical experience through application of this TDR sensor at a prototype bridge site.

4.2 Working Principle of Selected TDR Sensor

The working principle of the selected TDR scour sensor is briefly presented here. The details can be referred to a publication by the sensor vendor on the journal of Advances in Civil Engineering through the link < http://www.hindawi.com/journals/ace/2010/508172/>. The selected TDR scour sensor utilizes an electromagnetic pulse to locate the interface between water and soil. Within the TDR, an electromagnetic pulse is sent from one probe and returns through a parallel probe, both of which are buried vertically in the streambed. When the pulse encounters a change in the boundary conditions (i.e., the soil-water interface), a portion of the pulse's energy is reflected back to the source from the boundary. The TDR sensor determines the interface level between the soil and fluid by measuring the difference between times when the impulse was sent and when the reflection returned (see Fig. 4.1). The sensors can output continuous analog signal. Fig. 4.2 shows the lab testing results by the sensor vendor. The calibration of the selected TDR sensors in the lab set is shown in Fig. 4.3 and Fig.4.4 respectively.



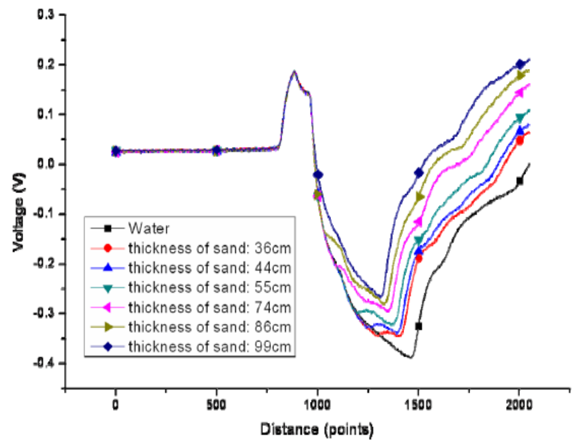


Figure4.1 Schematic plot of TDR scour measurement (courtesy of Bill Yu)

Figure4.2 Lab test results (courtesy of Bill Yu)

Fig. 11 shows the filed implementation of the TDR sensors in a bridge in Ohio State. The location of the scour sensor is first selected. The sensor location is 1 ft from the bridge pier and 6 ft from the side/edge of the bridge deck as shown in Fig. 4.5. A hole is drilled through the bridge deck to the riverbed by using a geotechnical drilling rig as shown in Fig. 4.6. The sensor is allocated vertically from the deck into the riverbed through the rig driller as shown in Fig. 4.7. Fig. 4.8 shows that the drilled hole was filled with cement mortar and the surface on the bridge deck was finished after the TDR sensor was installed in the place.

Figure4.3 Actual lab setting (courtesy of Bill Yu)

Figure4.4 TDR in sand layer (courtesy of Bill Yu)

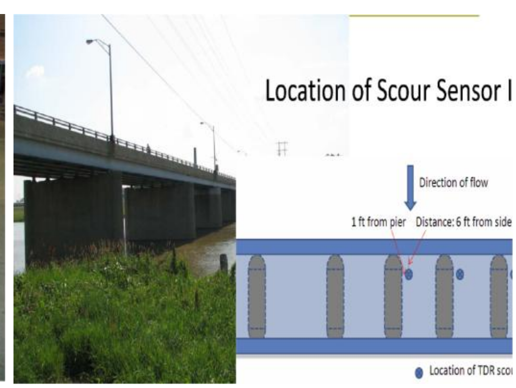


Figure4.5 Field implementation (courtesy of Bill Yu)

Figure4.6 Hole drilling (courtesy of Bill Yu)

Figure4.7 Sensor installation (courtesy of Bill Yu)

Figure4.8 Finishing of installation (courtesy of Bill Yu)

4.3 Configurations of TDR Sensor and Wireless Data Transmission System

The selected sensor vender has made efforts for developing the monitoring devices for the field bridge scour monitoring system that will be used for the lab evaluation and the field implementation for the phase II project. Based on the interim report made by the sensor vendor Bill Yu, the schematic drawing of the complete scour monitoring system is illustrated in Figure 4.9. The Components ③-⑦ constitute the control unit, which collects and sends TDR data wirelessly, as well as provides power to the system.

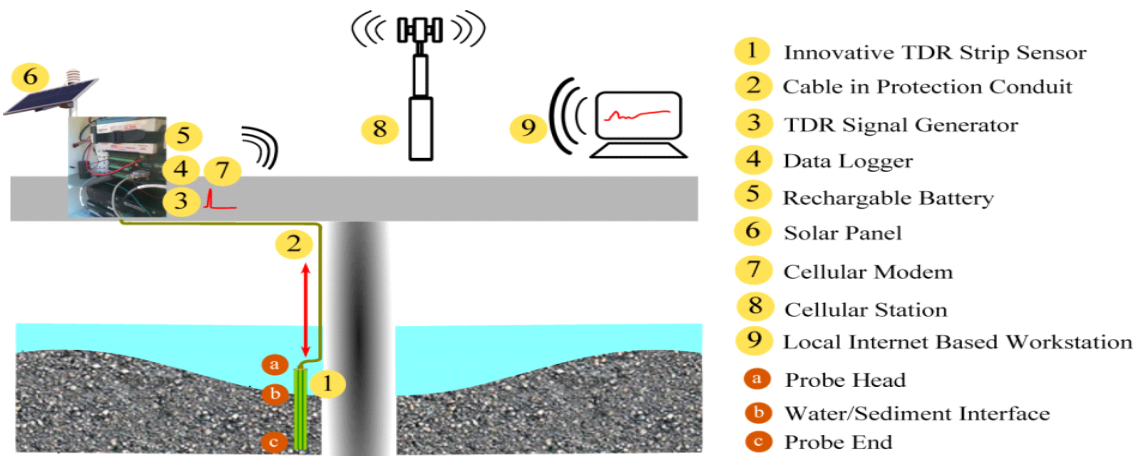


Figure4.9 Schematic Diagram of TDR Bridge Scour Monitoring System (courtesy of Bill Yu)

The TDR sensors were designed to be partially embedded in the riverbed (Figure 4.9①). Due to their capability for serial multiplexing, several strips of the TDR 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 4.9②). The control unit includes a TDR signal generator (Campbell Scientific® TDR 100) with a multiplexer (Campbell Scientific® SDMX50) (Figure4.9③), a data logger (Campbell Scientific® CR1000, Figure 4.9④), a rechargeable battery (Enersys® NP12-12T, Figure 4.9⑤) with a solar panel (Figure 4.9⑥) and a cellular modem (Figure 4.9⑦). 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). The monitoring data can be displayed at a website, which can be checked with any internet accessible terminals (e.g., PCs, Smartphones and etc.).

Components of the control unit are shown in Figure 4.10. The system can be powered with a solar panel and rechargeable battery.

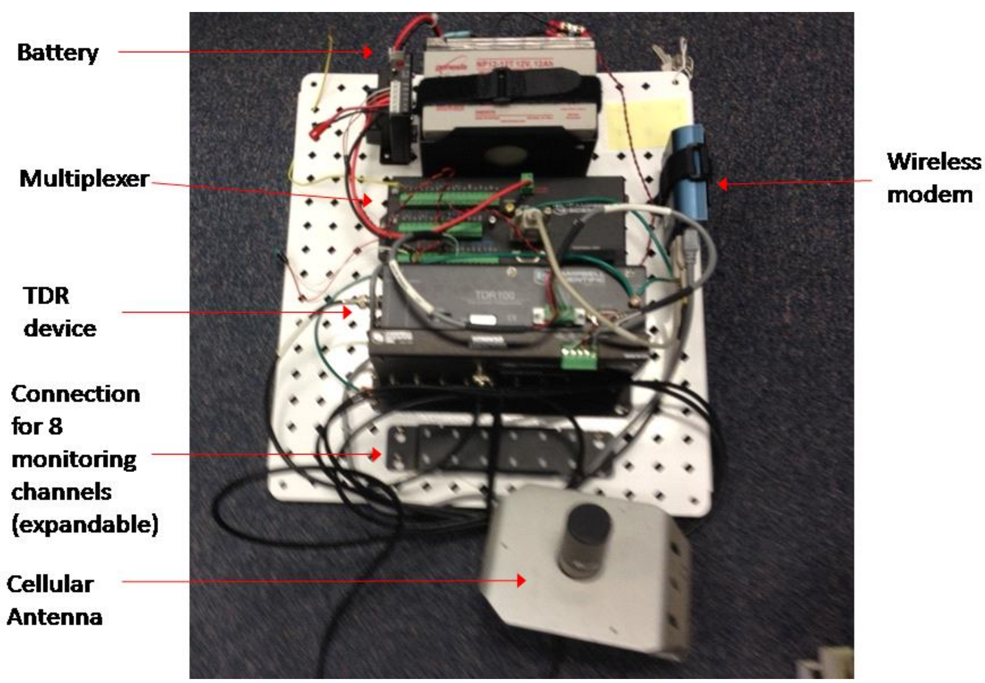


Figure4.10 Components of TDR monitoring system (courtesy of Bill Yu)

The Figure 4.11 shows the component of the web interface, where the TDR signals are displayed in real time. Parameters of the monitoring system, such as the battery voltage, solar panel output, etc., can also be displayed for diagnostic purposes. Users can access the website to review the scour signal characteristics.

