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Review of Methodologies to Assess Bridge Safety During and After Floods

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16. Abstract

This report summarizes a review of technologies used to monitor bridge scour with an emphasis on techniques appropriate for testing during and immediately after design flood conditions. The goal of this study is to identify potential technologies and strategies for Illinois Department of Transportation that may be used to enhance the reliability of bridge safety monitoring during floods from local to state levels. The research team conducted a literature review of technologies that have been explored by state departments of transportation (DOTs) and national agencies as well as state-of-the-art technologies that have not been extensively employed by DOTs. This review included informational interviews with representatives from DOTs and relevant industry organizations. Recommendations include considering (1) acquisition of tethered kneeboard or surf ski-mounted single-beam sonars for rapid deployment by local agencies, (2) acquisition of remote-controlled vessels mounted with single-beam and side-scan sonars for statewide deployment, (3) development of large-scale particle image velocimetry systems using remote-controlled drones for stream velocity and direction measurement during floods, (4) physical modeling to develop Illinois-specific hydrodynamic loading coefficients for Illinois bridges during flood conditions, and (5) development of holistic risk-based bridge assessment tools that incorporate structural, geotechnical, hydraulic, and scour measurements to provide rapid feedback for bridge closure decisions.

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EXECUTIVE SUMMARY

Scour is the primary cause of bridge failures in the United States. Although bridges are typically founded on stable foundations comprising piers, abutments, or caissons, these foundations can become unstable and unsafe for traffic if scour leads to loss of the soil providing support to the foundation. This effect is particularly pertinent during flooding or high flow conditions where the increased hydraulic action can result in the most onerous scour conditions, but access and observation of scour development can be impeded. Scour monitoring represents a useful option for bridge owners to enable observations of scour activities during and immediately after flood events to inform decision-making on the necessity of closing bridges to traffic for public safety. This study was conducted to investigate the state of practice for scour monitoring techniques that can be used during and immediately after floods to assist in bridge risk management.

The first stage of the project involved a comprehensive literature review of current technologies and state-of-the-art research on scour monitoring of bridges during and after floods. The review included existing technologies and innovative research in scour monitoring, focusing on approaches considered or used by other state departments of transportation (DOTs). In addition to a review of published literature, interviews were conducted with several state DOTs, including California, Indiana, Michigan, Mississippi, Missouri, and Texas, and other industry consultants, equipment manufacturers, and relevant agencies. The findings of these informational interviews were incorporated within the literature review and discussion of each of the technologies.

The second stage of the project consisted of an in-depth evaluation of three case histories for scour monitoring technologies that may be feasible for consideration based on the literature review performed. The case histories selected were (1) bridge-deployed kneeboard or ski-mounted echo sounder, (2) unmanned surface vessels using single-beam sonar, and (3) bridge-deployed truck with articulated crane arm. Discussion was provided on the advantages and disadvantages of each case history. In addition, other relevant technologies and approaches that may aid in informing bridge scour risk were reviewed.

For the final stage of this project, the research team made recommendations to IDOT for potential use of portable scour-monitoring systems that may be suitable in Illinois. The team recommended the adoption of low-cost floatation-based sonar measurement devices for rapid scour monitoring during and after floods. These systems offer an easy way to provide rapid indications of whether scour is an issue at bridge sites. Their low cost means multiple devices can be purchased and deployed across the state. Further research into other technologies, such as remote-controlled vessel systems to measure scour depth and unmanned aerial vehicles to measure streamflow characteristics, are also recommended to make these technologies viable in complementing rapid testing of the floatation-based sonar measurements. Finally, the team proposed development of an observation-based framework to incorporate scour measurements into a comprehensive system to assess scour risk at the portfolio of scour-critical bridges across Illinois.

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CHAPTER 1: INTRODUCTION

GENERAL BACKGROUND

Local scour is the removal, or erosion, of soil by hydraulic action, particularly in the proximity of submerged structures, such as bridge piers and abutments. Although bridges are typically founded on stable foundations comprising piers, abutments, or caissons, these foundations can become unstable and unsafe for traffic if scour leads to loss of the soil providing support to the foundation. From 1987 to 2011, scour was found to be the primary cause of bridge failures in the United States, accounting for approximately 21% of total bridge failures (Cook et al., 2015).

The Federal Highway Administration (FHWA, 2020) reports that there are approximately 620,000 highway bridges in the U.S. National Bridge Inventory. The inventory indicates there are more than 20,900 bridges in the United States that are deemed "scour critical" (FHWA 2020)—Figure 1. A bridge is considered scour critical if the observed or predicted scour would make the piers or abutments (FHWA, 2001; Lagasse et al., 2009) unsafe for traffic uses. In the state of Illinois, there were reported to be at least 106 scour critical bridges (about 0.4%)—Figure 2—and potentially more with unknown foundations, which can also be at risk for scour-related issues.

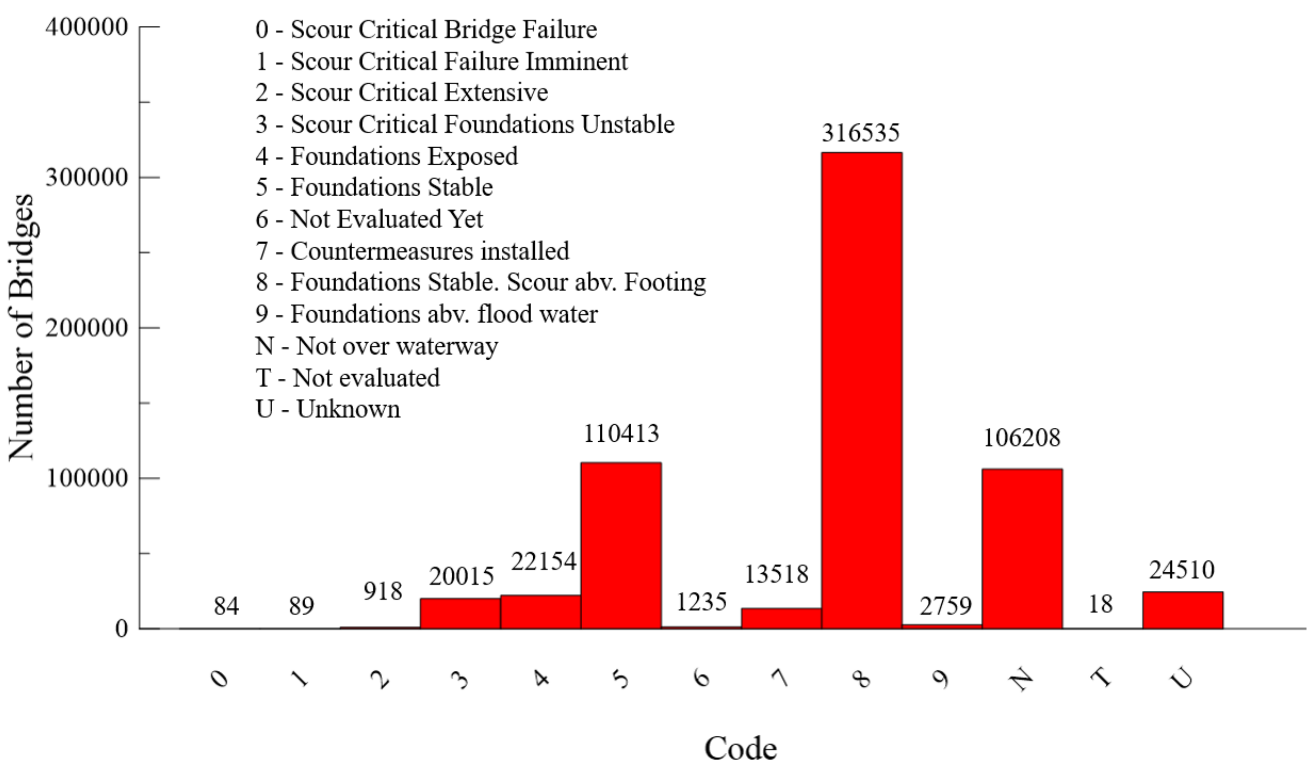

Figure 1. Chart. Breakdown of scour-critical categories.

Source: FHWA (2020)

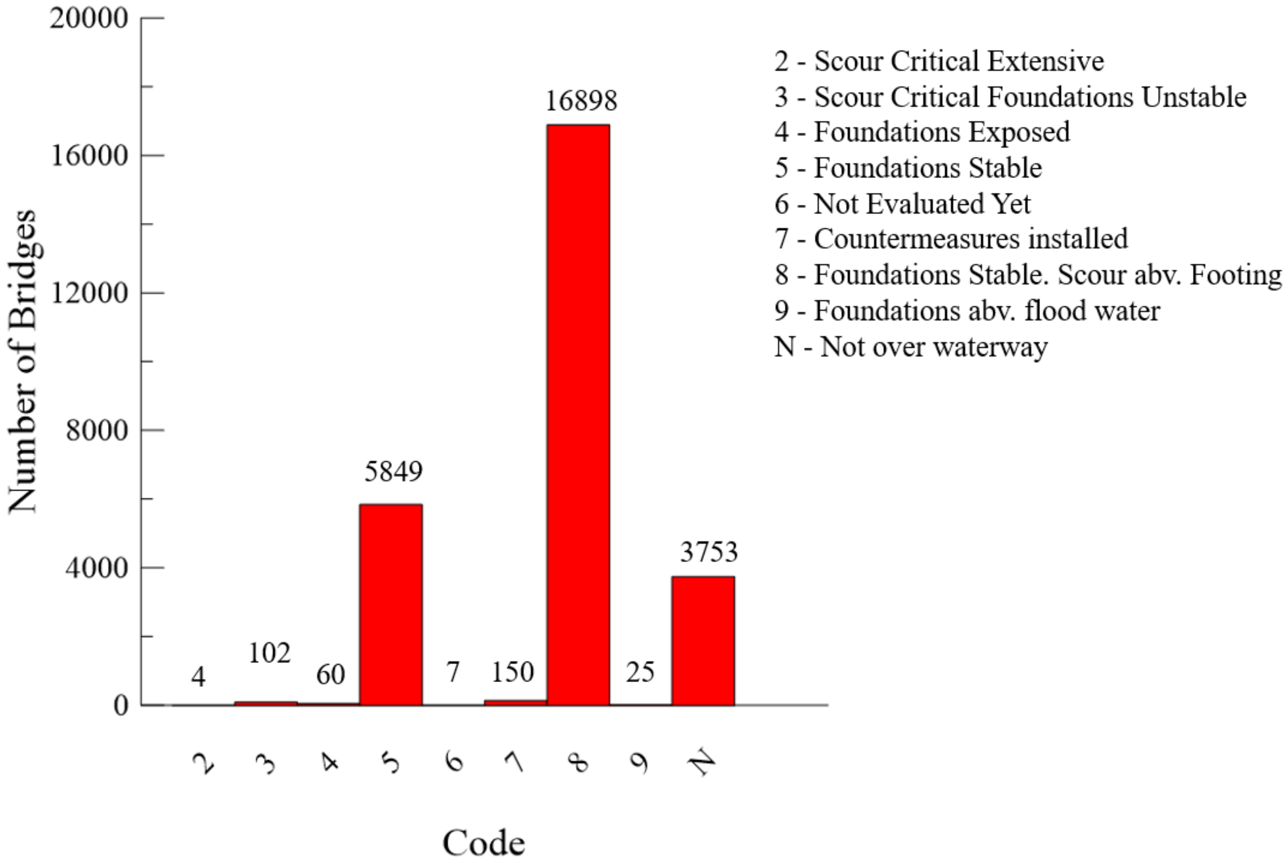

Figure 2. Chart. Breakdown of scour-critical bridges in Illinois.

Source: FHWA (2020)

Scour-critical bridges typically require some form of countermeasure to ensure safety. There are generally four types of countermeasures employed to mitigate or account for bridge scour (Lagasse et al., 2009): (i) hydraulic countermeasures to change the hydraulic conditions or the local bed material to physically prevent scour from occurring, (ii) structural countermeasures to modify pier and foundation geometries to reduce scour consequences, (iii) biotechnical countermeasures incorporating “engineering with nature” principles to prevent scour, and (iv) scour monitoring countermeasures to observe scour during operation.

Of these countermeasures, scour monitoring enables quantitative information about scour conditions to be gathered during the life of the structure. This allows bridge owners to understand the risk of bridge failure and make risk-informed decisions about potential rehabilitation based on present conditions, for both scour critical bridges and those with unknown foundations. There is substantial benefit in attaining knowledge about the conditions during and after potentially damaging flood events, as these represent scenarios in which the bridge condition can experience rapid onerous changes. This report is therefore concerned with reviewing fixed and portable instrumentation that may be used to quantify these changes during and after floods.

PURPOSE AND SCOPE

This report reviews the state of knowledge and practice for fixed and portable scour monitoring of bridges, with a particular emphasis on technologies and features pertinent to measurements during and immediately after flood events. The project comprised (1) a literature review of existing and trialed fixed and portable scour-monitoring equipment; (2) interviews with representatives from various state departments of transportation (DOTs) and relevant industry partners to learn from their experiences and gain lessons learned and recommendations; and (3) recommendations for potential use of scour-monitoring systems that may be suitable for use in Illinois-specific conditions. Interviews were conducted with several state DOTs, including California, Indiana, Michigan, Mississippi, Missouri, and Texas. Additionally, interviews were conducted with representatives from industry consultants, equipment manufacturers, and other relevant agencies, including Ayres Associates, AECOM, HR Wallingford, Voyis, Hydronalix, United States Geological Survey, and United States Army Corps of Engineers. The findings of these informational interviews are incorporated within the literature review and discussion of each of the technologies described herein, where relevant.

The literature review aimed to identify as many technologies available for scour monitoring as possible, with special attention to technologies that will be useful for monitoring during or immediately after floods and those that have been implemented or considered by state and federal transportation agencies in the United States. The Transportation Research Board's Transportation Research International Documentation (TRID) database was used to identify published research conducted by and for state and federal DOTs in the United States.

The remaining chapters in this report are presented as follows. Chapter 2 provides a general overview of bridge scour mechanics and scour-monitoring processes. Chapter 3 overviews the types of fixed scour-monitoring instrumentation. Chapter 4 describes the various components of portable scour-monitoring systems and provides a brief review of sonar technologies. Chapter 5 describes three primary case studies from state DOT experiences. Chapter 6 provides a general summary of other available technologies and approaches toward addressing the problem of scour, while Chapter 7 includes a general summary of the findings and subsequent recommendations for Illinois Department of Transportation in their selection and implementation of a scour-monitoring program.

CHAPTER 2: BACKGROUND

MECHANICS OF BRIDGE SCOUR

Scour in a riverine environment occurs when the erosive power of the flowing river is sufficient to remove the bed sediments (Richardson & Richardson, 2008). Generally, riverine scour can be subdivided into three broad categories that are of concern to transportation systems: (i) general scour, or the long-term degradation of bed level, regardless of the presence of submerged structures, (ii) contraction scour, or the overall lowering of the bed level due to cross-section flow constriction beneath bridges, and (iii) local scour, or the removal of sediment in the immediate vicinity of bridge piers and abutments. These categories are schematically illustrated in Figure 3. It is often a combination of these features that can lead to onerous bed conditions around bridge foundations, generating risk to the bridge system as a whole.

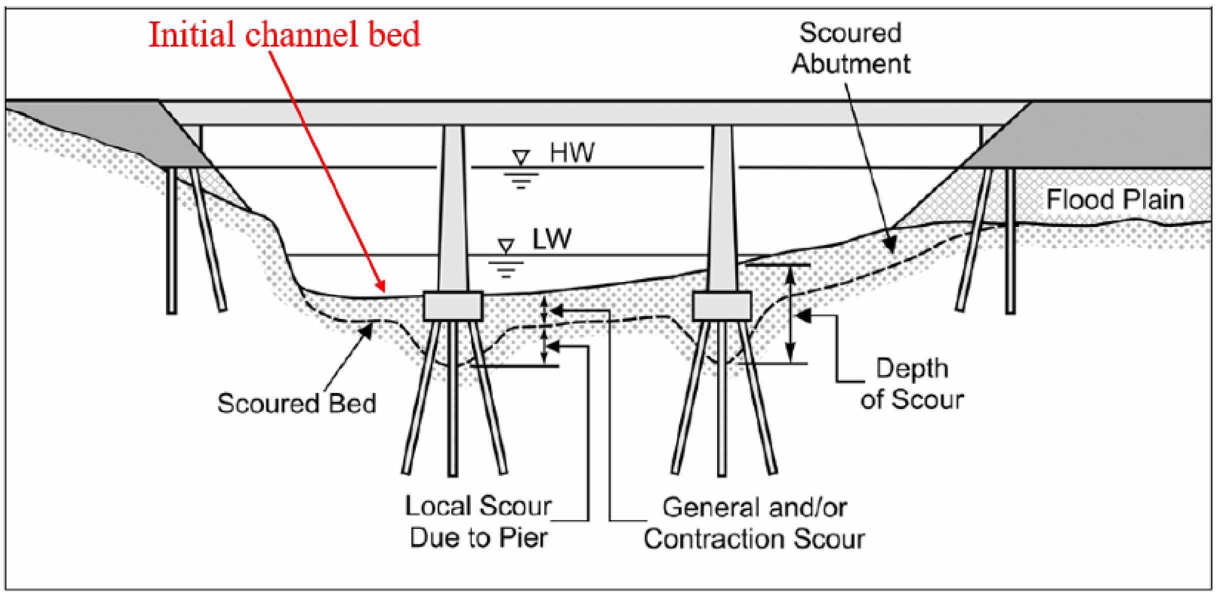

Figure 3. Diagram. Illustration of pier scour.

Source: Ettema et al. (2006)

Because most bridges are either founded on submerged piers or are single-span bridges founded on stream-projected abutments, local scour presents a focused risk at bridge foundations and supports and, hence, is of particular interest for monitoring systems. Local scour occurs due to blockage of the approaching flow, producing an area of locally accelerated flow and a complex field of vortices surrounding the structure (Figure 4 and Figure 5). This combination of accelerated flow and vortices can erode the bed sediment if the shear stress induced on the sediment exceeds the shear stress for threshold erosion, which in coarse-grained sediments is primarily a function of grain size and particle density and in fine-grained sediments may also be a function of the bulk soil density, plasticity index, among other properties. Different criteria to estimate sediment erosion conditions can be found in the ASCE Sedimentation Engineering Manual 110 (Garcia, 2008).

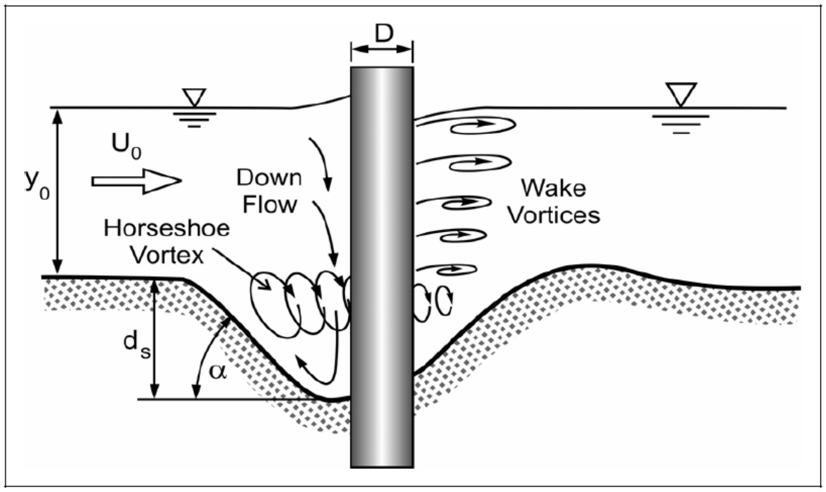

Figure 4. Diagram. Side view illustration of scour mechanism.

Source: Ettema et al. (2006)

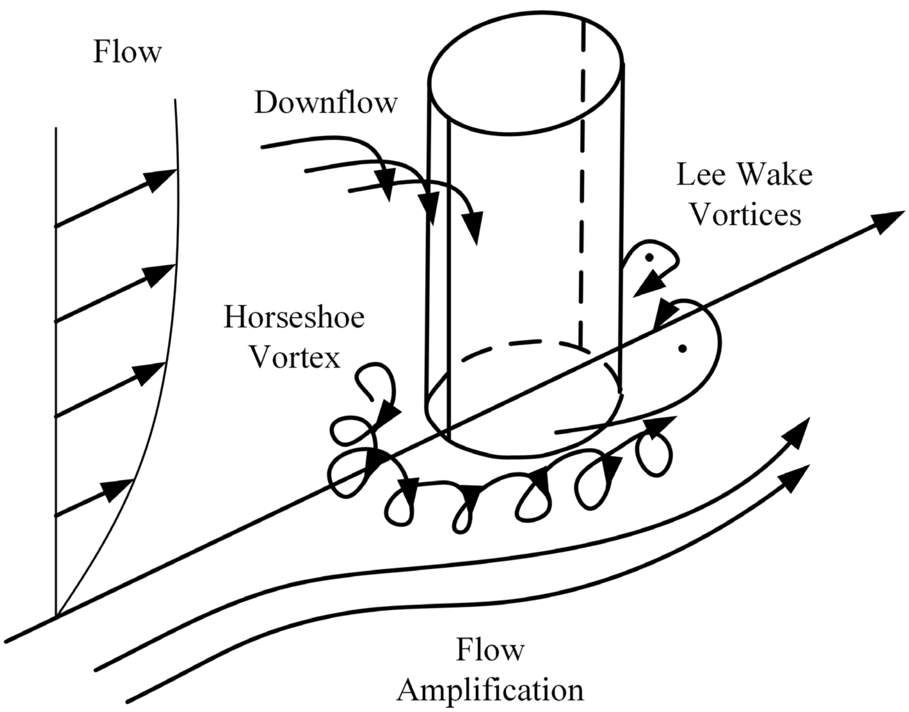

Figure 5. Diagram. 3D view illustration of scour mechanism.

If local scour occurs but the sediment away from the structure is not mobilized during a given flow event, this is known as clear-water scour. Because there is no sediment being transported toward the structure, this typically leads to net lowering of the bed level local to the structure. Net lowering will continue until the bed shear stress (due to the flow) within the scour hole is smaller than the shear stress required for particle entrainment. In contrast, live-bed scour refers to the condition where sediment is generally moving throughout the streambed, even away from the structure. Under this condition, sediment may be transported into and out of the scour hole, resulting in a more time-varying scour depth. This means that the instantaneous scour depth within a scour hole may vary even within a flood event (Figure 6). Therefore, the most onerous conditions from a geo-structural perspective (i.e., the deepest and widest scour hole) may occur during the midst of an extreme flood event, but there may be backfilling of the scour once the flood recedes. Understanding scour conditions during flood events (not only after the flood is over) may be extremely important in some circumstances to quantifying scour risk to bridges over time (Lopez & Garcia, 2001; Melville et al., 2008).

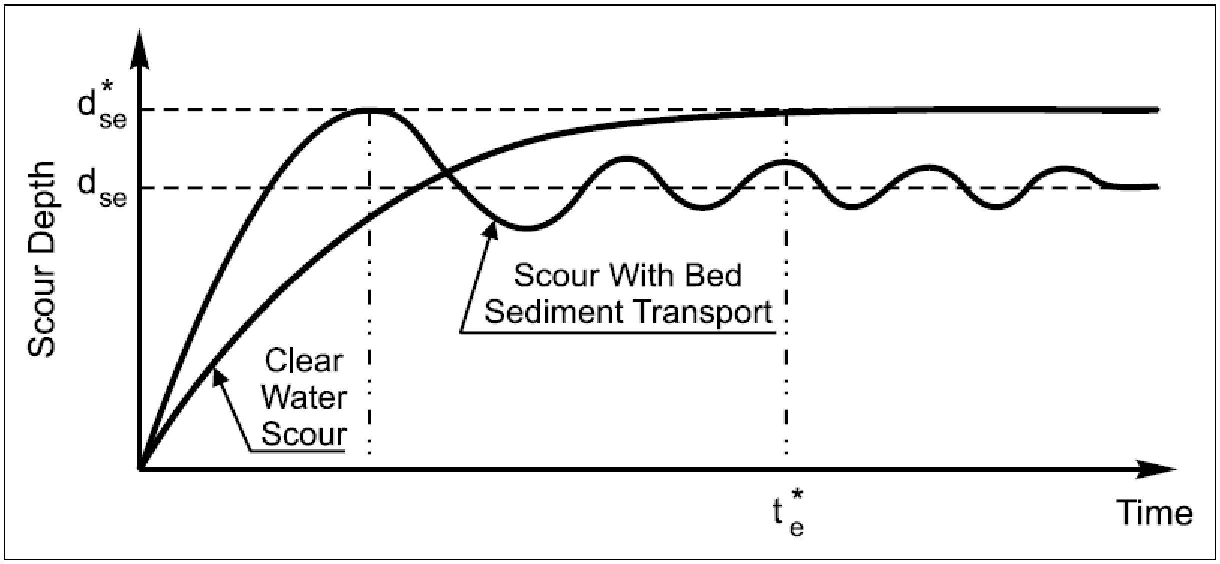

Figure 6. Graph. Fluctuation of scour depth with time for live-bed scour.

Source: Ettema et al. (2006)

ILLINOIS-CENTRIC SCOUR ISSUES

Recent Occurrences of Bridge Scour

This section discusses recent examples of bridge scour and failure. The examples are focused on events discussed with the Technical Review Panel during this research project.

Abutment Scour Collapse in LaSalle County, IL

After flooding that occurred from July 12–13, 2021, a bridge near Seneca, Illinois (structural number [SN] 050-3050) experienced scour-induced damage beneath one of the bridge abutments. The removal of supporting soil beneath the bridge approach eventually led to collapse of the approach road, as shown in Figure 7. A truck from the county highway department became wedged in at the location of the road collapse, but the driver was not injured.

Figure 7. Photo. Bridge collapse from rainfall in LaSalle County near Seneca, IL.

Source: Courtesy of Junior Senat, IDOT

Scour of a Spread Footing in Mercer County, IL

During a routine inspection in August 2018, a small township bridge (SN 066-5401) in Mercer County, Illinois, was observed to have experienced scour around an abutment spread footing (Figure 8). The bridge crosses a small stream, which experienced rapid filling and drawdown during flash flood–inducing storms. Although the bridge did not experience any structural issues because of this scouring, remediation was undertaken to rectify and prevent further scour (Figure 9).

Figure 8. Photo. Scour area under the spread footing in Mercer County, IL.

Source: Courtesy of Jeffrey Landers, IDOT and Rick Walker, Mercer County

Figure 9. Photo. Scour area after remediation in Mercer County, IL.

Source: Courtesy of Jeffrey Landers, IDOT and Rick Walker, Mercer County

Abutment Scour Issues in Morgan County, IL

A bridge that is situated along IL-104 in Morgan County, Illinois, was subjected to scour, as shown in Figure 10. A portion of the abutment/shoulder of the bridge was washed away during a flood, which resulted in subsequent failure of the adjacent roadway.

