Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Phase I of Roadmap towards Incorporating Intelligent Structure
Technology for Refining Bridge Inspection in Mississippi

5. Report Date

February 25, 2011

6. Performing Organization Code

7. Author(s)

Wei Zheng, Bin Peng, and Yung-Tsang Chen

8. Performing Organization Report No.

9. Performing Organization Name and Address

Dept. of Civil and Environmental Engineering
Jackson State University
Jackson, MS

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Organization Name and Address

Institute for Multimodal Transportation

1230 Raymond Road, Box 900

Jackson, MS 39204

13. Type of Report and Period Covered

Final Project Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Bridge scour refers to the removal of sediments from the bridge foundation by flood. It is the most detrimental cause for the majority of bridge failures in the United States. In the National Bridge Registry, there are 484,546 highway bridges over waterways. More than 85,000 of these bridges are considered vulnerable to scour, and about 26,000 of them are classified as "scour critical", which means the bridge is likely to fail in a major flood event. When a bridge is subjected to scour and flood, a management decision on its operation, closure, retrofitting, or replacement should be made based on assessment of its performance levels. The performance levels are actually associated with bridges' vertical and horizontal displacement and remaining load resistance, and may be determined through more realistic computational simulations. To that end, it is crucial to determine the structural system properties and loading characteristics and assess their accuracy. While a bridge's structural parameters are relatively easy to examine, the properties of a bridge's foundation, subgrade soil, and characteristics of flood impacts are deemed difficult to estimate. This difficulty is compounded if the buried portion of the bridge's foundation is unknown. Since the performance of scoured-bridges involves several uncertainties, it may be better addressed in terms of its performance reliability using probabilistic framework.

In this research, a Bayesian Inference probabilistic frame work for assessment of the performance of scoured bridges is proposed. An extensive literature review of pervious research, as well as current sensor technology, is conducted. Computational simulation of a real scoured bridge is also illustrated. Preliminary results show that the scoured bridge can be modeled using commercial available software such as SAP 2000. Effects of foundation soil, connection types, flood height, traffic loads, and scour depths can all be simulated in the finite element model. Results from computation simulation indicate that the traffic loads have very minor impacts on structural properties. Results also indicate that the fundamental frequencies of the structures vary with foundation soil, and the scour depth significantly affects the structure's natural frequencies. Effects of bridge connections and possible failure modes as a result of severe scour are also presented.

17. Key Words

Bridge scour, health monitoring, Bayesian Inference

18. Distribution Statement

No restrictions

19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	52	N/A

Form DOT F 1700.7 (8-72)
Reproduction of completed page authorized

Disclaimer

Phase I of Roadmap towards Incorporating Intelligent Structure Technology for Refining Bridge Inspection in Mississippi

Wei Zheng, Bin Peng, and Yung-Tsang Chen

Department of Civil and Environmental Engineering
Jackson State University
February 2011

Contents

Chapter 1 Introduction

Implementation of intelligent transportation systems is an interdisciplinary research frontier for managing transportation systems and securing their safe operation. The goal of this phase I research project is to initiate and supplement efforts for research and education in this frontier at JSU and to enhance JSU's ability for seeking funds from the National Science Foundation (NSF) and Mississippi Department of Transportation (MDOT) to support these efforts. This Phase I research project will lay out a roadmap towards developing and transferring smart damage diagnosis technologies for assessing bridge conditions and supporting decision-making for bridge maintenance in Mississippi.

The strategies for achieving these goals include the following: (1) supplement ongoing NSF funded interdisciplinary collaborative education in Intelligent Structure Technology (IST) with relevant authentic research; (2) establish an external advisory panel composing of researchers, bridge professionals, and sensing technology manufacturers in Intelligent Structure Technology in order to enhance research and education at JSU; and (3) recruit research associates, graduates, and undergraduates to form a multi-disciplinary team for conducting the proposed research and developing competitive research initiatives to secure further external funding.

The objectives of this phase I research project include the following: (1) identify and prioritize the detrimental bridge deteriorations in Mississippi and their measurable parameters; (2) identify available sensor technology for in-situ wireless monitoring of these parameters; (3) develop bridge analytical model at multi-level details that can correlate the identified bridge deteriorations with the above measurable parameters; and (4) formulate research initiatives and implementation plans to the NSF and MDOT for further funding for the phase II research project and its implementation in order to identify and address problems and needs.

1.1 Background

According to the Mississippi Department of Transportation, bridge scour is one of the most detrimental causes of bridge deterioration in Mississippi. Thus, the implementation of Intelligent Structure Technology in this project focuses particularly on structural health monitoring of bridge scour. Bridge scour refers to the removal of sediments from the bridge foundation by flooding. A study conducted by Shirole and Holt (1991) revealed that about 60% of more than 1,000 bridge failures over the past 30 years were caused by scour: an average of 20 bridge failures per year due to scour. A recent study by Lagasse et al. (2007) further indicated that the number of bridge failures caused by scour has increased due to the aging bridge infrastructure. In the National Bridge Registry, there are 484,546 highway bridges over waterways. More than 85,000 of these bridges are considered vulnerable to scour, and about 26,000 of them are classified as “scour critical”, meaning that the bridges are likely to fail in a major flood event. Among the population of bridges over waterways, there are 86,133 bridges with unknown foundations (NCHRP 2006), which pose significant risks for their users due to scour vulnerability concerns.

When a bridge is subject to scour and flooding, a management decision on its operation, closure, retrofitting, or replacement should be made based on assessment of its performance levels. These can be referred to those defined by earthquake engineering research community, i.e., Fully Operational, Operational, Life-safe Threaten, or Near Collapse (SEAOC 1995). These performance levels are actually associated with bridges’ vertical and horizontal displacement and remaining load resistance, and they may be determined through more realistic computational simulations. To that end, it is crucial to determine the structural system’s properties and loading characteristics and assess their accuracy. While a bridge’s structural parameters are relatively easy to examine, the properties of a bridge’s foundation, subgrade soil, and characteristics of flood impacts are deemed difficult to estimate. The difficulty of this task is compounded if the buried portion of the bridge’s foundation is unknown (e.g., deep foundation vs. shallow foundation).

Developing methods for identifying the types of bridge foundation vulnerable to scour and detecting scour damages is currently considered a top priority for transportation agencies. Various scour monitoring instruments have been developed and deployed on bridges including sensors for directly measuring scour depth and tilting of bridge piers. Lower cost vibration-based measurement devices have been explored for identifying foundation types and detecting scour damages. However, the data from in-situ measurement have not fully been used to assess the performance of scoured-bridges. Previous research in this aspect usually relies on deterministic system identification of parameters of a single model; however, it often yields ill conditioning (unidentifiable) or nonuniqueness, not addressing the inherent model uncertainties. Studies assessing the reliability of the performance of scoured bridges often adopted oversimplified structural models and did not consider the realistic performance of scoured bridges at different levels. Very few research projects have been conducted utilizing in-situ measurements, specifically those from vibration-based sensors, in assessing scoured bridge performance and addressing its uncertainties.

The effectiveness of the Bayesian approach on the assessment of scoured bridges has not been explored yet. Most applications of Bayesian inference were examined based on results from simple computational simulation. The examination of the application of Bayesian inference on a complex system, such as scoured bridges, however, can be quite challenging. For large numbers of degrees of freedom in a complex system and limited sensors that can be deployed, researching what in-situ monitoring schemes can efficiently capture the concerned characteristics in the system becomes crucial. With so many parameters in a complex system, there is a need to understand which parameters denominate the system performance and which ones do not. By doing so, the dimension of uncertain model parameters can be minimized to reduce computational efforts in statistical simulations without losing accuracy. Furthermore, the probabilistic model for the model prediction errors may strongly depend on a specific problem and its impact on the prediction of scoured-bridge performance. The techniques for efficiently obtaining samples from the specific probability density distribution should be explored for a specific problem of Bayesian inference.

1.2 Scope of Work

The implementation of Intelligent Structure Technology in this project is particularly focused on structural health monitoring of bridge scour. Since the performance of scoured bridges involves several uncertainties, such as the interactions between soil and foundation and between flood and piers, it may be better addressed in terms of its performance reliability using probabilistic framework. Due to the lack of sufficient studies on applying probabilistic-based monitoring to performance assessment of the scoured bridges, it is crucial to devote research efforts to this particular field. The project initiates research efforts for exploring how to effectively apply probabilistic approach of Bayesian inference to evaluate the performance of scoured bridges.

Through the efforts from this phase I project, the goal of the phase II research has been identified as the extension of probabilistic model class selection to evaluate system configurations, boundary conditions, and damage extents and to examine its effectiveness for the system performance assessment. Within the probabilistic framework for the next phase II research project, multiple models will be created to conceptualize all possible scenarios about system configurations (e.g., shallow foundation or deep foundation), boundary conditions, or damage extents (e.g., scour depth) based on available information and engineering judgment. The probability of each candidate model is assumed based on engineering judgment. Uncertain model parameters are selected as variables with pre-assumed statistical distributions. These models are then embedded into a class of probabilistic models in terms of the model prediction errors which are treated as uncertain parameters with pre-assumed statistical distributions. As effective in-situ measurements become available, the statistical distribution of the uncertain model parameters and the probability of each model can then be updated through Bayesian inference and be used to represent the system and its uncertainties for assessing the system performance reliability. With more evolving in-situ measurements available over time, the system performance reliability can be continually updated to represent the latest status of the system performance for the management decision-making.

This report presents the research outcomes from this phase I research project. These outcomes include four parts, i.e. (1) previous research work: an extensive literature review of previous works in bridge scour monitoring and detection has been conducted, (2) sensor technology: a brief review of current available sensors capable of monitoring bridge deterioration has also been conducted, (3) basic theory of Bayesian Inference: we proposed a framework based on Bayesian Inference in detecting the scour of bridge foundations. The basic theory and formulation of Bayesian Inference was described; and (4) computational simulation of a scoured bridge: to verify the applicability of the proposed probabilistic framework, computational simulation of a scoured bridge was conducted. It should be noted that Part (3) provided theoretical bases for the phase II project, whereas Part (4) showed some preliminary results that can be used for formulating the phase II research project; and (5) the conclusion of the phase I research project is shown in that last chapter of this report, where the needs for the future phase II research project is also identified.

Research objectives of the future phased II research have been identified as follows:

- To identify the critical parameters and mechanisms that dominate the performance of scoured-bridges and the associated reliability;

- To examine the statistical distribution of model prediction errors, and its impact on the accuracy of Bayesian inference and system performance assessment through simulations and lab tests;
- To explore the effectiveness of the probabilistic inference based on continuous on-site measurement for assessment of the performance of bridges under scour and flood hazard;
- To examine various statistical simulation and sampling techniques efficient for probabilistic model parameter updating and model selection for addressing performance of scoured bridges.

Tasks of the future phase II research will include the following:

1. Multi-physics and multi-scale computational simulation and sensitivity analysis of the performance of scoured bridges under traffic and flood loads;
2. Simulation and lab experiments for validating the proposed novel application of Bayesian inference for identifying the system configurations, boundaries, and damages;
3. Field measurement and data collection for identifying the impact of flooding and its statistical basis;
4. Development of computational tools for implementing the proposed framework and field calibration of fluid pressure and scour evolution models for assessing scour-critical bridges.

Desired research outcomes from the phase II research will be expected for

- Improving understanding of risk factors and vulnerability to the bridges subject to scour and flood hazards and their statistical characteristics;
- Providing knowledge for implementing Bayesian model updating and a computational and statistical basis for performance-based design of bridges under scour and flood hazards;
- Determining parameters that dominate the performance and that should be treated as uncertain ones in model updating for scoured bridges;
- Providing efficient schemes for continuous monitoring that can be widely deployed and effective data for implementing Bayesian inference to assess scoured bridges; and

- Providing practical guidelines and efficient computational tools that can automatically streamline tasks in probabilistic inference and performance reliability assessment for scoured bridges.

Chapter 2 Review of Previous Research

This chapter reviews relevant research in the literature in this field. Research work can be divided into two categories: (1) monitoring and assessment of scoured bridges, and (2) application of structural health monitoring through vibration-based measurement for assessing bridge scour. A new approach based on Bayesian inference probabilistic framework is also proposed in this chapter. Because the proposed approach utilizes computation simulation and incorporates in-situ data measurement, relevant review in computation simulation and sensor technologies are also performed. Lastly, since on-site sensor measurements are involved, how to efficiently and effectively collect the data and process them also becomes an important issue. Plan for data collection and analysis is also presented.