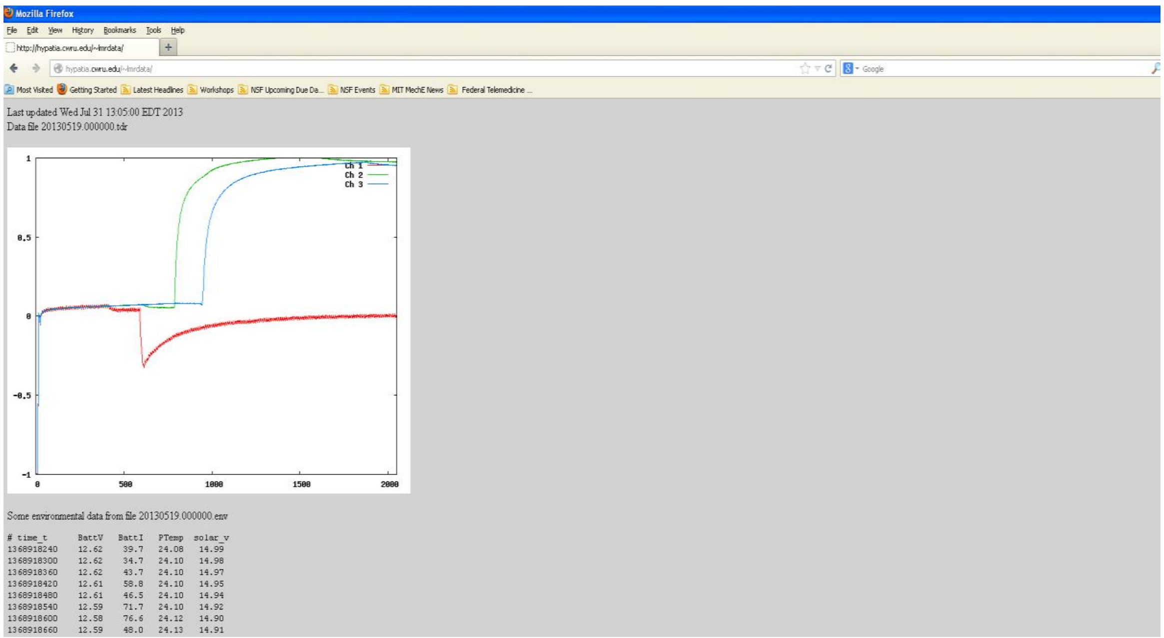


Figure4.11 Components of web interface (courtesy of Bill Yu)

The following future work for the Phase II project (Field Implementation) will be conducted as the development efforts evolving into field implementation stage:

1. Refinement of the user interface. The user interface will be further refined to improve the diagnosis function during the next stage of development for the field scour monitoring system.
2. Refine system hardware and integration.
3. Develop diagnosis software

4.4 Lab Evaluation and Demonstration of the Selected Scour Monitoring System

The fabrication and delivery of the selected scour monitoring system, however, were delayed by the vendor. The selected scour monitoring system just was delivered this month, which makes the research team unable to complete the lab evaluation of the system on time before writing the final report. The project team will try to complete the lab evaluation and demonstration of the selected scour monitoring system and report the results separately to MDOT later, even though the study is closed.

CHAPTER 5 DESIGN AND PLAN OF THE FIELD IMPLEMENTATION

5.1 Selected Prototype Bridge for Field Implementation and Evaluation

The Bridge Division of MDOT has selected a prototype bridge as the site for the field implementation and evaluation of the selected in-situ monitoring system in the Phase II project. The selected bridge is the SR 25 bridge #1.7A (Structure Key 11540) located on Lakeland Drive over the Pearl River in Jackson (see Fig.5.1). Based on regular underwater inspections, the river bed is considered fairly active and the scour development has been identified at this bridge site. According to the requirement of the Bridge Division, the installed TDR sensors are expected to measure scour development within a range of 15 ft. The tested TDR sensor will be installed near the upstream noses of the Bent 18, which is one of two main piers on the river. The MODT expects to implement in-situ sensors and data acquisition system to continuously monitor bridge scour at this site, evaluate their effectiveness, and obtain the hands-on experience and develop expertise in applying sensing technology for supplementing the current underwater visual inspection practice, which forms the necessity of the proposed Phase II project.

Figure5.1 SR 25 Bridge #1.7A on Lakeland Drive over the Pearl River in Jackson, Mississippi

5.2 Plan and Design for Phase II Project for Field Implementation

The phase II study is built on applicable outcomes form the Phase I Study. The goal of this phase II study is to explore the effectiveness of in-situ sensors for detecting and assessing bridge conditions through field implementation, and adopt suitable techniques for wirelessly acquiring and transmitting bridge condition data for supporting maintenance decision-making.

The objectives of the project are to:

1. implement the selected in-situ monitoring sensor to detect bridge scour;
2. develop wireless data acquisition and transmitting system for in-suit monitoring;
3. develop effective methods for validating the accuracy and reliability of the tested in-suit scour monitoring sensor; and
4. validate the effectiveness of the proposed technique in detecting and measuring scour for assessing existing bridges.

Expected outcomes of the phase II project are to:

1. answer questions concerned by the MDOT's Bridge Division about whether the selected TDR sensor can accurately detect and measure the scour around the bridge foundation; whether the sensor can be easily installed; and whether the sensor data can be transmitted to a MDOT District office in a consistent and timely manner;
2. gain hands-on experience in application of in-situ monitoring and data-driven evaluation for supplementing current visual inspection practice;
3. lay out technical foundation and professional preparation for wide application of in-situ monitoring of scour and other damages for bridge maintenance decision-making;
4. identify further research need for future wide application of in-situ condition monitoring and in-field damage detecting for supporting decision-making.

To achieve the above outcomes, the following major study tasks will be undertaken, which will be further explained and itemized in the detailed research plan:

- Finalize the details of the sensor deployment and the field installation at the selected bridge site based on the outcomes from the Phase I project and inputs from MDOT;
- Identify the suitable contractors for the sensor installation and coordinate with the MDOT traffic control division for the site traffic control and/or detouring;
- Install and set up scour sensors and wireless data acquisition system at the bridge site to collect scour data and transmit them from the site to the office desk computers;
- Monitor and analyze in-situ data to identify scour damages and validate the identified scour development with the results from regular underwater inspections; and
- Summarize and report the project progress and findings.

5.3 Proposed Field Installation Scheme

The selected TDR sensor will be installed at the site of the SR 25 bridge #1.7A (Structure Key 11540) located on Lakeland Drive over the Pearl River in Jackson, Mississippi, because the river bed at this bridge site is considered fairly active and scour issue has been identified at this bridge site. The entire bridge has 26 bents, in which Bent 1 to Bent 16 are equally spaced (spacing = 40 ft). From Bent 16 to Bent 19, however, the bridge span increases significantly. More specifically, span lengths for Bent 16-to-17, 17-to18, and 18-19 are 90 ft, 120 ft, and 90 ft, respectively, as shown in Fig. 5.2. Due to the lower riverbed and flood erosion, MDOT's inspectors have reported that Bent 18 has significant scour problem. The inspectors and bridge engineers from the Bridge Division concluded that it would be beneficial to monitor the scour progress at this bridge site for the safety of the public and traffic, and obtain hands-on experience from the field-implementation of in-situ scour monitoring. According to MDOT, the tested TDR sensor is expected to have a measurement range of at least 15 ft and will be installed near the upstream nose of Bent 18, which is one of two main piers on the river.

Fig. 5.2 shows a schematic drawing of the preliminarily-proposed installation locations of one tested TDR sensor at the designated bridge site. The TDR sensors are placed about 1 ft from the face of the pile cap, and 6 ft from the side of the bridge barrier. The procedures for this sensor implementation include first drilling a hole on bridge deck for accommodating the sensor, followed by hanging the sensor gradually down under the water as shown from Fig. 4.6 to Fig. 4.8. The contractor will then anchor the TDR sensor down the riverbed, properly arrange the cables as shown in Fig. 5.3, and then fill the hole with cement mortar. The data logger box will be placed on the side of the bridge for ease of data accessing as shown in Fig. 5.4 and Fig. 5.5.