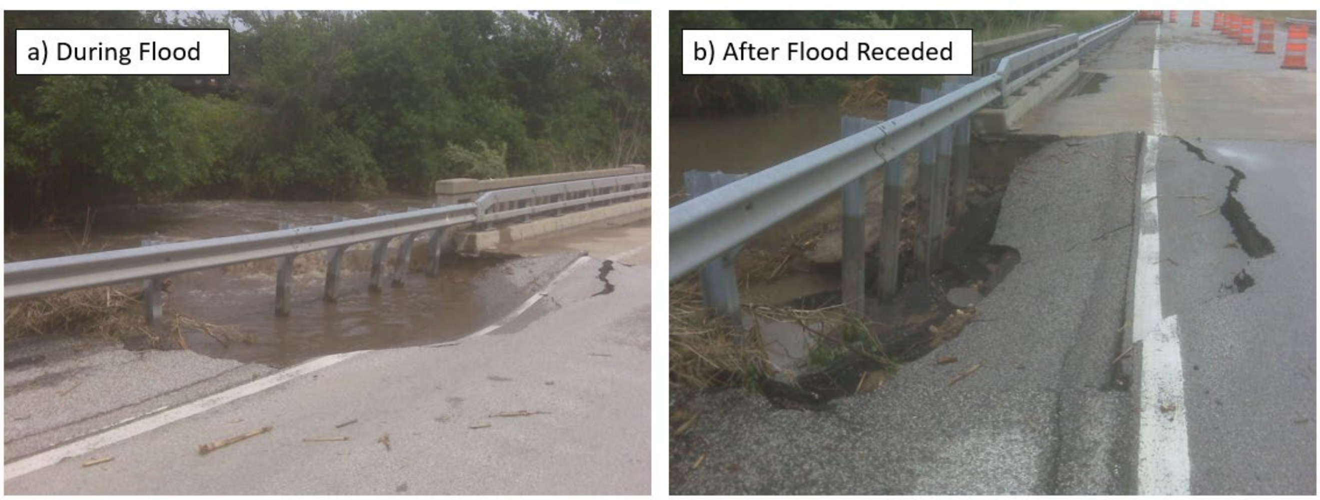

Figure 10. Photo. Washout of bridge at IL-104 in Morgan County, IL.

Source: Courtesy of Rick Walker, Mercer County

Stream Meandering and Directionality

Streams in Illinois are known to have a significant issue with stream migration, or meandering (Yen et al., 1998). Meandering occurs in response to a dynamic adjustment of a stream's flow and morphology toward an equilibrium condition (Abad & Garcia, 2006). Most streams and rivers evolve in their position over time due to erosion and deposition (Li & García, 2021). This is influenced by natural instabilities in the flow conditions, variations in sediment properties, and human interactions, including the presence of the bridge itself and other infrastructure (Motta et at., 2012a).

For bridges, meandering will affect the direction and velocity of the flow at the bridge location, and these changes in the flow characteristics can happen in a relatively short time frame within a bridge's life span (over a period of few years). For instance, bankfull flow discharge is known to have a frequency (return period) between two and five years. Each time there is enough excess rainfall and a stream experiences bankfull flow conditions, lateral channel migration via bank erosion is possible (Motta et al., 2012b). This affects both hydrodynamic loading on the structures (and hence the loads of concern by structural and geotechnical design) as well as hydraulic conditions that lead to scour. If the stream centreline location and geometry upstream of a bridge change, then this can potentially increase the flow rate and velocities expected at the bridge, increasing the forces on the structure and the depth of scour expected at the structure. A change in direction of the stream (relative to the bridge piers and abutments, which are stationary) due to meandering may lead to increase in scour depth because of the possible increase in equivalent projected area "blocked" by the bridge against the stream flow (Yen et al., 1998).

One way to quantify stream changes is by characterizing and monitoring the evolution of the bridge opening compared to both stream and floodplain width upstream of the bridge. For instance, the ratio of opening to stream width is a scour risk indicator for a bridge, where a higher ratio contributes to development of contraction scour. Hence, understanding how channel alignment and dimensions may change over time can inform bridge risk. In Illinois, meandering is a known issue that can occur over a bridge's life (Abad & García, 2006). This should be accounted for in structural, geotechnical, and hydraulic design. Another method used to monitor bridge sites for lateral migration is by capturing channel cross-sections during biennial bridge inspections. When these measurements are consistently taken at defined points along the bridge and compared to the baseline cross-section and subsequent measurements, migration rates can be quantified. Monitoring of meandering can play an important role in risk-based understanding of scour and overall stability risks for bridges (Abad et al., 2008).

Debris Buildup

Illinois bridges in certain regions of the state can experience significant levels of debris building up on their upstream sides. Figure 11 presents examples of Illinois bridges with debris building up near the piers and abutments. These bridges are reported to experience debris buildup every three or four years, which is sufficient to prevent general bridge inspections from being feasible. This presents issues for ensuring structural integrity because the bridge cannot adequately be inspected, causes health and safety risks for inspections, and increases the potential for scour due to enhancement of equivalent pier size and amplification of flow beneath the debris because of "rafting." The rafting phenomenon was found to substantially increase the scour depth during a physical model study conducted for the design of the Tanana River Railroad Bridge in Alaska (Waratuke et al., 2011).

Debris has two direct effects on scour around bridge elements. First, the presence of debris causes the equivalent size of the pier, for instance, to be larger. In other words, the flow is obstructed over a larger width of the stream, leading to enhanced velocity amplification and deeper scour hole depths. Second, when floating debris builds up at the water surface, this causes water to be funneled beneath these “rafts” of debris. This leads to faster water flow near the riverbed, increasing the scour depth (Waratuke et al., 2011). The presence of debris further complicates scour issues because this limits the ability to directly monitor the condition of the riverbed around the bridge unless (a) inspection can be conducted underwater beneath the debris, (b) inspection can be conducted from the side of the debris and the monitoring tool is able to visualize beneath the debris, or (c) monitoring tools are available that can physically punch through debris to gain access to the bed.

Figure 11. Photo. Examples of Illinois bridges with debris buildup.

Source: Courtesy of Rick Walker and Jeffrey Landers

AVAILABLE GUIDANCE AND PRACTICE FOR BRIDGE SCOUR

Three FHWA Hydraulic Engineering Circulars (HEC) are guidelines for bridge scour, stream stability, and scour countermeasures. *HEC-18: Evaluating Scour at Bridges* provides guidance for the design, evaluation, and inspection of bridges for scour (Arneson et al., 2012). *HEC-20: Stream Stability* provides instruction on the identification of stream instability problems at highway stream crossings (Lagasse et al., 2012). *HEC-23: Bridge Scour and Stream Instability Countermeasures—Experience, Selection and Design Guidance* provides guidelines for various types of scour countermeasures (Lagasse et al., 2009). HEC-18, HEC-20, and HEC-23 are used as a set for the design of bridges, particularly if countermeasure solutions need to be developed due to scour or stream stability concerns in the vicinity of a bridge. Additional bridge-scour prevention techniques and countermeasures are presented in Melville et al. (2008).

Plan of Action

The National Bridge Inspection Standards (NBIS) specifies that any bridge that is “scour critical” as well as bridges with item 113 = “7” (non-designed countermeasures installed) must have a Plan of Action (POA) developed to address scour potential and consequences. In Illinois, IDOT’s *Structural Services Manual* (2017) outlines requirements for POAs for scour-critical and scour-susceptible bridges. The purpose of the POA is to provide for the safety of the traveling public and to minimize the potential for bridge failure by prescribing site-specific actions that will be taken at the bridge to mitigate or correct the scour problem. A defined scour-monitoring method may be an important aspect of the POA and can incorporate various fixed and portable scour-monitoring instruments. The *Structural Services Manual* does additionally specify that stream cross-sections must be measured along the bridge after major storms, as defined by alert levels in the BridgeWatch system.

Federal Regulations

The federal requirements for bridge inspection are set forth in the National Bridge Inspection Standards (NBIS). The NBIS require bridge owners to maintain a bridge inspection program that includes procedures for underwater inspection. Further information can be found in FHWA Federal Register, Title 23, Code of Federal Regulations, Highways, Part 650, Bridges, Structures, and Hydraulics, Subpart C, National Bridge Inspection Standards (23 CFR 650, Subpart C). Based on the ruling enacted January 13, 2005, emphasis is placed on preparation of a POA to monitor known and potential deficiencies and to address critical findings and monitoring of bridges in accordance with the plan for bridges that are scour critical (23 CFR 650.313).

In addition to scour countermeasures, FHWA HEC-23 also contains guidance on the development of a POA. The two primary components of the POA consist of instructions for type and frequency of inspection as well as a schedule for design and construction of scour countermeasures. A POA includes the following: (1) management strategies, (2) inspection strategies, (3) bridge closure instructions, (4) countermeasure alternatives and schedule, and (5) miscellaneous information. A course (FHWA-NHI-135085) developed by the National Highway Institute and standard template for POA can be downloaded from FHWA's website. The state of Illinois requires that the POA be reviewed and updated per IDOT's *Structural Services Manual* Section 3.7.3, as follows:

> The POA must be maintained with the Bridge File containing all other inspection information related to compliance with the NBIS. A copy of the POA must also be available for use during field inspections and updated, if necessary, based on the conditions observed during each inspection.

IDOT has implemented the BridgeWatch Program to assist with the monitoring of scour-critical bridges. BridgeWatch is an alert system that centralizes precipitation data, geospatial information, and data on critical events across the United States through an interactive web interface. Alerts will be marked and dispatched to the personnel involved as soon as an environmental threat is detected at the monitored structure. IDOT's POA form is currently available on BridgeWatch. A "Scour Inspection" form is used to document scour inspection findings due to a "BridgeWatch alert," facilitating the usage of BridgeWatch in conjunction with the POA. Some of the inspection methods include visual observation of flow depth, visual inspection of any structural movement, and physical measurement of scour depth using plum lines or depth gage rods.

A typical IDOT POA should include (1) a consolidation of streamway, channel bed, and substructure information, (2) required actions to be taken based on scour evaluation, (3) type of scour monitoring that should be or has been implemented, (4) frequency of inspections, and (5) bridge closure plan.

Scour Monitoring as a Countermeasure

The most recent guidance from FHWA on scour-monitoring instrumentation can be found in HEC-23. Scour countermeasures, as defined in HEC-23, are "measures incorporated into the highway-stream crossing system to monitor, control, inhibit, change, delay or minimize stream instability and bridge scour problems." Based on their functionality, HEC-23 categorizes scour countermeasures into three general groups—hydraulic, structural, and monitoring. Hydraulic countermeasures include both river training structures that modify the flow and armoring countermeasures that resist erosive flow. Structural countermeasures consist of modifications of the bridge foundation. Monitoring countermeasures can comprise fixed instrumentation, portable instrumentation, or visual monitoring, which help inspectors determine bridge safety.

There are three main categories of scour-monitoring techniques—visual or physical inspection, fixed instrumentation, and portable instrumentation. Visual or physical inspection is the most straightforward method but is either primarily qualitative or requires human interaction (e.g., divers), increasing health and safety risks. Fixed and portable instrumentation provide quantitative measurements of scour development, which enable quantitative understanding of bridge safety risk. These latter two types of instrumentation provide the possibility of making quantitative measurements of scour during the development process and are the focus of this current report.

SONAR SYSTEMS

In the following chapters, several fixed and portable scour-monitoring techniques incorporate sonar technology to measure the depth to bed level. Hence, a short discussion on sonar technologies may prove useful. The word "sonar" originated as an acronym for "Sound NAvigation and Ranging." On a basic level, sonar works by emitting an acoustic pulse (i.e., a sound) through the water and measuring the amount of time required for the sound wave to bounce off a target and return to its source. This requires a sound source to produce the acoustic wave and an acoustic receiver to "listen" for the reflection. In many applications relevant to riverine environments, a single transducer is used to both emit and receive the acoustic pulse. As an emitter, the transducer converts electrical energy into sound waves. The sonar wave pulse is generated from an oscillating electrical signal with frequency characteristics that can be uniquely distinguished. The frequency of the emitted wave in a wider context also affects the penetration of the wave into the riverbed. When a sonar transducer emits an acoustic pulse in an isotropic medium, such as water, the sound wave travels in the shape of an inverted dome in all directions. The pulse is strongest directly below the transducer and weakens as the angle from the central axis increases (L-3 Communications SeaBeam Instruments, 2000). Once the sound wave reflects from a surface, such as the riverbed, the sound wave is received by the transducer acting as a hydrophone. The distance to the surface that produced the echo can be estimated, given the speed of sound in water, the position of the transducer, and accurate time measurements.

Sonar systems for use in scour monitoring generally fall into one of three categories: single-beam sonars, multi-beam sonars, and side-scan sonars. Modern fathometers and echo sounders are single-beam sonar systems that emit a single acoustic beam into the water (as shown in Figure 12). Within the footprint of the measurement, the strongest echo is usually returned to the unit as recorded as channel bed depth, which can lead to false returns in the presence of exposed bridge footings. These systems can be mounted on a fixed installation or on a vessel and are available relatively affordably through retail-grade “fish-finders.” Multi-beam sonars function similarly to single-beam sonars except that they simultaneously project a fanned array of sonar beams covering a “swath width,” allowing a denser coverage of measurement area. This enables direct 3D mapping of the riverbed to be attained. Side-scan sonar emits fan-shaped acoustic pulses through the water column. When mounted on a forward-moving vessel, successive sonar pings can be put together to form a continuous image along the direction of travel. Side-scan sonar is generally able to quickly and efficiently generate images of submerged structures or the channel bottom but does not provide quantitative data.

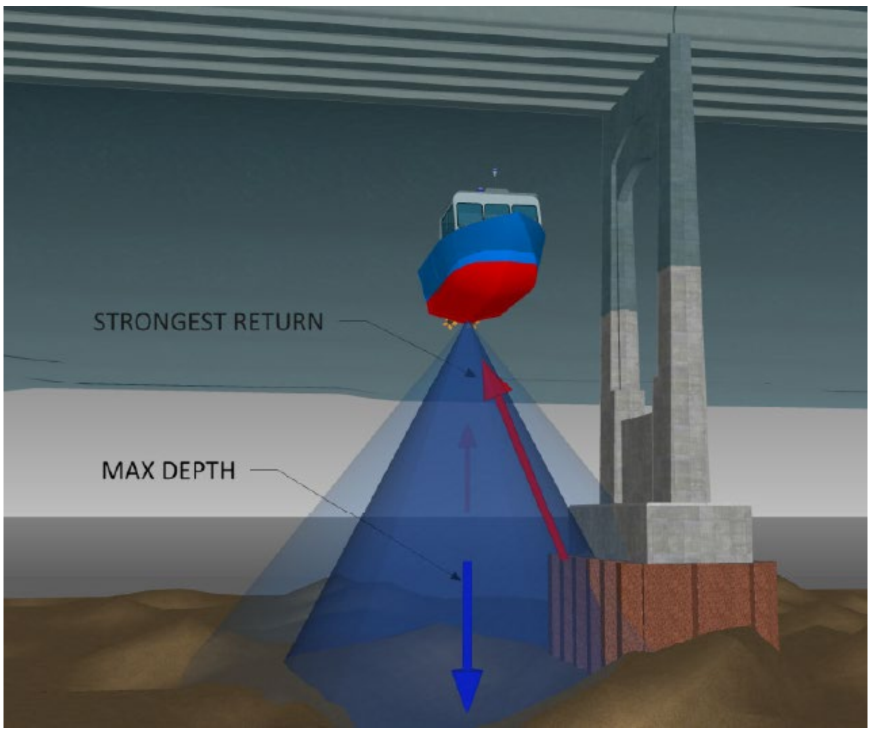

Figure 12. Diagram. Example of single-beam sonar.

Source: Shen, Forsyth, & Kilgore (2018)

CHAPTER 3: FIXED INSTRUMENTATION

Fixed instruments refer to measurement instrumentation that is permanently affixed to bridges to measure scour. These instruments are generally placed on a bridge structure, in the streambed, or on the banks near a bridge. Data from fixed instruments can be downloaded manually at the site or telemetered to another location. Fixed instruments are used when frequent or regular measurements are required. In recent decades, several types of fixed instruments have been developed for different types of sites and structures. A more detailed overview of fixed monitoring systems used by states are described in the current FHWA guidelines on scour countermeasures and monitoring, *Hydraulic Engineering Circular 23* (HEC-23), and Hunt (2009). This chapter overviews commonly considered technologies and briefly discusses their benefits and limitations. It also focuses on technologies that have had reasonably widespread usage within the United States. Additional technologies identified during the literature review but that have had limited use so far are described in Appendix A.

FIXED SONARS

Sonar scour monitors are mounted onto the pier or abutment face to take streambed measurements (Figure 13), and each sensor is connected to a datalogger. The sonar instrument measures the distance between the sonar head to the riverbed based on the speed of sound through water. These instruments can track both scour and refill processes and have been widely implemented (Ahamed et al., 2016; Hunt, 2005; Lagasse et al., 1997; Larrate et al., 2019; Weissman et al., 2001). The advantages and limitations of fixed sonars are listed below:

- Advantages: Fixed sonars are able to capture fully the time history of scour progression, including the infilling process. They are relatively commonly used and can be purchased inexpensively with off-the-shelf components.
- Limitation: They are only able to measure a discrete location within the sonar reach and their effectiveness may also be limited by the presence of debris.

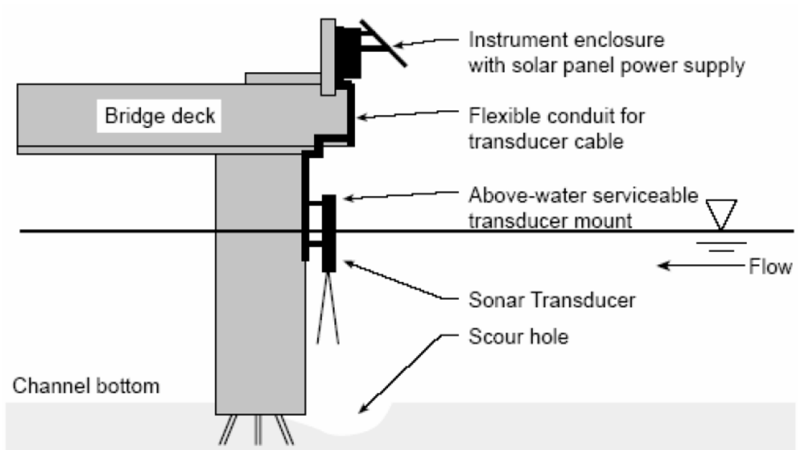

Figure 13. Diagram. Illustration of a fixed sonar.

Source: Ettema et al. (2006)

MAGNETIC SLIDING COLLARS

Magnetic sliding collars are rods or masts that are attached to the face of a pier or abutment and driven into the streambed (Figure 14). A collar with magnetic sensors is placed on the streambed around the rod. When the stream erodes and a scour hole is formed, the collar will slide into the hole and depth measurements are recorded. Magnetic sliding collars have been extensively tested in the field (Lagasse et al., 1997; Weissman et al., 2001). The advantages and limitations of magnetic sliding collars are listed below:

- Advantages: They are simple mechanical devices with relatively low cost.
- Limitations: They are only able to measure a discrete location where the rod is placed and can only obtain a maximum scour depth. Because the rod does not automatically retract, it can only measure an increase in depth.

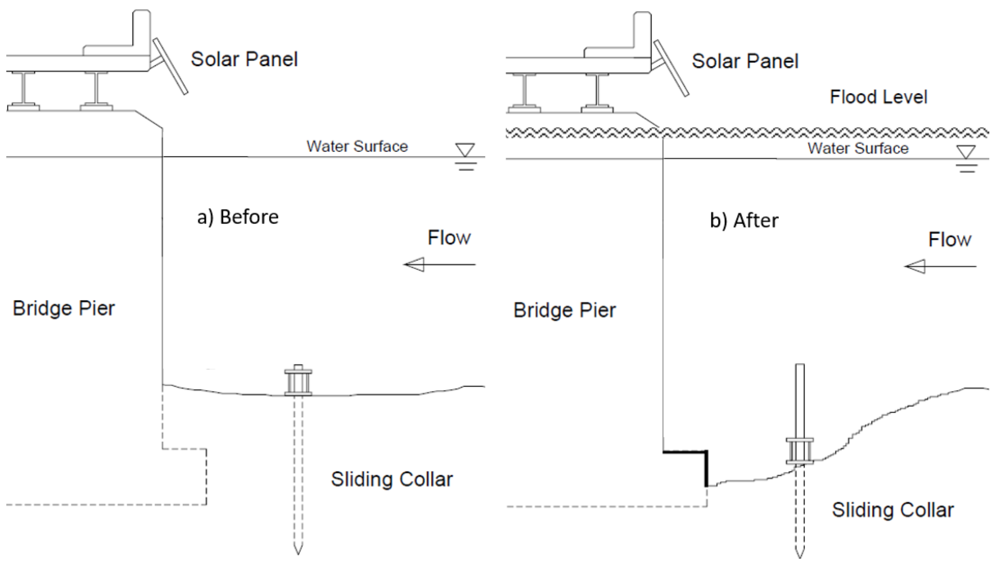

Figure 14. Diagram. Illustration of a magnetic sliding collar.

Source: Nassif et al. (2002)

FLOAT-OUT DEVICES

Float-out devices are transmitters buried in the channel bed at predetermined depths and locations. When scour develops to the extent that the transmitters are exposed to open water, the transmitter floats out to the surface and sends a radio signal with its unique identification signature (Figure 15). The signal will be detected by a receiver, and the scour depth corresponding to the float-out device can be known. The advantages and limitations of float-out devices are listed below:

- Advantages: They are low cost and easy to install; they only require burying the device.
- Limitations: While there are several ways to implement float-out devices (Luh & Liu, 2014; Papanicolaou et al., 2010), a common limitation is that they are only able to measure discrete

locations where float-out devices are buried. If the signal is not captured by the receiver, then there will be no warning to indicate the presence of a scour hole. There is also concern about battery life, as there is no way to ensure the transmitter will work when exposed.

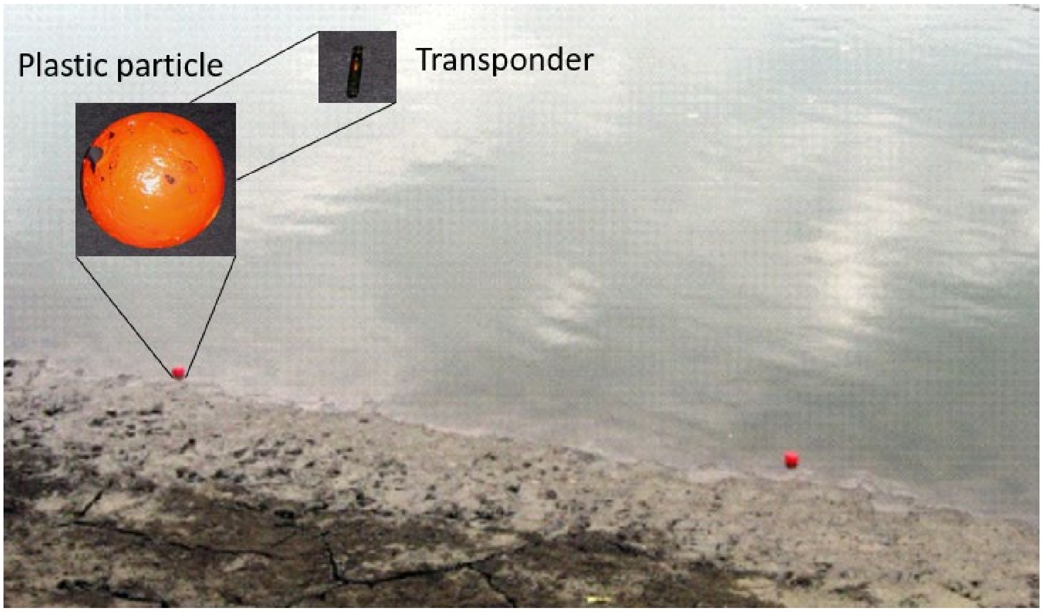

Figure 15. Photo. Float-out device in the form of a plastic particle containing a transponder.

Source: Papanicolaou et al. (2010)

TILT SENSORS

Tilt sensors or inclinometers are installed on bridge features (Figure 16) to measure the movement and position of the bridge. The devices generally measure the position of the bridge both parallel and perpendicular to the direction of traffic. An alert signal can be programmed to be sent out when the movement exceeds a certain limit. They are typically used in conjunction with other instruments that measure structural response such as accelerometers. The advantages and limitations of tilt sensors are listed below:

- Advantages: They are easier to install on the bridge structure compared to in the water channel. They provide indications of structural integrity as well as have potential for use as scour-detection measures.

- Limitations: Bridges are not rigid structures and movements can be induced due to all sorts of loading. It is not an easy task to determine the permissible movement of the bridge with an allowance for remedial action. Tilt sensors do not provide direct monitoring of scour, only whether the bridge has tilted or settled. They only provide indication of extreme circumstances when a bridge should be immediately shut down. Nevertheless, tilt meters have been widely used to provide some indication of scour effects (Fitzgerald et al., 2020; Gamage, 2020; Orsak, 2019).

Figure 16. Photo. Inclinometer installed on a bridge.

Source: Rensensys LLC (2020)

SOUNDING RODS

Sounding rods are manual mechanical gravity-based physical probes that rest just on top of the streambed and drop according to the change in streambed elevation with the use of a cable. Special care will need to be taken to ensure there is no penetration of the probe into the streambed, as that will severely hamper the accuracy of measurement. Sounding rods, also termed Brisco monitors, have been implemented in several states, including Iowa (Marks, 1993). The advantages and limitations of sounding rods are listed below:

- Advantages: They are not affected by air entrainment or high sediment loads.
- Limitations: Sounding rods can only measure discrete locations and are prone to poor accuracy due to streambed penetration. They also only measure the depth to the bottom of the scour hole and cannot measure refilling.

FIBER OPTIC SENSORS—FIBER-BRAGG GRATING

Fiber-Bragg grating (FBG) is a fiber-optic measurement technique that uses the response of light reflected from “etches” within an optic fiber to measure strain along the fiber. When used along a cantilever rod embedded into the riverbed (Figure 17), the change in strain (in terms of the natural frequency of the rod or location of strain variations) can be interpreted to indicate the level of the bed and, therefore, scour development. The advantages and limitations of Fiber-Bragg grating are listed below:

- Advantages: Fiber-Bragg grating provides continuous monitoring of the riverbed level. It can provide depth measurements for scour development and backfilling.

- Limitations: It is highly sensitive to the vibrations of the support structure used, either due to flowing water or traffic excitation. FBG interpretation is sensitive to bed sediment stiffness. It is only able to measure at discrete locations along the bridge. An interrogator to measure strains can be costly and post-test interpretation can be time-consuming.