2.1 Monitoring and Assessment of Scoured Bridges

Bridge scour is the most detrimental cause for bridge failures. Developing methods for detection of scour and maintenance of bridge foundations is currently considered a top priority for transportation agencies. In literature, considerable research efforts were devoted to scour monitoring. For example, Federal Highway Administration (FHWA) issued HEC-23, entitled "Bridge Scour and Stream Instability Countermeasures," which provides guidance on scour monitoring. In a recent study by Hunt (2009), an extensive survey of bridge owners on fixed scour monitoring was conducted. The survey revealed that 32 states have employed scour-monitoring sensors, and a total of 120 bridges were implemented with these sensors. Among the data collected, the scour depth is the main measured parameter. Note that only one state installed tilt sensors for measuring the rotation of the bridge due to scour or other causes. The installation and maintenance of these sensors have caused uncertainties for using scour-monitoring systems. In this survey, only 36% of the respondents stated that they planned to use the monitoring system in the future, 19% said no, and 45% were not certain. Less than half of the responses indicated that the scour monitoring data had been used for verification of the predictive scour equations, whereas 51% said it had not been useful.

While the scour was progressing, the scour-critical bridges may still be in service, which brings potential hazards to the traveling public. The commonly-used index to determine bridge vulnerability, i.e. scour depth, is only a condition index and has to be translated into an index of the performance reliability of a bridge, which can be meaningful for decision-making. In literature, Diamantidis and Arnesen (1986) conducted a research to investigate the scour impacts on bridge structures. The research considered the scour depth and width, soil properties, and pile stiffness and concluded that the pile reliability decreases almost proportionally with the scour depth. Daniels et al. (2007) studied the capacity of typical pile bents with various heights, bracing conditions, levels of gravity loading, and levels of scour. They found that the scour to any pile bent significantly reduces its flood water pushover load capacity. Hughes (2007) reported that bent pile buckling and pushover loads are not very sensitive to the soil subgrade modulus, and complete pile fixity can be assumed at approximately 1.5 meters below the ground line unless the value of the modulus is very small. In a recent study by Bennett (2009), he reported that the lateral load resistance bridge pile group will increase as scour depth increases. For evaluating the vulnerability of scoured bridges, Federico et al. (2003) proposed a simple procedure to assess the vulnerability of bridge piers in rivers. In this research, they suggested that further improvement on the vulnerability analysis could be achieved by: (i) following a more general examination of the geotechnical limit states of the foundation subsystem, (ii) analyzing the time evolution of scour phenomena, and (iii) carefully comparing between theoretical results and in-situ experimental measurements. It is worth noting that their assessment did not consider in-situ measurements.

2.2 Application of SHM through Vibration-Based Measurement for Assessing Bridge Scour

Structural Health Monitoring (SHM) Technology, which integrates dynamic response measurements and system identification, can be utilized to identify system properties and estimate damage by evaluating changes in structural responses. Application of SHM on bridge superstructures based on on-site vibration data has been extensively investigated. For example, full-scale bridge dynamic tests were conducted by several researchers (Salane et al. 1981, Manning 1985, Gregory et al 1985, DeWolf et al. 1992, and Huston et al. 1993). Results from previous research projects all indicated that dynamic characteristics of bridges can be identified using vibratory shakers, impact hammers, and traffic and wind loads. Decreases in amplitude at resonant frequencies and changes in computed stiffness coefficients were also found to be related to the member damage.

Although in the literature significant research efforts were devoted to identification of structural properties, studies on applying SHM to assessment of bridge substructures or foundations were very rare. Olson et al. (2005) conducted field dynamic tests on real bridges to evaluate the condition of scoured bridge substructures. They simulated the scour by gradually removing the soil around piles and observed obvious decreases in fundamental resonant frequencies measured at the top of piers with increasing damage. When comparing dynamic test results from two bridges with the similar superstructures but different foundations, i.e. shallow vs. deep foundations, they found that modal testing could not uniquely determine the correct foundation type. They also found that the structural parameter identification approach did not correctly identify the intact, excavated, or broken pile and thus did not seem suitable for bridge substructure damage detection. Note that in these dynamic tests, the impacts of flooding were not included and considered.

In a study by Suzuki et al. (2007), tilt sensors were used to real-time monitor inclination angle due to scour at the railway bridges. The decision on canceling trains is made based on the inclination angles of the bridge piers. The threshold angle for train suspension is derived from a geometric relationship between the inclination angle of the bridge pier and the maintenance limits of track irregularity. The inclination angle of the bridge pier is used as a performance index due to the fact that although inclination angle of a bridge pier is minute, it may result in reconstruction of the pier, which tends to take a long time, is quite expensive, and includes suspension of train service. In another study conducted by Samizo (2007), vibration sensors were mounted on a bridge pier to measure ambient vibrations caused by traffic or environmental loads in five-minute intervals. The vibration of a bridge pier is measured at different scour depth and water level. Bridge vibrations caused by the impact tests at a lower water level were also measured. He concluded that the natural frequencies of the piers decreases with decreasing soil level around foundations, and more accurate natural frequencies of the piers could be obtained from the data measured at 30-second intervals.

2.3 New Probabilistic Approach to Identifying System and Assessing Its Performance

The recently resurgent Bayesian inference could provide a theoretical basis for robustly characterizing modeling uncertainties. It answers an important question: how can we choose the best model class among the chosen classes and make predictions based on all model classes (Ching and Chen 2007). In previous research, the Bayesian inference was considered too complex and not accessible for applications; however, with advances in commutating technologies and innovative sampling methods, such as transitional Markov chain Monte Carlo, it is now considered doable to implement Bayesian inference for complex engineering systems. Although applications of Bayesian inference in civil engineering are still at an early stage, there is plenty of room to be explored (Yuen 2010). In recent years, the Bayesian Inference has been used for model selection in civil engineering. For example, Meyer et al. (2007) adopted Bayesian model selection to estimate uncertainties in conceptual models, parameters, and scenarios in hydrogeologic flow and contaminant transport. Hsu et al. (2009) explored Bayesian inference for multiple-model to estimate the runoff using long-term in-situ data. The proposed multiple-model approaches use the sequential Bayesian rule to update individual models' probability. A weighting factor for model combination was assigned to each model based on the probability. Beck et al. (2004) demonstrated Bayesian model selection for system identification for dynamic response of a single-degree-of-freedom nonlinear oscillator based on three candidate models. It was found that the calculated weighting factors changed in accordance with the excitation level and system status and demonstrated that there is no exact class of models for a real structure. The best class depends on system status and the system data that is used. Chen and Feng (2009) further illustrated the effectiveness of Bayesian inference for consistently estimating the system parameters and their uncertainties through two simulation examples and one shake table test.

2.4 Advances in Computational Techniques for Modeling Scoured Bridge System

Advances in computational techniques for the complex interaction between soil and foundation and between river flow and piers have been developed by researchers from different subfields in civil engineering. These advances are ready to be integrated together for modeling bridges under scour and flood for performance assessment. They are briefly presented in the following sections and will be adopted in the computational simulations.

Finite Element Model of Deep foundation: Simulation of the interaction between pile and soil has been categorized into two groups, i.e. Finite Element Method (FEM) and Beam-on-Winkler-Foundation (BWF or "p-y") method. Yang and Jeremic (2002) adopted FEM to generate "p-y" curves. Comparing the results generated from their proposed approach with those from experiments, their simulations were proven to be effective. Olson (2005) used FEM to estimate the parameters for determining bridge stiffness properties from the field data.

Group of Piles and Group Equivalent Pile: To assess pile group stiffness, lateral group action can be considered in p-y models by using adjustment factors for the p-y curves, termed “p-multipliers” (Brown et al. 2001, Bridge Software Institute 2010). Recently, a further simplified approach has been proposed by Mokwa (1999) and Mokwa and Duncan (2000), in which a group of piles is viewed as a Group Equivalent Pile (GEP). GEP employs the p-multiplier to modify the p-y curve of a single pile to account for the pile group effect. This approach has been adopted by Bennett et al. (2009) to analyze the lateral load resistance of group piles under different scour depths.

Pile Model in Layered Soil and Equivalent Soil:

Yang and Jeremi (2002) studied the behavior of a pile in layered soils using FEM method, and the results agree with centrifuge test data. They also found that soil layer effects are significant for the pile’s behavior at its head for some soil layering configurations. They also indicated that soil layer configurations should be considered in the modeling of the interaction between soil and pile. Through using different p-y curves for different soils, the Winkler Beam Foundation Model can also be used to model the soil layer effect.

Model of Shallow Foundation:

To use FEM for shallow foundation, Dreier (2008) assumed an elastic-plastic soil behavior according to a Mohr-Coulomb failure criterion. The parameters describing the elastic behavior of soil are the modulus of elasticity of soil and the Poisson’s ratio. The parameters describing the Mohr-Coulomb criterion are as follows: the cohesion, the frictional angle, and the dilatancy angle. These parameters can be used in FEM to model soil. Harden and Hutchinson (2009) developed a nonlinear Winkler Beam Foundation Model for shallow foundation. The NWBF model is composed of a serious of nonlinear springs placed vertically along the length of the footing and horizontally at the end of the footing. The constitutive relations used for the q-z, p-x, and t-x springs can be developed based on material models originally developed by Boulanger et al. (1999).

Model of Interaction Between Fluid and Foundation for Dynamic Analysis: Most software, e.g., LS-DYNA and ANSYS, includes a multi-physics solver to combine two physics of Computational Solid Dynamics (CSD) and Computational Fluid Dynamics (CFD) into one simulation. Debus et al. (2003) have validated ANSYS with a hybrid turbulence computational model to determine flow interaction with the bridge pier. Even with Reynolds numbers ranged from Re = 105 up to Re =

108 (flow speed 3.6 m/s to 4.6 m/s), the results for drag force were in agreement with data from the literature. Their analysis results suggested that flow force acting on piers fluctuates with dynamic forces, and the higher flow speed is, the higher the fluctuation. Tsenga el al. (2000) also made the similar finding about the fluctuation of drag force on piers. In LS-DYNA, Finite Element (FE), Eulerian, Arbitrary Lagrangian Eulerian (ALE), and Smoothed Particles Hydrodynamics (SPH) models can be used to simulate the fluid-structure interaction. In this research, different water levels (high, middle, low) and flow speeds (high, middle, low) will be simulated using LS-DYNA finite element software. In literature, using LS-DYNA to simulate fluid-structure interaction has been proposed (Yim 2008, Gao et al 2008). The ALE-RANS and k-ε turbulence closure model has been developed with LS-DYNA (Yim 2008), and allows more accurate simulation of dynamic interaction between structure and fluid. The predicted flow force from this new turbulence model matches the data from the 3-D wave basin experiment (Yim 2008, Gao et al 2008).

2.5 Current Fixed Monitoring Technologies

Scour is one of the main causes of bridge failure. It accounts for about 60% of bridge failures in the United States (Lagasse et al. 2007). Scour failure tends to occur suddenly. Monitoring describes activities used to facilitate early identification of potential scour problems. Monitoring could also serve as a continuous survey of the scour progress around bridge foundations. Fixed instrumentation, which is one of the effective means to ensure bridge safety, describes monitoring devices which are attached to bridge structures to detect scour at particular locations. Typically, fixed monitors are located at piers and abutments. The use of scour monitoring technology in the United State has led to the development of several fixed instruments suitable for different types of sites and structures. The recommended fixed monitors include sonars, magnetic sliding collars, floatout 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 also 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 onto 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's 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 detract from its reliability compared to a sonar or float-out device.

Float-out devices: Float-out devices consist of a radio transmitter buried in the channel bed at pre-determined depths. 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 its on-board power must be reliable for long periods without use.

Tilt-sensor: Tilt sensors measure movement of a bridge itself. A pair of tilt sensors or clinometers monitors the position of the bridge. Tilt sensors are relatively cheap and convenient to install. However, it is difficult to set the threshold of the magnitude of the measured titling 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 allows correlation of the processes affecting sediment transport 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, 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, which influences their accuracy. The best scour monitoring scheme is to combine various types of sensors to obtain more useful information for decision making.