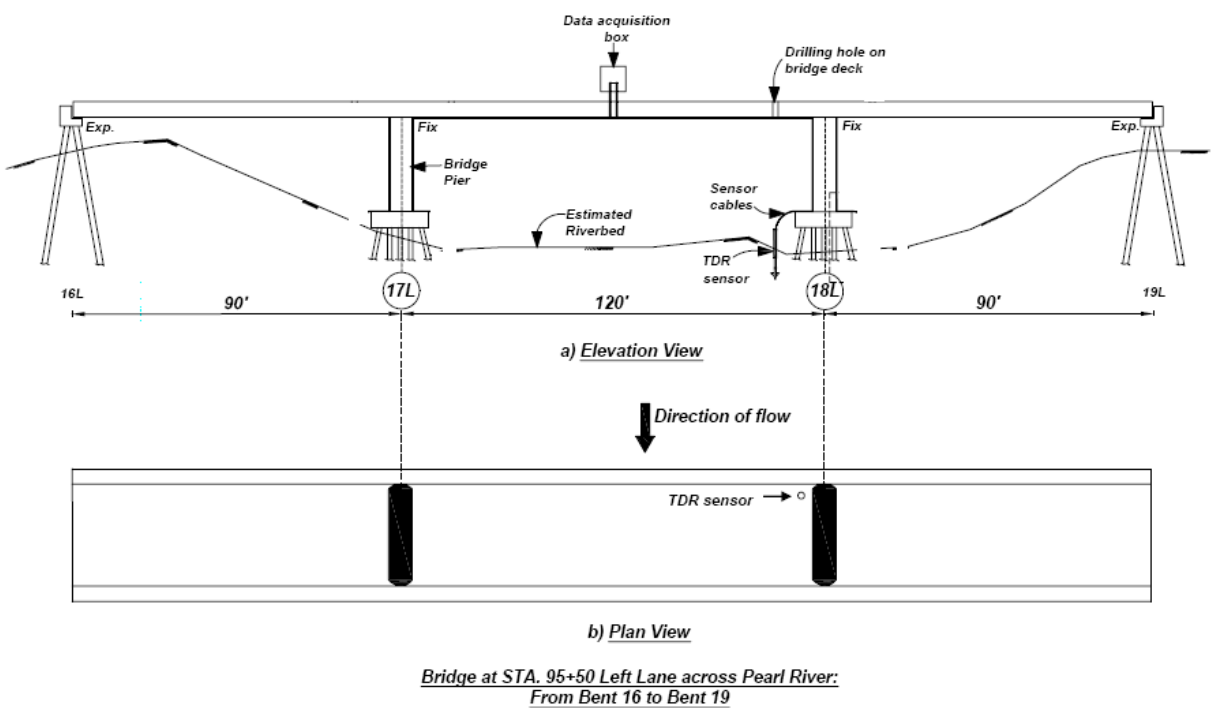


Figure5.2 Proposed Schemes for Scour Sensor Deployment at SR 25 Bridge #1.7A Site

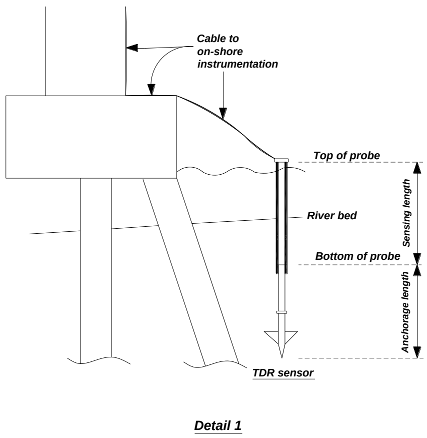


Figure5.3 Sensor installation (Hunter 2009)


Figure5.4 Data acquisition box


Figure5.5 Data logger

5.4 Detailed Plan and Research Tasks

To archive the aforementioned objectives and outcomes, the proposed Phase II project will include the following study tasks. The consultant team will mainly devote their efforts to complete each task, while the Technical Advisory Committee (TAC) of MDOT will provide the data related to the selected bridge site and coordinate with MDOT other division for traffic control during the field installation, as well as provide their inputs as needed. Those study tasks are further specified in following subtasks (the subtasks related to the service provided by MDOT are stated in the dark blue font).

Task 1- Design detailed construction documents and drawings for field installation

Subtask 1.1: If the proposed project is recommended for funding, the Technical Advisory Committee (TAC) will have its first meeting to further discuss details on the proposed project. The TAC members from MDOT will particularly provide their inputs on the preliminary design of in-field installation as presented in this proposal, as well as other data related to the selected bridge as needed, such as the geotechnical report on the bridge site.

Subtask 1.2: The consultant will recruit a research associate and students to form the consultant team to conduct the proposed study tasks. Under the direction of the consultant, the selected associate and students will perform the installation design, participate in the installation and set up of the in-situ system, monitor and analyze the real-time data, develop specification and assessment framework, and carry out other related work. Particularly, the research associate and students will also work closely with MDOT professionals to better address and verify the MDOT's needs and share the project findings and their experience with MDOT professionals. They will act as a technical liaison between the university and MDOT and function as research associates for both the university and MDOT.

Subtask 1.3: The consultant team will contact and work with the in-situ sensors vendor, i.e. the Case Western Reserve University, to obtain further technical specification on the in-field assembling and installation of the selected in-situ monitoring system.

Subtask 1.4: The consultant team will develop detailed construction documents and drawings for the in-field assembling and installation of the proposed monitoring system. Those documents and drawings will include the placement of the sensors, cables, and data acquiring and transmitting system, and details on their attachment to the riverbed and bridge system, as well as specifications and requirements for drilling operation holes in the bridge deck and refilling those holes, and the needs for traffic control or rerouting and their durations. The consultant team will deliver those construction documents and drawings to MDOT for review and comments.

Subtask 1.5: The TAC members from MDOT will review the aforementioned documents and drawings and provide their inputs and comments to the consultant team.

Subtask 1.6: The consultant team will finalize construction documents and drawings based on the TAC members' comments and submit the finalized construction documents and drawings as one of project interim reports.

Task 2 - Prepare for the field installation

Subtask 2.1: The TAC members from MDOT will provide a list of MDOT's contractors who may be capable of performing the field installation of the sensors, cables, and data acquiring system as specified in the construction documents and drawings.

Subtask 2.2: The consultant team will also identify additional potential contractors for the installation, and will provide the details of installation documents and drawings to those contractors identified by MDOT and the consultant team, and eventually seek the final bid from those contractors.

Subtask 2.3: The TAC members from MDOT will contact the MDOT traffic control division for coordinating and determining the time window for the field installation and implementation of traffic control and rerouting. This will be based on the identified installation needs and traffic control plan set up in Task 1.

Subtask 2.4: The consultant team will inform the sensor vendors and installation contractor with date for the field installation based on the time window provided by MODT.

Task 3- Field installation

Subtask 3.1: The MDOT's traffic control division will implement the traffic control or rerouting of traffic lanes over the selected bridge during the installation period.

Subtask 3.2: The contractors will install the in-suit monitoring system and restore the bridge deck after the installation. The inspectors and Engineers from the Bridge Division will be invited to observe the installation techniques and processes.

Subtask 3.3: The sensor vendor and consultant team will set up the in-suit monitoring and data acquisition system to obtain the data from the system. The inspectors and Engineers from the Bridge Division will be invited to observe the techniques for setting up the monitoring system. The subsequent seminar and specifications, which is planned to be provided to the inspectors and engineers from the Bridge Division by the consultant at later time, will include the details of installation and set-up of the selected in-situ monitoring.

Task 4-Test and validate the in-situ TDR scour monitoring system

Subtask 4.1: The sensor vendor and consultant team will link the in-situ data acquisition system to the wireless communication system and transmit the in-situ monitoring data to the computers in the offices at Jackson State University and the Bridge Division of MODT.

Subtask 4.2: The consultant team will convert the data in to the scour depth development using the software provided by the sensor vendor, monitor the scour depth development at piers of the selected bridge, and report any significant detected scour development to the Bridge Division of MODT.

Subtask 4.3: To validate the accuracy of the scour measurements of the tested TDR sensor, the consultant team will explore and develop the effective method for taking several real-time measurements of scour depths. Those validation measurements will be taken by using other reliable means rather than the tested TDR sensor. It is proposed to use other type of in-situ scour sensors to take those validation measurements. Among other available scour sensors, the sonar scour can accurately track the scour depth change. However, its accuracy could be affected by aerated flow that may exist during higher water seasons. The gravity-based dropping probe sensor, such as Magnetic Sliding Collar or Falling-Rod, can reliably measure the maximum scour depth during higher water seasons. The drawback of this type sensor is that it would be buried if the scour is refilled. Since the maximum scour depth during higher water seasons is always the major concern, the gravity-based dropping probe sensor will be first considered and explored for the validation measurements. Particularly for the validation purpose, those measurements do not need to be taken permanently. Thus, the rob or pipe, which guides the sliding or falling probe sensor, can be extended to the bridge deck level to avoid the underwater installation. The adoption or alternation of those sensors for will be further explored to better fulfill this subtask. It is expected that as a by-product of this project, the adopted gravity-based dropping probe sensor would be further developed as a portable scour measurement device, which the MDOT bridge inspectors can carry and use to take scour measurement at the needed bridge site. The measuring mechanisms of those alternate scour sensors can be referred to the section 2.2.