Figure 17. Photo. Monitoring bridge scour using fiber-optic sensors.

Source: Cai et al. (2014)

ACCELEROMETERS

Accelerometers can be installed on bridge features (Figure 18) to measure the vibration or acceleration motion of a structure. This allows for the measurement of the structural response, particularly for a change in boundary conditions (Prendergast & Gavin, 2014). As soil is removed from around the foundations due to scouring, the amount of soil providing resistance decreases and the soil-structure stiffness of the remaining soil changes. Because the natural frequency of the entire structural system depends on the structure and the soil-structure interaction, this scouring can lead to changes in the overall natural frequency of the bridge. Accelerometers can, in principle, be used to continuously monitor any changes in the natural frequency to detect scour (Fitzgerald et al., 2020; Gamage, 2020; Orsak, 2019; Briaud et al., 2011). This typically requires structural numerical modelling to identify the initial natural frequency and provide context as to how the natural frequency shifts due to scour. The advantages and limitations of accelerometers are listed below:

- Advantages: Accelerometers are easier to install on the bridge structure because they can be placed on the structure, instead of in the water channel. They have the potential to provide additional structural integrity information.

- Limitations: Accelerometers do not provide direct measurement of scour. Instead, they rely on back analysis. Scour development is inferred from changes in natural frequency, which is also affected by inaccuracies due to external factors such as traffic, hydrodynamic loading, and construction effects. Although this technique has been incorporated into bridges, particularly in Asia (Bao & Liu, 2021; Suzuki et al., 2008), the technology still requires further development before widespread deployment for scour monitoring.

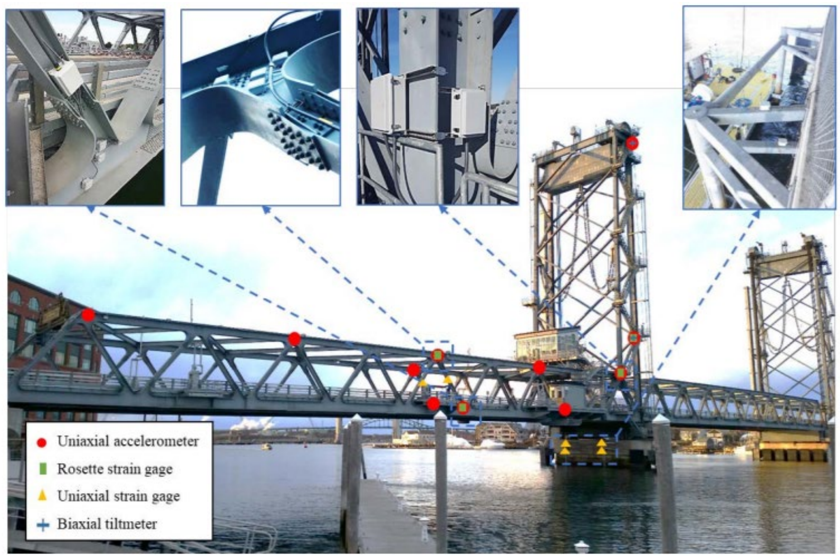

Figure 18. Photo. Illustration of accelerometers installed on a bridge.

Source: New Hampshire Department of Transportation (2019)

CHAPTER 4: PORTABLE INSTRUMENTATION

Portable instrumentation refers to measurement systems that are not permanently affixed to a particular bridge. This means that an individual instrument may be used at different points along a bridge or used at different bridges. However, portable instrumentation does not provide continuous quantitative measurements and the frequency of data collection depends on the inspection interval. Additionally, unlike some types of continuously acquired fixed monitoring systems, portable scour monitoring is generally not able to capture the dynamic process of scouring and infilling during a flood, unless the instrument can be actively deployed during the flooding event. In many cases, this is limited to time periods and locations where human inspectors can access the site or bring remotely operated equipment for use during flood events.

The overall framework of portable scour-monitoring systems includes four aspects that need to be considered (Mueller & Landers, 2000): (i) the measurement instrument, (ii) a system to deploy the instrument(s), (iii) a positioning system to track instrument location during measurements, and (iv) a data storage or transmission system. The following subsections briefly review each of these aspects.

SCOUR MEASUREMENT INSTRUMENTS

Physical Probing

Physical probes refer to any type of device that extends the reach of an inspector to enable measurement of the depth to the riverbed. Common types include sounding poles and weights (Figure 19). Sounding poles are long poles used to probe the channel bottom, and sounding weights are suspended 100 to 300 lbs. weights lowered from the side of the bridge to measure the depth of the channel bed. In both cases, measurements can only be taken at discrete locations and are dependent on site access, including avoidance of waterborne debris.

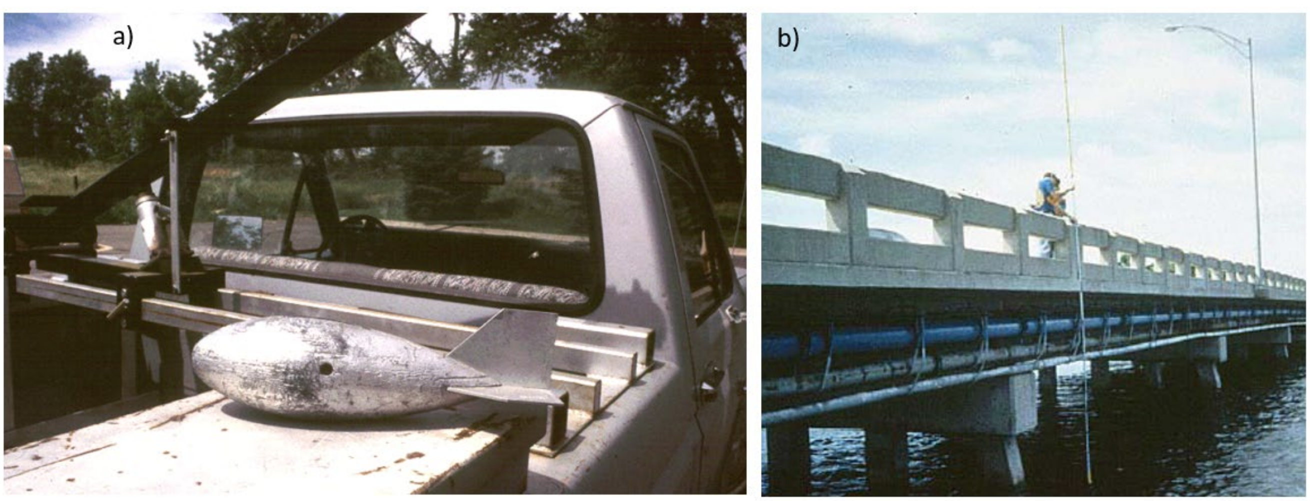

Figure 19. Photo. a) Sounding weight and b) sounding pole.

Sources: (a) Lagasse et al. (2009) and (b) Ettema et al. (2006)

The advantages and limitations of physical probing are listed below:

- Advantages: Physical probes are not affected by sensor air entrainment or water sediment concentrations. They are cost effective and provide inherent ground-truthing.

- Limitations: Physical probes only collect discrete data points. They have limited use in large water depths, high velocity environments, and areas with debris or ice accumulation. They require careful measurement and data recording due to the manual process as well as require active human manipulation, increasing health and safety risks.

Single-Beam Sonar

Sonar instruments measure the distance to the bed by measuring the time required to send and receive acoustic pulses reflected from the bed. Single-beam sonar or depth finders generally only provide information on the depth directly below the instrument. These are commercially available as low-cost fish finders or depth finders from the recreational fishing and boating industries. Single-beam sonar is among the most popular measurement type considered due to its relative ease of use and affordability. It is used in several case studies described in Chapter 5. Because single-beam sonar only provides point measurements, it must be positioned or manipulated into position to directly measure bed locations of interest (i.e., around a bridge footing). This requires careful coupling with deployment systems to ensure access to key locations. Generally, single-beam systems are available that enable continuous data collection and logging while the system is on site, and the processing of this data is relatively straightforward because 3D information is not required to be interpreted. In principle, single-beam sonar can be used as long as the instrument can be safely deployed to sight. The advantages and limitations of single-beam sonar are listed below:

- Advantages: It is a simple system that can be purchased off-the-shelf at recreational retailers (~$1,000–$5,000). Because of its low computational processing requirements, single-beam sonar does not require specially trained personnel to interpret the data. Single-beam sonar provides continuous, quantitative depth-to-bed measurements, as long as operators are on-site. Significant recreational industry development means systems are widely available and easy to use. Single-beam sonar could be an "on-the-fly" solution for rapid deployment.

- Limitations: Single-beam sonar only provides instantaneous depth data directly below the instrument; developing 3D results can be time-consuming. Logging of instrument positioning needs to be carefully controlled. Single-beam sonar does not provide direct ground-truthing, and it can have issues in shallow, turbid, and high velocity flows. Surface debris presence limits access, and submerged debris and animals can cause irregular readings.

Multi-Beam Sonar

Multi-beam sonar involves the use of near-simultaneous acoustic pulse emission and reception to develop 3D maps of the riverbed. Multi-beam sonar is essentially an evolution of single-beam sonar, where multiple (up to hundreds) of single-beam sonars are used at the same time. Multi-beam sonar is regularly used for hydrographic surveying in many environments, including riverine environments (Liu et al., 2012). Although sonar has been successfully implemented for portable scour monitoring, getting accurate measurements in shallow waters, high flow conditions, and sediment/debris-filled areas are difficult. These systems also generally require licensed surveyors or hydrographers for use and, in particular, for interpretation. The advantages and limitations of multi-beam sonar are listed below:

- Advantages: Multi-beam sonar provides a detailed, 3D map of riverbed conditions. It can provide extremely accurate details of the bed condition near structures. The actual surveying process is quicker than single-beam sonar if an equivalent 3D map is required.

- Limitations: Significant up-front and maintenance costs are required for these systems (>$100,000). Specially educated and experienced users are required to operate multi-beam sonar and interpret its data. Significantly more data is acquired, which also requires more interpretation time. Flow depth is its main limitation in shallow streams. Setup time is significantly longer than single-beam sonar systems. Multi-beam sonar is not an “on-the-fly” solution for rapid deployment.

Side-Scan Sonar

Side-scan sonar systems (or sometimes scanning sonar) are similar in concept to single- and multi-beam sonars, but generally only provide detailed images of the underwater environment. These systems do not generally provide quantitative data of the depth but do provide qualitative detail that could be interpreted to assess bed condition. Image analysis techniques exist to convert these images to quantitative data, but this requires post-processing and is a developmental technique. Low-cost varieties are sometimes provided coupled with retail-grade single-beam fish finders. These may be useful to provide more visual context for rapid emergency surveys but are not generally saved to be viewed later. Additional systems and development may be needed for this implementation. The advantages and limitations of side-scan sonar are listed below:

- Advantages: Side-scan sonar provides detailed images of the underwater condition and provides more context for decision-making. Low-cost varieties are sometimes available with recreational fish finders.

- Limitations: Side-scan sonar often requires specially educated operators. Survey-grade equipment is expensive (>$15,000), although recreation-grade equipment is more reasonable (<$10,000). Side-scan sonar does not provide quantitative information about the bed condition or depth. It requires interpretation to convert the data to quantitative data.

Green Laser

Green light lasers have been considered for underwater imaging of scour holes, particularly in Florida (Nagarajan & Arockiasamy, 2020). The laser emits a light with a specified wavelength to penetrate the water and reflect from the river/stream bed to a receiver in the laser scanner. The reflection from various angles allows the scour hole to be represented with thousands of points in a few seconds. A laser scanner could be mounted to a mobile platform to acquire a complete 360-degree in-water view of scour development. This technique is currently being explored by Florida Atlantic University and sponsored by Florida DOT. As the application of green lasers is a relatively new method in scour monitoring, it is still a work in progress, as field testing performed in the report does not explicitly show scour holes. Similar scanners have been used in the offshore industry for structural defect inspection and have been considered for scour monitoring. However, these systems require the laser to be relatively close to structures/the riverbed and water conditions must be relatively calm and clear for the laser light to propagate through the water cleanly. The advantages and limitations of green lasers are listed below:

- Advantages: Green lasers can provide very detailed 3D renderings of underwater features, including scour holes and structure integrity.

- Limitations: Green lasers are highly prone to errors due to water turbidity and refraction of obstacles. They need to be used in calm and relatively clear water. Due to laser light penetration requirements, the scanner must typically be within ~3 ft of surfaces being scanned. Commercial underwater laser scanners have significant upfront cost (>$30,000).

Ground-Penetrating Radar

Surface geophysical instruments use wave transmission and reflection/refraction measurements to quantify subsurface (ground) characteristics. These methods differ from sonar type methods in that they often utilize different types of waves to measure conditions (e.g., radar waves instead of acoustic waves), and they provide some measure of information about the underground condition, not just the surface. Ground-penetrating radar (GPR) has been explored for use as a scour-detection measurement over water. GPR uses electromagnetic radar waves, which can be emitted from either submerged or aerial positions. Although GPR equipment is relatively accessible, it does generally require post-processing conducted by trained specialists. Positive outcomes have been found using these systems in states such as New Hampshire and Rhode Island; however, in these cases, GPR was deployed from manned vessels at calm water conditions. The advantages and limitations of geophysical instrumentation are listed below:

- Advantages: Geophysical instrumentation provides good quality 2D cross-sections of bed condition. The equipment is commercially available and relatively cost effective (<$10,000). Systems could be used for other transportation-related purposes (roadway imaging, geotechnical site investigations).

- Limitation: Geophysical instrumentation has poor performance in clayey river bottoms, and it generally requires post-processing by specially trained experts. It has not been tested in flood conditions and is not usable in debris-laden environments.

DEPLOYMENT SYSTEM

The deployment system for scour monitoring is a critical component in ensuring good measurement by allowing optimal positioning of the instrument. Aspects related to deployment method are (i) accessibility to attain near-bridge measurements, (ii) ease of deployment and recovery, (iii) human health and safety, (iv) ability to deploy in rapid, flood conditions, (v) issues associated with debris- and ice-laden flows, and (vi) ability to gain spatial varied data.

Bridge Deck Deployment

The most straightforward deployment method is directly from the bridge deck. These methods increase in complexity from simple person-manipulated physical probes or hand-held tethered floats to vehicle-mounted crane units (Figure 20), and combinations thereof (Figure 21). Bridge deck deployment generally limits the lateral extent and bridge deck height from which measurements can be deployed. For particularly large bridges, bridge deck deployment is unlikely to be a useful option. Bridge deck deployment does generally entail health and safety risks, as workers must be employed to manipulate or physically control the measurement systems. In the case of flood conditions where bridge foundation conditions are unsure, this may pose a significant hazard to agency workers. Various techniques of bridge deck deployment are described in more detail in the case studies in the following chapters, but a brief description is provided here.

Rigid probes or sensors must be held and controlled directly by workers on the bridge deck. Although this enables relatively more accurate (but not very accurate) knowledge of sensor position, hand-held rigid deployment is not likely to be possible in many rapid-flow conditions. Hand-held rigid deployment also allows for only limited lateral extent of measurement away from the bridge deck and may not enable full access around bridge foundations.

Tethered systems generally involve the use of surface floats, which may be as simple as kneeboards or surf skis, and with single-beam sonar measurements beneath the float. This system requires less physical strength for manipulation than a rigid connection, but care must be taken to note the physical location of the float when measurements are taken. This can be difficult in swift waters where the float is continuously pulled downstream. A tethered system, in principle, allows more access to bridge foundations beneath the deck than rigid connections. However, they are not useful for measuring foundation conditions upstream of the bridge deck, where the most significant scour can often occur.

Use of a crane mounted either on a vehicle or on a towed bridge unit provides an alternative deck deployment method that alleviates some of the disadvantages of the other methods. A crane can be articulated at multiple points within the arm to enable better access beneath the deck for sensors and/or inspection personnel. This also provides for further lateral access upstream and downstream of the deck. However, use of personnel near the river environment adds to health and safety risks, particularly during high flood events. The ability for mobility is also lessened with crane arm usage because a single stabilized position on the deck is likely to be required during the inspection process and certain operational position envelopes must be maintained so that the crane remains stable from the deck.

Figure 20. Photo. Kneeboard with wireless sonar deployed with crane.

Source: Schall & Price (2004)

Figure 21. Photo. Tethered unmanned surface vessel deployed with a crane.

Source: Schroeder et al. (2019)

Water Surface Deployment

Instruments can be deployed from the water surface via manned vessels (Figure 22), and unmanned surface vessels (USVs) allow measurements from the water surface (Figure 23).

For deployment from manned vessels, instrumentation systems may be towed, manually controlled, or deployed from winches on the boats. Manned vessel deployment is typically utilized for routine bridge inspection of hydrographic surveys, although these generally occur in calm water conditions. Although this technique enables better access around bridge piers than is possible from the bridge deck and significant survey flexibility, the requirement for personnel on the water adds health and safety risks and generally limits this form of deployment to non-flood conditions.

The use of USVs, potentially automated but generally remote controlled, is an area that is promising and increasingly considered for bridge inspections, even during flood conditions. Unmanned deployment systems significantly reduce safety concerns for personnel, as many of these systems can be controlled from the riverbank—out of the water and off the potentially unsafe bridge. USV deployment to date has primarily used single-beam sonar and retail side-scan technologies for measurement. Another advantage is that controlling USVs can generally be done by DOT personnel, with appropriate training, and their small size can allow even better access to areas around bridge piers and abutments than manned vessels. They are, however, limited in terms of pay load and the range of measurement equipment that can be used. Other issues associated with USVs include potential loss of signal when USVs are driven behind large piers, battery life, and risk of damage due to debris or extreme water conditions. The reported ranges of top speed (presumably in still water) were 6.5 ft/s to 25 ft/s (Schroeder et al., 2019) while reported ranges of flow speed in which USVs have been found to perform well were up to 5 m/s (16 ft/s) (HR Wallingford, 2017).

Figure 22. Photo. Manned vessel for scour instrumentation.

Source: Schroeder et al. (2019)

Figure 23. Photo. Testing of an unmanned vessel for scour instrumentation.

Source: Schroeder et al. (2019)

Underwater Deployment

With advancement in technology, autonomous underwater vessels (AUVs) are another possible deployment method. This technology has been utilized in the offshore industry for many years for underwater inspection. When equipped with various types of sonar systems or laser scanners, these systems may provide high-definition detailed scour and structural inspection data. Because these systems are underwater, they are typically controlled through a preprogrammed automated process. However, AUVs are typically equipped with sensors to detect and avoid collisions with structures or debris. This technology is well-advanced for use in general deeper ocean conditions, but AUVs for use in riverine environments remains in the early development stage. However, recent work has been conducted in the past few years for exploring these technologies in some mid-Atlantic states, as described in a University Transportation Research Center project (Omidvar & Horinem, 2018). (A potential vessel is shown in Figure 24.) To date, it appears that AUV use in riverine environments has only been developed to the conceptual stage and deployment in test tanks.

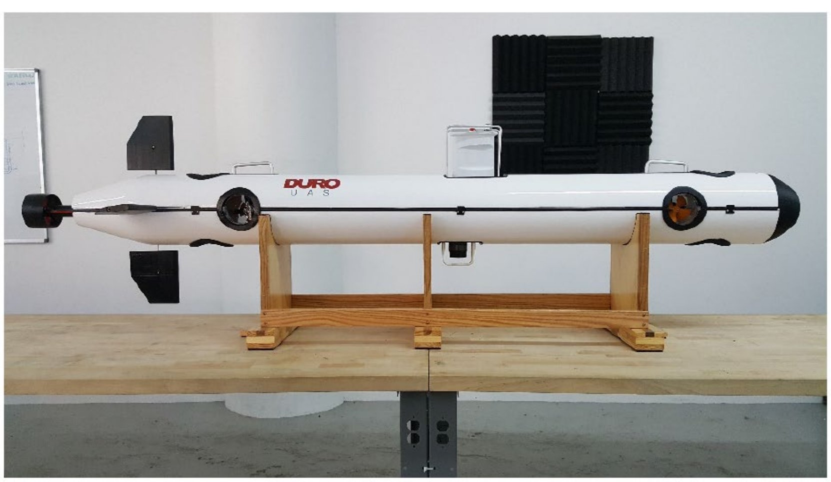

Figure 24. Photo. Prototype of an autonomous underwater vessel under development.

INSTRUMENT POSITIONING DURING MEASUREMENT

To provide accurate measurements to evaluate scour, it is necessary to know the location of the instrument when measurements are taken. In other words, personnel should know the precise location of any particular measurement relative to the bridge foundation. Location includes the 2D spatial position (e.g., latitude and longitude, or position along and transverse to the bridge axis), as well as the vertical position. These positioning errors may not be a significant issue during most flood conditions, unless the local surface elevation changes significantly around the pier (e.g., due to eddies). Even in rough conditions, readings may still provide reasonable indicative findings for informing bridge shutdown but can require some experience developed through use over time. A summary of the main location-determination methods is provided, primarily with reference to their use on portable instrumentation.

<u>Visual and Physical Measurement:</u> Visual and physical measurement requires personnel to directly make a position measurement. Approximate visual position measurements are numerical distances to the location of measurement or observation referenced to a feature of a bridge or study reach, while physical measurements may be made using tag line, tape, pre-surveyed stationing, or other instruments. These systems are prone to human error during measurement and recording.

<u>Range-Range Systems:</u> Range-range systems, or Terrestrial Electronic Positioning Systems, utilize Electronic Distance Measurement (EDM) techniques to measure the position of a target. Most range-range systems operate by either resolving travel phase delays of a modulated electromagnetic carrier pulse between the target and a land-based reference transmitter or by measuring the two-way travel time of a coded electromagnetic pulse between these two points. Range-range systems operate in one of two modes: (1) fixed land-based stations with a mobile transmitter where return signals are interpreted or (2) fixed transmitting stations with a mobile receiver where signals are transmitted to a receiver. They are similar to satellite positioning systems (i.e., GPS) with the exception that travel distances from satellites are one way.

In particular, microwave (a type of electromagnetic wave) range-range systems measure the round-trip travel time of a pulse generated at the target to a land-based station and back to the target (mode 1). Land-based stations act as a transponder that is capable of receiving, processing, and retransmitting the wave signal. Microwave range-range positioning systems were first used in the early 1970s before going into decline with the advent of GPS. Range-range positioning employs the trilateration method, where the coordinates of the intersection of two or more measured ranges are obtained from known reference points/land-based stations.

<u>Global Positioning Systems:</u> GPS are a type of range-range system that utilizes satellites as fixed stations rather than land-based stations. The accuracy of GPS can be improved through making differential corrections with instruments such as a real-time kinematic differential GPS (DGPS). DGPS is used to determine the errors associated with satellites by ground-truthing against a known location on the ground. GPS data collection can be hampered by the loss of satellite coverage due to blockage by trees or bridge substructures.

Range-Azimuth Systems: Range-azimuth positioning is a forward traverse computation from a reference point to the intersection of an angular and distance observation for a target, typically generated from the same reference station (USACE, 2013). The angular azimuth observation can be made by transits, theodolites (mounted telescope that displays horizontal/vertical angles), or total stations, while the distance measurement can be taken by any EDM device such as laser EDM or infrared light EDM. Although a once widely utilized positioning method, range-azimuth systems are now typically employed only when GPS positioning cannot be obtained, such as due to satellite blockage. Range-azimuth surveys are now mostly performed using engineering survey total stations (which combine an EDM with an electronic theodolite) for projects located within four miles of a shoreline/riverbank. The position of the target is determined by measuring the range using a laser and the corresponding azimuth/ordinates through the theodolite. The latest generation of total stations can provide direct, real-time XYZ coordinates of a target (USACE, 2013). Robotic or fully automated total stations like the Krupp-Atlas Polarfix can automatically track a target and transmit the measured ordinates to other devices.

Vessel Compensation Systems: Portable instruments collect data in a moving reference position, where the position is based on the location of the data collection sensor. For example, a simple echo sounder will record the distance to the channel bed and a corresponding time stamp. If the horizontal position of the echo sounder can be determined at the respective time stamps, then the depth measurement can be located relatively accurately. This reference position is subjected to constant change, particularly if the instrument is deployed via a vessel/vehicle. The movements of a typical vessel can be categorized into roll, pitch, yaw, and heave, as illustrated in Figure 25. Roll is defined as the rocking of the boat from the sides, whereas pitch is defined as the rocking of the boat from the front to back. Yaw is defined as the change of compass orientation of the vessel, and heave is defined as the up-down movement of the vessel from hydraulic action. Because the direction and angle of the sonar wave will be altered with these vessel movements, it is necessary to account and correct for them. For single-transducer systems such as single-beam sonar, this compensation is seldom accounted for, unless the surveying is performed in a coastal environment with significant wave action or a very accurate measurement is required.

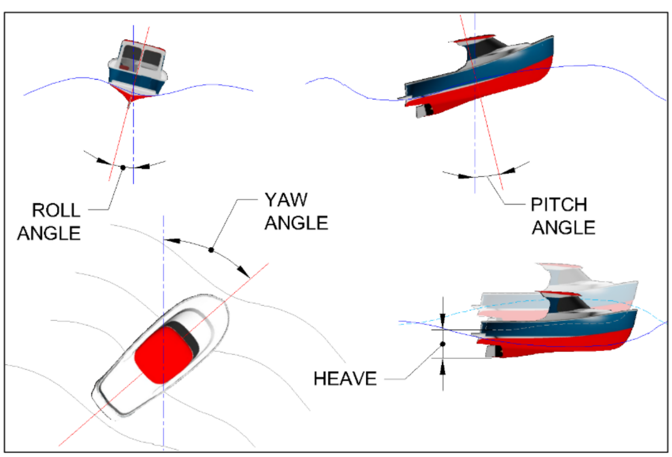

Figure 25. Diagram. Illustration of types of vessel motions.

Source: Shen et al. (2018)

DATA STORAGE AND TRANSMISSION

For both fixed and portable instrumentation system, there is a need to record the data collected (manually if automated recording is not available, for instance with physical probing), store the data collected (if automatically and digitally collected), and transmit the data for processing if required.

Some systems may not need data storage if the goal is to focus on spot measurements to ensure bridge safety. However, if automated systems (e.g., USV-mounted sonars systems) are used, then keeping a record is useful for the project. Data-storage devices include hydrometeorological dataloggers, laptops, computers, and personal digital assistants (PDAs). While dataloggers provide compact storage, they are generally not user friendly due to their unique programming and connectivity with other devices. Laptops and PDAs are generally used due to their ability to visualize and simplify the data collected even during the data collection process. Data can be transmitted via four main options: (1) hard drive exchange, (2) wired data transmission, (3) Wi-Fi transmission, or (4) satellite transmission.

Hard drive exchange is a physical exchange of a storage device (such as a hard drive) between personnel so that the data can be transmitted from one location to another. This is a very simple method, but it requires manual labor and a storage device. The advantages and limitations of hard drive exchange are listed below:

- Advantages: Hard drive exchange is simple and low cost.
- Limitations: It requires a physical exchange, which can be slow depending on the distance of the data transfer.