Based on the review of these scour monitoring methods, discussion will be made with professionals from MDOT to determine the suitable scour sensors that can be used in the future field implementation.

2.6 Plan for Data Collection and Analysis

Frequency of data collection: Based on the survey of NCHRP (NCHRP 2010), 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 data collection. Thess included the frequency with which the fixed monitors record data and how often the data is 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 once 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 is collected and reviewed under normal circumstances can 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 was collected also varied. It included every 15 minutes, hourly, twice daily, daily, and bi-weekly.

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 satellite connection. The respondents used one of the three systems. The majority of respondents used telemetry to retrieve the bridge scour monitoring data. The automatic system can be connected to a base computer or to a network for retrieval through the Internet. The Internet was the most common system of retrieval: 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 at the bridge sites. Respondents provided multiple modes for downloading at a particular bridge. Satellite and local retrieval at the bridge site were the most frequently reported modes, followed by the landline. The cellular phone 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 Figure 2.1.

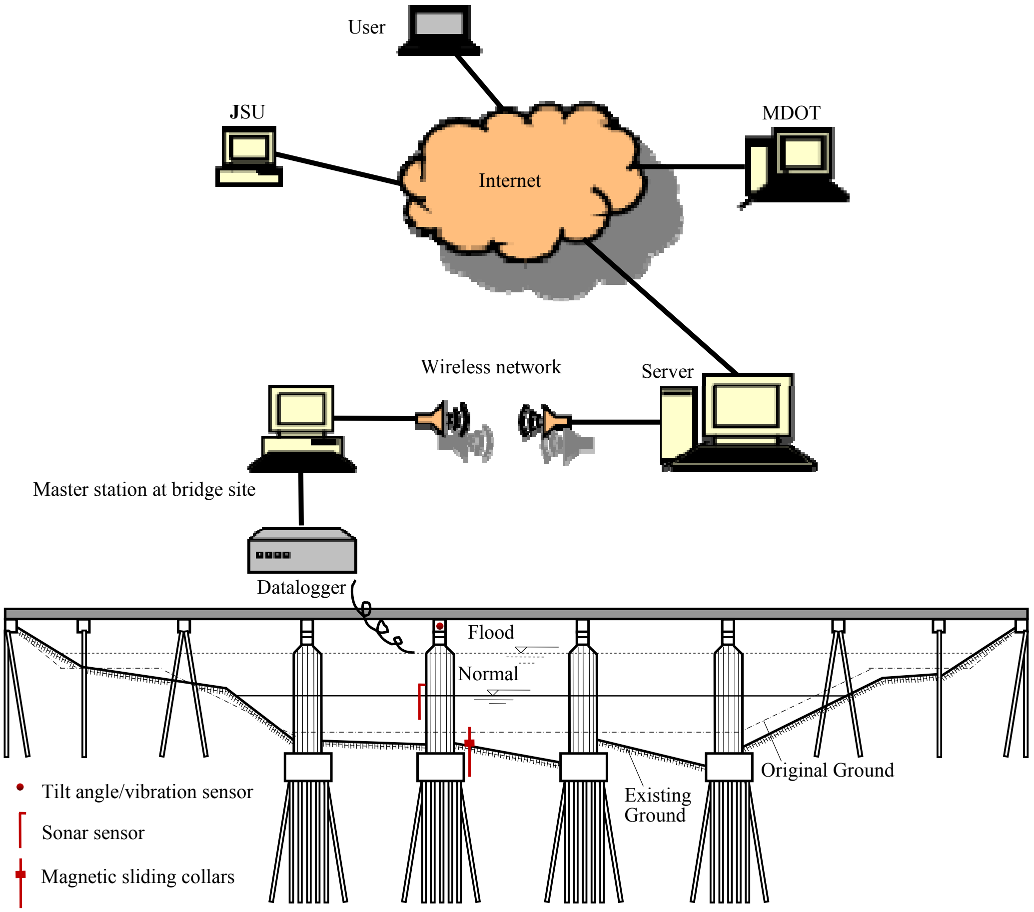


Figure 2.1 Sketch of data collection and transmission

2.7 Summary

Because the performance assessment of scoured bridges is inevitably complex, methods to efficiently and effectively inspect the bridge under scour and flood conditions becomes an important task for state department of transportation officials. The structural health monitoring system may provide an effective means to diagnose the bridge performance in a timely manner. On-line, real-time structural health monitoring systems provide a unique approach to monitor bridge responses during scour and detect any structural damage. Since the SHM technique often relies on deterministic system identification of parameters of a single bridge model to identify damage extent and locations, it often yields ill conditioning (unidentifiable) or non-uniqueness, not addressing the inherent model uncertainties. The assessment of scoured bridges also includes several uncertainties such as the interactions between soil and foundation and between piers and flooding; it may be better addressed in terms of its performance reliability using probabilistic framework.

This report initiates an innovative approach for performance assessment of scoured bridges. The approach incorporates the in-situ measurement into the proposed Bayesian framework in hopes of reducing the known model uncertainties and parameter uncertainties when creating the bridge model using finite element method. The basic theories of Bayesian Inference are explained in the following chapter (Chapter 3), and the bridge model using finite element method is also built, as described in Chapter 4. This bridge model considers several effects such as effects of scour depths, traffic loads, and soil properties. The model is expected to serve as the basis model for future application of probabilistic approach.

Chapter 3 New Paradigm for Assessing Scoured-Bridges and its Theoretical Basis

This chapter briefly describes the theory of Bayesian Inference. To incorporate Bayesian Inference, a new paradigm for assessing scoured-bridges based on Bayesian Inference is discussed. The relevant numerical simulation of Bayesian Inference and reliability assessment in the literature is also reviewed in this chapter.

3.1 Theoretical Basis of Bayesian Inference

Bayesian methods of model assessment and hypothesis testing have the advantage that they only use the axioms of probability because it is meaningful to calculate the probability of a model or hypothesis based on data (Cheung and Beck 2010). In contrast, analysis of multiple models or hypotheses is very difficult in a non-Bayesian framework (Berger and Pericchi, 1996). Bayesian framework for model updating and selection has been proposed and developed for applying for civil infrastructures. Its basic framework is presented below based on synthesis of literature (Beck and Katafygiotis 1998, Katafygiotis et al. 2002, Beck and Yuen 2004, Cheung and Beck 2010).

3.1.1 Defining a Class of Multiple Models

It is assumed that multiple mathematical models have been chosen to specify a class of models $\boldsymbol{M} = \{M_j\!: j = 1, 2, \ldots, N_M\}$, which describe the relation between model input vectors $\boldsymbol{Z}$ and its output vectors $\boldsymbol{X}$. Uncertain parameters vectors $\boldsymbol{\alpha_j}$ need to be assigned a value to choose a particular model $M_j(\boldsymbol{\alpha_j})$ within $\boldsymbol{M}$. Vectors $\boldsymbol{\alpha_j}$ may be different for each model M_j in the class of models $\boldsymbol{M}$. Since $\boldsymbol{\alpha_j}$ is always associated with a specific model M_j, the subscript j is dropped from $\boldsymbol{\alpha_j}$ in the following for convenience. Thus any specified model M_j in model class $\boldsymbol{M}$ must provide a relation between the model input $\boldsymbol{Z}$ and output $\boldsymbol{X}$ as $\boldsymbol{X}=q(\boldsymbol{\alpha}, \boldsymbol{Z}, M_j)$. Once such as a class of structural models is selected, two general types of uncertainties need to be quantified by using a probability model. The first type is model parameter uncertainty, which arises because the values of parameters $\boldsymbol{\alpha}$ are uncertain. The second type is model uncertainty, which arises because the modeling errors lead to an uncertain error in the response prediction given by any model M_j in $\boldsymbol{M}$. The fundamental idea of Bayesian model updating is to set up probabilistic models describing these types of uncertainties, which are then updated by applying Bayes' theorem with the available data.

If $\boldsymbol{Y}$ is system output measured by sensors, and $\boldsymbol{X}$ presents the true system output for the degrees of freedom of the system with numbers of N_d , then the error from model prediction and measurement noise, which is the difference between the model output and the measured system output, can be represented by $\boldsymbol{e}=\boldsymbol{Y}-\boldsymbol{X}$. To describe the uncertainty in the prediction and measurement error $\boldsymbol{e}$ for the degrees of freedom of the system, a class of probability model P is chosen parameterized by the prediction error parameters $\boldsymbol{\sigma}$ for a specific model M_j**.** The probability model P describes a function h_N giving the probability density function of a sequence of N_d prediction errors for a specific M_j in $\boldsymbol{M}$ with N_d sets of measured data; that is

$$p(\mathbf{E}(\alpha)|\boldsymbol{\sigma}, P)=h_N(e(1;\ \alpha),e(2;\ \alpha),.....,e(N_d;\ \alpha);\ \boldsymbol{\sigma}) \tag{3.1}$$

where $p(\bullet)$ denotes probability density function, $\mathbf{E}(\alpha)$ denotes the sequence of prediction errors $\{e(j;\alpha);j=1,......,\ N_d\ \}$ with N_d sets of measured data for a specific model M_j. It can be reasonable to assume that $e(j;\ \alpha)$ is a zero-mean stationary normally distributed stochastic process with a standard deviation of $\boldsymbol{\sigma}$, which is assumed to be equal for all DOF of the model M_j. Thus, vectors $\boldsymbol{\sigma}$ for all DOF of the model M_j will be reduced to a single parameter σ. The selection of the classes $\boldsymbol{M}$ and P allows a class of probability models to be defined, parameterized by vector $\theta = [\alpha^T, \sigma]^T$. The total number of parameters is equal to $N_\theta= N_\alpha+1$ for a specific model M_j.

Within the above framework, an input-output probability model $p(\boldsymbol{X}|\boldsymbol{Z},\theta, M_j)$ can be chosen for each model M_j in the model class $\boldsymbol{M}$. This probability model quantifies the uncertainty in the system output when the input is given. The $p(\theta \mid M_j)$ represents the prior probability density of θ under the model M_j in the model class $\boldsymbol{M}$, and $p(\theta,| M_j)d\theta$ represents the probability of the probability model $p(\boldsymbol{X}|\boldsymbol{Z},\theta, M_j)$, that is the prior probability density of θ that gives a measure of the initial relative plausibility of the model M_j in the set of class model $\boldsymbol{M}$.

3.1.2 Updating Model Parameter PDF for Each Model M_j in the Model Class $\boldsymbol{M}$

If input–output data D are available from the system, this information can be used with Bayes' Theorem to update the initial plausibility $p(\theta|M_j)$ of each probability model $p(\boldsymbol{X}|\boldsymbol{Z},\theta, M_j)$. The updated plausibility is expressed by the posterior PDF of the model parameters as

$$p(\theta\ |D, M_j) = c^{-1}\, p(D|\ \theta, M_j)p(\theta \mid M_j) \tag{3.2}$$

where $c = p(\mathrm{D}|\ M_j) =\int p(\mathrm{D}|\theta, M_j)p(\theta|\ M_j)\ d\theta$ and $p(\mathrm{D}|\ \theta, M_j)$ represents the likelihood function: the probability of getting the data D based on the predictive $p(\mathrm{X}|\mathrm{Z},\theta, M_j)$.

If the available input-output data D contains the measured input vector Z_n and output (or response) vector Y_n for N_d DOF of the system with multiple sets of measurement at different time, and the total number of sets of these measurements is N_t (i.e., $n= 1,2,\ldots\ldots, N_t$), then the likelihood function $p(D|\ \theta, M_j)$ can be represented as the following:

$$p(D\,|\,\theta,M_j)=\frac{1}{\left(\sqrt{2\pi\sigma}\right)^{N_t\cdot N_d}}\cdot\exp\left[-\frac{1}{2\cdot\sigma^2}\cdot\sum_{n=1}^{N_t}\left\|Y_n-L_0\cdot q\left(\alpha,Z_n,M_j\right)\right\|^2\right] \tag{3.3}$$

Where $L_0\bullet q(\alpha, Z_n, M_j)$ is the predicted response at measured N_d DOFs of the system based on the model M_j, model parameter vector α, and input Z_n at each measurement. $\|.\|$ denotes the Euclidean norm (2 norms) of a vector. The most probable model parameter $\theta=[\alpha T,\ \sigma]^T$ is obtained by maximizing the posterior PDF in Equation (3.2).