Subtask 4.4: The consultant team will compare the scour measurement obtained from the subtask 4.3 with the measurement obtained from the tested TRD sensor to validate the effectiveness of the tested system and make necessary adjustment on the calibration coefficient that convert the change of data measurement into the scour depth development. The subsequent seminar and specifications, which is planned to be provided to the inspectors and engineers from the Bridge Division by the consultant at later time, will include the details of monitoring and analysis of data from in-situ monitoring.

Task 5- Report the project progress and disseminate project findings

Subtask 5.1: The consultant team will write the quarterly reports to TAC and describe the project progress and unexpected problems.

Subtask 5.2: The consultant team will summarize the experience of application of the in-situ monitoring obtained from this project, and examine the needs for applying the in-situ monitoring and measurement-analysis-based approach into the inspection practice.

Subtask 5.3: The consultant team will present the findings, communicate with peers in the similar research field, and obtain fresh ideas for addressing the assessment of scoured bridges from other states at the TRB annual meeting in Washington DC.

Subtask 5.4: The consultant team will present the findings and recommendation to the TAC of MDOT and seek their inputs through the TAC meeting. The consultant team will write the final report and send it to TAC for review and comments

Subtask 5.5: The TAC will review and make comments on the final reports and future research needs in the in-situ monitoring and in-field measuring for assessing health condition of the bridge and other structures.

Subtask 5.6: The consultant team will finalize the final report based on the TAC's comments and submit it to MDOT.

CHAPTER 6 COMPUTATIONAL FRAMEWORK FOR MONITORING AND ASSESSING SCOURED BRIDGES

To assess the performance of scoured bridges with existence of various uncertainties, the study proposes and explores the novel application of probabilistic framework to quantify uncertainties associated with scoured bridge assessment based on the Bayesian inference and calculate the reliability of the performance of scoured bridge based on the quantified uncertainties. This framework is studied here based on the principle that the best scour monitoring design should be the combination of different type sensors to obtain various useful information to help the decision-maker for reliably estimating bridge safety. This presented computational framework can be particularly used when the vibration measurements are available to inference the bridge scour and supplement the direct measurement of the bridge scour. This computational framework is established based on relevant literature (Hsu et al. 2009; Beck and Katafygiotis 1998; Beck and Yuen 2004), and presented below. The computational model of scoured bridge is proposed and presented subsequently in the section of the numerical simulation.

6.1 Defining Classes of Multiple Models and their Uncertain Model Parameters

If there are uncertainties associated with model parameters for the structural model M_j of a system, the uncertain model parameters can be denoted as a vector $\boldsymbol{\alpha_j}$ with dimension of N_α and may take many possible different values. As a result, the structural model M_j would correspond to a class of models for different $\boldsymbol{\alpha_j}$ and can be referred to as a model class M_j. If there are uncertainties associated with the structural model of a specific system, several different forms of the structural model may be established. As a result, multiple model classes may be considered for the system and can be denoted as $\boldsymbol{M} = \{M_j: j = 1, 2, \ldots, N_M\}$. The vector $\boldsymbol{\alpha_j}$ may be different for each model class M_j in the model classes $\boldsymbol{M}$, but is always associated with a specific model M_j. Thus, the subscript j is dropped from $\boldsymbol{\alpha_j}$ for convenience. For a given model parameter $\boldsymbol{\alpha}$, the model class M_j defines a specific relation between the model input vector $\boldsymbol{Z}$ and the output vector $\boldsymbol{X}$, i.e., $\boldsymbol{X}=q_i(\boldsymbol{\alpha},$

$\boldsymbol{Z}$, M_j).

6.2 Establishing Likelihood Function for Bayesian Inference

Bayesian Inference essentially provides a probabilistic computational framework for quantifying uncertainties associated with model parameters and model classes based on Baye's Theorem by using available measurement data. The key for applying Bayesian inference is to establish the likelihood function $f\,(D|\,\boldsymbol{\theta}, M_j)$, which defines the likelihood of getting the measurement data D given parameter vector $\boldsymbol{\theta}$ **,** which is the parameter vector that contains the uncertain parameters of structural model $\boldsymbol{\alpha}$ and uncertain parameters of probabilistic model $\boldsymbol{\sigma}$ as discussed subsequently. For the model updating or damage identification, the likelihood function usually is established based on the probability distribution of the prediction error, i.e. the difference between the measured system outputs at the specified locations from sensor networks and the predicted system outputs at the corresponding locations from the structural model with the given parameter $\boldsymbol{\theta}$. It can be formulated in the time domain or in the spectrum domain for vibration-based damage identification. For details in this regarding, readers may refer to the reference (Huston and Gardner-Morse 1993; Olson 2005). The presented study adopts the likelihood function in the time domain, which is outlined as follows.

If available measurement data $\boldsymbol{D}$ contains the measured input vector $\boldsymbol{Z_n}$ and output (or response) vector $\boldsymbol{Y_n}$ at the time $t= n\cdot\ \Delta t$ for N_d of the measured Degree of Freedom (DOF) of the system, and if the total number of time series of measurement sets of outputs is N_t (i.e., $n= 1,2,\ldots\ldots, N_t$), then the prediction error vector $\boldsymbol{e_n}$ of the selected DOF of the structural model M for a given structural model parameter vector $\boldsymbol{\alpha}$ at the time $t= n\cdot\ \Delta t$ can be expressed as

$$e_n = Y_n - L_0 \cdot q(\boldsymbol{\alpha}, Z_n, M_j) \tag{1}$$

where $q(\boldsymbol{\alpha}, \boldsymbol{Z_n}, M_j)$ is the predicted outputs at all Degree of Freedom (DOF) of the structure model

M_j for a given structural model parameter vector $\boldsymbol{\alpha}$ and input $\boldsymbol{Z_n}$ at time $t = n \cdot \Delta t$; L_0 is the selection matrix with only nonzero element equal to 1 in each row for converting the output vector $q(\boldsymbol{\alpha}, \boldsymbol{Z_n}, M_j)$ at all DOF of the structural model M_j into the output vector at the measured DOF, so that $L_0 \cdot q(\boldsymbol{\alpha}, \boldsymbol{Z_n}, M_j)$ is the predicted system outputs at N_d of measured Degree of Freedom (DOF) of the model M_j ; and $\boldsymbol{e}_n$, Y_n, and $L_0 \cdot q(\boldsymbol{\alpha}, \boldsymbol{Z_n}, M_j)$ are vectors with N_d dimensions.

It is usually assumed that the prediction error at different time point and at different DOF (or locations) are independent, and assumed that the prediction error $\boldsymbol{e_n}$ at time $t = n \cdot \Delta t$ is a zero-mean stationary normally-distributed stochastic process with a standard deviation of σ**,** which is equal for all DOF of the model and all time points. Then, the likelihood function $p(\mathbf{D} \mid M_j, \theta)$ can be represented by the probability density function of joint distribution of multiple (total number $N_t \cdot N_d$) independent normal distributed statistical variables as the following

$$p(D \mid M_j, \theta) = \frac{1}{\sqrt{2\pi}\sigma^{N_t \cdot N_d}} \cdot \exp\left[-\frac{1}{2 \cdot \sigma^2} \sum_{n=1}^{N_t} \sum_{j=1}^{N_d} [Y_n^{(j)} - \{L_0 \cdot q(\theta, \mathbf{Z_n}, M)\}^{(j)}]^2 \right] \tag{2}$$

where $\boldsymbol{\theta} = \{\boldsymbol{\alpha}^T, \sigma\}^{\mathrm{T}}$ is the uncertain parameter vector; $Y_n^{(j)}$ is the j-th component of the vector Y_n ; and $\{L_0 \cdot q(\boldsymbol{\alpha}, Z_n, M_j)\}^{(j)}$ is the j-th component of the vector $L_0 \cdot q(\boldsymbol{\alpha}, Z_n, M)$.