Wired data transmission employs cables and connectors to transmit data along a channel, where the cabling provides connectivity between servers, computers, and other network devices. Data is transferred in the form of voltage levels, which make up a digital signal, which is then transmitted to another storage device/instrument. There are many types of cables, but the most common ones are twisted pair, coaxial cable, and fiber optics. Table 1 illustrates the difference between these connections.

Table 1. Comparison between Wired Connections

Types of Wired Connections	Description	Pros	Cons
Twisted Pair	Twisted copper wires covered with protective shield	Cheapest	Can be interfered by magnetic fields, lower data transmission rates
Coaxial Cable	Single copper conductor surrounded with foil and braided shield	Better data transmission rates and less signal attenuation	More expensive than twisted pair
Fiber Optics	Thin flexible fiber that uses light pulses generated by laser / injection diode to transmit data	Data transmission not affected by electromagnetic fields, highest speed data transmission	Most expensive

The advantages and limitations of wired data transmission are listed below:

- Advantages: It typically has higher data-transfer speed over wireless transmission options.
- Limitations: It may have high sunk costs associated with installation of cables, depending on transmission distance, and fixed locations for cable connections are generally required for data transmission.

Wi-Fi transmissions use radio waves to send and receive digital signals and, by extension, data. Data is converted by a router or a wireless adaptor into digital signals before being sent to another router, which will first decode the signal and further transmit it to a gateway device operated by a broadband internet provider. A separate device can now access the internet using Wi-Fi to retrieve the transmitted data. It can also alternatively be transferred to another device directly if both devices are equipped with a router/adaptor rather than using the internet as an intermediary. The advantages and limitations of Wi-Fi transmission are listed below:

- Advantages: Wi-Fi transmissions are easy to install and provide flexibility in terms of locations with access to Wi-Fi.
- Limitations: Coverage may be limited depending on location, and data transfer rate is typically slower than wired connections.

Satellite transmissions communicate data by using radio waves to send signals to antennas on Earth. The antennas then capture the signals and process the information coming from those signals before transmitting them to devices, and vice versa. Satellite transmissions consist of space and ground segments. When a signal is sent to the satellite (space segment) through a device, the satellite amplifies the signal and sends it back to the receiver antenna, which is located on Earth (ground segment). Satellite transmissions provide multichannel capabilities, wide bandwidths (maximum rate of data transfer across a given path), and high data transmission rates (Sobolewski, 2003). The advantages and limitations of satellite transmissions are listed below:

- Advantages: Satellite transmissions have high-speed data transmission due to radio wave amplification.
- Limitations: They have a high cost.

Both Wi-Fi and satellite data transmissions are considered wireless data transmissions, where radio waves are used as a medium for transmitting and receiving data. Information is transmitted through the air, without requiring any cables, in a wireless communication technology network. In the context of portable instrumentation, most commercial measuring devices (e.g., single-beam echo sounder) have built-in datalogging systems that can store and display data. The decision on which method of data transmission to utilize depends significantly on the available technologies or equipment (presence of satellite coverage, Wi-Fi connection, etc.) on the site itself. A low-cost and convenient method based on available equipment is recommended for data transmission.

CHAPTER 5: CASE STUDIES

Based on the literature review conducted, three portable measurement systems that have been implemented, either in practice by other DOTs or in the applied research stage, are reviewed in this chapter. The review focuses on technologies that have been explored or used at other state DOTs or nationally. These technologies are given focus because they may represent those with the most potential for short- to medium-term consideration for IDOT.

CASE STUDY 1: BRIDGE-DEPLOYED KNEEBOARD OR SKI-MOUNTED ECHO SOUNDER

Among the least expensive and easily deployed approaches to portable measurements is the bridge-deployed single-beam sonar (depth finder) attached to a small flotation device and tethered to personnel on the bridge deck. The general implementation of this approach is using a retail-grade fish finder/echo sounder to track the depth to the bottom directly beneath the flotation device. By manipulating the flotation device into positions of interest, the riverbed condition can be mapped, although depending on the setup, this may require manual reading and recording of the data. This section focuses on experiences with flotation device-mounted sonars reported by state DOTs and USGS (Mueller & Landers, 2000).

Selected Systems

Texas DOT (TxDOT) has utilized a water ski–mounted single-beam sonar (i.e., a retail fish finder) for bridge inspection for nearly three decades (Jones, 1992). This water ski–mounted form, known as a Shi-Flow (Figure 26), comprises a water ski with a rope tether that is mounted with the fish finder pointed down toward the riverbed. Originally, the sonar systems were connected via coaxial cable to the visual display on the bridge deck. However, the most recent iteration used by TxDOT utilizes a Vexilar Sonar Phone, which is a retail wireless fish finder commonly available at sporting goods stores. Versions of this can be purchased for less than $500 and can record depth readings with time. More advanced versions are synced with built-in GPS, although the accuracy of positioning is not known. Discussions with representatives from TxDOT indicate that a child-sized ski is typically used because it is easier to control. The Shi-Flow is generally deployed by placing it in the water on the upstream side of the bridge and floating it downstream with the flow (similar to the kneeboard method shown in Figure 27). Sonar measurements can be continuously taken during this process and can in principle be used to map the riverbed elevation. Care is needed for controlling the path of the ski and careful recording of the relative position when measurements are taken, because the ski cannot be controlled directly and there is typically no advanced position recording system for this affordable, portable test.

Figure 26. Photo. Shi-Flow device.

Source: Image courtesy of TxDOT

Figure 27. Photo. Personnel guiding the kneeboard-mounted sonar with attached rope.

Source: Mueller & Landers (2000)

Similar systems have also been developed and deployed by USGS (Mueller & Landers, 2000). Based on a review of field implementation of different DOTs to date in 2000, USGS implemented this approach using a kneeboard to enhance water surface stability during high flow rates, particularly with highly turbulent water around piers (Mueller & Landers, 2000). The kneeboard is about 1.4 m long and 0.5 m wide with an eye bolt mounted at the front for attaching a tether to maneuver the board. They also considered using a combined flotation system with two parallel water skis rigidly attached with cross bracing, but initial tests were not promising. Modern implementation of kneeboard deployment could utilize the same retail sonar equipment described previously for the Shi-Flow.

Minnesota DOT has also developed a similar floating deployment system, and it is typically deployed by hand with a tethered cable, as shown in Figure 28.

Figure 28. Photo. Floating deployment system utilized by Minnesota DOT.

Source: Bartelt (2017)

Research Outcomes

The USGS research project described deployment of the kneeboard-mounted echo sounder during six major floods: 1) 1993 Upper Mississippi River Basin flood, 2) 1994 Brazos River flood, 3) 1995 California floods, 4) 1995 Missouri floods, 5) 1996 Illinois and Indiana floods, and 6) 1997 Minnesota floods. In each scenario, the instruments were reported to work reasonably well during flood conditions. The authors noted that the equipment was easy to transport, deploy, and maneuver, enabling rapid monitoring of scour. The system was reported to have been submerged in a large eddy vortex in the Mississippi River and a standing wave in California but was able to be successfully extracted with no damage in both cases. The system was not able to produce useful data in the standing wave condition, due to air entrainment, but did work well in velocities greater than 10 ft/s. The kneeboard method was reported to provide equivalent accuracy in streambed measurement to sonar-installed sounding weights, while providing greater flexibility and access.

Current Status

Water ski–mounted systems, such as the Shi-Flow, have been utilized in several states, including Texas and Arkansas. Discussions with Mississippi DOT representatives indicate they are currently considering adopting Shi-Flow as a standard scour-monitoring tool. The primary issues reported are air entrainment beneath sonar transducer, limiting signal and performance, and ski stability during high flow rates. The latter was noted as an issue by Arkansas DOT in very turbulent waters (Mueller & Landers, 2000).

Recent discussions with Texas DOT indicate that Shi-Flow is commonly used for post-flood rapid inspections and that it is their primary means for inspection during high flow events. One advantage that was noted was the ability to monitor readings from personnel’s cell phones, which aids in ease and rapidity of monitoring. The process taken by TxDOT for these measurements is paraphrased as follows: (1) locate a position of known and fixed elevation on the bridge, (2) measure the distance to the surface water level, (3) take sonar measurements with the device in the water, and (4) plot results on a cross-section to make decisions about bridge closure, considering expected continued flow conditions, soil properties, foundation conditions, etc.

CASE STUDY 2: UNMANNED SURFACE VESSELS USING A SINGLE-BEAM SONAR

Ayres Associates was contracted by the Michigan Department of Transportation (MDOT) to explore use of USVs for scour monitoring and to develop a working prototype (Schroeder et al., 2019). Through the project, several USVs on the market, along with a system built by Ayres, were compared, tested, and rated. Focus for this project was given to portable scour instrumentation that achieves the following criteria: (1) able to evaluate stream/river characteristics during storm events at bridge locations; (2) operable in turbulent waters, high currents, and near debris; (3) able to conduct bathymetric surveys of streambed and at bridge pier locations of between 3 to 30 ft deep; (4) able to view underside of bridge; and (5) can be rapidly deployed. A final system was selected for testing, and three trials were conducted as part of the research.

Selected System

After the review and site testing of commercially available systems, the USV Emergency Integrated Lifesaving Lanyard (EMILY) from Hydronalix was selected as the final candidate for the proposed portable scour-monitoring device. The system was reported to perform well in trials, especially because it is designed for rough wave conditions due to its intended beach rescue use and is equipped with a side-scan sonar, single-beam sonar echo sounder, and above-water cameras. The model used by MDOT is a single hull fiberglass vessel (Figure 29), approximately 4.3 ft in length and weighing approximately 40 lbs. Battery life for this vessel was reported to be 3 to 4 hours before a change, although the battery life would be reduced depending on the speed of the vessel. However, discussions with MDOT indicate that for regular use, the battery life is estimated to be approximately 45 minutes to 1 hour.

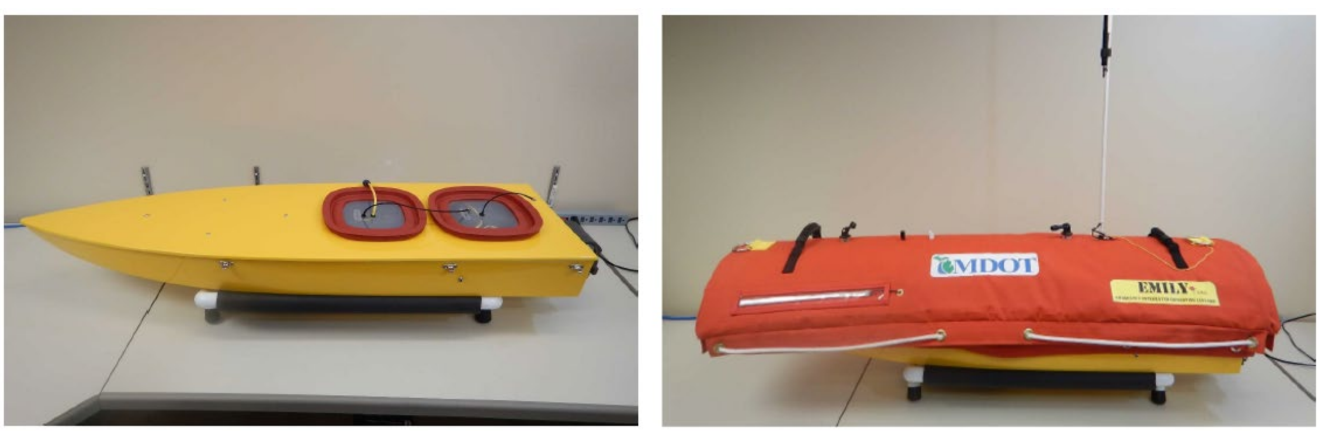

Figure 29. Photo. Sonar EMILY without and with flotation device.

Source: Schroeder et al. (2019)

Figure 30. Photo. a) Boat remote control and b) Humminbird survey control unit.

Source: Schroeder et al. (2019)

The EMILY vessel is controlled via a remote control, similar to other retail remote control vehicles (cars, boats, drones). The EMILY vessel was equipped with a Humminbird echo sounder (Figure 30), side scan, and GPS units, which were provided by Hydronalix as an off-the-shelf product brand, because they have working agreements arranged with Humminbird to provide these systems. A Latitude 7424 Rugged Laptop was used for data acquisition, equipped with the SAR Hawk software for measurement post-processing and real-time visualization.

Note that other combinations of systems could be utilized and may be available from other companies at similar price points. The system described here is the one selected for MDOT and is commercially available from Hydronalix with the same features in their “DOT” package. Indicative costs for this system from the manufacturer are approximately $40,000 to $50,000 per unit. For instance, discussions with HR Wallingford in the United Kingdom indicated that they manufacture similar vessels, available for approximately $40,000 to $45,000 (at the time of writing), which have been tested in waters with flows up to 5 m/s.

Research Outcomes

Three site demonstrations were performed to trial the EMILY model for MDOT in Michigan in 2018. In general, although there were minor complications due to loss of signal and batteries, the EMILY model was reported to perform well at the three sites. The review of different instruments did reveal that other sonar manufacturers have the potential for more highly rated systems; however, use of equipment as recommended by the vessel manufacturer can often ease long-term usage and maintenance issues. If USV-style vessels are considered in the future, given the rate of technological development, it will likely be worth conducting another survey of available manufacturers and equipment to explore how options may have changed.

Current Status

Following the commissioned research project, Michigan DOT proceeded to purchase four units of the EMILY vessel. An additional unit was subsequently purchased by a local consultant. These units are currently in use incorporating the Hummingbird depth/fish-finder unit, down/side-scan sonar imaging. Discussions with MDOT representatives indicate that the units are being used relatively regularly throughout the state, with notes as follows:

- Used to inspect bridges downstream of a dam failure incident to ensure bridge safety due to unforeseen upstream water release. This was done after the incidences and is believed to have enabled the bridges to be opened sooner and with higher confidence.
- Used occasionally (estimated 15% to 20% of total use cases) at peak flood flows to provide imagery of bridge foundations. Further work is needed to develop standard methods for these inspections, especially with respect to boat positioning. No detailed information was available on the return period of flows, debris present, etc. but use/results have been positively received.
- Used often (estimated 80% to 85% of total use cases) for routine inspections. Although diver inspections are still required at normal (~5 year) intervals, the USV systems have enabled MDOT to keep a closer eye on bridges of concern between major inspections and monitoring of specific scour holes to ensure they are not growing.
- Used occasionally for culvert inspections. This was conducted by attaching a 360-degree GoPro to the top of the USV with LED lights and has been favorably viewed by the DOT.
- Used occasionally for post-construction inspection of foundations/riprap placed for scour protection.
- Debris in the water is still a problem, but inclusion of the side-scan system allowed imaging from a distance to be acquired. This provides some useful, but not quantitative, information.
- Single-beam sonar type systems are easy to use. It is estimated that personnel can become familiarized and comfortable with the equipment (controls and data acquisition) with one to two days of training. Training was initially provided by Hydronalix.

Discussions were also held with the manufacturer, Hydronalix. They indicated that Montana DOT and Hawaii DOT had also initiated or received EMILY units of a similar configuration to Michigan DOT. In both cases, it is understood that the interest was in both bridge scour monitoring as well as internal culvert inspections.

Discussions with representatives from the California DOT (CalTrans) also indicate that they are commencing a research project to explore use of a similar remote-controlled boat with a single-beam or potentially multi-beam sonar attached. This research is in the early phases and will be conducted in a similar fashion to that in Michigan—first identifying different options and determining whether the selected options work in flood conditions.

The Missouri DOT indicated they have three similar remote-controlled catamaran-type vessels that are owned by the state and shared by districts. These are equipped with single-beam sonars and have been used to monitor scour holes. They use a model sold by the Seiler company intended for hydrographic surveys. It is understood that these have not generally been used during flood conditions.

CASE STUDY 3: BRIDGE-DEPLOYED TRUCK WITH ARTICULATED CRANE ARM

This study was conducted by Ayres Associates under the NCHRP Project 21-07 (Schall & Price, 2004) with the goal of developing a portable scour-monitoring device capable of measuring scour for a wide variety of bridge geometries and under extreme conditions, including flood events. The key criteria in technology selection were based on cost and portability. Several options were explored in the project, and the most promising at the time was found to be the fully instrumented articulated arm truck (Figure 31). This concept built upon earlier work by Minnesota DOT (Schall & Price, 2004). The study also included a literature review of portable instrumentation that serves as a thorough and valuable reference for these technologies.

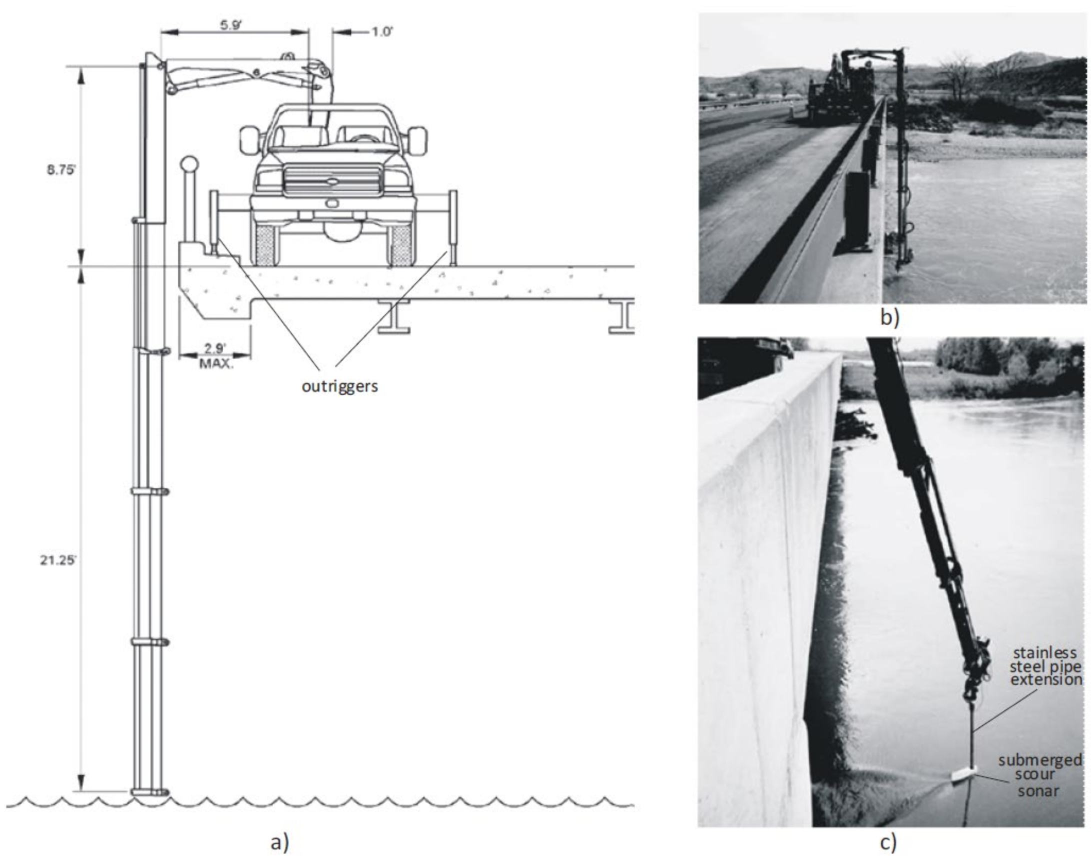

Figure 31. Diagram and Photo. a) Schematic diagram of truck with articulating-arm crane over bridge with reach dimensions, b) photograph of truck with crane in operation, c) close-up photograph of crane with sonar transducer mounted on pipe extension.

Source: Schall & Price (2004)

An extension of the project was further conducted and detailed in Lyn et al. (2010), where the horizontal positioning system of the truck was enhanced.

Selected System

Based on the alternative technologies selected, a complete articulated arm truck was developed and tested in field trials. The articulated arm truck was designed using readily available components and multi-purpose parts whenever feasible. A flatbed Ford F-450 was used as the transportation base with hydraulic lift legs to stabilize the truck during crane operation. The truck was also modified to have a castor system that allowed driving of the truck with the crane deployed. The crane selected for implementation was the Palfinger 4501C, which had a maximum reach of 36 ft and a lifting capacity of 600 lb. The crane was capable of near 360-degree rotation on the truck bed and was equipped with two articulation joints for manipulation. At the time of fabrication (~2002), the cost of the truck and crane was about $50,000, and the cost of instrumentation was about $25,000 (for a total of $75,000).

The truck was equipped with sonar instrumentation placed at the bottom of the crane arm. The sonar equipped on the truck could be deployed off the end of the crane with the streamlined probe, or as a cable-suspended operation while direct probing was possible off the end of the crane, as shown in Figure 31-B and Figure 31-C. A kneeboard with a wireless depth-finding sonar was also developed that could be deployed from the rigid frame or through cable-suspended operation. A streamlined sounding weight probe with a wireless sonar was also developed for use up to 30 ft (9.1 m) below the bridge deck, as shown in Figure 32. Data collection and processing occurred with a laptop computer connected to Campbell CR10 dataloggers.

Figure 32. Photo. Sounding weight with wireless sonar.

Source: Schall & Price (2004)

Positioning was originally controlled by a 10-turn potentiometer to measure the position and angle of the crane and rotator base. The location of the end of the crane can be determined with an assortment of tilt and displacement sensors, while a standard surveying measuring wheel is used to locate the position of the truck on the bridge deck. Test results indicate that the low-cost (between $5000 to $8000), sub-meter grade GPS receiver could not provide the level of accuracy and repeatability needed for scour-related measurements at that time. Later development at Purdue University improved this positioning through a so-called HEXAMITE positioning system, as shown in Figure 33.

Figure 33. Photo. Truck with HEXAMITE positioning system.

Source: Lyn et al. (2010)

Research Outcomes

Detailed field testing was conducted to evaluate the performance of the articulated arm truck at various sites across the country, representing a range of bridge and site conditions. Testing was performed in several states, including Colorado, Alabama, Minnesota, Wisconsin, Missouri, Indiana, and Idaho in 2002. An example of the data collected from the sonar measurements is shown in Figure 34, which consists of a plan view, a cross section, and contour data of the streambed at a bridge crossing in Indiana.

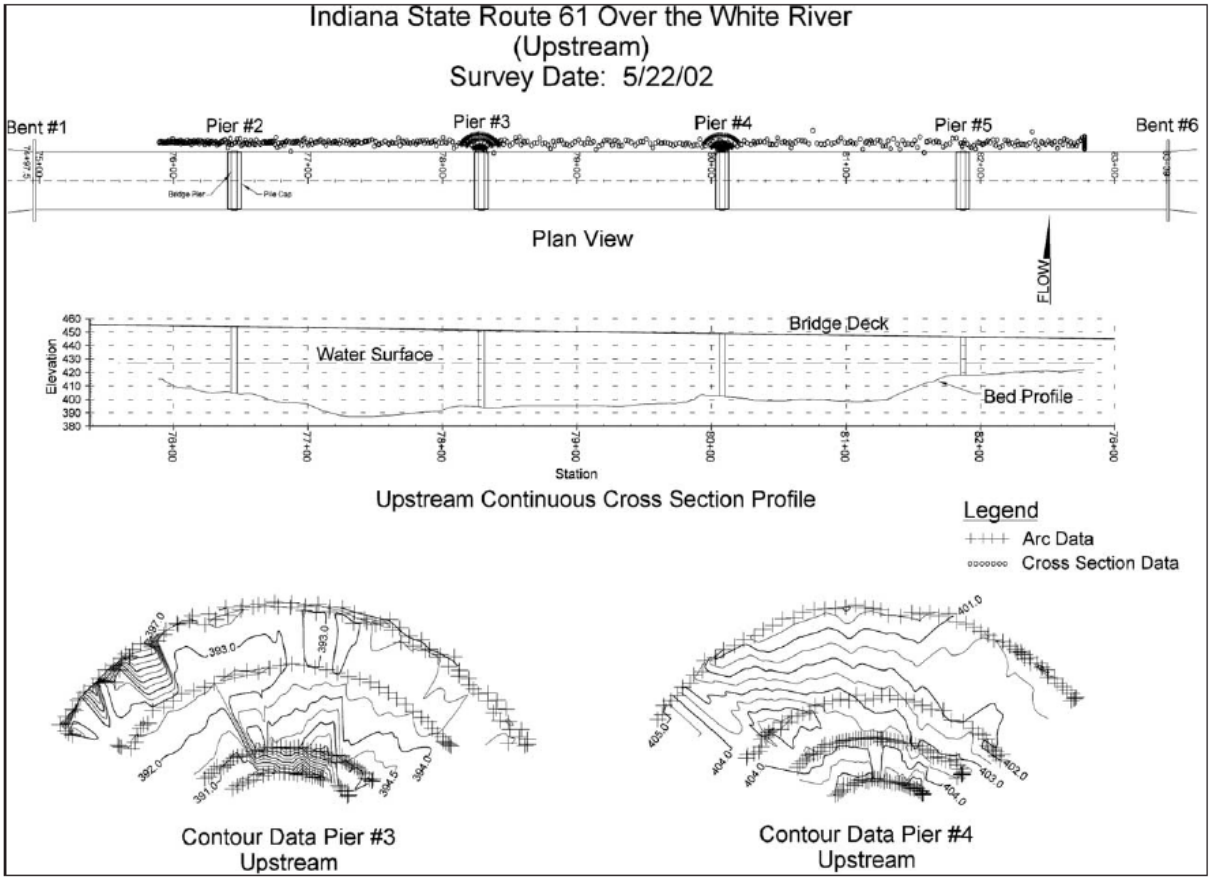

Figure 34. Diagram. Typical results obtained with the articulated-arm truck.

Source: Schall & Price (2004)

Current Status

After the initial research project, the originally developed truck was transferred to Indiana DOT (InDOT). The truck was subsequently developed further, particularly relating to improving positioning measurements, by Purdue. However, InDOT has not found significant use for the system since receiving the truck, beyond a few additional controlled tests. Issues reported for further use and lessons learned include:

- Need for internal personnel to support use of any monitoring system to ensure its continued use.
- Need for continued maintenance support and funding.
- Need for specially trained personnel to be continuously active with using the system.
- Difficulty in controlling the system and tracking positioning.
- Difficulty in getting personnel comfortable with using the system due to its complexity.

CHAPTER 6: OTHER TECHNOLOGIES AND APPROACHES

In addition to measurement of scour hole development, bridge stability during floods is affected by hydraulic conditions, hydrodynamic loading on the bridge, and geotechnical effects when foundations are subject to scour. Developing robust risk-informed assessments of bridges requires understanding how all these aspects are affected by floods and due to scour. This chapter reviews three technologies that can contribute to better understanding these aspects.