3.1.3 Assessing the Probability of Each Model M_j in the Model Class $\boldsymbol{M}$

If Bayesian model class assessment is performed based on a set of candidate model classes $\boldsymbol{M} = \{M_j : j = 1, 2, \ldots, N_M\}$ for modeling the system behavior, the posterior probability $P(M_j\,|D,\boldsymbol{M})$ of each model M_j in the model class $\boldsymbol{M}$ can be calculated based on the data D by using Bayes' Theorem:

$$P(M_j\,|D, \boldsymbol{M}) = p(D|M_j)P(M_j\,|\,\boldsymbol{M})\,/p(D|\,\boldsymbol{M}) \tag{3.4}$$

Here, $P(M_j\,|\,\boldsymbol{M})$ 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 *a priori*. The PDF $p(D|M_j)$ is called the *evidence* (or sometimes *marginal likelihood*) for model class M_j that is provided by the data D; from the Theorem of Total Probability, it is given by

$$p(D|M_j) = \int p(D|\ \theta,M_j)p(\theta\,|M_j)\,d\theta \tag{3.5}$$

and

$$p(D|\,\boldsymbol{M})=\sum_{j=1}^{N_M} p(D|M_j)P(M_j\,|\,\boldsymbol{M}) \tag{3.6}$$

The model with largest probability $P(M_j\,|D, \boldsymbol{M})$ will be the most plausible model in the model class $\boldsymbol{M}$.

3.1.4 Robust Prediction Based on Most Plausible Model and Model Class Averaging

One of the most useful applications of Bayesian model updating is to make robust predictions about future events based on past observations. Let D denote data from available measurements on a system. Based on the most plausible model M_j, all the probabilistic information for the prediction of future responses $\boldsymbol{X}$ is contained in the *robust* predictive PDF for M_j given by the Theorem of Total Probability:

$$p(\mathbf{X}|D,M_j) = \int p(\mathbf{X}|\,\theta,D,M_j)p(\theta\,|D,M_j)\,d\theta \tag{3.7}$$

where the predictive PDF of the model M_j is weighted by the posterior probability of its model parameters. Many system performance measures can then be expressed as the expectation of some function $\boldsymbol{g(X)}$ as follows:

$$E[g(\mathbf{X})\,|D,M_j] = \int g(\mathbf{X})p(\mathbf{X}|D,M_j)\,d\mathbf{X} \tag{3.8}$$

One important special case is $g(\mathbf{X}) = I_F(\mathbf{X})$, which is equal to 1 if $X \in F$ and 0 otherwise, where F is a region in the response history space that corresponds to unsatisfactory system performance. Then the integral in Equation (3.8) is equal to the robust "failure" probability $P(F\,|D,M_j)$.

If a set of candidate model classes $\boldsymbol{M} = \{M_j\!: j = 1, 2, \ldots, N_M\}$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:

$$p(\mathbf{X}|D, \mathbf{M}) = \sum_{j=1}^{N_M} p(\mathbf{X}|D,M_j)P(M_j\,|D, \mathbf{M}) \tag{3.9}$$

where the robust predictive PDF for each model class M_j is given by Equation (3.7) and is weighted by its posterior probability $P(M_j\,|D, \mathbf{M})$ from Equation (3.4). Equation (3.9) is also called posterior model averaging. The prediction of system performance based on the model averaging can then be expressed as the expectation of some function $g(\mathbf{X})$ as follows:

$$E[g(\mathbf{X})\,|D, \mathbf{M}] = \int g(\mathbf{X})p(\mathbf{X}|D, \mathbf{M})\,d\mathbf{X} \tag{3.10}$$

3.2 New Paradigm for Assessing Scoured-Bridges Based on Bayesian Inference

A new paradigm for assessing the scoured-bridge performance will be based on Bayesian Inference. In this research, different monitoring schemes will be examined for providing efficient in-situ data for the proposed probabilistic inference. One monitoring scheme includes the sensors for directly detecting scour depth and measuring the vibration acceleration and tilting of piers. The other only includes the sensors for measuring the pier vibration acceleration and tilting. The flood monitoring system that includes sensors for detecting flood speed and depth and flood pressure on the piers may be added to the above monitoring schemes. The effectiveness and efficiency of these four different monitoring schemes will be examined. If they are not effective, other efficient monitoring schemes will be explored and developed.

Implementation of the proposed probabilistic paradigm will include two parts. The first part is the model parameter updating and model selection by using in-situ measurement. In this part, the in-situ data measured at the bridge piers under free vibration caused by traffic and flood will be used as the data for Bayesian inference. Two approaches of the time-domain method and frequency-domain method will be explored in Bayesian inference. In the time-domain method, the time of history of traffic and flood impact will be modeled as model inputs, and the acceleration response measured at the bridge pier will be used as model outputs. The input-output Bayesian inference, which is applied for the time-domain method where the time history of inputs and outputs are explicitly known or measured, will be adopted to infer the system conditions. In frequency-domain method, the vibration of bridge system caused by traffic and flood will be approximated as ambient vibration by assuming that the input from the traffic and flood impact is a broad-band stochastic process adequately modeled as stationary Gaussian white noise. Thus, a special input-only Bayesian inference-Bayesian of Spectral Density approach developed by Katafygiotis and Yuen (2001) will be used to identify the major model frequencies, where the only outputs of system modal properties are explicitly known, and the input excitations are not needed. In this method, the Fourier transform of the measured system output of vibrations will be used to build the Spectral Density Estimator, which probability distribution can be closely approximated by a Chi-square distribution and used to build the likelihood function for Bayesian inference. The modal frequencies and modal shapes can be quantified and used to further identify the model parameters and model presentation for the system.

The second part of the proposed paradigm is to assess the performance reliability based on identified model representation and model parameter distributions. The performance reliability considered here concerns the probability of performance deterioration and failure only due to scour damages under flood impact. It is assumed that the major impacting model parameters are scour depth, flood impact, and soil properties. If other parameters are identified as critical parameters through the proposed sensitivity analysis, they will also be included into the model parameter updating process in the first part of the paradigm. The limit state function or performance function can be expressed as

$$g(\boldsymbol{X})=g(X_1,X_2,\dots,X_N)=L(X_1,X_2,\dots,X_N)-R(X_1,X_2,\dots,X_N) \tag{3.11}$$

where $\boldsymbol{X}= X_1,X_2,\dots,X_N$ presents the model parameters. In one case, the $L(X)$ could represent the bridge's horizontal resistance under its full traffic loads or reduced traffic loads, while $R(X)$ represents the expected flood impact load; or in the other case, $L(X)$ could represent the specified allowable lateral deflection under which the traffics can tolerate, while $R(X)$ represents the bridge lateral displacement under the expected flood impact. Thus, $g(\boldsymbol{X})\leq 0$ presents the failure at the specified performance level.

If $\boldsymbol{f}(\boldsymbol{X})=\boldsymbol{f}(X_1,X_2,\dots,X_N)$ presents statistical distribution or probability density function of the model parameters, which could be updated through Bayesian inference by using continuous in-situ monitoring measurements as presented in the section 3.1, then, the system failure probability at the specified performance can be expressed as

$$P_f=\int_{g(X)\leq 0} f\,(X_1,X_2,\cdots X_N\,)\mathrm{d}X_1,\mathrm{d}X_2,\cdots,\mathrm{d}X_N \tag{3.12}$$

The above failure probability integral is actually equivalent to the expression in Equation (3.8). Figure 3.1 illustrates the graphical representation of the relation of the performance function $g(\boldsymbol{X})$ and statistical distribution of model parameters $\boldsymbol{X}$ (a two dimension vector). The probability integral can be obtained through statistical simulation by using efficient sampling techniques. For each sample, the structural performance response, such as lateral load resistance under given vertical traffic load or lateral displacement under given flood impact load in the performance function $g(\boldsymbol{X})$, will be determined through pushover analysis using the identified model representation (based on model averaging).

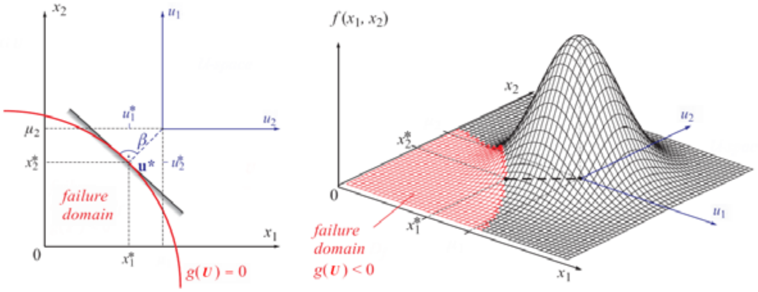


Figure 3.1 Illustration of limit state function, statistical distribution of model parameters, and failure probability

3.3 Numerical Simulation of Bayesian Inference and Reliability Assessment

The implementation of the above Bayesian inference and reliability assessment requires the evaluation of an integral with posterior PDF. Certain properties of the posterior PDF can be very complicated. It may be high-dimensional, multimodal, very peaked, or with flat regions. The integral usually cannot be done analytically. An exceedingly challenging task for implementing the proposed approach is to explore effective mathematical methods to do the simulations. Various Markov Chain Monte Carlo (MCMC) simulation methods and sampling techniques, such as Gibbs Sampling and the Metropolis-Hastings algorithm, have been used to more efficiently solve the Bayesian model updating problem. Software to implement several of the approaches described above is available.For example, BICREG does Bayesian model selection and accounting for model uncertainty (www.research.att.com/~volinsky/bma.html). The recently-developed effective methods for using MCMC simulation for system identification of civil infrastructure includes adaptive Metropolis-Hastings method, transitional Markov chain Monte Carlo method (Ching and Chen 2007), and Hybrid Monte Carlo simulation (Cheung and Beck 2009). These techniques can be readily used for the above Bayesian Inference and will be explored for assessing scoured bridges.

Chapter 4 Computational Simulation of Scour-Critical Bridges

In this chapter, finite element software is used to build the structural model of a scour-critical bridge in Mississippi. Bridge structural properties (frequencies and mode shapes) can be identified using designated moving truck loads. Possible failure modes of the bridge subjected to scour and flood can also be simulated. The deterministic-based finite element model can be used as a basis for the subsequent probabilistic-based Bayesian Inference framework. In the computational simulation, a prototype bridge is modeled by using finite element software. The major input data for the simulation includes the different types of traffic load, scour depth, soil properties, and connections between bridge components. This input data is determined based on examining common practice for bridge constructions. The output data is obtained from the static pushover analysis and dynamic time-history analysis based on the finite element model of the selected the prototype bridge. The output data includes the modal properties, i.e. natural reference, lateral displacement, the time-history of the acceleration, and the failure modes of the bridge.

4.1 Analytical Modeling of a Scour-Critical Bridge in Mississippi

4.1.1 Description of the No. 127.9 Bridge on U.S. Highway 61

The bridge traverses the Sunflower River bypass channel and was constructed in 1964 under project number SP-61-3. The bridge consists of 9 spans, with a total length of 510 feet. The superstructure is supported by 4 interior piers on 25 piles each, two interior bents of 12 piles each, two interior bents of 5 piles each, and two end abutments of 11 piles each. Located on U.S. highway 61 about nine miles south of Valley Park, the bridge has provided service to the traveling public for over 30 years, and there was no indication of structural problems. However, significant scour was found during a previous bridge inspection, which is plotted in Figure 4.1. To ensure the safety and serviceability of the bridge, the Mississippi Department of Transportation (MDOT) requests monitoring for possible scour critical-conditions that may cause structural instability.

A robust analytical model is essential for the structural performance assessment using in-situ monitoring data. Before instrumentation, the analytical model can be used to preliminarily calculate the performance of the entire bridge, which is difficult to investigate by field inspection. After instrumentation, the calculation results can be correlated to field monitoring data, and the analytical model can be updated in a deterministic or probabilistic manner. The updated model and the monitoring data will form a solid basis for the comprehensive evaluation of this scour-critical bridge.