6.3 Updating Model Parameter PDF for Each Model Mj through Baye's Theorem

If the input-output data D are available from sensor networks deployed at the system, this information can be used with Bayes' Theorem to update the prior probability density function PDF $p(\theta|M_j)$ of model parameters and obtain the posterior probability density function PDF $p(\theta|M_j)$ of model parameters as the following:

$$p(\theta \mid D, M_j) = \frac{p(D \mid \theta, M_j) \cdot p(\theta \mid M_j)}{p(D \mid M_j)} \tag{3}$$

where $p(D| \boldsymbol{\theta}, M_j)$ is the likelihood function as defined in the Eq. 2; $p(D| M_j)$ is the model evidence (or marginal likelihood) and actually is a normalization constant that makes the integral of the right side in Eq. 3 over all spaces of parameters $\boldsymbol{\theta}$ to be equal to 1, thus can be determined as the following:

$$p(D \mid M_j) = \int p(D \mid \theta, M_j) \cdot p(\theta \mid M_j) d\theta \tag{4}$$

6.4 Assessing Probability of Each Model Class Mj in the Model Classes M

If the model evidence as defined in the Eq. 4 is available for the model class M_j and the prior probability of model is assumed based on prior knowledge or experience for each model class among candidate model classes $\boldsymbol{M} = \{M_j : j = 1, 2, . . . , N_M \}$, the posterior probability of the model class M_j can be obtained based on the data D by using Bayes' Theorem as the following:

$$P(M_j \mid D, M) = \frac{p(D \mid M_j) \cdot P(M_j \mid \boldsymbol{M})}{\sum_{j=1}^{N_M} p(D \mid M_j) \cdot P(M_j \mid \boldsymbol{M})} \tag{5}$$

Where $P(M_j \mid \boldsymbol{M})$ is the prior probability of model class M_j and can be taken to be $1/N_M$ if it is reasonable to consider all model classes to be equally plausible; $p(D|M_j)$ is the model evidence for model class M_j as defined in Eq. 4 with the measurement data D.

6.5 Robust Prediction based on Most Plausible Model

Based on the most plausible model M_j for the system , all the probabilistic information for the prediction of responses $\boldsymbol{X}$ of the system with available measurements D can be obtained by the theorem of Total Probability:

$$p(\boldsymbol{X}|D,M_j) = \int p(\boldsymbol{X}| \theta,D,M_j) p(\theta |D,M_j) \, d\theta \tag{6}$$

where the predictive function $p(\boldsymbol{X}| \theta,D,M_j)$ of the model M_j, e.g. is weighted by the posterior probability of its model parameters.

6.6 Robust Prediction Based on Model Class Averaging

If a set of candidate model classes $\boldsymbol{M} = \{M_j: j = 1, 2, . . . , N_M\}$ contains several models that have comparable probability, all or several of them could be considered for predicting a system. The probabilistic information for the prediction of future responses $\boldsymbol{X}$ is contained in the robust predictive PDF based on the model class $\boldsymbol{M}$, which is given by the Theorem of Total Probability:

$$p(\boldsymbol{X}|D, \boldsymbol{M}) = \sum_{j=1}^{N_M} p(\boldsymbol{X}|D,M_j)P(M_j|D, \boldsymbol{M}) \quad (7)$$

where the robust predictive function for each model class M_j is given by Eq. 6 and is weighted by the posterior model probability $P(M_j|D, \boldsymbol{M})$ as defined in Eq. 5.

6.7 Statistical Simulation for Implementing Computational Framework

The posterior PDF of model parameters as defined in Eq. 3 usually cannot be obtained explicitly. This is not only because that the posterior PDF may have a complicated format, but also because that the calculation of posterior PDF needs assessment of the model evidence $p(D|M_j)$ and requires the evaluation of an integral over the space of model parameters as indicated in Eq.4, which cannot be evaluated analytically due to higher dimensions of the parameter vector θ. The evaluation of the likelihood function also needs the calculation of the predicted response from the structural finite element model. This makes analytical evaluation of the posterior PDF of model parameters impossible. Thus, the posterior PDF of uncertain model parameters defined in Eq. (4) are often evaluated and represented alternatively by using statistical samples drawn from posterior PDFs through probabilistic simulation.

One commonly-implemented probabilistic simulation for drawing samples from the specified PDF is the Markov Chain Monte Carlo (MCMC) algorithm proposed by Hastings (Chib 1995). Based on well-defined criteria, the MCMC algorithm creates a chain of samples which statistical distribution can resemble the target PDF by either accepting or rejecting the proposed samples within the spaces of model parameters of interest. The standard MCMC algorithm, however, may not be efficient when a very sharp peak or multiple peaks in the target PDF, because the drawn samples can become ‘‘stuck’’ in one local peak and cannot move to all the other spaces of parameters of interest. Considering the properties or shapes of the posterior PDFs are not known beforehand, Chen et al. (Ching and Chen 2007) had proposed the Transitional Markov Chain

Monte Carlo (TMCMC), which is intended to be applied in all cases (e.g., very peaked PDFs and multiple-peaked PDFs). The idea behind the TMCMC is to avoid the problem of sampling from difficult target PDFs but sampling from a series of PDFs that converge to the target PDF and are easier to sample. Since this approach is based on the ratio of the posterior PDF obtained from Eq.3, the constant of model evidence in denominator of Eq.3 can be ignored in the following procedures. This approach was established based on the technique initiated by in Beck and Au (2002) and includes consideration of a series of intermediate PDFs as below:

$$p_i(\theta) \propto p(\theta \mid M_j) \cdot p(\mathbf{D} \mid \theta, M_j)^{q_i} \tag{8}$$

where $i=1,2,\ldots,m$, and $0 < q_1 < q_2 < q_3 < \ldots < q_m = 1$

1. the index i denotes the stage number of intermediate PDFs. This method uses an easy convergence of sequence of intermediate PDFs, in which the first PDF in the sequence is the prior PDF $p(\theta|M_j)$ when $q_i=0$, and the last PDF in the sequence is the posterior PDF $p_i(\theta|D,M_j)$ $= p(\theta|M_j)\cdot\ p(D|\ \theta,M_j)$ as defined in Eq. 2 when $q_i=1$. It is assumed that the change between two adjacent intermediate PDFs is so small that samples for the next stage PDF can be efficiently derived based on samples obtained from the current PDF. By using the data obtained from samples of those intermediate PDFs, the model evidence $p\ (D\ |M_j)$ as defined in Eq. 4 can also be obtained for the selected model class M_j, which allows calculating the model probability as defined in Eq. 5. The TMCMC algorithm has been developed in Matlab by Ching et al. (2007) and adopted in the proposed computational framework.

6.8 Assessment of Reliability-Based Performance of Scoured Bridges

The bridge failure is defined as the state in which the bridge no longer meets the expected performance for a specific load or hazard level. It can be determined by comparing the expected bridge performance index $\boldsymbol{Z_e}$ with the actual performance index $\boldsymbol{Z} = f(\theta, Q)$, which is predicted by using the structural model, where θ is the model parameter vector, and Q is the load parameter vector of a given specific load or hazard level, e.g., the expected traffic or flood load. When the scoured bridge is evaluated for a given specific load or hazard level, the load parameter can be given as the deterministic parameter with a specific value. If the performance index is the bridge's deformation, then $g(\theta)= Z_e - Z= Z_e - f(\theta, Q)\leq 0$ indicates the structure failure. If the performance index is bridge's capacity, then $g(\theta)= Z - Z_e = f(\theta, Q) - Z_e \leq 0$ indicates the structure failure. In either case, $g(\theta)\leq 0$ specifies the failure domain in the model parameter space (see Fig.6.1).

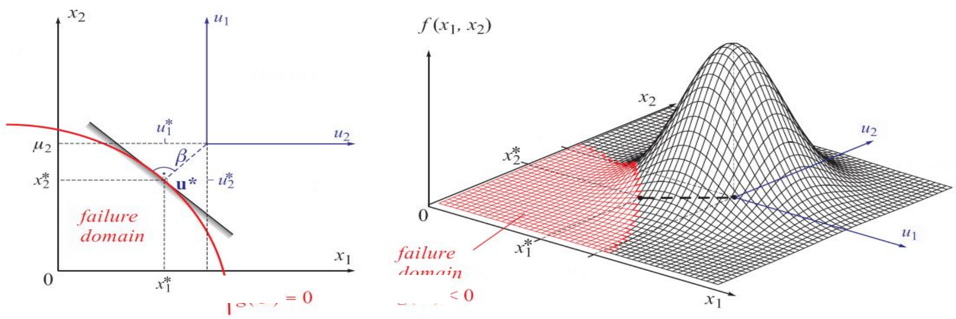


Figure6.1 Limit state function, statistical distribution of model parameters, and failure probability

When $p(\boldsymbol{X}|\theta,D,M_j)$ in the Eq. 6.1 is selected to be the probability of failure event F of the bridge predicted for a specific given model parameter θ, this means that $p(\boldsymbol{X}|\theta,D,M_j) = 1$ when the bridge fails, i.e., $g(\theta)\leq 0$, or $p(\mathbf{Z} \mid \theta, D, M_j) = 0$ otherwise. If only the most plausible model M_j is adopted as indicated in Eq. 6, the probability of failure of system $P_f(Z)$ based on all model parameter θ is actually equal to the volume of the failure event domain (see Fig. 1). Thus, the probability of failure $P_f(Z)$ for the scoured bridge can be calculated by using Monte Carlo sampling averaging as following:

$$P_f(Z)=p(\mathbf{Z}|D,M_j)=\int p(\mathbf{Z} \mid \theta,D,M_j)p(\theta \mid D,M_j)\, d\theta = \frac{1}{K}\sum_{k=1}^{K} p(Z \mid \theta_k, D, M_j) = \frac{n_k}{K} \qquad (9)$$

where θ_k is the sample of model parameters obtained from the Monte Carlo simulation, K is the total number of samples of θ_k, and n_k is the number of the cases, in which the structural failures occur, i.e. $g(\theta_k)\leq 0$ or $p(Z| \theta_k ,D,M_j) =1$ among the model parameter samples θ_k, $k=1,\dots,K$.