LARGE-SCALE PARTICLE IMAGE VELOCIMETRY

Particle image velocimetry (PIV) is an image-analysis technique that is used to quantify the flow field (e.g., of flowing water) or strain field (e.g., of a structural beam) using consecutive images taken from a fixed location (Adrian, 1991). PIV essentially works by comparing pixel patterns between consecutive images with a known time increment. Processing algorithms can identify how pixel patterns shifted between the images, providing a quantitative map of the displacements in the field of interest. This technique is widely used in fluid mechanics to quantify water flow fields and vortex dynamics around objects in flowing water (Martin & Garcia, 2009).

PIV concepts have also been used on a larger scale in the field to measure surface-flow velocity characteristics along coasts and in rivers (Fujita & Komura, 1994; Muste et al., 2008; Yen, 2017; Jin & Liao, 2019; Liu et al., 2021)—in this case the technique is called large-scale particle image velocimetry (LS-PIV). LS-PIV uses the same principles as lab-scale PIV but relies on tracking patterns of the water surface from pictures taken typically from the riverbank or bridge deck to quantify the surface velocity. Since images are typically taken at some angle to the water surface, there is some post-processing required to undistort images for velocity processing. Various work, including for the Iowa DOT (Muste et al., 2008) and recent review for Caltrans (Yen, 2017), has shown that LS-PIV is promising for providing on-the-fly stream discharge and local velocity measurements. Imaging for use with LS-PIV analysis has been conducted from several locations, including on bridge deployment (Patalano et al., 2015 [Figure 35]; Jin & Liao, 2019 [Figure 36]), unmanned aerial vehicles (Liu et al., 2021), and even with cell phones (Tsubaki et al., 2015).

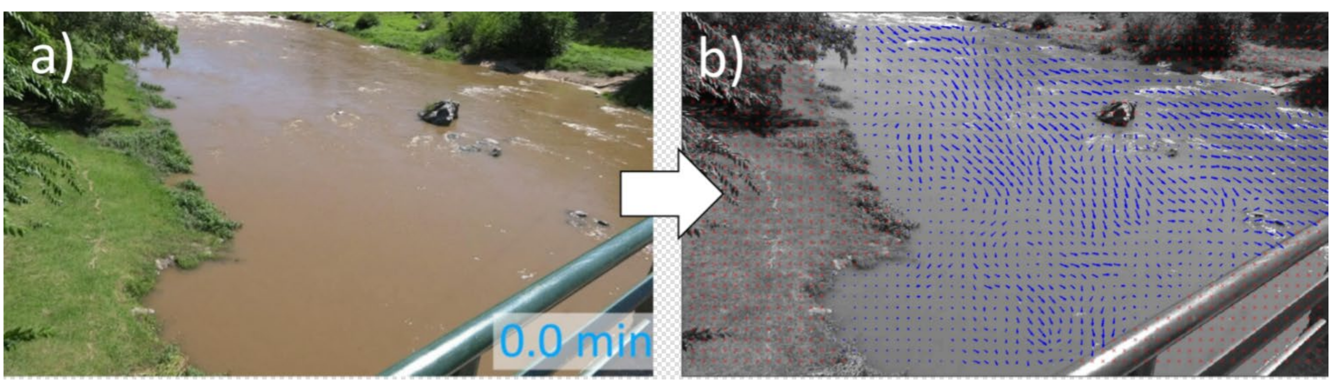

Figure 35. Photo. Example PIV measurements taken from a bridge deck on the San Antonio River, Cordoba, Argentina.

Source: Patalano et al. (2015)

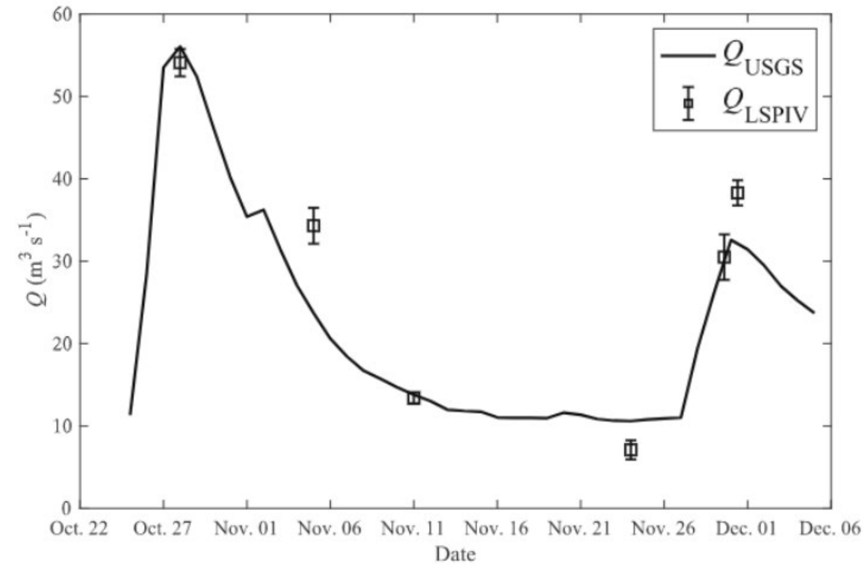

Figure 36. Graph. Comparison of discharge measurements from LS-PIV and USGS measurements in the Milwaukee River.

Source: Jin & Liao (2019)

There are several implementation issues that need to be considered before LS-PIV could reliably be incorporated for bridge flood assessment:

- PIV, in general, relies on the presence of relatively distinct patterns (i.e., brightness contrasts) on the water surface to track the movement of artificial and natural tracers (debris) on the water surface. Sometimes natural bubbles or foam in the water can provide enough contrast for good imaging but this usually results in sparse surface water velocity estimates. In most cases, artificial tracers (such as wood chips) are required to achieve good measurements of the surface flow velocities along the cross section of the bridge opening. Limits to natural seeding for typical Illinois conditions or procedures for environmentally friendly artificial seeding in the field need to be investigated.

- Changes in light and reflectance can affect LS-PIV measurements. If the positions from which the pictures are taken is not stationary, this can lead to erroneous velocity vectors being generated. There is a need for standard equipment and procedure development to minimize these errors.

- Post-processing can be somewhat computationally demanding. There is a need to develop efficient and convenient tools to post-process data on the fly. This could be incorporated with a risk-assessment spreadsheet for use in the field to incorporate site conditions and upstream predictions of flood stage to provide for more accurate scour risk assessment during floods (Lopez & Garcia, 2001).

Some form of LS-PIV technologies could be used to better inform stream flow conditions during floods and inform on-the-fly bridge scour risk assessments. This would include site-specific measurement of flood conditions at bridges (and other locations) and velocities occurring around a bridge during flood conditions. If incorporated with a statewide assessment and database of bridge conditions for scour-critical bridges, the live measurements at particular bridges could provide a more accurate risk assessment during floods. Knowledge of the site-specific velocity conditions during flooding provides specific input into scour prediction calculations, which could be linked to geotechnical stability calculations to provide updated risk of negative bridge performance (Lopez & Garcia, 2001).

SPECIFIC HYDRODYNAMIC COEFFICIENTS FOR INUNDATED BRIDGES

Loading on bridges during floods is strongly affected by the structural configuration of the bridge and the hydraulics of extreme flooding scenarios. Loading is particularly important in the case of partially and fully inundated bridges, where the water is at or above the bridge deck, respectively. To develop a holistic approach to considering bridge stability, accurate methods are needed to assess hydrodynamic loading conditions due to the flood water. During flooding, bridge piers and decks may be loaded in the direction of the flow (i.e., a drag force transverse to the bridge longitudinal axis), vertically normal to the flow direction (i.e., a lift force), and a rolling-moment (i.e., overturning moment) (Figure 37). The most common methods to assess these loading conditions are through physical scale modelling in a hydraulic flume (Denson, 1982; Kerenyi et al., 2009; Bennett & Ponnampalam, 2009) and computational fluid dynamics (CFD) numerical modelling (Kerenyi et al., 2009; Guo et al., 2010).

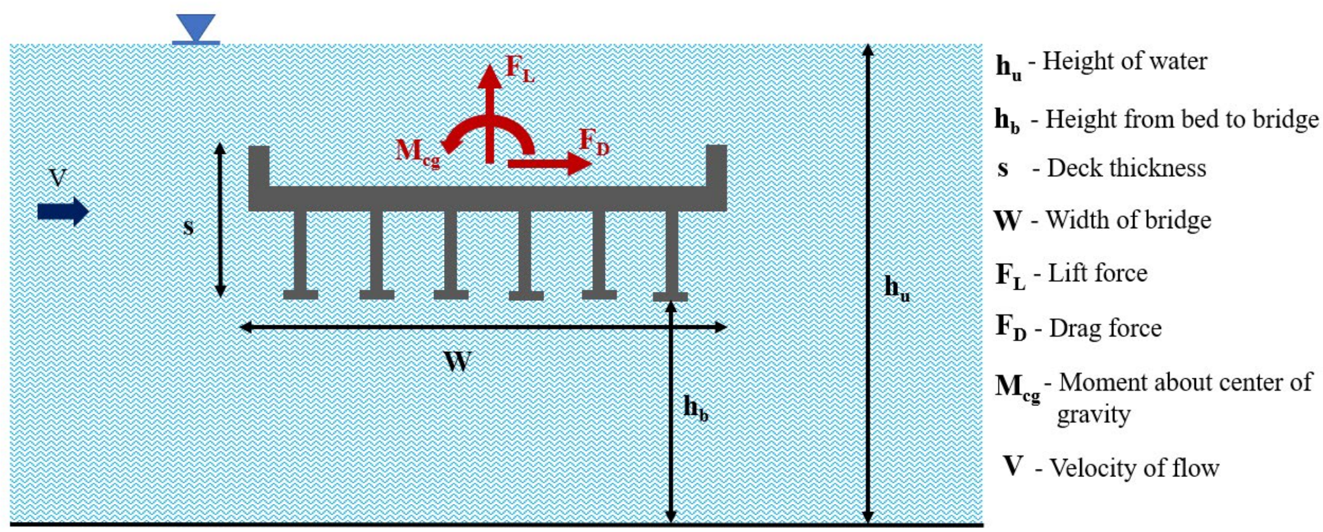

Figure 37. Diagram. Schematic of loading on bridge decks during flooding.

Physically modelling on representative bridge structures can be used to develop more accurate force coefficients for calculating the forces acting on a bridge in different inundation scenarios (Figure 38). Although general guidance does exist for generic bridge geometries and flooding scenarios (Kerenyi et al., 2009), determination of specific coefficients representative of bridges in certain states and the unique flooding conditions in each state can provide additional accuracy in structural and geotechnical bridge design. For instance, Denson (1982) conducted a series of scaled physical models to provide bespoke force assessments for bridges specifically representative of those built in Mississippi.

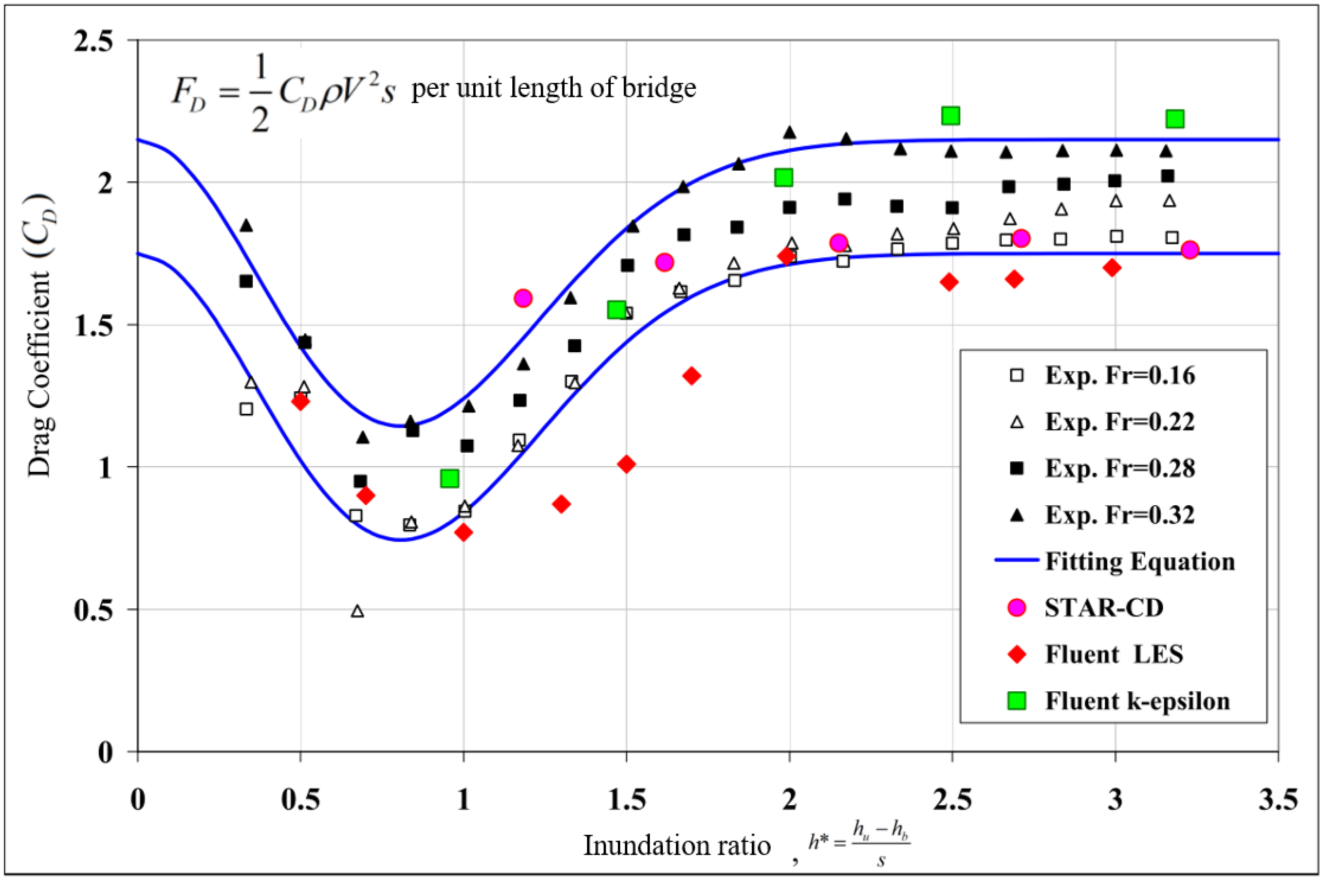

Figure 38. Graph. Example drag coefficient results for inundated bridge comparison experimental and numerical results.

Source: Kerenyi et al. (2009)

Numerical modelling is often used to extrapolate physical modelling results and scale the results to the full scale in the real world. CFD analyses can be compared and validated against physical model test results and then used to calculate the forces on different types of structures or to verify the response at full scale. This is increasingly feasible with the availability of high-performance super computers and enables a large parametric space to be explored in a relatively short period of time, compared with physical models of each individual bridge. These results could then be used to further develop a database and classifications for the development of rapid stability assessment tools.

Results from physical and numerical modelling could be used to develop a database of force coefficients across a range of bridge types and flooding conditions. Flooding conditions that may affect the forces include (i) flood inundation depth, (ii) flow velocity, and (iii) direction of attack (which may be affected by meandering). Coupling physical modelling with numerical modelling enables a large database of parameters to be assessed. This could then be combined with a database of the Illinois bridge inventory classified to allow bridge and flood condition-specific force estimation.

EFFECT OF SCOUR ON FOUNDATION RESPONSE

The presence of scour holes around bridge foundation elements leads to changes in the foundation's capacity and serviceability, which can cause onerous bridge settlements. Several recent physical and numerical studies have explored how local and general scour affects the capacity of piles and bridge foundations (Liu & Garcia, 2007; Qi et al., 2016; Chortis et al., 2020; Ciancimino et al., 2021). The key findings of these works are summarized as follows:

- Any scour hole will reduce the capacity and stiffness of foundation elements.
- For deep foundations, the reductions are more pronounced for the lateral and moment capacity of foundations than the vertical capacity. For shallow foundations (footings), the reductions are also severe for vertical capacity, leading to potential for localized foundation settlement.
- The geometry of the scour hole affects how much capacity is lost due to scour. Local scour reduces the capacity less than general scour because less soil is removed close to the foundation. Centrifuge physical modelling results by Ciancimino et al. (2021) indicate that the moment capacity is reduced by 19% to 38% for local scour but is reduced by 48% for general scour at the same maximum depth.
- Lateral pile load-displacement stiffness can reduce significantly (by more than 50%) in the presence of wide scour holes of significant depth (Chortis et al., 2020) (Figure 39).

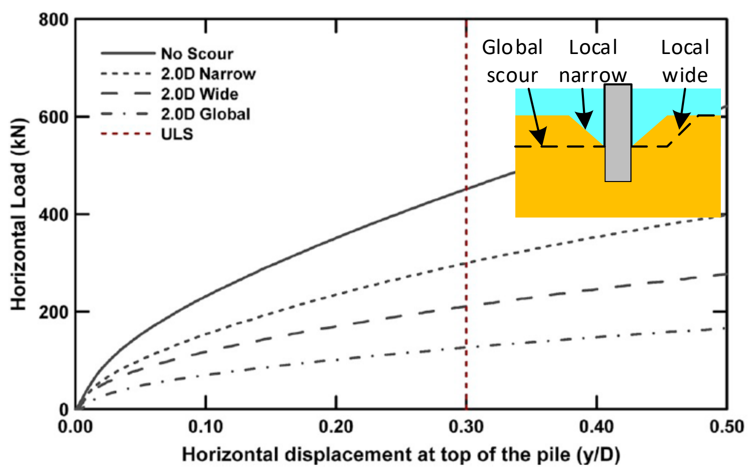

Figure 39. Graph. Example differences in lateral pile response with scour hole geometry.

Source: Chortis et al. (2020)

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

This study has provided a brief summary of different scour-monitoring techniques that have been used or considered for monitoring scour around bridge foundations and abutments, including both fixed and portable monitoring systems, and other risk-assessment techniques. This includes a review of publicly available literature and several informational interviews with state DOTs and relevant industry providers and consultants. A summary of the literature review with pertinent findings for monitoring bridges during floods is as follows:

1. Fixed instrumentation (Chapter 3) can be useful for monitoring specific bridges and bridge features of concern as well as for monitoring the growth of already formed scour holes.
    a. Some fixed techniques provide continuous monitoring and thus enable quantification of maximum scour hole depth during floods, prior to infilling. This enables more accurate estimates of scour risk and potential for automated alerting of dangerous conditions during flooding.
    b. Fixed systems have a track record of use throughout the United States but are at risk of damage due to debris and ice in Illinois waters. Fixed systems are also potential targets for vandalism or theft.
    c. Low-cost/single-use (e.g., float-out) systems are available for spot monitoring but only provide single alerts when designated scour depths at specific locations are achieved. Buried systems add uncertainty due to uncertain battery life and difficulty in independently verifying systems but will remain functional for years.
    d. Automated interpretation and alert systems must be setup to ensure fixed scour monitoring achieves the ultimate goal of accurately alerting local officials to bridge risk. Robust alert systems and backup power/communications are required for successful implementation. State-wide protocols should be set up to ensure that alert communications can be reacted to at any time.
2. Portable instrumentation (Chapter 4) is useful for targeted monitoring of bridges during flood events. They provide flexibility for measuring scour development at different bridge sites and parts of bridges but do not provide time-continuous measurements like fixed monitoring.
    a. Remote or autonomous measurement systems that do not require personnel to be in the water significantly reduce health and safety risk for agency personnel. Bridge deck deployment reduces this risk somewhat but still requires risk to personnel on the bridge. Systems that can be remotely controlled from riverbanks provide the lowest health and safety risks.
    b. Portable scour monitoring is not limited to specific sites, and costs can be shared across districts and localities with shared-use systems.
    c. Debris and ice accumulation remain an issue for portable systems. Remote-controlled systems equipped with side-scan sonar provide some potential methods for visualizing beneath debris but are not quantitative.

   d. Multi-beam sonar provides better fidelity of measurement than single-beam sonar but is significantly more expensive and requires specialist surveyors for acquisition and interpretation.

3. Case studies of portable instrumentation implemented by various DOTs (Chapter 5) provide several potential avenues for equipment that may be useful for further consideration by IDOT.
   a. Manually controlled flotation devices (water ski or kneeboard mounted) with single-beam sonars have been used by several state DOTs with success during flood conditions for many years.
      i. Controlling the device can be troublesome during flooding, but simple designs with retail equipment allows for, at minimum, indicative insight into bridge condition even in rough conditions.
      ii. Access is limited to certain low height bridges (approximately < 30 feet) and there is only limited access around the bridge pier. However, the front of the pier (where the maximum scour depth often occurs) can generally be accessed.
      iii. Care is needed in recording measurements and relating these to specific positions. Data provided is indicative with some uncertainty but may suffice for determining whether to close the bridge to traffic until flooding recedes.
      iv. They are low cost and can be widely available due to retail parts being available at many sporting goods stores.
   b. Remote-controlled vessels with single-beam and side-scan sonars have recently been deployed by several states, with a thorough study recently conducted by Michigan.
      i. Remote control provides the lowest risk for personnel safety and provides best access to different parts of the bridge.
      ii. Experience from other DOTs suggests that commercially available vessels are capable of working even in relatively swift flood waters.
      iii. They have additional potential use for IDOT for culvert inspections.
      iv. They are significantly higher in cost than manually controlled devices and are generally only available from particular vendors.
4. Large-scale PIV (Chapter 6) may provide another technology to augment scour risk assessments by providing site-specific, during-flood measurements of flow velocities. These could be used to update scour risk assessments, in conjunction with fast portable physical measurements, to make on-the-fly safety assessments, as described in the Recommendations section.
   a. Images for analysis could be taken from truck-mounted cameras or from unmanned aerial vehicles (UAVs or drones).
   b. Efficient processing packages are needed to process the data and would need to be developed. Tools such as these can be developed relatively easily with modern cloud-computing technologies.

RECOMMENDATIONS

The following recommendations are provided for consideration based on this review:

1. For bridges of significant concern (where scour holes may already exist or where closing the bridge to traffic provides differential consequences, for instance to traffic flow), fixed instrumentation should be considered to continuously monitor scour conditions. If possible, systems that provide continuous monitoring (e.g., sonar based) are recommended as opposed to those limited to specific maximum depths only (e.g., float-out sensors).
2. Acquisition of low-cost floatation-based sonar measurement devices (e.g., Shi-Flow) is recommended. These systems offer an easy way to provide rapid indications of whether scour is an issue at bridge sites. Their low cost means multiple devices can be purchased and deployed across the state. It is recommended to develop a consistent procedure for use and implement hands-on training workshops to ensure consistency across districts.
3. Further research is recommended to consider options for a remote-control vessel system for measuring scour at specific bridges of importance. This would complement rapid testing from the flotation device with more detailed data to assess conditions. It is recommended that an initial exploratory study be conducted to assess options available from different vendors, as technology may have developed, and costs may have changed since ~2017 when the Michigan study was conducted.
4. Further research is recommended to explore the use of unmanned aerial vehicles (UAVs or drones) to capture imagery for use in LS-PIV analysis. This technology would provide site-specific detailed velocity and direction information to inform scour risk at specific bridge sites.
    a. Research is first needed to develop the LS-PIV systems that could be used in Illinois. This may comprise (a) acquisition of UAV and camera equipment, (b) development of an efficient post-processing program to calculate water velocities, (c) lab-scale testing of the LS-PIV system under controlled settings at ~3 m channel width scale, and (d) field testing of the LS-PIV under real-world settings at ~20 m channel width scale. Focus should be on UAV systems that are stable under expected environmental (wind) conditions and can be used by IDOT and local personnel.
5. Research is further recommended to develop a comprehensive system to assess risk at the portfolio of scour-critical bridges across Illinois and to inform this risk incorporating (a) measurements of scour development using portable equipment and (b) hydraulic conditions during flooding using LS-PIV. The following recommendations are described in Figure 40.
    a. Develop a specific calculation module to assess bridge scour risk (e.g., bankfull flow discharge, maximum scour depth and effect of this on foundation capacity). This should incorporate all pertinent inputs that affect bridge stability when subject to scour (Figure 40). For the specific conditions at each bridge site characterized by a rating curve (discharge vs stage), the hydraulic conditions that are expected to lead to unsafe bridge conditions should be determined. This should account for changes in hydrodynamic loading due to flooding and foundation response due to scour.

b. Develop a database of scour-critical bridges with bridge scour risk assessments conducted for each using assumed design conditions, including a flood frequency analysis at bridge locations to assess critical flow conditions for scour (Lopez & Garcia, 2001).
c. When a triggering event occurs at a scour-critical bridge, conduct both rapid portable scour measurement to identify any scour development at the site and LS-PIV measurement to calculate event-specific velocity and attack angle conditions.
d. Input these findings into a scour assessment module, in addition to predictions of future flood stages (return periods of 2, 5, 10, 50, 100 years), to provide updated scour depth predictions for potential flooding scenarios.
e. Risk of the bridge is assessed based on observed and predicted conditions, incorporating (i) scour hole measurement, (ii) updated forces on the bridge due to flood stage, inundation, flow velocity, and direction, and (iii) updated foundation stability assessment based on scour hole measurements.
f. Go/No-Go stage for assessing whether the bridge remains opened based on flow conditions (discharge and stage), estimated loads and predicted scour depths.
g. The above recommendations could be incorporated into a series of calculation packages with a user interface/cellphone app to provide near-instantaneous feedback to inspection personnel based on the measurements and conditions in the database.