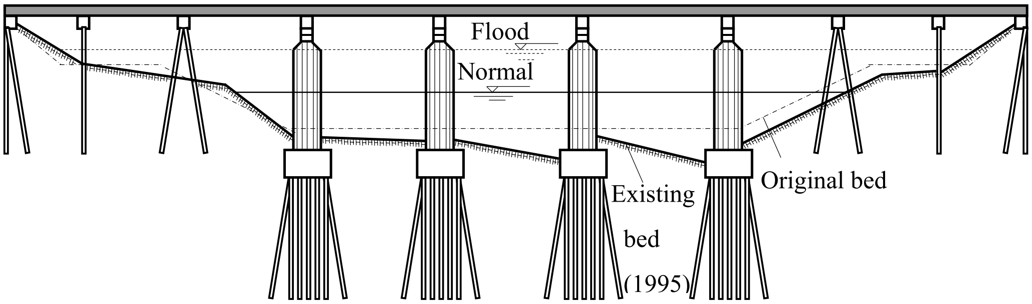


Figure 4.1 Sketch of the scour in No. 127.9 Bridge on U.S. Highway 61

4.1.2 Analytical Model of the Bridge Considering Bridge Superstructures, Soil Springs, and Traffic Loads

The bridge to be modeled is a complex structural system in which the decks, the piers or bents, and the piles embedded in a variety of ground soil are embraced. The supporting conditions keep changing due to the development of scour. The change in support is nonlinear and is a function of time and depth. This can be slow in regular seasons and significant during a major flood event. The properties of ground soil and the configuration of ground soil layers are critical to the stability of the structural system. The laterally-supporting stiffness of piles embedded in soft soil could significantly decrease even under a minor scour condition, making the structure vulnerable to the P-△ effect caused by a vertical load. The laterally supporting stiffness of piles embedded in hard soil could be highly insensitive to scour depth, giving no obvious warning before the scour develops to a danger level. An analytical model may only be valid by incorporating the soil properties and soil layer configuration.

Under scour conditions, the re-distribution of self weight and traffic loads depend significantly on the lateral stiffness of the girders, which relates to the connection details of girders and of the girder and pier. The strongly connected girder will transfer the moments of a severely-scoured pier to the adjacent ones and will confine the deformation of the pier. If the girder has been designed in a plastic manner, the peak values of load effects will decrease. The weakly-connected girder has confinements on piers, and each pier will work independently. The connection will be damaged if the scour at a certain pier is more severe than that at adjacent piers, and the severely scoured parts will collapse or be washed away. The connection stiffness of girders, and the connection stiffness between girder and pier are critical parameters in an analytical model for simulating the failure model of the scour-critical bridge.

In different stages of scour, the traffic loads on the bridge can have different impacts on bridge stability. Under slight or moderate scour conditions, the added mass due to traffic will change the structural properties of the bridge, decreasing its lateral stiffness and making it more vulnerable to lateral deformation. The traffic loads can be crucial if the substructure loses most of its lateral confinement due to severe scour. The slim piles with a long unconfined length will deform excessively or even buckle under the vertical load. That may result in the collapse of bridge. The traffic load must be considered in the analytical model.

A traditional bridge model, which is concerned only with the superstructure and the substructure, is inadequate to cover these issues. This brings the need to create a new bridge scour model. An analytical model considering all effects is proposed in this research. In the model, the girder is represented by solid elements–each with eight nodes. Each node has six degrees of freedom (DOFs), i. e., three translations along the x, y, and z axis and three rotations about the x, y, and z axis. The piers are modeled using frame element, which has two nodes, and each node has six DOFs, just like the node in the solid element. The pile caps are modeled using the same solid elements for girders. The piles are modeled using the same frame elements for piers, of which the section and the arrangement of rebars are different. The ground soil is modeled using spring elements confining the nodes of pile and pier. The connection of the different parts of girder, the connection between girder and pier, and the boundary conditions on the abutment are also modeled using spring elements. It costs 3370 solid elements, 5706 frame elements, and 5953 spring elements to build the finite element bridge model, which is shown in Figure 4.2.

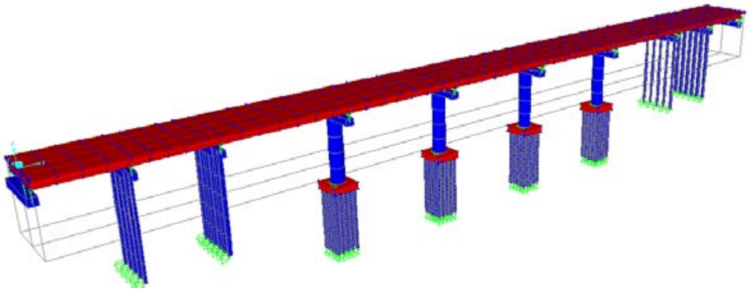
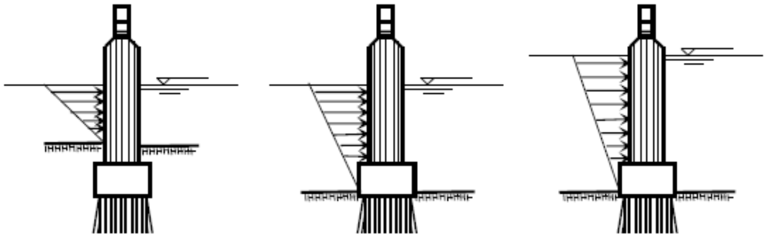


Figure 4.2 The finite element model of the No. 127.9 Bridge on U.S. Highway 61

4.1.3 Static Nonlinear Push-Over Analysis

Static nonlinear analysis (push-over) is used to investigate the performance and the failure modes of the scour-critical bridge. In the analysis, lateral force on bridge pier, which represents the push of river flow, is increased gradually. The pattern of the lateral force is chosen to simulate the possible scour conditions and flood level, as shown in Figure 4.3. Plastic hinges formed at different parts of the bridge system during the loading procedure. The moment-rotation curve of the plastic hinge is governed by the section properties of concrete members, of which the arrangement of rebar, the axial resistance of section, and the axial force are critical. A desirable plasticity can be seen in the moment-rotation curve of a properly designed section, while the brittle behavior is inherent in the moment-rotation curve of an under or over-reinforced section. The ratio of axial force to axial resistance of sections can change the moment-rotation curves. A large axial force to axial resistance ratio can significantly reduce the plasticity and could result in a dangerous brittle failure of the member. The method recommended in FEMA 370 is used in the analysis to couple the axial force with the moment-rotation curve.



(a) Before scour (b) After scour (c) After scour and in flood

Figure 4.3 The water pressure applied on piers

4.2 Performance of the Scour-Critical Bridge

4.2.1 Effects of Soil Properties

The bridge piles and parts of the bents of the bridge are embedded in soil. The soil properties can be determined by field test, and then modeled for analytical analysis. The pile-soil interaction can be simulated using the well-known p-y curves, in which p represents lateral soil pressure caused by movement of piles, and y represents the soil displacement. The p-y soil spring models of the clay, the limestone, and the sand, as can be seen in Figure 4.4, are used in this analysis to simulate different types of soil a bridge foundation may be built on. Multiplying the distributed press p by a representative length, the p-y model can be transformed to the force-deformation model of spring element, which represents the soil around a pile node in the complete analytical model. The confinement of soil on the piles and embedded bent parts are simulated by all spring elements. Variation of basic natural frequency with scour depth for three different types of soil is plotted in Figure 4.5. As can be seen from Figure 4.5, the fundamental natural frequency increases as soil hardness increases and decreases as scour depth increases. The frequency decrease resulting from increasing scour depth is more rapid for the bridge built in hard soil than that built in soft soil.

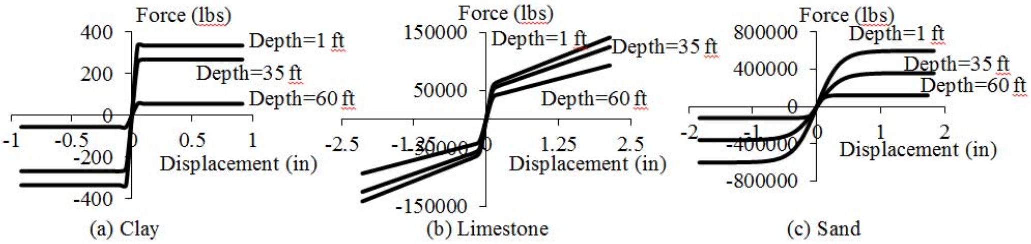


Figure 4.4 The constitutive model of soil springs for different types of soil

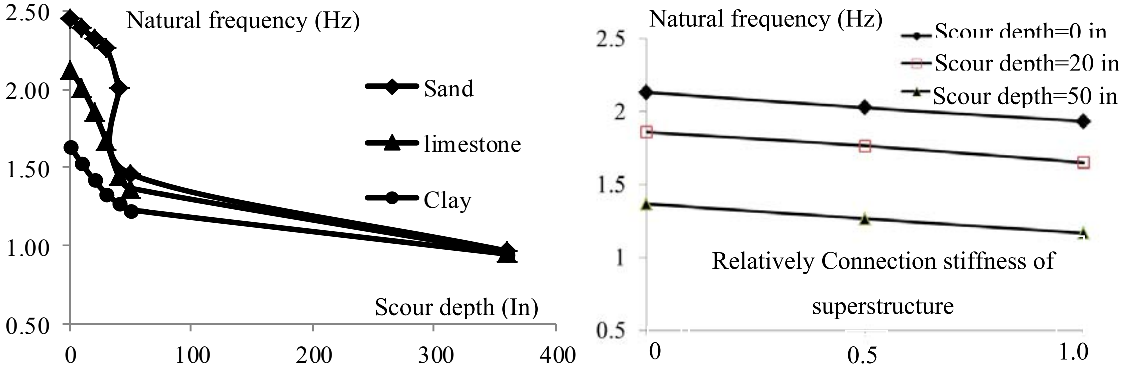
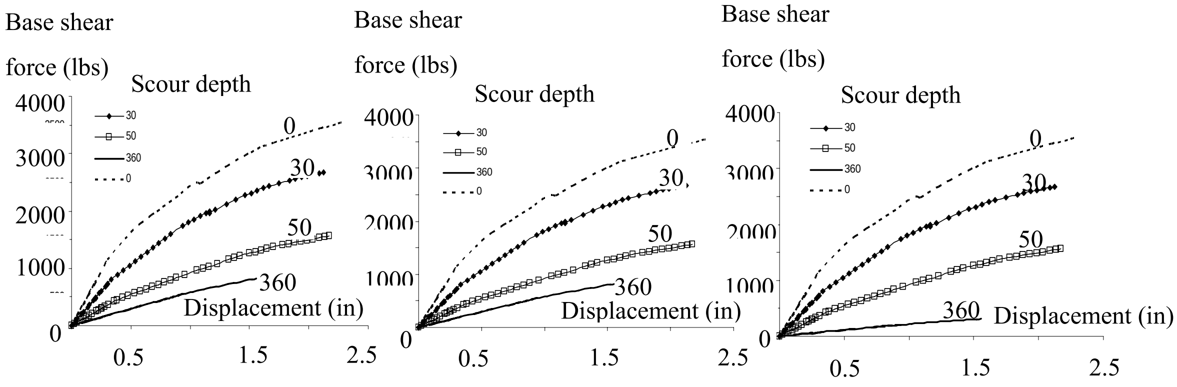


Figure 4.5 Variations of natural frequency

4.2.2 Impact of Traffic Loads

The dynamic effects caused by the traffic would not significantly change the properties of bridge [Peng and Zheng 2011]. In this research, the traffic load is simulated as static loads applied to the bridge deck. Heavy traffic is simulated by multiplying the weight of superstructure by 1.2, whereas moderate traffic is simulated by multiplying the weight of superstructure by 1.1, and light traffic is simulated by multiplying the weight of superstructure by 1.05.

The calculated load-deformation curves under different scour depths are shown in Figure 4.6. Because the equivalent static load is far smaller than the self-weight of the bridge superstructure, the traffic loads barely disturb the peak value of lateral force and the corresponding deformation under small scour depth. However, if the scour depth increases to a certain extent, the bridge will be sensitive to the P-△ effect caused by the traffic load. It should be noted that a small increase of vertical load can make the bridge unstable. This situation could be worse if accompanied by a high level of river flow from flooding. The coupled increase of axial and lateral force is fatal to a scoured bridge. Restricting or closing off traffic is recommended for bridges subjected to moderate or severe scour, especially during the flood season.