For the structure system with very small probability of failure, using samples drawn from statistical simulation to calculate the probability of failure is usually not efficient. This is because that larger numbers of samples are required as indicated in the following estimation, if the meaningful accurate probability of failure can be achieved (Duzgun et al. 2011; Katafygiotis and Zuev 2007):

$$n = \frac{1 - P_f(Z)}{\text{cov}^2 \cdot P_f(Z)} \tag{10}$$

where *cov* is the coefficient of variation (COV) associated with the estimated probability of failure based on Eq. 9. Duckett (2005) had suggested the upper bound of the acceptable probability of failure of new structures can be taken as 10^{-4} per year. If the deviation of the estimated probability of failure in terms of COV is 10%, the numbers of required samples for calculating the probability of failure based on Eq. 9 will 10^{+6}. For existing structures, however, Diamantidis et al. (2007) recommended the acceptable probability of failure can be 10 times of the acceptable probability of failure for a new structure. Thus, the acceptable failure probability for scoured bridges can be taken as 10^{-3} per year. If the actual probability of failure is 10^{-2}, the number of required samples drawn from posterior PDF of model parameters is about 10^{+4}. Thus, if the probability of failure of bridges with considerable scour damage is larger, the method in Eq. 9 can be efficiently used for assessing its performance reliability, because samples of the uncertain parameters about the bridge system have been obtained for model updating and damage identification through the Bayesian inference.

CHAPTER 7 NUMERICAL STUDY OF SCOUR DETECTION AND ASSESSMENT

To examine the effectiveness of proposed framework, the vibration measurements of a prototype bridge subject to scour and environmental variations under dynamic excitation was simulated by using a finite element model. They were used as the input data for the presented numerical study. The prototype bridge is the No. 127.9 bridge on Highway 61 in Mississippi, which has 8 piers and 9 spans with a total bridge length of 510 feet. In the numerical study, uncertainties associated with this bridge include three categories: (i) extents and locations of scour; (ii) soil properties, and (iii) variations of temperature and humidity.

7.1 Model and Parameters Related to Uncertainties

Bridge structural model

The software SAP2000/Bridge is used to establish the structural model of the selected bridge. All bridge decks, girders, and piers are modeled by using the real section properties of the bridge. The groups of piles under bridge piers are represented by an equivalent pile, which sectional properties are determined based on the Group Equivalent Pile model proposed by Mokwa **(**2001**).** All members of bridge are assumed to be linearly elastic under the vibration with the small amplitudes. The bridge model is shown in Fig. 7.1.

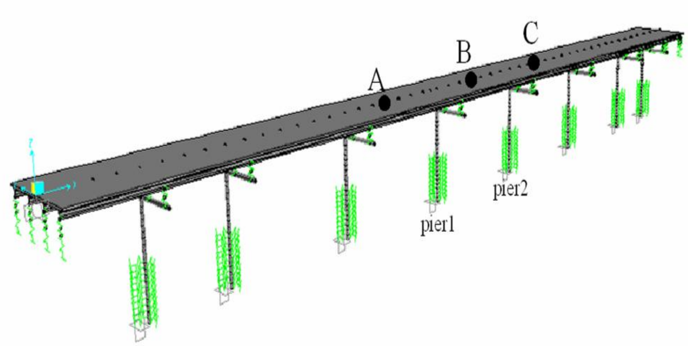


Figure7.1 Model of the prototype bridge using SAP2000/Bridge

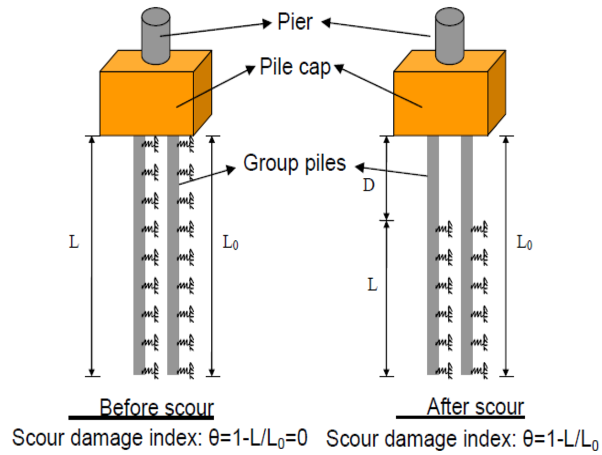


Figure7.2 Definition of the scour damage index

Parameterizing Scour Damages and their Uncertainties

The scour around piles is parameterized by uncertain parameter θ_i, which schematic definition is illustrated in Fig. 7.2. This definition is based on the assumption that the soil around piles can be represented by a series of springs. When the scour parameter θ_i =0, it indicates no scour occurs and piles are restrained by full soil around piles; when the θ_i =0.7, it indicates that 70 % of the surrounding soil acting on the upper portion of piles was washout, or 70 % of total series of soil springs on the upper portion of piles has been removed. In this simulation example, the middle two piers of the prototype bridge, namely Pier 1 and Pier 2 located in the main water channel as shown in Fig. 7.1 are considered more vulnerable to scour than other piers. Thus, scour damage occurring around Piers 1 and 2 is parameterized by two unknown parameters, θ_1 and θ_2.

Parameterizing Soil Properties of Riverbed Subbase and Their Uncertainties

In the bridge model, the soil around piles is modeled by using serials of discrete soil springs as mentioned in the above (see Fig.7.2). To parameterize the uncertainty in soil properties, soil stiffness coefficient parameter k is introduced and defined as the ratio between the stiffness of soil spring obtained based on actual soil properties and the stiffness of the soil spring obtained based on initially-estimated soil properties in terms of the soil p-y curve. Therefore, when k=0.5, it indicates that the actual stiffness of soil spring is 50% of the initially-estimated stiffness of soil spring. Although the different soil spring stiffness may be adopted to represent different types of soil at different depths, the uniform soil layers were assumed for simplicity in the study. Thus, there is only one parameter k for considering the uncertainty related to soil properties.

Parameterizing Impacts of Environmental Variations and Their Uncertainties

The parameters ΔT and ΔH are used to parameterize the change of the environmental temperature and humidity respectively from the selected reference environmental conditions at the bridge site. The temperature variation Δt_i and humidity variation Δh_i in the bridge structural members may vary from one member to another, depending on the geometric location and material type of the member. Those variations can affect the structural member's stiffness and mass and eventually impact the vibration measurements. Theoretically, the temperature variation Δt_i or humidity variation Δh_i of the i-th structural member is the function of the environmental temperature variation ΔT and humidity variation ΔH respectively, i.e., $\Delta t_i=F_t(\Delta T)$ and $\Delta h_i=F_h(\Delta H)$.

Although the above relations may be determined through the field sensor measurements and interpolation based on solar irradiance and other physics law, they can be complicated and cannot be determined accurately. Thus, there could be uncertainties about modeling the variations of temperature and humidity among structural members for different materials and at different locations. Thus, different competing models can be considered to define the temperature variation and humidity variation at different structural members in terms of environmental temperature variation ΔT and environmental humidity variation ΔH, which are presented as different model classes in the subsequent section.

Once the above model is defined, the temperature variation Δt_i or humidity variation Δh_i in different structural members can be determined. In the bridge's finite element model, it is assumed that the Δt_i and Δh_i do not vary within the i-th individual finite element of structural members. Thus, the Young's modulus of the material of the i-th individual finite element member can be determined as $E_i= (1+\alpha_T\cdot\cdot\ \Delta t_i)\cdot E_0$, where E_i and E_0 are current and original elastic moduli of the material respectively, α_T is the thermal expansion coefficient. Similarly, if the humidity variation is Δh_i, the mass density of material may be set to $D_i=(1+\alpha_H\cdot\cdot\ \Delta h_i)\cdot D_0$, where D_i and D_0 are the current and original mass density of the material, α_H is the humidity coefficient. Since the Δt_i or Δh_i for each individual structural element are defined by functions $\Delta t_i=F_t(\Delta T)$ and $\Delta h_i=F_h(\Delta H)$, there are only two uncertain parameters ΔT and ΔH for parameterizing environmental variations for a given model. In such a manner, the impact of environmental variations is incorporated into the bridge system model.