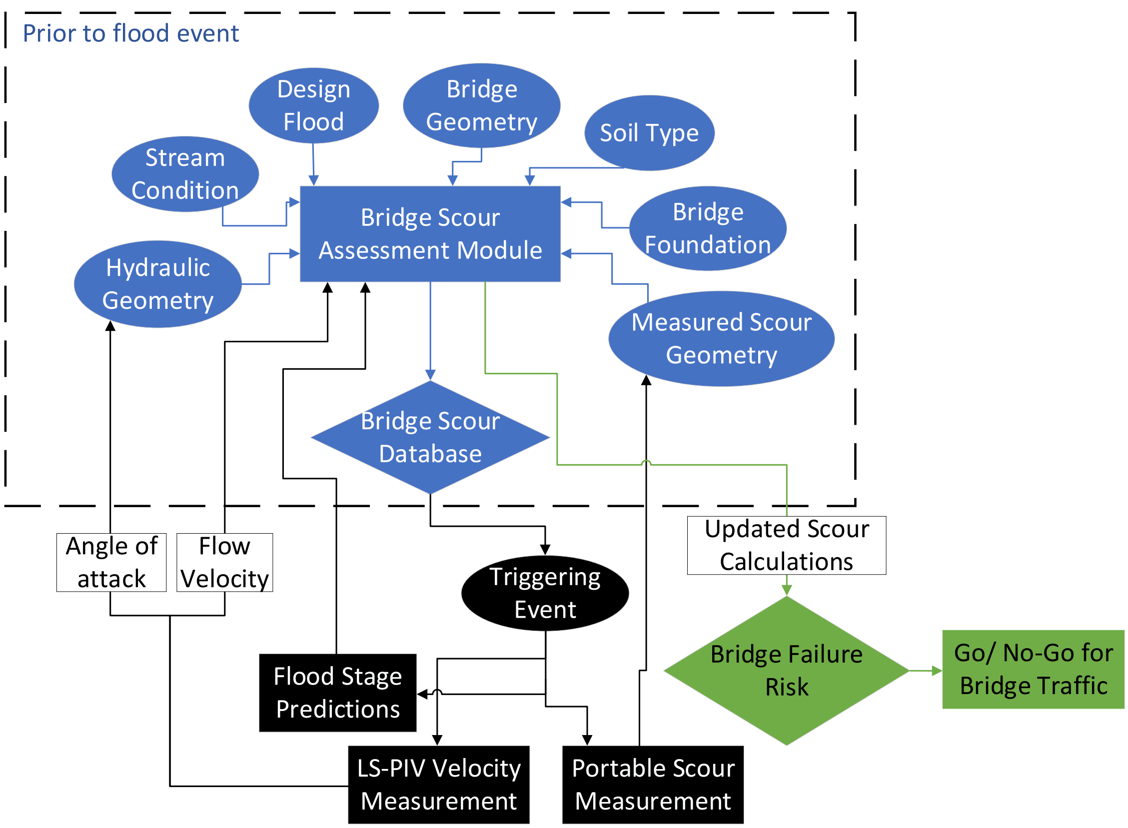

Figure 40. Chart. Flowchart for implementing portable scour measurement and LS-PIV into bridge scour risk assessment.

REFERENCES

Abad, J. D., & Garcia, M. H. (2006). RVR Meander: A toolbox for re-meandering of channelized streams. *Computers & Geosciences*, *32*, 92–101.

Abad, J. D., Rhoads, B. L., Guneralp, I., & Garcia, M. H. (2008). Flow structure at different stages in a meander-bend with bendway weirs. *Journal of Hydraulic Engineering*, *138*(8), 1052–1053.

Adrian, R. J. (1991). Particle-imaging techniques for experimental fluid mechanics. *Annual Review of Fluid Mechanics*, *23*(1), 261–304. https://doi.org/10.1146/annurev.fl.23.010191.001401

Ahamed, T., Shim, J., Jo, H., & Duan, G. (2016). *Feasibility Test of Low-Cost Sonar Sensors for Bridge Scour Monitoring*.

An, H., Yao, W., Cheng, L., Draper, S., Zhao, M., Tang, G., Zhang, Y., & Hortin, P. (2017). Detecting local scour using contact image sensors. *Journal of Hydraulic Engineering*, *143*(4), 04016100. https://doi.org/10.1061/(asce)hy.1943-7900.0001266

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., & Clopper, P. E. (2012). *Hydraulic Engineering Circular No. 18—Evaluating Scour at Bridges, Fifth Edition*. Federal Highway Administration.

Ba, Q., Zhao, X.-F., & Li, L. (2012). Bridge scour monitoring system based on active thermometry. *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2012*, *8345*(April 2012), 83453A. https://doi.org/10.1117/12.915060

Bao, T., & Liu, Z. (2021). Bridge scour characteristic curve for natural frequency-based bridge scour monitoring using simulation-based optimization. *Structural Control and Health Monitoring*, *28*(8). https://doi.org/10.1002/stc.2773

Bartelt, N. (2017). *Countermeasure Design, Implementation, and Monitoring*. Minnesota Department of Transportation.

Bath, W. R. (1999). *Remote Methods of Underwater Inspection of Bridge Structures*. Federal Highway Administration.

Bennett, M., & Ponnampalam, K. (2009). *Water Flow Forces on Bridges*. 2–9.

Boujia, N., Schmidt, F., Chevalier, C., Siegert, D., Boujia, N., Schmidt, F., Chevalier, C., Siegert, D., & Van, D. P. (2018). Bridge scour monitoring technique using the vibratory response of rods embedded in the riverbed. *Proceedings of 7th Transport Research Arena TRA 2018*.

Briaud, J. L., Hurlebaus, S., Chang, K., Yao, C., Sharma, H., Yu, O., Darby, C., Hunt, B. E., & Price, G. R. (2011). *Realtime monitoring of bridge scour using remote monitoring technology*. Texas Department of Transportation. http://tti.tamu.edu/documents/0-6060-1.pdf

Brooks, C., Wienert, M., & Banach, D. (2018). *Bridge Scour Technology Transfer*. Michigan Department of Transportation.

Browne, T. M., & Asce, M. (2010). *Underwater Acoustic Imaging Devices for Portable Scour Monitoring*.

Cai, C. S., Kong, X., Xiong, W., & Hou, S. (2014). *Monitoring Bridge Scour Using Fiber Optic Sensors*. Louisiana Department of Transportation. http://www.ltrc.lsu.edu/downloads.html

Chen, G. D., Tang, Y., Chen, Y. Z., Li, Z. C., Guo, C. R., Fan, L., Bao, Y., Hu, X. Y., & Klegseth, M. (2016). *Smart Rock Technology for Real-time Monitoring of Bridge Scour and Riprap Effectiveness—Design Guidelines and Visualization Tools*. U.S. Department of Transportation.

Chortis, G., Askarinejad, A., Prendergast, L. J., Li, Q., & Gavin, K. (2020). Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. *Ocean Engineering*, *197*(February). https://doi.org/10.1016/j.oceaneng.2019.106838

Ciancimino, A., Jones, L., Sakellariadis, L., Anastasopoulos, I., & Foti, S. (2021). Experimental assessment of the performance of a bridge pier subjected to flood-induced foundation scour. *Geotechnique*. https://doi.org/10.1680/jgeot.20.P.230

Cook, W., Barr, P. J., & Halling, M. W. (2015). Bridge failure rate. *Journal of Performance of Constructed Facilities*, *29*(3), 04014080. https://doi.org/10.1061/(asce)cf.1943-5509.0000571

Crotti, G., Isidori, D., Cigada, A., Ballio, F., Inzoli, F., Concettoni, E., & Cristalli, C. (2016). A hydraulic monitoring system on a bridge over the River Esino, Italy. *Journal of Civil Structural Health Monitoring*, *6*(3), 377–384. https://doi.org/10.1007/s13349-016-0179-2

Das, S., & Badal, C. (2019). A liquid pendulum based optical tilt sensor. *Sensors and Actuators, A: Physical*, *285*, 543–549. https://doi.org/10.1016/j.sna.2018.11.054

Denson, K. H. (1982). *Steady-state drag, lift, and rolling-moment coefficients for inundated inland bridges*.

Devault, J. E., & Hudson, W. B. (1998). *NCHRP-ID043—Robotic System for Underwater Bridge Inspection and Scour Evaluation*. Transportation Research Board.

Devi, G., & Kumar, M. (2018). *Review paper of different scouring monitoring techniques and instruments*. https://www.researchgate.net/publication/338866833

Ding, Y., Yao, Q., Zhang, Z., Wang, X., Yan, T., Yang, Y., & Lu, H. (2018). A new method for scour monitoring based on fiber Bragg grating. *Measurement: Journal of the International Measurement Confederation*, *127*(May 2017), 431–435. https://doi.org/10.1016/j.measurement.2018.03.053

Ettema, R., Nakato, T., & Muste, M. (2006). *An Illustrated Guide for Monitoring and Protecting Bridge Waterways Against Scour*. Iowa Highway Research Board.

Federal Highway Administration (FHWA). (2001). *ACTION: Revision of Coding Guide, Item 113—Scour Critical Bridges*. https://www.fhwa.dot.gov/engineering/hydraulics/policymemo/revguide.cfm

Federal Highway Administration (FHWA). (2020). *LTBP InfoBridge Web Portal*. https://infobridge.fhwa.dot.gov/BarStackChart

Fitzgerald, P. C., OBrien, E. J., Malekjafarian, A., & Prendergas, L. J. (2020). Acceleration-based bridge scour monitoring. *June*, 220–226. https://doi.org/10.3850/978-981-11-2723-6_24-cd

Fujita, I., & Komura, S. (1994). Application of video image analysis for measurements of river-surface flows. *Proceedings of Hydraulic Engineering*, *38*, 733. https://doi.org/10.2208/prohe.38.733

Funderburk, M., Todd, M. D., Netchaev, A., & Loh, K. J. (2021). *Active scour monitoring using ultrasonic time-domain reflectometry to detect a soil interface*. *1159113*(March), 36. https://doi.org/10.1117/12.2582457

Gamage, K. D. K. K. (2020). *A vibration-based bridge scour monitoring technique*. University of Cambridge.

Garcia, M. H., Editor-in-Chief. (2008). *Manual of practice 110—Sedimentation engineering: Processes, measurements, modelling, practice*. American Society of Civil Engineers.

Godhavn, J. (2000). High quality heave measurements based on GPS RTK and accelerometer technology. *Institute of Electrical and Electronics Engineers*.

Guo, J., Admiraal, D. M., Zhang, T. C., & Afzal, B. (2010). *Computational design tool for bridge hydrodynamic loading in inundated flows of Midwest rivers*. Mid-America Transportation Center.

Haas, C., Weissmann, J., & Groll, T. (1999). *Remote bridge scour monitoring: A prioritization and implementation guideline*. Texas Department of Transportation.

Harasti, A., Gilja, G., Varga, M., & Fliszar, R. (2021). ScourBuoy-concept for scour monitoring system. *EGU General Assembly 2021*.

Hartle, R. A., Ryan, T. W., Mann, J. E., Danovich, L. J, Sosko, W. B., & Bouscher, J. W. (2002). *Bridge inspector's reference manual, Volume 1* (FHWA NHI Publication No. 03-001). Federal Highway Administration.

Hayes, D. C., & Drummond, F. E. (1995). *Use of fathometers and electrical-conductivity probes to monitor riverbed scour at bridge piers*.

HR Wallingford. (2017). *The ARC-Boat*. http://www.ceehydrosystems.com/wp-content/uploads/2017/01/HR_WALLINGFORD_ARC_BOAT-Brochure.pdf

Hubbard, P. G. (1955). Field Measurement of Bridge-Pier Scour. *Proceedings of the Thirty-Fourth Annual Meeting of the Highway Research Board*.

Huizinga, R. J. (2010). *Bathymetric Surveys at Highway Bridges Crossing the Missouri River in Kansas City, Missouri, using a Multibeam Echo Sounder, 2010*. U.S Department of the Interior.

Hunt, B. E. (2005). *Establishing a Scour Monitoring*.

Hunt, B. E. (2009). *NCHRP Synthesis 396—Monitoring Scour Critical Bridges*. Transportation Research Board. https://doi.org/10.17226/22979

Illinois Department of Transportation (IDOT). (2014). *Memorandum: Revised Scour Design Policy* (p. 15).

Illinois Department of Transportation (IDOT). (2021). *Structure Information & Procedure Manual*.

Illinois Department of Transportation. (2017). *Structural Services Manual—2017*. Illinois Department of Transportation. https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Inspection/Structural Services Manual.pdf

Jin, T., & Liao, Q. (2019). Application of large-scale PIV in river surface turbulence measurements and water depth estimation. *Flow Measurement and Instrumentation*, *67*(April), 142–152. https://doi.org/10.1016/j.flowmeasinst.2019.03.001

Jones, K. (1992). Scour detection during high water. *Technical Quarterly, 7(3)*, 1-3.

Kerenyi, K., Sofu, T., & Guo, J. (2009). *Hydrodynamic forces on inundated bridge decks* (Report No.

FHWA-HRT-09-028). Federal Highway Administration. http://www.fhwa.dot.gov/publications/research/infrastructure/hydraulics/09028/

Kong, X., Ho, S. C. M., Song, G., & Cai, C. S. (2017). Scour monitoring system using fiber bragg grating sensors and water-swellable polymers. *Journal of Bridge Engineering*, *22*(7), 04017029. https://doi.org/10.1061/(asce)be.1943-5592.0001062

L-3 Communications SeaBeam Instruments. (2000). *Multibeam Sonar Theory of Operation*. L-3 Communications SeaBeam Instruments.

Lagasse, P. F., Clopper, P. E., Pagan-Ortiz, J. E., Zevenbergen, L. W., Arneson, L. A., Schall, J. D., & Girard, L. G. (2009). *Hydraulic Engineering Circular No. 23—Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance—Third Edition*. Federal Highway Administration.

Lagasse, P. F., Richardson, E. V., Schall, J. D., & Price, G. R. (1997). *NCHRP Report 396—Instrumentation for measuring scour at bridge piers and abutments*. National Academy Press.

Lagasse, P. F., Zevenbergen, L. W., Spitz, W. J., & Arneson, L. A. (2012). *Hydraulic engineering circular No. 20—Stream stability at highway structures—Fourth edition*. Federal Highway Administration.

Larrate, F., Chollet, H., Battist, L., Dela Longa, Y., & Chevalier, C. (2019). A French Experience of Continuous Scour Monitoring on Real Sites. *38th IAHR World Congress - "Water: Connecting the World," 38*(November 2020), 2066–2072. https://doi.org/10.3850/38wc092019-0410

Lin, Y. Bin, Lai, J. S., Chang, K. C., Chang, W. Y., Lee, F. Z., & Tan, Y. C. (2010). Using mems sensors in the bridge scour monitoring system. *Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A/Chung-Kuo Kung Ch'eng Hsuch K'an*, *33*(1), 25–35. https://doi.org/10.1080/02533839.2010.9671593

Lin, Y., Chang, K., Lai, J., Tan, Y., & Lee, F. (2008). Monitoring scour depth at bridge pier by using MEMS sensor. *Engineering*, 272–275.

Liu, X. & Garcia, M. H. (2007). A 3D numerical model with free water surface and mesh deformation for local sediment scour. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *134*(4), 203–217.

Liu, W. C., Lu, C. H., & Huang, W. C. (2021). Large-scale particle image velocimetry to measure streamflow from videos recorded from unmanned aerial vehicle and fixed imaging system. *Remote Sensing*, *13*(14). https://doi.org/10.3390/rs13142661

Lopez, F., & Garcia, M. H. (2001). Risk of sediment erosion and suspension in turbulent flows. *Journal of Hydraulic Engineering*, *127*(3): 231–235.

Lueker, M., Marr, J., Ellis, C., Winsted, V., & Akula, S. R. (2010). *Bridge Scour Monitoring Technologies: Development of Evaluation and Selection Protocols for Application on River Bridges in Minnesota*. Minnesota Department of Transportation. https://doi.org/10.1061/41147(392)95

Luh, Y. P., & Liu, C. Y. (2014). Bridge's Scour Monitoring System. *Lecture Notes in Electrical Engineering*, *293*(December 2013). https://doi.org/10.1007/978-3-319-04573-3

Lyn, D., Cooper, T., & Das, R. (2010). *A Truck-Mounted Scour Inspection System for INDOT* (Vol. 21). Indiana Department of Transportation. http://www.purdue.edu/jtrp

Malekjafarian, A., Kim, C.-W., O'Brien, E. J., Prendergast, L. J., Fitzgerald, P. C., & Nakajima, S. (2020). Experimental demonstration of a mode shape-based scour-monitoring method for multispan bridges with shallow foundations. *Journal of Bridge Engineering*, *25*(8), 04020050. https://doi.org/10.1061/(asce)be.1943-5592.0001586

Marks, V. J. (1993). *Evaluation of Brisco Scour Monitors*. Federal Highway Administration.

Martin, J. E. & Garcia, M. H. (2009). Combined PIV/PLIF measurements of a steady density current front. *Experiments in Fluids*, 46, 265–276.

Melville, B. W., Parola, A. C., & Coleman, S. E. (2008). Bridge-scour prevention and countermeasures. In *Manual of Practice No 110: Sedimentation Engineering*, edited by M. H. Garcia (pp. 543–579), American Society of Civil Engineers. https://doi.org/10.1061/9780784408148.ch11

Motta, D., Abad, J. D., Langendoen, E., & Garcia, M. H. (2012a). The effects of floodplain soil heterogeneity on meander planform shape, *Water Resources Research*, https://doi.org/10.1029.

Motta, D., Abad, J. D., Langendoen, E., & Garcia, M. H. (2012b). A simplified 2D model for meander migration with physically-based bank evolution, *Geomorphology,* 163–164, 10–25. https://doi.org/10.1016/j.geomorph.2011.06.036

Mueller, D. S., & Landers, M. N. (2000). *Portable Instrumentation for Real Time Measurement of Scour at Bridges*. Federal Highway Administration.

Mueller, D. S., Landers, M. N., & Fischer, E. E. (1995). Scour measurements at bridge sites during 1993 Upper Mississippi River Basin flood. *Transportation Research Record*, *1483*, 47–55.

Muste, M., Fujita, I., & Hauet, A. (2008). Large-scale particle image velocimetry for measurements in riverine environments. *Water Resources Research*, *46*(4), 1–14. https://doi.org/10.1029/2008WR006950

Nagarajan, S., & Arockiasamy, M. (2020). *Non-Contact Scour Monitoring System for Railroad Bridges*. Florida Department of Transportation.

Nassif, H., Ertekin, A. O., & Davis, J. (2002). *Evaluation of Bridge Scour Monitoring Methods*. Federal Highway Administration.

National Bridge Inspection Program (NBIP). (2019). *Channel Cross-Section Documentation*. Illinois Department of Transportation. https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Reports/Highways/Bridges/NBIP Metric 15 Inspection Procedures.pdf

New Hampshire Department of Transportation. (2019). *Living Bridge: Creating a Benchmark for Bridge Monitoring*. Federal Highway Administration.

Olimpio, J. (2000). *Use of a Ground-Penetrating Radar System to Detect Pre- and Post-Flood Scour at Selected Bridge Sites in New Hampshire, 1996–98*. U.S Department of the Interior.

Omidvar, M., & Horinem, B. (2018). *Portable Bridge Scour Monitoring Using Autonomous Underwater Vehicles Technology Development and Risk Assessment-based Platform for Deployment Prioritization*. University Transportation Research Center.

Orsak, J. (2019). *A New Method for Detecting the Onset of Scour and Managing Scour Critical Bridges*. U.S. Department of Transportation.

Özcan, O., & Özcan, O. (2018). Multi-hazard assessment of RC bridges using unmanned aerial vehicle-based measurements. *Baltic Journal of Road and Bridge Engineering*, *13*(3), 192–208. https://doi.org/10.7250/bjrbe.2018-13.412

Palanisamy, R. P., & Sim, S. H. (2015). Bridge scour monitoring using Extended Kalman Filter. *International Conference on Advances in Experimental Structural Engineering*, March.

Papanicolaou, T., Elhakeem, M., & Tsakiris, A. (2010). *Autonomous Measurements of Bridge Pier and Abutment Scour Using Motion-Sensing Radio Transmitters*. Iowa Department of Transportation.

Passaro, V. M. N., Cuccovillo, A., Vaiani, L., Carlo, M. De, & Campanella, C. E. (2017). Gyroscope Technology and Applications: A Review in the Industrial Perspective. *Sensors (Basel)*, *17*(10). https://doi.org/10.3390/s17102284

Patalano, A., Garcia, C., Brevis, W., Bleninger, T., Guillen, N., Moreno, L., & Rodriguez, A. (2015). Recent advances in Eulerian and Lagrangian large-scale particle image velocimetry. *E-Proceedings of the 36th IAHR World Congress, 2015*.

Prendergast, L. J., & Gavin, K. (2014). A review of bridge scour monitoring techniques. *Journal of Rock Mechanics and Geotechnical Engineering*, *6*(2), 138–149. https://doi.org/10.1016/j.jrmge.2014.01.007

Qi, M., Li, J., & Chen, Q. (2016). Comparison of existing equations for local scour at bridge piers: parameter influence and validation. *Natural Hazards*, *82*(3), 2089–2105. https://doi.org/10.1007/s11069-016-2287-z

Rensensys LLC. (2020). *Scour Critical Bridges Monitoring*. https://www.resensys.com/r20/wireless-sensor-document-application/scour-inspection-bridges-tilt-solar-camera-water-level.html

Richardson, E. V., Pagan-Ortiz, J. E., Schall, J. D., & Price, G. R. (2003). Monitoring and Plans for Action for Bridge Scour. *9th International Bridge Management Conference*, *April*, 70–84.

Richardson, J. R., & Richardson, E. V. (2008). Bridge scour evaluation. In *Manual of Practice No 110: Sedimentation Engineering*, edited by M. H. Garcia (pp. 505–542), American Society of Civil Engineers. https://doi.org/10.1061/9780784408148.ch10

Rizzo, P., & Enshaeian, A. (2021). Challenges in bridge health monitoring: A review. *Sensors*, *21*(13). https://doi.org/10.3390/s21134336

Schall, J. D., & Price, G. R. (2004). *NCHRP Report 515—Portable Scour Monitoring Equipment*. Transportation Research Board. https://doi.org/10.17226/13719

Schroeder, B., Haug, P., Alvarado, A., & Baribeau, S. (2019). *Unmanned Surface Vessels for Bridge Scour Monitoring*. Michigan Department of Transportation. www.michigan.gov/mdotresearch.

Shen, J., Forsyth, R., & Kilgore, R. (2018). *Underwater Inspection of Bridge Substructures Using Imaging Technology*. Federal Highway Administration.

Sobolewski, J. S. (2003). Data Transmission Media. *Encyclopaedia of Physical Science and Technology (Third Edition), 2003*, 277–303. https://doi.org/10.1016/b0-12-227410-5/00165-4

Suzuki, O., Masui, Y., Abe, M., & Samizo, M. (2008). Development of Multifunction Scour Monitoring Device for Railway Bridge Piers Part1: Background and Concept. *Fourth International Conference on Scour and Erosion 2008*, 263–266.

Swartz, R. A., Rajbandari, B., & Winter, B. D. (2014). *Autonomous Scour Monitoring of Bridges and Embankments Using Bio-Inspired Whisker Flow Sensor Arrays*. 1–5.

Tang, F., Chen, Y., Guo, C., Fan, L., Chen, G., & Tang, Y. (2019). *Field Application of Magnet-Based Smart Rock for Bridge Scour Monitoring*. https://doi.org/10.1061/(ASCE)BE.1943

Tang, F., Chen, Y., Li, Z., Hu, X., Chen, G., & Tang, Y. (2019). Characterization and field validation of smart rocks for bridge scour monitoring. *Structural Health Monitoring*, *18*(5–6), 1669–1685. https://doi.org/10.1177/1475921718824944

Tang, F., Chen, Y., Tang, Y., Li, Z., & Chen, G. (2021). Smart rock technology for local scour monitoring of bridge structures. *ASCE Earth and Space 2021*, 455–463.

Tang, D., & Zhao, M. (2021). Real-time monitoring system for scour around monopile foundation of offshore wind turbine. *Journal of Civil Structural Health Monitoring*, *11*(3), 645–660. https://doi.org/10.1007/s13349-020-00467-4

Topczewski, Ł., Cieśla, J., Mikołajewski, P., Adamski, P., & Markowski, Z. (2016). Monitoring of scour around bridge piers and abutments. *Transportation Research Procedia*, *14*, 3963–3971. https://doi.org/10.1016/j.trpro.2016.05.493

Tsubaki, R., Fujita, I., Yu, K., & Muste, M. (2015). Large-scale particle image velocimetry (LSPIV) implementation on smartphone. *E-Proceedings of the 36th IAHR World Congress, 2015*.

U.S. Army Corps of Engineers (USACE). (2013). Hydrographic surveying. In *Engineering and Design Hydrographic Surveying EM 1110-2-1003*. https://doi.org/10.4324/9780203127087-10

Wang, K., & Lin, C. P. (2021). Applicability and limitations of time domain reflectometry bridge scour monitoring system in general field conditions. *Structural Health Monitoring*, *20*(3), 1074–1089. https://doi.org/10.1177/1475921720944587

Wang, C. Y., Wang, H. L., & Ho, C. C. (2012). A piezoelectric film type scour monitoring system for bridge pier. *Advances in Structural Engineering*, *15*(6), 897–905. https://doi.org/10.1260/1369-4332.15.6.897

Waratuke, A. R., Hernandez, J., Landry, B. J., & Garcia, M. H. (2011). Tanana River Railroad Bridge-Movable-bed Model Testing of Bridge Scour due to Local Erosion, Flow Contraction and Debris Accumulation, Ven Te Chow Hydrosystems Laboratory, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Sponsored by Hanson Professional Services, Inc. and the Alaska Railroad Corporation.

Weissman, J., Chun, H. T., & Haas, C. (2001). Pilot installation of a bridge scour monitoring site. *Transportation Research Record*, *1749*, 68–72. https://doi.org/10.3141/1749-11

Whitlow, R. D., Haskins, R., McComas, S. L., Crane, C. K., Howard, I. L., & McKenna, M. H. (2019). Remote bridge monitoring using infrasound. *Journal of Bridge Engineering*, *24*(5), 04019023. https://doi.org/10.1061/(asce)be.1943-5592.0001375

Yen, B. C., Garcia, M. H., Troy, C. D., & Armbruster, J. (1998). *Stream Channel Migration Effects on Bridge Approaches and Conveyance*. Illinois Transportation Research Center. https://idot.illinois.gov/Assets/uploads/files/Transportation-System/Research/Illinois-Transportation-Research-Center/1998.09.01 - Stream Channel Migration Effects on Bridge Approaches and Conveyance - IA-H5 FY94.pdf

Yen, K. (2017). Flood flow estimation using large scale particle image velocimetry (LSPIV). In *Caltrans Division of Research*. Caltrans Division of Research. https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/flood-flow-pi-0208171-a11y.pdf

Young, C. B. (2016). *Developing a bridge scour warning system* (Report No. K-TRAN: KU-14-1). Kansas Department of Transportation.

Yu, X., & Yu, X. (2010). *Field Monitoring of Scour Critical Bridges: A Pilot Study of Time Domain Reflectometry Real Time Automatic Bridge Scour Monitoring System*. Federal Highway Administration.

Zhang, H., Li, Z., Chen, G., Reven, A., Scharfenberg, B., & Ou, J. (2021). UAV-based smart rock localization for bridge scour monitoring. *Journal of Civil Structural Health Monitoring*, *11*(2), 301–313. https://doi.org/10.1007/s13349-020-00453-w

Zhao, X., Li, W., Yan, X., Ba, Q., Zhang, X., & Li, L. (2018). Progress of active thermometry method in submarine pipeline scour monitoring. *ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2018*, *2*(2). https://doi.org/10.1115/SMASIS2018-8232

APPENDIX A: OTHER AVAILABLE INSTRUMENTATION TECHNOLOGIES

OTHER FIXED INSTRUMENTATION

Piezometric Film

The piezoelectric film sensing device can be constructed by mounting thin piezoelectric films along rods embedded into the channel bed at a fixed distance. A voltage is generated from the vibration or deformation of the piezoelectric film. The piezoelectric film embedded in the soil of the riverbed is undisturbed, resulting in a much smaller output voltage as compared to the part that is enduring the water currents. The soil-water interface can easily be identified based on the voltage signal recordings. This technology has been tested in both laboratory and field (Lagasse et al., 1997; C. Y. Wang et al., 2012)

Limitations: Only measure discrete locations at the embedded rods. Very sensitive to structural and hydrodynamic vibrations (Lagasse et al., 1997).