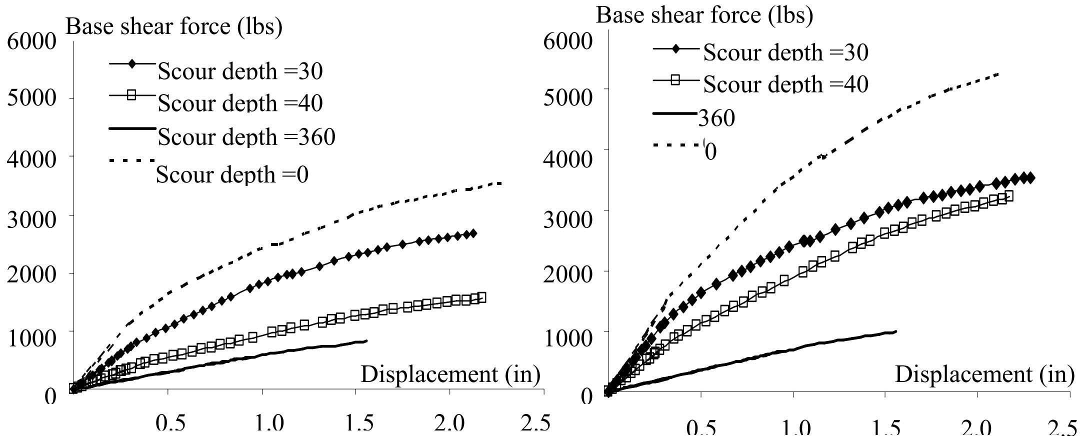
(a) Light traffic load (b) Moderate traffic load (c) Heavy traffic load

Figure 4.6 Base shear force of the bridge with varied scour depth under traffic load

4.2.3 Effects of Structural Connection

Considering the physical condition, the scour depth and the flow velocity can vary from pier to pier. The lateral force and the confinement to the piers are therefore different from each other. The distribution of inner forces and deformation substantially depend on the connection between girder and pier and the connections among girder parts. A strong connection between girder and pier can force the girder deforming with the severely scoured pier and result in high moment and shear force at the connection. A strong connection between girder parts can transfer the inner forces and deformation, whose value can be very high locally at the severely scoured pier, across the entire girder. Mitigating the peak value of inner forces and deformation, the integral result from strong connections is conducive to preventing the bridge's local collapses because of severe scour at a specific pier.

The calculated load-deformation curves for the bridge with continuous and discontinuous superstructure are shown in Figure 4.7. At a same scour depth, the peak value of deformation in a weakly-connected model is several times that of a well-connected model. The good connection is more desirable when severe scour occurs at several piers. Adequate ductility of the connections allows for the redistribution of load effects preventing the bridge from instability or failure. However, strong connections are not favorable in the superstructure of bridges when the temperature effects are taken into account. A comprehensive calculation is necessary for the connection design of superstructures of bridges subject to scour.



(a) Discontinuous superstructure (a) Continuous superstructure

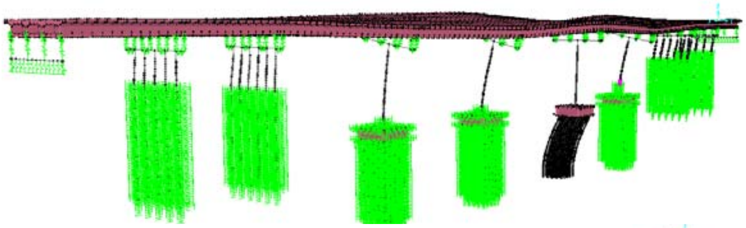
Figure 4.7 Base shear force of the bridge with different superstructure

4.3 Failure Modes of the Scour-Critical Bridge

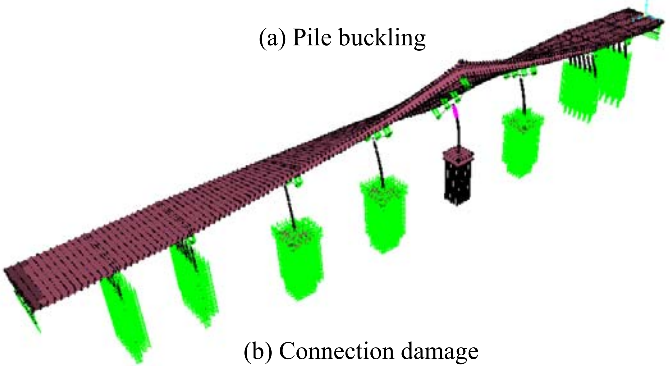
The calculation shows that scour-critical bridges could fail in different modes depending on the input parameter and structural properties, as shown in Figure 4.8. The buckling of pile or pier is the result of local and severe scour. The river flow washes out the soil confining the piles and makes the slim piles unstable. If the superstructure is weakly-connected and does not offer effective confinement, the slim pile resisting the weight of the pier and the superstructure is vulnerable to buckling.

The peak value of load effects could occur at the connection if the extent of scour is significantly different for pier to pier, and the superstructure is well connected. The concentrated inner force could locally break the connection and then trigger progressive damage within the structure. The ductility of connection is essential to postpone the collapse of the entire structure in this failure mode. A connection with favorable ductility can yield and endure a large deformation before being snapped. The adequately-deformed connection holds much of the input energy and allows the redistribution of load effects in the other parts of the structure.

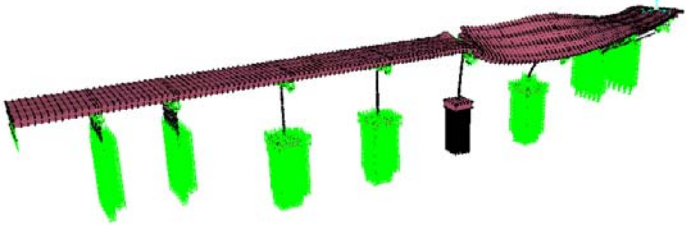
The girder can slide if it is not well connected to the scoured pier which is resisting the push of a high level of river flow. The girder will become a cantilever or fall down when it slides off the supporting area of the pier top. Monitoring the tilting of piers is indispensible for preventing the falling girder of the scour-critical bridge, especially in a major flood event. The special failure mechanism of the scour-critical bridge revealed by its failure modes is different from that of scour-free bridges. To enhance the reliability of the bridge, field inspection and comprehensive simulation shall be conducted before counter measurements.



(a) Pile buckling



(b) Connection damage



(c) Girder sliding

Figure 4.8 Possible failure modes of the scour-critical bridge

4.4 An Alternative Approach to Detect Scour at Bridge Foundation

4.4.1 The Analytical Model of the Bridge System

To overcome the limitations in current approaches, a new framework for a vibration-based approach to detecting scour is developing, as shown in Figure 4.9. Through measuring the dynamic properties of scour-critical bridges which is closely related to the scour depth and updating the analytical model to generate results to better fit the measured data, evaluation of scour can be made. The updated analytical model can be expanded to establish a multiphysics model in which the influence of river flow can be considered. Neither interruption of the transportation nor installation of delicate instruments is needed. Furthermore, the data provided by vibration tests or instrumented sensors can be continuously reused to improve the analytical model and provide more precise results. The method is illustrated by the same bridge mentioned in section 4.1.1.

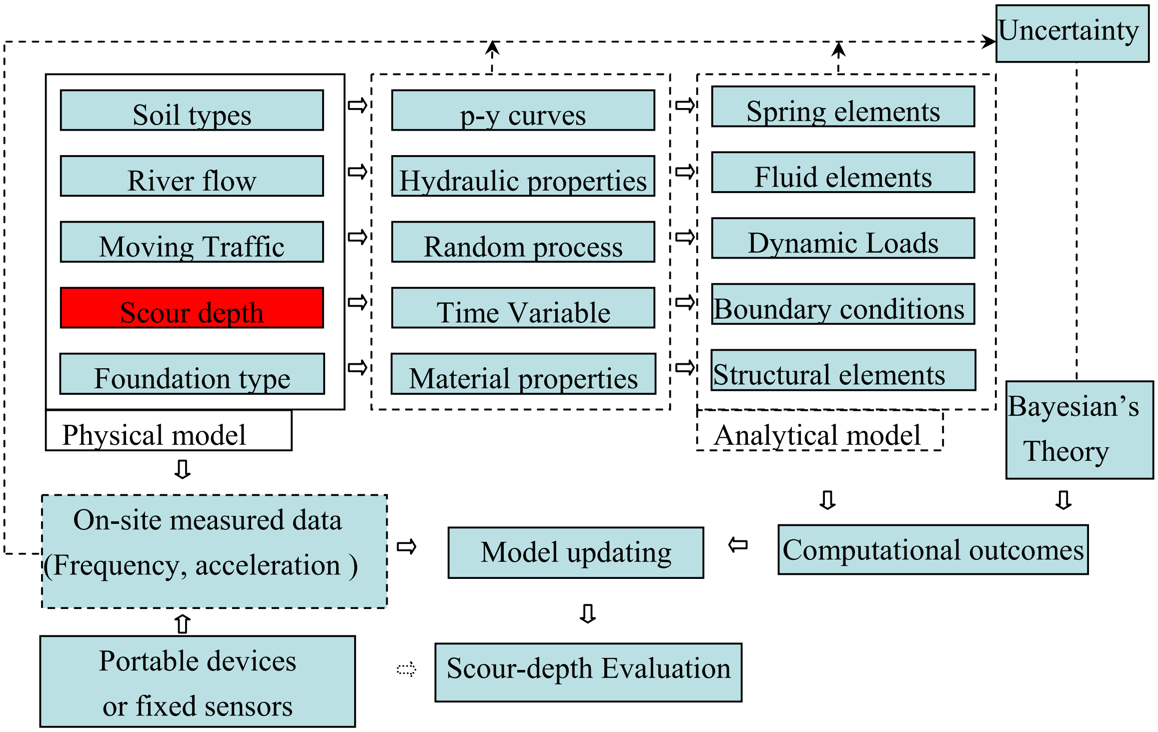
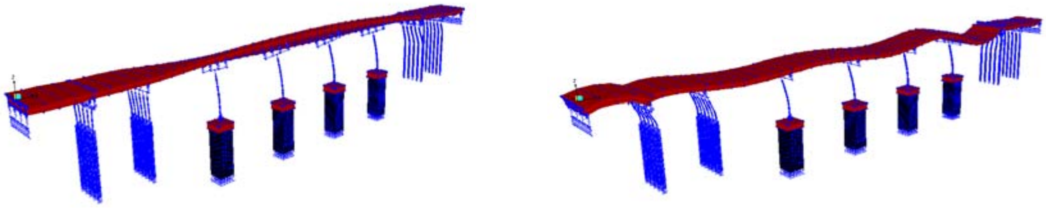


Figure 4.9 A flexible vibration-based scour-depth evaluation

To evaluate the scour conditions at the bridge foundation, a base line analytical model is established. Three packages of computational software including FB-MultiPier, SAP2000/Bridge, and LS-DYNA are used to conduct the major task. The FB-MultiPier is used to generate the p-y curves of the riverbed soils. The curves are then input as properties for the spring elements which are used to represent the soils in a Finite Element (FE) model of the entire bridge system built using the SAP2000/Bridge. The FE mesh generated from SAP2000/Bridge can be imported into the LS-DYNA to realize a multiphysics model. The input parameters for the evaluation are assumed scour depth, traffic load, ambient excitation, and river flow. The scour depth is supposed to change in increments. The ambient excitation represents the synthesized impacts from all environmental effects. The output parameters of the analytical model are the dynamic properties and responses of the bridge system including frequencies, natural modes, and statistics characteristics which can also be measured through vibration tests.

The FB-MultiPier is first used to identify the p-y curve of soil around the piles. Based on the p-y curve, the soil is replaced by spring elements in the following FE analysis. The SAP2000/Bridge is then used to establish the FE model of the entire bridge system. The scour is simulated by removing the spring elements around the pier and bent members. While dynamic properties of the bridge can be calculated using the analytical mode, as shown in Figure 4.10, some of these dynamic properties and responses can be determined through the measurement of vibration caused by different loads at different stages during the life of the bridge without interrupting normal transportation. The analytical model parameters can be adjusted so that the calculated results can match the measured results. If the measured dynamic properties change and the bridge is scour-critical, it is reasonable to adjust the scour depth in the analytical model so that calculated results can match the measured results. The impacts of other structural deficiencies or damages can either be determined using damage localization algorithms or omitted if they do not occur or are actually negligible. Thus, the natural frequencies measured at, before, and after scour development can be used to correlate with the analytical model to detect the scour. The challenge of unidentifiable conditioning or non-uniqueness associated with the above process will be solved through Bayesian inference of model selection and assessment as discussed in the subsequent section.