Model classes for modeling distributions of environmental variations

Due to uncertainties associated with modeling of distributions of temperature and humidity within structure members, five competing model classes are considered in the numerical study to present these distributions and their associated uncertainties. Even though additional model classes for model distributions of humidity can be used, it is assumed for simplicity in this study that all structural members' humidity variations are the same as the environmental humanity variation, i.e., $\Delta h_i=\Delta H$ for all structural members. The five selected model classes have the same type of finite element structural model as presented, but vary in modeling structural members' temperature changes in terms of environmental temperature change. Even though more realistic distribution of temperature may be derived, the selected distributions of temperature within structure members were taken as following assumed forms for simplicity in demonstration.

Table 7.1 Five model classes and their descriptions

Model class	Model difference in the relation between the structural element's temperature Δt_i variation and the environmental temperature variation ΔT
M1	For all deck elements, $\Delta t_i = \Delta T\text{-}10$; *and for all pier and pile elements,* $\Delta t_i = \Delta T\text{-}40$
M2	For bridge elements, $\Delta t_i = \Delta T$
M3	The temperature variations vary along the horizontal direction along the bridge lane with $\Delta t_i = \Delta T\text{-}5$ *for structural elements* on the left end and $\Delta ti = \Delta T\text{-}40$ *for structural elements* on the right end, while the value of structural elements between them are obtained though linear interpolation.
M4	The temperature variations vary along the vertical direction with $\Delta t_i = \Delta T\text{-}10$ *for structural elements* on the top end and $\Delta t_i = \Delta T\text{-}50$ *for structural elements* on the bottom end, while the value of structural elements between them are obtained though linear interpolation.
M5	The temperature variations vary along both vertical direction and horizontal direction. For deck elements, the temperature variations vary linearly from $\Delta t_i = \Delta T\text{-}5$ for deck *elements* on the left end to $\Delta ti = \Delta T\text{-}40$ for deck elements on the right end. For pier and plile elements, the temperature variations vary linearly from $\Delta t_i = \Delta T\text{-}10$ for the *elements* on the top end to $\Delta ti = \Delta T\text{-}50$ for the elements on the bottom end.

For the model class M1, the temperature changes of all deck elements is modeled as $\Delta t_i = \Delta T\text{-}10$, while the temperature changes of all pier and pile elements are defined as $\Delta t_i = \Delta T\text{-}40$. This implies there is a lag in the temperature change of structural members relative to the environmental temperature changes. For the model class M2, the temperature change of all structural elements, such as deck, piers, and pile, s was assumed as $\Delta t_i = \Delta T$, which is the same as the environmental temperature variation. For the model class M3, the structural member's temperature variation is assumed to change along the bridge lane direction from $\Delta t_i = \Delta T\text{-}5$ for structural elements on the left end to $\Delta t_i = \Delta T\text{-}40$ for structural elements on the right end, while the temperature variation of structural elements between them were obtained by using linear interpolation. The pier and pile element's temperature change takes the same value of the deck element that is above the pier and pile elements. For the model class M4, the structural member's temperature variation is assumed to change along the vertical direction. The temperature variation of elements at the top was assumed as $\Delta t_i = \Delta T\text{-}10$, and the value of $\Delta t_i = \Delta T\text{-}50$ was assigned to elements at the bottom. The temperature variations for elements between the top and bottom elements were obtained by using linear interpolation. For the model class M5, it considers that linear varying distribution of the temperature on both deck and piers. The temperature variation of deck was assumed to change from $\Delta t_i = \Delta T\text{-}5$ on the left end to $\Delta t_i = \Delta T$-40 on the right end, and the values of structure elements between them changes linearly. The temperature variation on the top end of the pier was assumed as $\Delta t_i = \Delta T\text{-}10$ while the value of $\Delta t_i = \Delta T\text{-}50$ was assigned to the bottom end. The values for structural elements between them change linear. The differences of five model classes are summarized in the Table 1.

7.2 Obtaining Simulated Vibration Measurements for Numerical Study

In this numerical study, it is assumed that the real bridge system can be represented by the model class M1. Thus, the vibration measurements are simulated by using the bridge computational model class M1 with model parameters: θ_1= 0.7, θ_2 =0.0, k=0.5, ΔT=50, and ΔH=60. The dynamic excitation to the bridge is the ground horizontal acceleration of a zero-mean white noise with time interval is 0.02 second in the direction perpendicular to the bridge spans. The horizontal acceleration response at three joints in the bridge deck elements, Point A, B, and C as shown in Fig. 7.2, are taken as vibration measurements. These acceleration responses are calculated at a time step of 0.02 second with assumption of a damping ratio of 5% assigned to all modes. Total number of time-history samples is 200 at each measurement point. To simulate measurement errors, a white noise with 10% of the noise-to-sign ratio (in the root-mean-square) is added to the simulated vibration measurements.

7.3 Implementing Probabilistic Computational Framework

For each model class M_j ($j=1,2,..,5$), the acceleration responses of the bridge system were calculated at the three above selected joint points once a set of uncertain model parameters {θ_1, θ_1 ,k, ΔT, ΔH} are given. The prior PDFs of parameters {θ_1, θ_1, k, ΔT, ΔH, σ} are taken as uniform distribution within a specific range for each model parameter. Those predicted response were used with the measured bridge dynamic responses to evaluate the likelihood function for specific given parameters. The posterior PDF of the model parameters are obtained through transitional Markov Chain Monte Carlo (TMCMC) approach (Ching and Chen 2007) implemented through Matlab code. Through the Open Application Programming Interface (OAPI) developed in SAP2000 software, the model parameters can be input into the bridge finite element model in SAP2000/Bridge program, and dynamic response from the SAP2000/Bridge model can be obtained for TMCMC sampling process. Through TMCMC, statistical samples of model parameters which distribution can approximate posterior PDF of model parameters can be obtained. Meanwhile, the model evidence for the given model class can be obtained from TMCMC. For each model class with given set of measurements, the TMCMC algorithm was run with N=1000 samples for each intermediate stage (or level). About 14 stages were needed to obtain the posterior PDF of uncertain parameters from the prior PDF each model class. With the computer equipped with Intel Core 2 Quad CPU running at 2.40G hertz and a total of 2.96 GB of memory, the average computational time of the probabilistic simulation to obtain the posterior PDFs of model parameters and model evidence of each model class was about 13 hours.

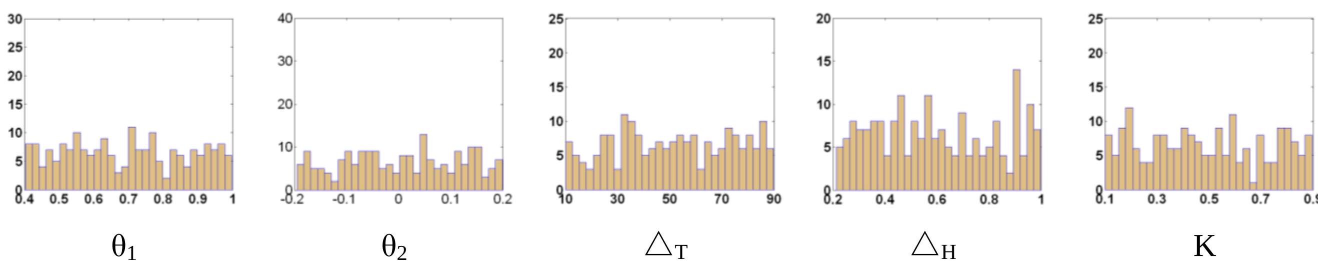
7.4 Results from Probabilistic Inference of Numerical Study