Time-domain Reflectometers

Time-domain reflectometers comprise a series of vertically buried pipes that emit an electromagnetic pulse to determine the location of changing boundary conditions, i.e., soil-water interface. By monitoring the round-trip travel time of the pulse in real time, the distance to the respective interfaces can be computed, which provides information on the changes in streambed elevation. The effects of both hydraulic and ice conditions on the erosion of the riverbed can be captured with this method. Time-domain reflectometers have been successfully tested in the lab (Funderburk et al., 2021) and implemented in the field (Wang & Lin, 2021; Yu & Yu, 2010). The advantages and limitations of time-domain reflectometers are listed below:

- Advantages: They are robust devices that are highly resistant to ice, high velocity flows, and debris.
- Limitations: They are expensive devices and can only measure discrete locations.

Contact Image Sensors (CIS)

The CIS is an optical sensor that tracks the evolution of the soil-water interface based on the difference in the reflectivity of light from different media. It is a type of optical device for image scanning normally used in photocopiers. A CIS consist of three main components – a light source, a lens, and an image sensor array. The reflected light from the environment surrounding the sensor is gathered by the lens and directed at the image sensor array. The sensor then records the image according to the intensity of light that is detected by the image sensor. When the sensor is buried in sediment, a strong reflection of light will be detected while a much lower reflection will be detected if sensor is exposed to water. This sudden change in sensor reading is used to detect scour around piles.

Limitations: No reports detailing field tests on this technology have been published to date, but model tests using the sensors in the lab setting have been published (An et al., 2017). The technology is also found to accurately work for suspended sediment concentrations of less than 40 kg/m^3, which might differ from the site conditions.

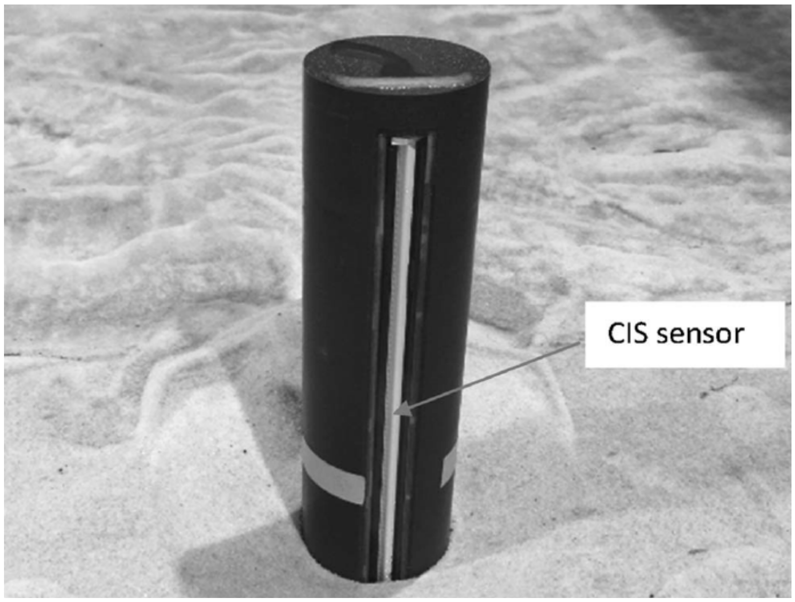

Figure 41. Photo. Picture of CIS sensor fitted to a 50 mm diameter model.

Source: An et al. (2017)

Smart Rocks

Smart rocks consist of one or more stacked magnets encased in a concrete ball that can automatically roll to the deepest point of a scour hole around the bridge and provide its location through remote measurement over time (Tang et al., 2019). As the smart rock is placed at a scour-critical area near a bridge or abutment, the environmental magnetic field changes. By measuring the change in magnetic field with a magnetometer (which can be a fixed station or deployed with an Unmanned Aerial Vehicle UAV), the location of the smart rock can be determined (Zhang et al., 2021). Maximum scour depth can be monitored by continuously tracking the location of the smart rock. There are several types of spherical smart rocks to date, including the Arbitrary Oriented System (AOS), Automatically Pointing South System (APSS) and Automatically Pointing Upward System (APUS) (Tang et al., 2021). The main difference between the types of smart rock is related to the direction that the magnet is pointing to, resulting in differences in parameters associated to its orientation. Smart rocks have been successfully tested in the lab and implemented in the field (Chen et al., 2016).

Advantages: Smart rock has a permanent service life due to its magnetic nature and is able to survive stringent conditions due to the high strength of the concrete casing.

Limitations: Smart rock is prone to be washed away during a flood and is only able to monitor a limited range in its location area. Smart rock is also not able to account for the refilling process of the scour hole and only able to obtain the maximum scour depth.

Whisker Flow Sensor Arrays

Whisker flow sensors array are part of a novel monitoring approach utilizing an embedded array of bio-inspired, magnetostrictive whisker-shaped flow sensors that detect water flow. The differentiation of dynamic (free) and (buried) static signals allow for the description of the state of scour. Fluid structure interaction for whiskers will create significant dynamic signals when flow rates are high while static signals will be recorded if whiskers are buried.

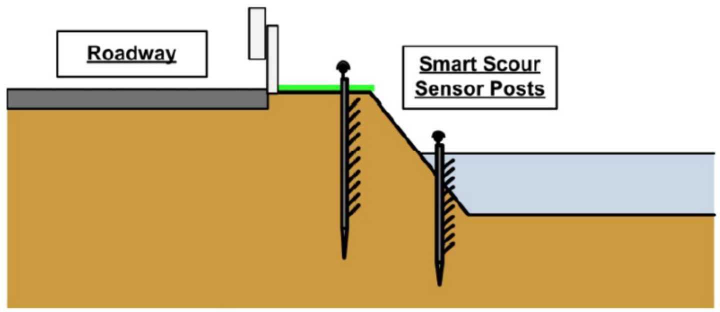

Figure 42. Diagram. Illustration of whisker sensors.

Source: Swartz et al. (2014)

Limitation: No reports detailing field tests on this technology have been published to date. Only research papers describing laboratory flume tests on the sensors are available (Swartz et al., 2014). Even with modified airfoil whiskers that greatly enhances the sensitivity of the sensor system, false positive and false negative results will still occur. Measurements can also only be made in discrete locations.

Electrical Conductivity Probes

Electrical conductivity devices can determine the location of the sediment surface by detecting the differences in electrical conductivity of the soil and water using two needle probes. If the material between the two probes changes, the electrical current detected between the probes will change. The approximate elevation of the riverbed is determined by comparing the conductivities between surface-water flow and submerged bed material from equally spaced sensors mounted on the probe.

Limitation: Electrical conductivity signals are sensitive to water temperature, salinity and turbidity. During high flow events, as discharge increases, the concentration of sediments in the water increases. The voltages measured in the water flow cannot be distinguished from measurements made at the shallowest sensor in the submerged bed material. There are also other issues such as the corrosion of electrodes with time and vulnerability of the system to damage by debris. Likely due to such limitations, information on the implementation of the probes found is not in the recent years (Hayes & Drummond, 1995; Hubbard, 1955).

Micro-electro-mechanical systems (MEMS) pressure sensors

MEMS devices combine small mechanical and electronic components on a silicon chip by means of micro fabrication technology. Silicon MEMS pressure sensors are divided into two general classes: (1)

piezo-resistive type and (2) capacitive type. Most piezo-resistive and capacitive sensors are designed and signal-conditioned to behave linearly as a function of pressure. The sensors are generally installed at an equally spaced along a probe which is partially buried in the seabed. By using the MEMS sensors, the dynamic pressure attributed to the impact forces by flow velocity, turbulence or sediment particle movement in the deposition and scouring processes can be measured and resulting scour depth can be identified.

Limitations: No reports detailing field tests on this technology have been published to date. Only research papers describing laboratory flume tests on the sensors are available (Lin et al., 2010, 2008).

APPENDIX B: SUMMARIES OF RELEVANT PAPERS & REPORTS

REPORT SUMMARIES

Title: Portable Bridge Scour Monitoring using Autonomous Underwater Vehicles Technology Development and Risk Assessment-based Platform for Deployment Prioritization

Authors: Mehdi Omidvar, Brent Horine

Date: September 2018

Organization: Manhattan College

Summary: In this study, a cost-effective framework was presented to conduct bridge scour assessment using autonomous underwater vehicles (AUV). An existing AUV, the Harbor AUV from DURO AUS, was further adapted for use in bridge scour monitoring. Software and hardware developments, as well as required instrumentation were described. Improvements were applied on fabrication, upgrades on motor components for riverine environment applications, navigation, processors and instrumentation for collection of bathymetric data. Image processing algorithms and codes were developed to automatically segment and identify key components relevant to scour quantification using readily available acoustic images. The autonomous path finding algorithm was developed using a multi-objective optimization based on interval programming (MOOS-IvP). While the navigation system is still in the testing phase for full autonomy, simulations were conducted on autonomous navigation using state-of-the-art simulation environment for AUVs.

To facilitate the use of AUVs in monitoring programs, a New-York state specific RISK assessment model based on HYRISK was implemented on a geographic information system (GIS)-based platform for AUV deployment prioritization. The system is designed to draw raw data from National Bridge Inventory (NBI) and to identify bridges with the highest risk in dollar amount, computed from an evaluation of the probability of failure and cost of failure.

Title: Evaluation of Bridge Scour Monitoring System

Author(s): Han Nassif, A. Oguz Ertekin, Joe Davis

Date: March 2002

Organization: Rutgers University

Summary: The main objective of this study is to implement and evaluate the National Cooperative Highway Program (NCHRP) Project 21-3 "Instrumentation for measuring Scour at Bridge piers and Abutments" designated systems for monitoring scour. The project considers two systems – the magnetic sliding collar (MSC) and sonar fathometers. These two fixed scour monitoring systems are deployed and installed at Route 35 Matawan Bridge and Route 46 Passaic River Bridge over Dundee in New Jersey. Based on the measurement results, it is found that the MSC and sonar devices complement each other to provide a clear and accurate picture of the scour condition at each site. Based on the evaluation, while both instruments are not susceptible to physical damage due to debris and ice, there are prone to false measurements due to such disturbances. Further evaluation on the advantages and limitations of the MSSC and sonar devices are also performed in this study.

Title: Developing a Bridge Scour Warning System

Author(s): C. Bryan Young

Date: September 2016

Organization: University of Kansas

Summary: This research project surveyed in-situ and ex-situ monitoring options with particular attention on warning system options in the public domain for cost-effectiveness. In-situ monitoring includes portable or fixed devices for detecting bridge scour while ex-situ options refer to statewide systems that issues scour alerts to trigger bridge closures and/or inspections based on hydrologic conditions such as rainfall or streamflow. Types of ex-situ monitoring discussed includes real-time modelling, flash flood warning systems, vendor options provided by external companies and public domain options include USGS gauges, iNWS (interactive National Weather Service) system. This project provides an extensive range of options available for statewide monitoring system targeted at various hydrologic thresholds for scour detection.

Title: Bridge Scour Technology Transfer

Author(s): Colin Brooks, Michelle Wienert, David Banach

Date: February 2018

Organization: Michigan Technological University

Summary: This report is a summary of the Bridge Scour Technology Transfer Event, which was held on October 5th, 2017 in Michigan. The event invited scour experts and bridge engineers from MDOT and companies to attend and discuss current topics and trends in scour analyses, modelling and monitoring. The discussion included scour risk management, data management and acquisition, scour design approach and the implementation of plan of action for scour. One highlight of the presentations include a bathymetric boat survey research project used for flow and scour monitoring.

Title: Bathymetric Surveys at Highway Bridges Crossing the Missouri River in Kansas City, Missouri, using a Multibeam Echosounder, 2010

Author(s): Richard J. Huizinga

Date: 2010

Organization: USGS

Summary: This report details the bathymetric surveys conducted by USGS in cooperation with Missouri DoT on the Missouri River in the vicinity of nine bridges at seven highway crossings in Kansas City, Missouri. A multibeam echo sounder mapping system was used to obtain channel bed elevations for river reaches that ranged from 1640 to 1800 ft long and extending from bank to bank in the main channel of the Missouri River. Bathymetric data were collected in this report around every pier that was in water, except those at the edge of water or in extremely shallow water or surrounded by large debris. Equipment and methods used to obtain the bathymetric results are described and survey quality assurance and control measures are discussed. Bathymetric surveys results are shown in figures with channel bed depth contour lines. It is noted in the report that the results are not indicative of the maximum scour depth as measurements do not account for the maximum scour during flooding. Maximum estimated error is 2.8 ft but majority of the measurements have errors of 0.5 ft or less.

Title: A New Method for Detecting the Onset of Scour and Managing Scour Critical Bridges

Author(s): John Orsak

Date: September 2019

Organization: SENSR Monitoring Technologies LLC

Summary: This report details the development and testing of a CX1 monitoring device which measures acceleration in three dimensions and tilt in two directions relative to vertical. The average tilt, dynamic tilt and lateral accelerations were deemed the key performance indicators for scour. Temperature is measured separately to investigate its potential influence on CX1 monitoring device. The device was field tested in six bridges spanning across different states, where the subsequent results were used to develop a scour alert methodology where the raw data is transformed into actionable information that is useful to bridge owners through the epoch method.

Title: A Truck-Mounted Scour Inspection System for INDOT

Author(s): Dennis Lyn, Thomas Cooper, Ranadeep Das

Date: March 2010

Organization: Purdue University

Summary: This report discussed the development of an acoustic (HEXAMITE) positioning system, based on acoustically measuring distances from transmitters attached to the scour sonar house to an array of receivers of known fixed positions. The system was intended to provide a more robust and easier-to-use means of determining the position of the sonar scour monitor than the original mechanical positioning system developed in Schall & Price 2004 "Portable Scour Monitoring Equipment". Lab tests, along with stationary and moving truck field tests were performed to investigate the system's the real-time tracking of the end of the crane. Results showed that the system is accurate to 1 ft horizontal and 1 ft vertical range when compared to measurements made from total stations. The development of a web application that graphically displays stream gaging data from USGS and relevant data on scour critical bridges on a map was also discussed in this report.

Title: An illustrated guide for monitoring and protecting bridge waterways against scour

Author(s): Robert Ettema, Tatsuki Nakato, Marian Muste

Date: March 2006

Organization: University of Iowa

Summary: This report was intended to complement the FHWA "Bridge Inspection's Reference Manual" (Hartle et al., 2002). The report provides an explanation of the scour and erosion processes that may occur at bridge ways and describes the main components of a bridge waterway and the variables that affect the channel shape and stability. The report also detailed the monitoring procedures, types of bridge inspections and the available instrumentations for both portable and fixed scour monitoring. Finally, the report closed off by outlining and illustrating the concepts for scour protection and repair of bridge waterways.

Title: Autonomous Measurements of Bridge Pier and Abutment Scour using Motion-sensing Radio Transmitters

Author(s): Thanos Papanicolaou, Mohamed Elhakeem, Achilleas Tsakiris

Date: January 2010

Organization: University of Iowa

Summary: This report detailed the development and testing of two portable Radio Frequency Identification (RFID) systems (made by Texas Instruments and HiTag) for the purpose of bridge scour monitoring. The systems comprise of (1) Passive cylindrical transponder. (2) Low frequency reader and (3) Antenna. An anti-collision feature was developed for the HiTag system that prevents interference from nearby particles during readouts of smart particles. Investigation was conducted to determine the optimal particle to house the transponder. Comprehensive laboratory tests (for e.g. pier models) were performed in either a flume or sand box, with results indicating that both systems are able to predict maximum scour depth. Limited field testing was also performed in Racoon River, IA to test the C++ code for particle detection and determine the performance of each systems including transponder orientation, transponder housing material, maximum antenna-transponder detection distance, minimum interparticle distance and antenna sweep angle. The maximum distance of antenna-transponder detection was found to be ~0.7m.

Title: Bridge Scour Monitoring Technologies: Development of Evaluation and Selection Protocols for Application on River Bridges in Minnesota

Author(s): Matthew Lueker, Jeff Marr, Chris Ellis, Vincent Winsted, Shankar Reddy Akula

Date: March 2010

Organization: University of Minnesota

Summary: The report described the development of developed a Scour Monitoring Decision Framework (SMDF) that aids engineers to select the best fixed monitoring technology for a particular bridge site. The SMDF is a Visual Basic for Applications (VBA) enabled Excel workbook that accepts site-specific information about one bridge site and compares the information to critical characteristics for the fixed scour monitoring equipment. The site-specific information includes important details on bridge structure, stream channel and scour characterization which are all variables of scour critical bridges which can impact the application of scour monitoring. The application will output a list of ranking in the SMDF along with an overview of characteristics illustrating the effect of the calculated score. The scoring is based on a weighing factor to each contributing variable and an approximate cost will also be determined from the framework. The SMDF was tested on five bridges and a bridge was subsequently selected for the development of fixed scour monitoring work plans based on the output from SMDF.

Title: Non-contact Scour Monitoring System for Highway Bridges

Authors: Sudhagar Nagarajan, Madasamy Arockiasamy

Date: November 2020

Organization: Florida Atlantic University

Summary: This report explored the feasibility of a potential non-contact green laser-based scour monitoring technique through laboratory and field tests. The technique is based on the use of a laser ranging sensor with signal wavelength in the green spectrum (approx. 500 nm) of Electro Magnetic Radiation (EMR). The report also detailed the implementation of a mathematical model based direct georeferencing technique to derive 3D coordinates of scour hole using the green laser mounted on a mobile platform. The authors utilized a Mobile Mapping System (MMS) to acquire a complete 360-degree view of the scour. Though the technology was able to produce relatively accurate results, the low levels of turbidity and shallow depth of water during field experiments limited the comprehensiveness of the report.

Title: Monitoring Scour Critical Bridges (NCHRP Synthesis 396)

Authors: Beatrice E. Hunt

Date: 2009

Organization: STV Incorporated

Summary: This report documents the extent of fixed scour monitoring system usage in the United States. Surveys were sent out to all states and responses detailed 56 sites where fixed monitoring has been implemented. The survey questionnaire covered many aspects of the fixed installations, including problems encountered during system implementation. The most common problems associated with fixed monitoring were floating debris, coast of maintenance and information transfer to appropriate personnel. This report further details several case studies of scour monitoring system implementation. The report also summarized the data quality requirements of measurement, side specific factors and selection process of monitoring instrument into a selection matrix. A section of the report was dedicated to a discussion of new instrumentations, innovative solutions, and on-going research for scour monitoring.

Title: Remote Bridge Scour Monitoring: A Prioritization and Implementation Guide

Author(s): Carl Haas, Jose Weissmann, Tom Groll

Date: May 1999

Organization: University of Texas at Austin, University of Texas at San Antonio

Summary: The report presented a method for the prioritization of bridge sites for mechanical scour monitoring based on a logical method that uses a coding algorithm from Bridge Inventory, Inspection and Appraisal Program (BRINSAP) database. The BRINSAP database contains bridge records and provides a comprehensive account of the physical and functional characteristics of each bridge in the state of Texas. The report described the development of a conceptual framework for analyzing the cost and benefits of remote scour monitoring that was calibrated through an engineer's judgement and based on parameters chosen from a ranking survey. A section of the report was dedicated to discussing the evolution of the scour screening process with comparisons made between other prioritization developed such as CAESAR developed by University of Washington and HYRISK developed by FHWA.

Title: Remote Methods of Underwater Inspection of Bridge Structures

Author(s): W. R. Bath

Date: July 1999

Organization: Sonsub Inc.

Summary: This report features the development of a portable trailer mounted bridge scour inspector (2.4m by 7.6m by 2.4m) that was field tested under flood conditions (1994 Georgia floods) for inspecting bridge scour in the vicinity of piers from the bridge deck. The bridge inspector comprises of a remotely controlled hydraulically operated arm that can deploy a multitude of devices including a video camera, a scanning sonar and underwater light. While the arm is limited to a maximum extension of 15m, and minimum of 4.5m, the inspector was successful in producing bathymetric surveys of the channel bed.

Title: Robotic system for underwater bridge inspection and scour evaluation

Author(s): James E. Devault, William B. Hudson, Mustaque Hossain

Date: June 1997

Organization: Kansas State University

Summary: This report described the development of a semi-autonomous robotic system capable of providing underwater inspection of bridge substructures located in rivers and streams. The instrumentation system consists of a team two identical mobile robots designed to travel along opposite surfaces of the structure while connected to one another by a cable and winch system. The system, which is remotely controlled, is capable of positioning a sensor platform in close proximity to underwater bridge support structures and provide sensory information such as videos or images to support the evaluation and documentation of structural and scour condition. The report detailed the design and fabrication of the prototype robotic system and creation of the user-interface. The robotic system, equipped with a consumer-grade digital camera (Hitachi model VM-H100LA), was experimented in a 1500-galleon polypropylene tank measuring 8 ft in diameter where its performance under submerged operations and turbid water conditions were examined.

Title: Use of a Ground-Penetrating Radar System to Detect Pre- and Post-flood scour at selected bridge sites in New Hampshire, 1996-1998

Author(s): Joseph R. Olimpio

Date: 2000

Organization: USGS

Summary: This report detailed the usage of ground-penetrating-radar (GPR) survey techniques by USGS to study streambed scour at 16 post-flood bridges in New Hampshire. Of the 16 post-flood bridges, 22 GPR cross sections at 7 bridges were compared and presented in the report. The GPR system utilized used a 300 MHz signal to penetrate through depths up to 20 ft of water and 32 ft of streambed material.

Data were collected with a GPR equipped small inflatable boat that can be maneuvered by the operator. Information gathered included existing scour hole dimensions, infilled thickness, previous scour surfaces, streambed materials and depth to foundation or riprap materials at pre- and post-flood conditions, forming a continuous profile of the streambed. The report also provided descriptions of GPR data collection techniques, equipment used, and interpretations of data collected from the various bridge sites.

TECHNICAL PAPER SUMMARIES

Fiber Optics

Title: A hydraulic monitoring system on a bridge over the River Esino, Italy

Author(s): G. Crotti, D. Isidori, A. Cigada, F. Ballio, F. Inzoli, E. Concettoni, C. Cristalli

Date: June 2016

Organization: Politecnico di Milano, Italy

Summary: The paper analyses and discusses an innovative device named BLESS (Bed Level Seeking System) that is used to detect level of the bed. Field tests are conducted in Sciasciano Bridge (Province of Ancona, Italy). BLESS is based on fibre optics techniques, in particular fibre Bragg grating (FBG) that is developed by the Loccioni Group. The paper discusses the use of BLESS as compared to the use of conventional sonar instrument. The device is placed close to the pier and partially buried in the bed. BLESS has proved to be an efficient instrument to detect the typical dynamics of the bed near structures like piers that includes development of scour hole and its refill process during floods.

Title: A new method for scour monitoring based on fiber Bragg grating

Author(s): Yong Ding, Qingxiong Yao, Zhendong Zhang, Xin Wang, Tengteng Yan, Ye Yang, Hui Lv

Date: March 2018

Organization: Nanjing University of Science and Technology (China)

Summary: This paper discusses the feasibility of scour depth determination based on lateral soil pressure measurement with the use of fibre Bragg grating (FBG) as the sensing element. The pressure difference between the earth pressure and water pressure on either side of the FBG allows determination of the mud surface. The sensors are typically arranged at a distance of 1m away from each other with some sensors buried beneath the bed. The technology is only tested under static flow conditions in the lab and have yet to undergo any field tests.

Title: Bridge Scour monitoring system based on active thermometry

Author(s): Qin Ba, Xue-Feng Zhao, Le Li

Date: April 2012

Organization: Dalian University of Technology (China)

Summary: This paper proposes a bridge scour monitoring system based on active thermometry, which utilizes the concept of different patterns of temperature change in water and soil after heating. The monitoring system is a thermal cable that is comprised of a heating belt, DS18B20 thermometer and packing elements. The soil-water interface can be identified by analysing acquired temperature-time histories. The system was tested in lab experiments and proved to be feasible and efficient.

Title: Progress of Active Thermometry Method in Submarine Pipeline scour monitoring

Author(s): Xuefeng Zhao, Xu Yan, Xinwang Zhang, Weijie Li, Qin Ba, Le Li

Date: Sept 2018

Organization: Dalian University of Technology (China), University of Southern California

Summary: In this paper, several scour monitoring techniques based on active thermometry method was introduced. Lab tests involved using a DS18B20 digital temperature sensor, a Brillouin distributed optical fiber sensor and a Raman sensing sensor to monitor the surface heat exchange pattern in the heating process in different mediums like sand and water to validate the concept. The authors proposed the use of a submarine pipeline scour monitoring system based on Brillouin distributed optical fiber sensing technique.

Title: Scour Monitoring system using Fiber-Bragg Grating sensors and water swellable polymers

Author(s): Xuan Kong, Siu Chun Michael Ho, Gangbing Song, C.S. Cai

Date: Jan 2017

Organization: University of Houston

Summary: The present study aims to develop an innovative scour monitoring system using fiber Bragg grating (FBG) sensors and water swellable polymers. The polymer material swells to several times the original volume upon absorption of water, and the expansion induces a measurable tension on the FBG sensor. The scour monitoring system is vertically embedded in the soil, with the shift of measured wavelength indicating a change in soil elevation. A prototype sensor system for proof-of-concept was fabricated, and several tests were conducted in the laboratory under static waters to verify the functionality of the device. The results indicate that the system is capable of monitoring scour long term.

Structural Monitoring

Title: A review of bridge scour monitoring techniques

Author(s): Luke J. Prendergast, Kenneth Gavin

Date: April 2014

Organization: University College Dublin (Ireland)

Summary: The paper presents a critical review of existing scour monitoring equipment and methodologies with a particular focus on those using the dynamic response of the structure to indicate the existence and severity of the scour phenomenon affecting the structure. The paper discusses the following instruments, 1) single-use devices such as float-out device and tethered buried switches, 2) Fiber-Bragg grating sensors, 3) Pulse or radar devices such as TDR and GPR, 4) Driven or buried rod devices such as magnetic sliding collar, 5) Sound wave devices such as echo sounder, 6) Electrical conductivity devices such as a probe and 7) Tilt meters and accelerometers. The paper places a focus on low-maintenance non-intrusive structural health monitoring to detect and monitor scour development. The work of Prendergast et. al. 2013 was developed in this paper using a numerical model to assess the applicability to full scale bridge monitoring.