(a) The torsion mode, period = 2.378s (b) The bending mode, period = 5.283s

Figure 4.10 Natural periods and mode shapes of the bridge

4.4.1 Measurement of the Dynamic Properties under Normal Traffic Loads

The dynamic properties of the bridge can be measured under traffic load without interrupting normal transportation, as shown in Figure 4.11. From the spectrum of the dynamic response measured at the bridge pier under normal traffic loads, the natural frequency of a bridge system can be determined. For example, the left plots of Figures 4.12a and 4.12b show the time histories of vertical acceleration response obtained at station A under two different traffic loads which are represented by 22 and 12 moving vehicles, respectively, and obtained from computational simulation for this feasibility study. The response spectra of these two time histories of acceleration are shown in the right plots of Figures 4.12a and 4.12b. The results show that the dominant frequencies in the two spectra are the same and are very close to the first natural frequency determined from modal analysis of a whole system. This indicates the vibration measurements at the tops of piers, which are caused by normal traffic loads composing of randomly positioned passing vehicles, can be used to determine the natural frequencies of bridge system. The natural frequencies measured at, before, and after scour development can be used to correlate with the analytical model to detect the scour.

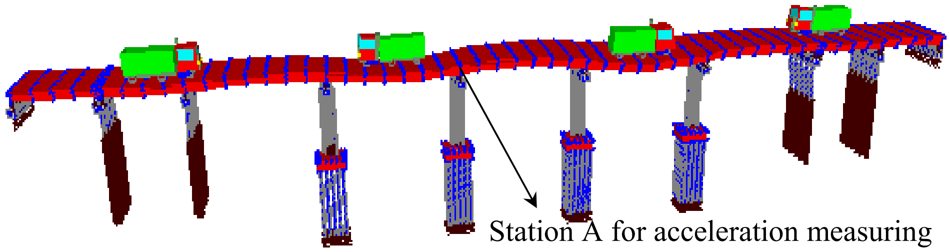
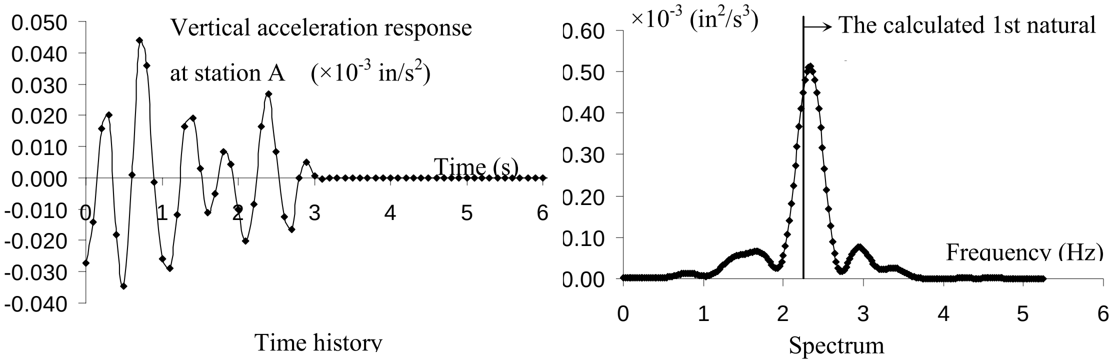
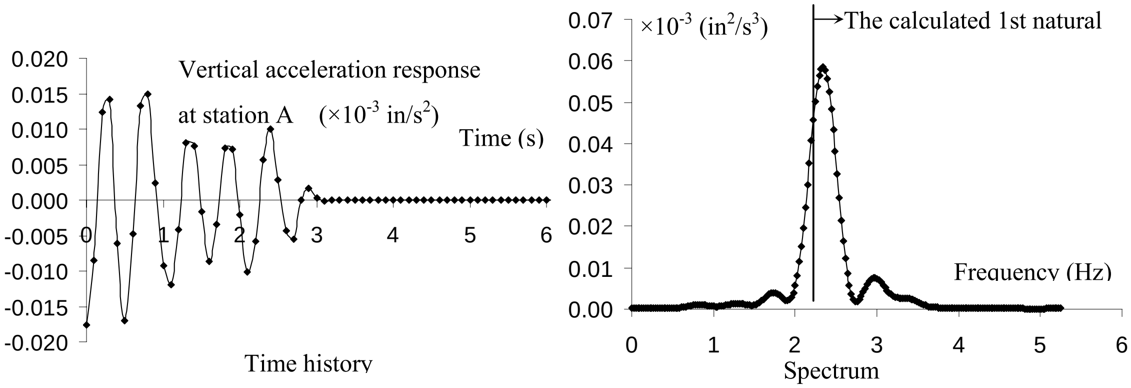


Figure 4.11 Bridge deformation under traffic loads



(a) The acceleration responses under the traffic load represented by 22 moving vehicles



(b) The acceleration responses under the traffic load represented by 12 moving vehicles

Figure 4.12 Acceleration response at station A under traffic loads

Through vibration-based measurements, the natural frequencies of the bridge can be easily determined. Some statistical parameters of the bridge such as the root-mean-square acceleration responses can also be determined through acceleration measurements. The computational simulation results indicate that these measurable parameters are sensitive to scour depth. Figure 4.13 demonstrates that the change of the first and second natural periods of bridges as scour depth increases. Figure 4.14 illustrates the change of the root-mean-square acceleration responses as the scour depth increases. These results indicate that the relations between scour depth and the measurable dynamic properties of the scour-critical bridge are systematic. The sensitivity of these measurable parameters makes it applicable for using vibration-based measurements to evaluate scour depth.

However, the change in some modal parameters, like the change of frequency shown in Figure 4.13, may be small, and it is not only influenced by the scour depth but also by other environmental factors. To choose the most sensitivity modal parameters to scour depth and separate the influence of other factors, local and global sensitivity will be conducted, and the factors on which the desired model solutions are the most dependent can be ranked. Modal parameters, which are the most sensitive to, and dominantly affected by scour depth, will be chosen for assessment.

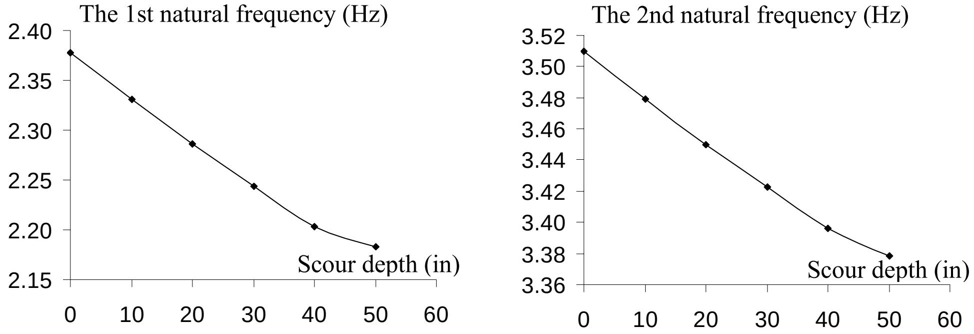
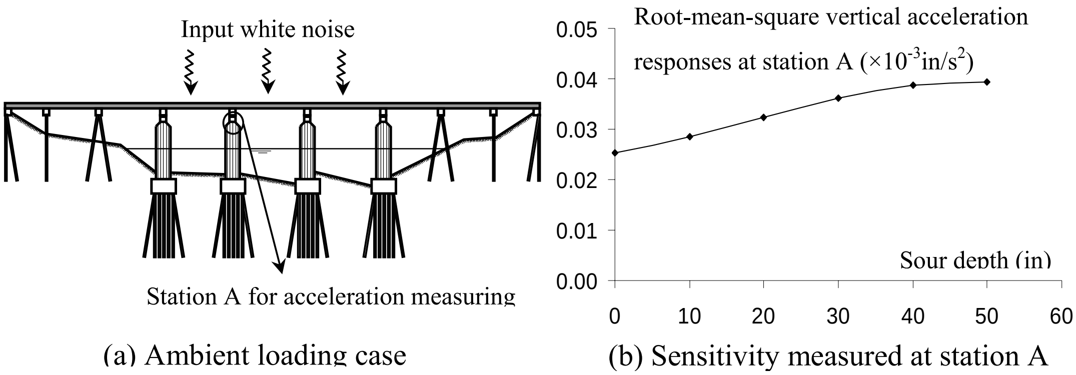


Figure 4.13 Sensitivity of frequency to scour depth

Preliminary results from computational simulation of a prototype bridge shows that the scour depth development results in significant changes of the bridge dynamic properties, and these dynamic properties can be determined through measuring the vibration caused by normal traffic load through vibration-based sensors. Recent development in Bayesian inference for system identification and model selection can address unidentifiable or non-uniqueness conditioning in identifying scoured foundation. Advancement in multiphysics computational tools can be used to characterize the impact of river flow on dynamic properties of scoured bridges. These new technologies provide solutions to the challenges in application of the proposed approach.



(a) Ambient loading case

(b) Sensitivity measured at station A

FIGURE 4.14 Sensitivity of the acceleration responses to scour depth

Chapter 5 Conclusions and Future Research

Conclusions: Scour around bridge substructures is one of the most detrimental factors endangering bridges over waterways in the Unites States. The alterative approach to detecting scour may be adopted through the integration of on-site measurement of bridges' vibration response and computational efforts and the correlation of system response and properties. It can be used not only to evaluate scour development as a supplement for current approach to directly monitoring scour development and also to provide an efficient way for evaluating the impact of scour on a bridge's structural integrity. Comparing with previous research, the proposed approach for the scour monitoring system is inexpensive and can be easily installed. Neither interruption of the transportation nor installation of delicate instrument and excitatory devices is needed. Thus, they can widely be applied to help the state DOT evaluate and manage scour-critical bridges. Based on the results presented in this report, the following concluding remarks can be made:

1. The performance and the possible failure mode of the scour-critical bridges are significantly determined by the soil properties, the traffic loads, and the connections of the superstructure. The evaluation of scour-critical bridges will not be reliable without considering the coupled effects of scour depth and soil property, traffic load, or superstructure connection.
2. The coupled effects of scour depth and soil properties, traffic loads, or superstructure connections on the bridge can be revealed by nonlinear static analysis using the complete analytical model. The proposed bridge model, embracing the soil, substructure, and superstructure, is essential in the evaluation of scour-critical bridges. The confinement of soil, the redistribution of load effects, and some possible failure modes can be simulated by using a detailed bridge model.
3. The global stiffness of the bridge decreases as a function of soil stiffness. The part of the bridge that will damage first and trigger the entire bridge failure depends significantly on sub-grade soil properties. A severe scour on a bridge built in soft soils would result in the unstable failure of the bridge before its material is damaged.
4. The traffic load will become critical in assessing the bridge performance when the scour depth is substantial, because the P-△ effect caused by the traffic loads posed high risks of pile buckling on the severely scoured bridge. A control of

traffic volume on scour-critical bridges may be necessary for scoured bridges during flood seasons.

5. The redistribution of loads can be better achieved and have more favorable effects in delaying bridge's failure in a well-connected bridge than in weakly-connected bridges. However, internal forces at the joints in a well-connected bridge could be high. Resistance and ductility of these joints must be ensured.
6. The scour-critical bridge can be susceptible to failure due to pile or pier buckling, superstructure connection breaking, or girder falling. Specific countermeasures are required for each failure mode.

Future Research: Extensive research efforts for assessment of scour-critical bridges have been made over the decades. However, the limitations of the existing practice and research have hindered the wide application of scour monitoring and effective use of monitoring data to assess scoured bridges for decision-making. The recently-resurgent Bayesian probabilistic framework could provide a new promising approach to tackling the above challenge. Nevertheless, the developments and applications of this probabilistic approach are very limited for assessing scoured bridges. The following research is needed for helping engineers to reliably assess the performance of scoured bridges and guide bridge owners to make optimal decisions on prioritizing mitigation efforts for scoured bridges:

1. Development of effective methods for detecting scour, assessing its impact based on vibration, and tilting measurement using low-cost instrumentation that can be easily deployed on the upper portion of bridge piers;
2. Characterization of the impact of flood speed and depth on the pier's dynamic properties through both multi-physics computational simulation and field measurements;
3. Application of multi-physics computational modeling for more realistic simulation of performance and a failure mechanism of bridges under combined scour and flood hazards;
4. Integration of structural health monitoring and probabilistic inference for identifying foundation configurations, properties, and damage; and
5. Development of a probabilistic framework for assessing the performance reliability of scoured bridges and a probabilistic database of distribution and variation of various parameters governing the performance of scoured bridges.