Identified Scour and System Parameters

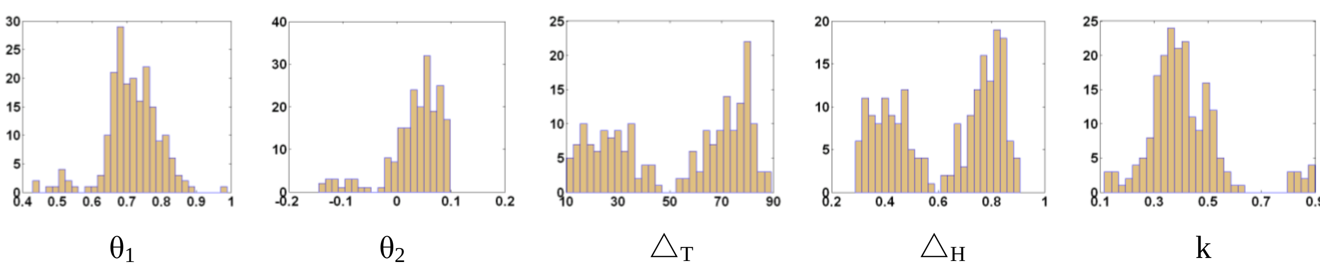
The effectiveness of the proposed probabilistic inference can be examined through comparing the identified parameters and their statistical properties with the pre-set parameters that were used to generate the simulated vibration-based measurements. Identification results obtained from five model classes were tabulated in Table 2. Overall, the results form the probabilistic inference with the accurate mode class M1 show that the relative errors of the most-likely parameters were generally small (<10%). The histograms of prior and posterior PDFs of the parameters θ_1, θ_2, K, ΔT, and ΔH with the model class M1 were shown in Fig. 7.3. It can be seen from Fig. 7.3 that the prior PDFs of the unknown parameters were generated approximately as uniformly distributed values between the specified values. These histograms of posterior PDFs exhibited multi-peaks in the PDFs for parameters of temperature and humidity ΔT and ΔH. The accuracy of identified values from other model classes M2, M3, M4, and M5 is reduced, since those model classes deviate from the true system that generates the measurement data.

Table 7.2 Model selection for temperature distribution

Parameter (true value)	Model 1	Model 2	Model 3	Model 4	Model 5
θ_1 (0.7)	0.71	0.815	0.894	0.933	0.775
θ_2 (0)	0.03	0.043	-0.089	-0.120	-0.100
Δ_T (50)	52.63	32.178	58.195	85.099	78.590
Δ_H (0.6)	0.62	0.630	0.566	0.918	0.689
K (0.5)	0.41	0.552	0.471	0.547	0.365
Model evidence p(D/M) (COV)	5.043e-42 (38.1%)	1.154e-193 (9.11%)	2.387e-166 (7.41%)	1.974e-72 (26.7%)	1.034e-170 (8.2%)



(a) Prior PDF



(b) Posterior PDF

Fig. 7.3 Histograms of the PDFs for unknown parameters $\theta_1, \theta_2, \Delta_T, \Delta_H$, k

Bayesian inference indicates the probability of model class M1 based on Eq. 5 is 1.00 among five competing model classes M_i (i=1, 2, ..., 5), since the model class M1 is the model class same as the one that is used to generate measurement data. Among the five model classes, the class model M2 is assumed the uniform distribution of temperature variation, which is the same as the environmental temperature variation and does not consider the temperature variation lag in the bridge element. As a result, the M2 has the least model evidence or model probability.

Table 7.3 Model probabilities for model selection

Competing model classes					**Prior Model Probability**					**Posterior Model Probability**				
M1	M2	M3	M4	M5	M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
					0.20	0.20	0.20	0.20	0.20	1.00	0.00	0.00	0.00	0.00
	M2	M3	M4	M5		M2	M1	M4	M5		M2	M3	M4	M5
						0.25	0.25	0.25	0.25		0.00	0.00	1.00	0.00
	M2	M3		M5		M2	M3		M5		M2	M3		M5
						0.33	0.33		0.33		0.00	0.55		0.45
	M2	M3				M2	M3				M2	M3		
						0.50	0.50				0.00	1.00		
		M3		M5			M3		M5			M3		M5
							0.50		0.50			0.55		0.45

If the candidate model classes do not include the model class M1, the best model classes are M4 based on the calculation of the model probability. The model class M4 actually has the same temperature distributions in the deck elements as the true system presented by the model class M1, while the pier and pile elements in the M4 have the similar temperature distributions as those of the true system M1. The model class M3 and M5 have the same distribution of temperature variation in the deck elements, but differs in the pier and pile element. As a result, they have the comparable model evidence or model probability. The calculated model probabilities for different selected model classes are summarized in Table 3. These results indicate the Bayesian inference can be effectively used to rank the model classes based on how closely they represent the true system. However, if the candidate model classes do not contain the model class that closely resembles the true distribution of temperature variation among the bridge structural element, the identified scour damages could have larger errors.

Scoured bridge performance reliability assessment

The samples from the posterior PDFs of uncertain parameters based on the most plausible model class M1 were obtained from the proceeding procedures and ready to be used for reliability-based performance assessment. In this illustration, the load of river flow with the velocity of 2.5 ft per second at the full height of piers was determined as the static pressure acting on the circular piers of the bridge based on the AASHTO code (2012). The flood load is calculated based on the pressure as a uniform distributed load and applied to piers in the bridge model. The expected performance of the bridge is defined as the statue in which the maximum lateral displacement of the bridge deck does not exceed the specified value, e.g., 1.5 inch under the given flood. The possible lateral displacement of the bridge deck under the given load of river flow was obtained by running M1 model for each sample from the posterior PDFs of uncertain parameters. For 1000 available samples of the posterior PDFs of uncertain parameters obtained from TMCMC during the model updating and damage identification, there are 12 samples of the parameters that make the lateral displacement lager than 1.5 inch. Based on Eq. 9, the probability of failure to meet the expected performance was determined as 12 out of 1000, e.g., 1.2%, which exceeds the acceptable probability of failure of an existing structure, implying that the countermeasure should be taken before the expected flood arrived. However, the deviation of this estimated probability of failure in terms of COV based on Eq. 10 is 0.29. If it is intended to achieve the usually-accepted deviation value 0.1 (Cheung and Beck 2010), it implies that the number of samples should be about 8300 based on Eq.10 in order to obtain the estimate with desirable accuracy.

7.5 Limitations of Current Study and Future Research Directions

The presented numerical study is intended to demonstrate the proof of the concept. It only includes limited numbers of uncertain model parameters with limited numbers of statistical samples of uncertain model parameters, and adopts simplified models of impacts of environmental variations. The performance reliability of the bridges with very small probability of failure could not be estimated accurately with small numbers of samples of uncertain parameters. As numbers of unknown parameters and numbers of statistical samples of those parameters increase, the TMCMC may lead to an unacceptable computational load. To make the presented approach suitable for practical application, the future research should focus on two aspects: (1) developing efficient algorithms for reducing the high computational demands of probabilistic simulation of large structures; and (2) adopting more robust approach to distinguishing impacts of environmental variations from those caused by damages on the measured structural dynamic response.

CHAPTER 8 SUMMARY AND CONCLUSION

The bridge substructures across waterways in Mississippi are frequently subject to scour due to flood current. Scour is the major cause of bridge failure from floods in Mississippi. This research project seeks to investigate the instrumentation and computational modeling that can monitor bridge and correlate substructure deterioration with the remainder of bridge's capacity. It is expected to supplement current underwater inspection of bridge substructures with more reliable measurement-and-analysis-based approaches, and also provides wireless instrumentation platform for the future MDOT research to monitor other critical components of transportation systems.

Through this study, the bridge scour was prioritized as the major the detrimental bridge substructure deterioration in Mississippi waterways. The scour-monitoring sensor of the time domain reflectometers (TDRs) sensor with wireless data transmission system has been selected for the field implementation of scour monitoring. A bridge near Jackson was selected for implementing the field test of the selected scour monitoring system for the phase II study. The field installation plan and design was completed for the implementation of the selected sensor for the next phase II project. Due to the unexpected and uncontrolled delay of fabrication and delivery of the selected scour monitoring system by the subcontracted vendor, the project team is left with no time to complete the lab evaluation and demonstration of the selected scour monitoring system on time. The project team will try to do and report it later.

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As the part of the study, the computational model of the scoured bridge and probabilistic inference framework for quantifying uncertainties are proposed and examined for correlating the measurement data with structural performance of bridge systems. This computational framework is intended to assess the bridge performance and its associated uncertainties for given scour conditions based on dynamic measurements. The reliability of the performance scoured bridge can be predicted based on quantified uncertainties associated with the bridge damage models and scour damage. The application and effectiveness of proposed assessment approach are illustrated and examined through a numerical simulation of a selected prototype bridge.

The future research should focus on the field implementation of the selected scour monitoring sensors at the selected bridge site with wireless data transmission system, and utilize the combination of different type sensors to obtain useful information from multiple perspectives to verify the scour sensor measurements, particularly in combining the scour direct measurements with the bridge performance measurements, such as pier titling measurements and dynamic vibration measurements of bridges under traffic load. To make the presented computational framework suitable for practical application, the future research should also focus on developing efficient algorithms for reducing the high computational demands of probabilistic simulation of large structures with more unknown model parameters and structural damage; adopting more robust approach to distinguishing impacts of environmental variations from those caused by damages on the measured structural dynamic response; and assessing the effectiveness and efficiency of the presented computational framework through various field measurements.

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