Title: Acceleration-based Bridge Scour Monitoring

Author(s): P.C. Fitzgerald, E.J. Obrien, A. Malekjafarian. L.J. Prendergast

Date: June 2018

Organization: University College Dublin (Ireland) and Delft University of Technology (Netherlands)

Summary: The paper focuses on safety assessment of bridges using vibration-based structural health monitoring with camera-based techniques. This paper investigates the use of a drive-by approach (where sensors are installed on a passing vehicle) to detect scour. Numerical modelling was performed to illustrate the accelerations obtained from a passing vehicle. A wavelet coefficient subtraction technique was applied on the accelerations to detect the presence of scour. It is found that wavelet coefficients obtained from accelerometer data can be good indicator of the presence of scour.

Title: Bridge scour characteristic curve for natural frequency - based bridge scour monitoring using simulation - based optimization

Author(s): Ting Bao, Zhen Liu

Date: May 2021

Organization: Chongqing University (China), Michigan Technological University

Summary: This study provides a comprehensive investigation into the predominant natural frequency (PNF)-scour depth relationship termed the bridge scour characteristic curve (BSCC) and proposes a simulation-based optimization approach to predict the BSCC with a few measured points. The proposed approach integrates the Winkler-based numerical model into a global optimization technique to predict the subgrade modulus and whole BSCC. The results are validated using published examples and numerical modelling. This study serves to improve the application of frequency-based scour monitoring.

Title: Bridge Scour Monitoring using Extended Kalman Filter

Author(s): Rajendra P. Palanisamy and Sung-Han Sim

Date: Aug 2015

Organization: Ulsan National Institute of Science and Technology (Korea)

Summary: This paper proposes a scour monitoring method using Extended Kalman Filter (EKF) that uses time history responses in conjunction with a structural model to identify scour depth. The concept is based on vibration-based monitoring technique that monitor dynamic response rather than the change in modal properties to identify scour. The developed method is validated numerically with no field or lab tests.

Title: Bridge scour monitoring technique using the vibratory response of rods embedded in the riverbed

Author(s): Nissrine Boujia, Franziska Schmidt, Christophe Chevalier, Dominique Siegert, Damien Pham Van Bang

Date: April 2018

Organization: University of Paris Est (France)

Summary: This paper proposes a monitoring technique based on the dynamic response of rods embedded in the riverbed. The rod is made of aluminium and dynamic response is measured using accelerometers from an induced vibration. Lab tests were conducted to investigate the influence of stiffness of soil on the frequency of the rod. A further 3D numerical model was developed to validate the lab experiments. Using both the numerical and experimental results, an analytical model based on a simplified cantilever model is proposed to correlate measured frequencies of sensor to scour depth.

Title: Experimental Demonstration of a Mode Shape-based Scour Monitoring Method for Multispan Bridges with Shallow Foundations

Author(s): Abdollah Malekjafarian, Chul-Woo Kim, Eugene J. OBrien, Luke J. Prendergast, Paul C. Fitzgerald, and Syunsuke Nakajima

Date: 2020

Organization: University College Dublin (Ireland)

Summary: This paper experimentally investigates a vibration-based scour monitoring approach applicable to bridges with multiple simply supported spans on shallow foundations.

A novel scour indicator is proposed whereby the mode shape amplitude at one pier is compared with the mean of the mode shape amplitudes at the remaining piers in a process that creates a mean-normalized mode shape (MNMS). Significant increase in MNMS (mean normalized mode shape) suggests presence of scour and the location can then be identified. Damage detection methods based on changes in mode shapes are an alternative to natural frequency-based approaches, and can be advantageous in detecting local damage, and are not highly prone to issues such as changes in temperature. The method is tested using a scaled experimental model of a bridge traversed by a vehicle. The experimental mode shapes are extracted from acceleration signals arising from vehicle crossing using an output only modal identification technique, namely frequency domain decomposition (FDD).

Title: Remote Bridge Monitoring Using Infrasound

Author(s): R. Danielle Whitlow, Richard Haskins, Sarah L. McComas, C. Kennan Crane, Issac L. Howard, Mihan H. McKenna

Date: 2019

Organization: US Army Engineer Research and Development Center

Summary: This study highlights the use of infrasound monitoring, a geophysical technique utilizing acoustics below 20 Hz, as one possible solution for noncontact, noline-of-sight bridge health monitoring. Air perturbations caused by resonance of structures create infrasound that propagates far distances while retaining critical frequency information. Infrasound monitoring allows for remote acoustic detection of natural frequencies of structure. The monitoring system is implemented on a steel bridge (Br 18-0009) in Northern California via a network of three arrays composed of infrasound sensors ranging from 2.6 to 24 km. Geotool software package was adopted for the data processing. The frequencies detected via infrasound monitoring were validated with data collected by on-structure accelerometers.

Title: Real time monitoring system for scour around monopile foundation

Author(s): Dongyue Tang, Ming Zhao

Date: July 2020

Organization: Tongji University (China)

Summary: A real time safety scour monitoring system is established for a monopile foundation in this study according to results of numerical analyses. Inclinometers and accelerometers are used as sensors as part of the field tests in Jiangsu Rudong Offshore Wind Farm to obtain a dynamic response. Time and frequency domain analyses were conducted on the measurements obtained, which was further used to develop a numerical model to determine early warning values and indicators, thus forming a scour safety monitoring system.

Sonar Technology

Title: A French experience of continuous scour monitoring on real sites

Author(s): Frédérique Larrarte, Hugues Chollet, Louis Battist, Christophe Chevalier

Date: September 2019

Organization: University of Gustave Eiffel

Summary: This paper investigates the implementation of inexpensive commercially available sensors for scour monitoring. The paper focused on measurement of water surface level and flow velocity as part of the equation-based scour parameters. Water levels are measured using Ljnus LNU06V3-82-3G ultrasonic device and velocity profile measured using ultrasonic Ub-flow UBF156 by Ubertone. Both devices are mounted on a floating board device.

Title: Establishing a Scour Monitoring

Author(s): Beatrice E. Hunt

Date: 2005

Organization: This paper describes and evaluates the scour monitoring strategy employed for three bridges on the South Shore of Long Island, New York, and the Woodrow Wilson Bridge over the Potomac River in Washington, DC. The main mode of monitoring is through sonar for these bridges. The scour monitoring program is custom designed for each bridge site. The type of monitoring instrument employed depends on the geometry of the bridge substructure and on the channel characteristics. The location of the monitors on the substructure units are selected in consideration of accessibility for servicing, protection against vandalism, any potential ice or debris forces. The paper also provides several suggestions in the design of a scour monitoring program – 1) review of available data to assess scour conditions, 2) hydraulic, scour and stability analyses of the bridge to determine scour critical bridges and critical scour depth and 3) evaluation of scour countermeasure alternatives.

Title: Feasibility Test of Low Cost Sonar Sensors for Bridge Scour Monitoring

Author(s): Touhid Ahamed, Jaeho Shim, Hongki Jo, Guohong Duan

Date: 2016

Organization: University of Arizona

Summary: This paper details the work done to improve the measurement quality of low-cost sonar sensors, particularly in flood conditions, by identifying the measurement noise characteristics caused by flow turbulence and pseudo echoes of sediment particle, and providing appropriate signal processing strategies. Performances of low-cost sonar sensors are characterized and tested in turbid water and turbulence flow conditions in a cylindrical water tank in University of Arizona. The sonar system consists of two Airmar SS510 sonar transceiver. A 3D velocity profiler (Vectrino Profiler) was used to measure water velocity near the sonar sensing during experiments.

Title: Monitoring of scour around bridge piers and abutments

Author(s): Lukasz Topczewski, Juliusz Ciesla, Pawel Mikolajewski, Pawel Adamski, Zenon Markowski

Date: April 2016

Organization: Road and Bridge Research Institute (Poland)

Summary: This paper presents the principles of sonar scour monitoring near bridge supports and selected results from sonar measurements at a bridge in Gora Kalwaria on the Vistula River in Poland. Sonar ultrasonic waves are deemed the best solution due to poor visibility in water. The paper proposes 2D scanning sonar for scour monitoring of bridge pier walls and 2D/3D scanning sonar for monitoring of bottom of bridge pier. The monitoring system was not tested during a flood event.

Title: Review of different scouring monitoring techniques and instruments

Author(s): Geeta Devi, Munendra Kumar

Date: Jan 2018

Organization: Delhi Technological University (Delhi)

Summary: This paper discusses Artificial Intelligence (AI) monitoring techniques such as Artificial Neural Network (ANN), adaptive neuro-fuzzy inference system (ANFIS) and Group method of data handling (GMDH). Apart from monitoring techniques, monitoring instruments such as single use devices, pulse/radar device, Fiber-Bragg grating, driven/buried rod devices, sonar devices and electrical conductivity devices are discussed. AI techniques are fundamentally dependent on scour prediction equations and models. The AI techniques discussed in this paper are based on sonar measurements due to the ease of use and high accuracy.

Title: Pilot Installation of a Bridge Scour Monitoring Site

Author(s): Jose Weissmann, Huong Tung Chun, Carl Haas

Date: Dec 1999

Organization: University of Texas at San Antonio

Summary: A pilot scour monitoring system was installed at the Mustang Creek bridge crossing on FM-1157 in Jackson County, Texas. It consists of four ultrasonic sensors manufactured by Data Marine mounted on four bridge piers. The CR10X datalogger from Campbell Scientific is programmed to send out alerts when threshold for water level and scour are reached. The hardware and software of the monitoring system was extensively tested in the laboratory before field installation. The hardware and software setup is proven to be suitable for ultrasonic sensors and magnetic sliding collar.

Time Domain Reflectometry

Title: Active scour monitoring using ultrasonic TDR to detect soil interface

Author(s): Morgan L. Funderburk, Michael D. Todd, Anton Netchaev, and Kenneth J. Loh

Date: March 2021

Organization: University of California San Diego

Summary: The objective of this study is to develop scour depth monitoring sensors using ultrasonic time domain reflectometry (UTDR). The scour sensor is based on an aluminium strip with two piezoelectric macro fiber composites (MFCs) bonded at one end. The aluminium strip function as a rod-like sensor that is driven or buried at the desired monitoring location. The MFCs are used to sense ultrasonic Lamb wave pulses propagating in the aluminium strip, which changes with distance between soil interface to the MFCs. The sensor was tested in a controlled and dry laboratory setting using various material interfaces. It was found that the time-of-flight of the response pulse within residual Lamb signature could be used to accurately determine the location of scour depth.

Float-out Devices

Title: Bridge's Scour Monitoring System

Author(s): Yuan Ping Luh, Ying Chang Liu

Date: Dec 2013

Organization: National Taipei University of Technology

Summary: A bridge scour monitoring system based on float-out devices integrated with RFID, Wireless Charging and GIS (Geographic Information System) technology is proposed. A prototype system is installed at Yufeng bridge upstream of Dahan river in 2010. The monitoring depth resolution of the system is one meter. The system has functioned successfully and recorded scour data during the 2012 TALIM typhoon in Taiwan. The monitoring system has demonstrated capability to monitor scour depth and raise alarm if necessary.

Smart Rock Technology

Title: Characterization and field validation of smart rocks for bridge scour monitoring

Author(s): Fujian Tang, Yizheng Chen, Zhaochao Li, Xiuyan Hu, Genda Chen, Yan Tang

Date: 2019

Organization: Dalian University of Technology (China), Missouri University of Science and Technology, Tongji University (China)

Summary: In this study, two types of smart rocks (arbitrary oriented system AOS and automatically pointing south system APSS) are proposed, characterized and validated for bridge scour monitoring. Algorithms are developed to pinpoint the location of the smart rock and effect of smart rocks on geomagnetic field is numerically studied. Calibration test is performed in the lab, and validation test conducted in a large flume in the Hydraulic Engineering Lab at Turner-Fairbank Highway Research Center, VA, USA. A principle for effective monitoring is also proposed.

Title: Field Application of Magnet-based Smart Rock for Bridge Scour Monitoring

Author(s): Fujian Tang, Yizheng Chen, Chuanrui Guo, Liang Fan, Genda Chen, Yan Tang

Date: 2019

Organization: Dalian University of Technology (China), Missouri University of Science and Technology

Summary: In this study, a smart rock whose direction is always pointing downwards, is proposed to monitor bridge scour depth. An algorithm was developed to localize the position of the smart rock based on the intensities of measured ambient magnetic field (AMF) and total magnetic field (TMF). Field tests were conducted at the I-44W Roubidoux Creek Bridge in Waynesville, Missouri at three different times. The algorithm successfully localized the position of the smart rock with an error ranging from 0.26m to 0.33m, which is reasonable for engineering applications.

Title: Laboratory validation of buried piezoelectric scour sensing rods

Author(s): Faezeh Azhari, Kenneth J. Loh

Date: Dec 2015

Organization: University of Toronto, University of California-San Diego

Summary: This study focuses on evaluating the use of a driven piezoelectric scour sensing rod, where the real‐time dynamics of the voltage response of the sensing rod is used to determine scour depths using the inverse relation between natural frequency and the rod's exposed length. A poly (vinylidene fluoride) polymer strip that is developed in-house, forms the main sensing component of this prototype sensor. A single PVDF film covers the entire sensor length, allowing continuous measurements. After confirming the viability of the sensing concept through various idealized lab tests to validate the sensing mechanism, the response of the sensors was studied in scour conditions simulated in a laboratory flume. The proposed sensor identifies scour depths from changes in the measured natural frequency of the exposed (cantilevered) portion of the rod. The rod sensor can be driven into the streambed where scour depth measurements are desired.

Title: Smart Rock technology for local scour monitoring of bridge structures

Author(s): F. Tang, Y. Chen, Y. Tang, Z. Li, G. Chen

Date: 2021

Organization: Dalian University of Technology (China), Missouri University of Science and Technology

Summary: This study provides a comprehensive review on the smart rock technology, including sensing principles, evaluation, localization algorithm, effective monitoring range and field tests to monitor local scour depth of bridge piers and abutments. As of the published date, three types of smart rock technology are developed – 1) Arbitrary oriented system (AOS), 2) Automatically pointing south system (APSS) and 3) Automatically pointing upward system (APUS). A comparison was also made between smart rock and other technologies such as optical fiber sensor, ground penetration radar, sonar, magnetic sliding collar etc. Field test of the smart rock was successfully conducted at US63 bridge over the Gasconade River located near Vienna, Missouri.

Title: UAV-based smart rock localization for bridge scour monitoring

Author(s): Haibin Zhang, Zhaochao Li, Genda Chen, Alec Reven, Buddy Scharfenberg, Jinping Ou

Date: Jan 2020

Organization: Missouri University of Science and Technology, Harbin Institute of Technology (China)

Summary: In this study, an unmanned aerial vehicle (UAV) is proposed as a mobile station for measurement of magnetic fields for the implementation of smart rock to determine maximum scour depth. The UAV was equipped with a three-axis high resolution magnetometer and global positioning system (GPS). The effects of UAV speed, motor current and GPS accuracy on the smart rock positioning were investigated in an open field. Field tests were conducted at the I-44 Roubidoux Creek Bridge in Waynesville, Missouri demonstrated a ~0.3m accuracy of smart rock positioning. The monitoring system was also able to capture scour data during a flood event in 2019. A comparison is made between the proposed UAV method and the previous crane-based smart rock positioning method.

Title: Smart Rock technology for local scour monitoring of bridge structures

Author(s): F. Tang, Y. Chen, Y. Tang, Z. Li, G. Chen

Date: 2021

Organization: Dalian University of Technology (China), Missouri University of Science and Technology

Summary: This study provides a comprehensive review on the smart rock technology, including sensing principles, evaluation, localization algorithm, effective monitoring range and field tests to monitor local scour depth of bridge piers and abutments. As of the published date, three types of smart rock technology are developed – 1) Arbitrary oriented system (AOS), 2) Automatically pointing south system (APSS) and 3) Automatically pointing upward system (APUS). A comparison was also made between smart rock and other technologies such as optical fiber sensor, ground penetration radar, sonar, magnetic sliding collar etc. Field test of the smart rock was successfully conducted at US63 bridge over the Gasconade River located near Vienna, Missouri.

Magnetic Sliding Collar

Title: Field measurements and simulation of bridge scour depth variations during flood

Author(s): Jau-Yau Lu, Jian-Hao Hong, Chih-Chiang Su, Chuan-Yi Wang, Jihn-Sung Lai

Date: June 2008

Organization: National Chung Hsing University (Taiwan, China)

Summary: In this study, field experiments were performed at the Si-Lo Bridge in the lower Cho-Shui River, Taiwan using a sliding magnetic collar, a steel rod and a numbered-brick column. By separating each scour component, a methodology for simulating temporal variations of total scour depth under unsteady flow conditions is proposed using the concept of primary vortex from Kothyari et. al. 1992. The numbered-brick column is placed 100m upstream of bridge piers where the maximum value of general scour depth can be determined from the number of washout bricks during typhoons.

Portable Instrumentation

Title: Multi-hazard Assessment of RC bridges Using Unmanned Aerial Vehicle-based measurements

Author(s): Orkan Ozcan, Okan Ozcan

Date: May 2018

Organization: Istanbul Technical University, Akdeniz University (Turkey)

Summary: A practical unmanned aerial vehicle (UAV)-based scour measurement method was proposed to increase the measurement accuracy and reduce implementation costs. The proposed methodology involves the generation of 3D point cloud using UAV derived aerial photos. The Structure-from-Motion (SfM) technique was adopted instead of the conventional topographical survey methods. The method has been implemented in shallow and clear-water riverbeds at the Bogacayl Bridge in Antalya, Turkey. The amount of scour was detected by longitudinal and transverse cross-sections along the bridge with considerable accuracy, with the measurements used to develop a 3D finite element model.

Title: ScourBuoy – concept for scour monitoring system

Author(s): Antonijia Harasti, Gordon Gilja, Matej Varga, Robert Fliszar

Date: April 2021

Organization: University of Zagreb (Croatia)

Summary: The paper presents ScourBuoy, an integrated functional scour monitoring system during flood conditions based on commercially available technical devices. The system consists of a single beam echo sounder, multi-GNSS device for 3D positioning, compass and motion sensor for pitch and roll data. ScourBuoy prototype was built using a small-scale pipe float with an 80mm inner diameter hole, which was used as an holder for an aluminum pipe. The prototype is currently under development within the R3PEAT Project (Remote Real-time Riprap Protection Erosion Assessment on Large Rivers).

Title: Underwater Acoustic Imaging Device for Portable Scour Monitoring

Author(s): Terence M. Browne

Date: 2010

Organization: Collins Engineers Inc.

Summary: This paper provides an overview and evaluation of current sonar technologies with a focus on underwater acoustic imaging, which can provide photo quality visual images of submerged elements and channel bottom elevation. Sonar technologies evaluated includes fathometers, multi-beam swath sonar, side-scan sonar, sector-scan sonar, lens-based multi-beam sonar, and geophysical sub-bottom sonar profilers. Despite the advancement of sonar technologies, it is determined that human interaction still plays a vital role in the evaluation of scour. The paper directs readers to look at the Underwater Bridge Inspection Manual 2010 by FHWA for further information.

Camera-based Technologies

Title: Pier Scour monitoring system by bed-level image tracking

Author(s): Wen-Yi Chang, Jihn-Sung Lai, Teng-Yi Yu, Franco Lin, Lung-Cheng Lee, Whey-Fone Tsai, Ching-Hsiung Loh

Date: 2014

Organization: National Applied Research Laboratories (Taiwan, China)

Summary: A scour monitoring system with a micro camera tracking bed-level images is proposed in this paper. Two image recognition algorithms – brightness intensity segmentation (BIS) and particle motion detection (PMD) have been developed in-house to recognize the bed-level position and obtain scour-depth evolution through a series of scour image processing. Through laboratory experiments of pier scour in a flume at the Hydrotech Research Institute of National Taiwan University, the study demonstrates that the proposed system is able to accurately monitor the scour depth evolution in real time.

Other Technologies

Title: Scour Monitoring Development for Two bridges in Texas

Author(s): C. Yao, C. Darby, S. Hurlebaus, G. R. Price, H. Sharma, B.E. Hunt, O.Y. Yu, K.A. Chang, J.L. Briaud

Date: 2010

Organization. University of Texas A&M

Summary: This paper demonstrates two cases of bridge scour monitoring systems developed for two bridges in Texas. The TBS is a float-out device invented by ETI Instrument Systems Inc. Other instruments used in the project include a water stage sensor, tilt sensor, motion sensor and sonar sensor. Lab experiments were conducted in a 2D flume at Texas A&M University. Field tests were conducted at US59 bridge over Guadelupe River in 2009 and State Highway 80 bridge over San Antonio River. The lessons learnt from the two systems led the authors to the conclusion that Tethered Buried Switches (TBS) for early warning sensors should be preferred. Acceleration and frequency-based behavior tracked by motion sensors are very complex in full scale bridges, hence unable to be demonstrated successfully in field tests.

Title: Electromagnetic Sensors for Underwater Scour Monitoring

Author(s): Andrea Maroni, Enrico Tubaldi, Neil Ferguson, Alessandro Tarantino , Hazel McDonald, Daniele Zonta

Date: Jul 2020

Organization: University of Strathclyde (UK)

Summary: This paper illustrates the concept, development and deployment of a scouring monitoring system consisting of smart probes equipped with electromagnetic sensors. The EnvironSCAN probe developed by Sentek sensor technologies and provided by Soil Moisture Sense UK are designed to observe changes in the dielectric permittivity of the medium (air, water, refilled soil and saturated soil) around bridge foundations, allowing the detection of scour depths and refilling process. The monitoring system was installed on the A76 200 Bridge in New Cumnock (Scotland) and has provided continuous monitoring for at least two years. The system was able to record scour data after a peak flood event. Measurements were validated with visual inspection.

Title: Methods for monitoring scour from large diameter heat probe tests

Author(s): Mohsen Amirmojahedi, Shatirah Akib, Hossein Basser and CH Raymond Ooi

Date: 2016

Organization: University of Malaya (Malaysia)

Summary: In this study, a large-scale tube consisting of heating and temperature sensing elements is developed in-house, and its application for detecting saturated soil and water is analyzed. Thermal properties of soil and water are different, making thermal sensors usable for scour monitoring. The sensor is made up of a heating wire, a thermistor and a container probe. Laboratory experiments validated the application of the thermal sensors for scour-monitoring purposes. Three methods are proposed for analyzing data obtained from a heat probe to determine scour. The heat probe was also tested at the Seri Setia Bridge that spans the Putrajaya River located in Putrajaya, Malaysia.

Title: Bridge Scour: Prediction, Modeling, Monitoring and Countermeasures – Review

Author(s): Lu Deng, C.S. Cai

Date: May 2010

Organization: Louisiana State University

Summary: This paper presents a comprehensive review of the up-to-date work on scour at bridge piers and abutments. The review consists of 1) prediction of bridge scour, 2) numerical and laboratory models, 3) field tests and laboratory experiments, 4) techniques and instruments for scour monitoring and 5) scour mitigation countermeasures. Scour monitoring instruments discussed includes radar, sonar, time domain reflectometry, fiber optic sensors, magnetic sliding collar and steel rods.

Title: Monitoring and Plans for Action for Bridge Scour (conference paper)

Author(s): Everett V. Richardson, Jorge E. Pagan-Ortiz, James D. Schall, Gerald R. Price

Date: November 2016

Organization: Owen Ayres & Associates, Colorado State University, FHWA, ETI Instrument Systems Inc.

Summary: This paper describes both fixed and portable instruments for scour monitoring and experiences related to their installation. Fixed instruments detailed includes instrument shelters, driven rods, sounding rods, fathometers and buried devices. Portable instruments discussed includes physical probes, sonar devices, and geophysical instruments. The paper also touched on the essential components of a plan of action for scour monitoring.

Title: Autonomous Scour Monitoring of Bridges and Embankments Using Bio-Inspired Whisker Flow Sensor Arrays

Author(s): R. Andrew Swartz, Baibhav Rajbandari, Benjamin D. Winter

Date: September 2014

Organization: Michigan Tech

Summary: This paper presents a novel monitoring approach utilizing an embedded array of bio-inspired, magnetostrictive whisker-shaped flow sensors that detect water flow. The differentiation of dynamic (free) and (buried) static signals allow for the description of the state of scour. Fluid structure interaction for whiskers will create significant dynamic signals when flow rates are high while static signals will be recorded if whiskers are buried. In this paper, the effectiveness of signal processing and scour detection algorithms are explored for water-coupled magnetostrictive whisker sensors of varying geometries to determine their sensitivity and thresholds for false alarms and missed alert conditions under varying flow rates. Laboratory flume tests (one-meter-wide scour flume) were conducted to test the sensors.

Title: A Piezoelectric Film Type Scour Monitoring System For Bridge Pier

Author(s): Chung-Yue Wang, Hao-Lin Wang, Chun-Che Ho

Date: 2012

Organization: National Central University, Taiwan

Summary: This paper presents an upgraded piezoelectric film type sensor for real-time scour monitoring. The sensing device can be constructed by mounting thin piezoelectric films along the rod at a fixed distance. A voltage is generated from the vibration or deformation of the piezoelectric film. The piezoelectric film embedded in the soil of the riverbed is undisturbed, resulting in a much smaller output voltage as compared to the part that is enduring the water currents. The soil-water interface can easily be identified based on the voltage signal recordings. The upgrade presented in this paper involves an improved installation method and measuring technique. The signal processing technique is introduced through performance tests in laboratory flume for the novel piezoelectric film type scour monitoring.

Title: Using MEMS sensors in the bridge scour monitoring system

Author(s): Yung-Bin Lin, Jihn-Sung Lai, Kuo-Chun Chang, Wen-Yi Chang, Fong-Zuo Lee, Yih-Chi Tan

Date: Jan 2010

Organization: National Taiwan University (Taiwan, China)

Summary: In this study, micro-electro-mechanical system (MEMS) pressure sensors are integrated with the wireless Zigbee network on a sensor board for real time scour monitoring. A wireless MEMS scour monitoring system has been developed in-house and tested in the laboratory flume at the Hydrotech Research Institute of National University of Taiwan. Absolute fluid pressure can be measured directly by the MEMS pressure sensor, hence identifying the dynamic pressures attributed to impact forces from flow velocity, turbulence or sediment particle movement. The system is determined to be able to measure scour and redeposition process along with the variation of water levels at a bridge pier.

Title: Detecting Local Scour Using Contact Image Sensors

Author(s): Hongwei An, Weidong Yao, Liang Cheng, Scott Draper, Ming Zhao, Guoqiang Tang, Yu Zhang, Philip Hortin

Date: November 2016

Organization: University of Western Australia

Summary: This paper presents a novel contact image sensor (CIS) to monitor the local scour process around a model pile in flowing water. The CIS is an optical sensor that tracks the evolution of the soil-water interface based on the difference in the reflectivity of light from different media. When the sensor is buried in sediment, a strong reflection of light will be detected while a much lower reflection will be detected if sensor is exposed to water. This sudden change in sensor reading is used to detect scour around piles. This paper details a series of physical model tests to measure local scour around piles under steady current and tidal conditions to test the sensitivity and performance of the CIS.

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