Although computational simulations of a scoured bridge have been conducted, the application of Bayesian Inference and the field implementation of a real bridge structure have not been done yet. The in-situ monitoring of a scoured bridge is deemed crucial since this data from the in-situ mornitoring can be used to refine the finite element model of the bridge, reduce the uncertainty of the model, and identify scour damage.. The on-site measurements will be incorporated into future research activities to further improve the proposed framework. Verification of the proposed probabilistic framework via testing a truss bridge model and a scoured bridge is also one of the objectives of future research. In addition, research development in relevant fields has provided effective tools to rigorously tackle the above challenges. Advancement of computational modeling provides effective tools for characterizing and simulating the bridge performance under combined scour and flood hazards. The Bayesian probabilistic framework has the potential to enable a widely applicable scour monitoring system through vibration-and-tilting-based sensors and offers a new approach to improving assessment of performance of bridges under combined scour and flood hazards.

References

Avila, C.M.C., Racin, J.A., and Davies, P. (1999). “Talk to your bridges and they Will talk back—Caltrans bridge scour monitoring program,” Proceedings of the ASCE Hydraulic Engineering Conference, Seattle, Washington.

Beck, J. L., and Katafygiotis, L. S. (1998). “Updating models and their uncertainties. I: Bayesian statistical framework.” *Journal of Engineering Mechanics*, ASCE, 124(4), 455–461.

Beck, J. L., and Yuen, K. V. (2004). “Model selection using response measurements: Bayesian probabilistic approach.” *Journal of Engineering Mechanics*, ASCE, 130(2), 192-203.

Bennett C. R., Cheng L, and Han, J. (2009). “Evaluation of behavior of a laterally loaded bridge pile group under scour conditions.” *Structures Congress 2009: Don’t Mess with Structural Engineers - Expanding Our Role*, ASCE, Austin, 290-299

Berger, J. O., and Pericchi, L. R. (1996). “The intrinsic Bayes factor for model selection and prediction.” *Journal of the American Statistical Association*, 91(433), 109-122.

Boulanger, R. Curras, C., Kutter, B., Wilson, E. and Abghari, A. (1999). “Seismic soil-pile-structure interaction and experiments and analyses.” *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 125, 750-759.

Brown, D. A., O’Neil, M. W., Hoit, M., McVay, M., El Naggar, M. H., Chakrabory, S. (2001). “Static and synamic lateral loading of pile groups.” *NCHRP Synthesis of Highway Practic 461*. Transportation Research Board, Washington D.C.

Bridge Software Institute (2010). *FB-MultiPier v4.14 – Overview*. http://bsi-web.ce.ufl.edu/products/overview.aspx?software=7.

Chen, Y. B., and Feng, M. Q. (2009). “Structural health monitoring by recursive Bayesian filtering.” *Journal of Engineering Mechanics*, ASCE, 135(4), 231-242.

Cheung, S. H., and Beck, J. L. (2010). “Calculation of posterior probabilities for Bayesian model class assessment and averaging from posterior samples based on dynamic system data." *Computer-Aided Civil and Infrastructure Engineering*, 25, 304–321.

Ching, J. and Chen, Y. J. (2007). "Transitional Markov Chain Monte Carlo Method for Bayesian model updating, model class selection and model averaging." *Journal of Engineering Mechanics*, ASCE, 133(7), 816-832.

Daniels, J., Hughes, D., Ramey, G., and Hughes, M. (2007). "Effects of pile bent geometry and levels of scour and P loads on bent pushover loads in extreme flood/scour events," *Practice Periodical on Structural Design and Construction*, ASCE, 12(2), 96-108.

Debus, K., Berkoe, J., Rosendall, B., and Shakib, F. "Computational Fluid Dynamics Model for Tacoma Narrows Bridge Upgrade Project." *Proceedings of the FEDSM'03: 4th ASME.JSME joint fluids engineering conference*, Honolulu, Hawaii, 2003.

Deng L., and Cai C. S. (2010). "Bridge Scour: Prediction, Modeling, Monitoring, and Countermeasures—Review". *Practice periodical on structural design and construction,* ASCE, 15(2), 125-134.

DeWolf, J., Bagdasarian, D.A., and O'Leary, P. N. (1992). "Bridge condition assessment using signatures." *Nondestructive Evaluation of Civil Structures and Materials Conference sponsored by the FHWA and the National Science Foundation,* Boulder, CO, 171-179.

Diamantidis, D., and Arnesen, K. (1986). "Scour effects in piled structures - A sensitivity analysis." *Ocean Engineering*, 13(5), 497-502.

Dreier D. (2008). "Influence of soil-structure interaction on structural behaviour of integral bridge piers." *The 7th fib PhD Symposium*, Stuttgart, Germany.

Federico, F., Silvagni, G., and Volpi, F. (2003). "Scour vulnerability of river bridge piers." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 129(10), 890-899.

Gao, C. Yim, S. C., Del Pin, F. and Cook, G. (2008). "A particle finite element solution for ALE RANSE coupled fluid-structure interaction systems." *27th Symposium on Naval Hydrodynamics*, Seoul, Korea, 2008.

Gregory, A. E., Yang, N. C., and Young, R. C. Y. (1985). "Bridge inspection by dynamic loading technique." *Proceedings of the ASCE National Convention*, Denver, CO.

Harden, C. W., and Hutchinson, T. C. (2009). "Beam-on-nonlinear-Winkler foundation modeling of shallow, rocking-dominated footings." *Earthquake Spectra*, 25(2), 277-300

Hsu, K. L., Moradkhani, H., and Sorooshian, S. (2009). "A sequential Bayesian approach for hydrologic model selection and prediction." *Water Resour. Res., 45*, W00B12, doi:10.1029/2008WR006824.

Hughes, D., Ramey, G., and Hughes, M. (2007). "Bridge pile bent number of piles and X-bracing system: Impact on pushover capacity as scour increases," *Practice Periodical on Structural Design and Construction*, ASCE, 12(2), 82-95

Hunt, B. E. (2009). "Monitoring Scour Critical Bridges." *NCHRP Synthesis of Highway Practic 396*. Transportation Research Board, Washington D.C.

Huston, D., and Gardner-Morse, M.G. (1993). "Modal identification of cable-stayed pedestrian bridge." *Journal of Structural Engineering*, ASCE, 119(11), 3384-3404.

Katafygiotis L. S., Papadimitrioub, C., and Lama, H. F. (1998). "A probabilistic approach to structural model updating." *Soil Dynamics and Earthquake Engineering*, 17, 495–507.

Katafygiotis, L. S., and Yuen, K. V. (2001). "Bayesian spectral density approach for modal updating using ambient data." *Earthquake Engineering and Structural Dynamics*, 30(8), 1103–1123.

Katafygiotis, L. S., and Lam, H. F. (2002). "Tangential-projection algorithm for manifold representation in unidentifiable model updating problems." *Earthquake Engineering and Structural Dynamics*, 31, 791–812.

Lagasse, P.F., Clopper, P.E., Zevenbergen, L.W., and Girard, L.W. (2007). "Countermeasures to protect bridge piers from scour." *NCHRP Synthesis of Highway Practice 593*. Transportation Research Board, Washington D.C.

Manning, D.G. (1985). "Detecting defects and deterioration in highway structures." *NCHRP Synthesis of Practice . 118,* Transportation research board, Washington, D.C.

Marr, J. (2010). "Bridge Scour Monitoring Technologies: Development of Evaluation and Selection Protocols for Application on River Bridges in Minnesota," St. Anthony Falls Laboratory, University of Minnesota.

Mazurek, D., DeWolf J. (1990). "Experimental study of bridge monitoring technique." *Journal of Structural Engineering*, ASCE, 116(9), 2532-2549.

Meyer, P.D., Ye, M., Rockhold, M.L., Neuman, S.P., and Cantrell, K.J. (2007). "Combined Estimation of Hydrogeologic Conceptual Model, Parameter, and Scenario Uncertainty with Application to Uranium Transport at the Hanford Site 300 Area," NUREG/CR-6940; PNNL-16396, Pacific Northwest National Laboratory, Richland, WA.

Mokwa, R. L. and Duncan, J. M. (2000). "Development of p-y curves for partly saturated silts and clays with both cohesion and friction." *ASCE Geotechnical Special Publication*, GSP No. 100, New Technological and Design Developments in Deep Foundations, Proceedings of the GEO-Denver Conference 2000, 224-239.

Mokwa, R. L. (1999). *Investigation of the resistance of pile caps to lateral loading.* Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Civil and Environmental Engineering Department, September.

NCHRP. (2006). "Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations," NCHRP Web-only document 107. Transportation Research Board, Washington D.C.

NCHRP. (2010). "Monitoring scour critical bridges." *NCHRP Synthesis 396*. TRB, Washington D.C.

Olson, L. D. (2005). “Dynamic Bridge Substructure Evaluation and Monitoring.” *Federal Highway Administration rep. No. FHWA-RD-03-089*, Federal HighWay Administration, Washington, D.C.

Peng, B., Zheng, W. (2011). “An Alternative Approach to Detecting Scour at Bridge Foundation.” *Proceeding of the Annual meeting of TRB*, Washington, D. C.

Samizo, M., Watanabe, S., Fuchiwaki, A., and Sugiyama, T. (2007) “Evaluation of the Structural Integrity of Bridge Pier Foundations Using Microtremors in Flood Conditions,” *Quarterly Report of Railway Technical Research Institute*, Tokyo, Japan.

Salane, H. J., Baldwin, J. W., and Duffield, R. (1981). “Dynamics approach for monitoring bridge deterioration.” *Transportation Research Record*, Number 832, 21–28.

Salawu, O. S., and Williams, C. (1995) “Bridge assessment using forced-vibration testing,” *Journal of Structural Engineering*, ASCE, 121(2), 161–173.

SEAOC (1995) *Performance Based Seismic Engineering of Buildings*, Vision 2000 Committee, Sacramento, California.

Shirole, A. M., and Holt, R. C., “Planning for a compressive bridge safety assurance program,” Transportation Research Record 1290.

Stein, S. M., Young G. K., Trent, R. E., and Pearson, D. R. (1999). “Prioritizing scour vulnerable bridges using risk,” *Journal of Infrastructure Systems,* 5, 95-101.

Stein, S., Sedmera, K. (2007). “Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations”, *NCHRP Web-Only Document 107*. TRB, Washington D.C.

Suzuki, O., Masato, A., Shimamura, M., and Matsunuma M. (2007). “A health monitoring system for railway bridge piers.” *Proceedings of the 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Vancouver, Canada.

Tsenga, M. H., Yenb, C. L., and Songc, C. C. S. "Computation of three-dimensional flow around square and circular piers." *International journal for numerical methods in fluids*, Vol. 34, 2000, pp. 207-227.

Yang, Z., and Jeremic, B. (2002) "Numerical study of the effective stiffness for pile groups." *International Journal for Numerical and Analytical Methods in Geomechanics*, 27(15), 1255-1276.

Yanmaz, A.M. (2002). "Dynamic reliability in bridge pier scouring", *Turkish Journal of Engineering and Environmental Sciences,* Vol.26, No: 4, pp367-375.

Yim, S. C. (2008). *Modeling of Complex Coupled Fluid-structure Interaction Systems in Arbitrary Water Depth*. Coastal and Ocean Engineering Program Rep. OMB 0704-0188, Oregon State University, Corvallis, OR.

Yuen, K.V. (2010). Bayesian Methods for Structural Dynamics and Civil Engineering. John Wiley & Sons (Asia) Pte Ltd.

Warren, G. E., and Malvar, L. J. (1993). "Structural assessment of reinforced concrete piers using the impact load method." *Proceedings of the International Conference on Nondestructive Testing of Concrete in the Infrastructure*, Dearborn, MI, 378–390.

Woodward, C., Minor, J., White, K., and Idriss, R. (1994). "Nondestructive evaluation of fracture critical bridge," *Structural materials technology, proceedings of the nondestructive testing conference*, Atlantic City, NJ.