

WIRELESS SMART ROCKS FOR REAL TIME SCOUR MONITORING

By Genda Chen, Ph.D., P.E., F. ASCE, David Pommerenke, Ph.D., and Rosa Zheng, Ph.D.

Missouri University of Science and Technology (formerly University of Missouri-Rolla)
in Collaboration with J. Sterling Jones Hydraulic Research Laboratory at the Turner-Fairbank Highway Research Center in Federal Highway Administration

INTRODUCTION

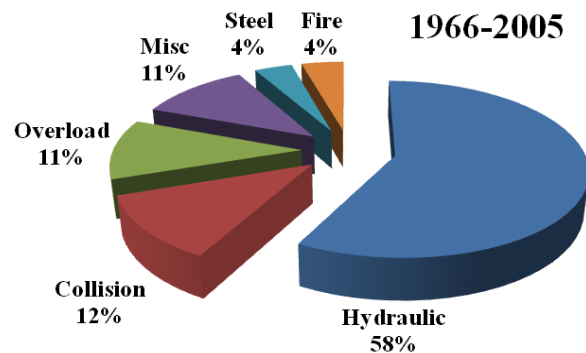
This summary article briefly reviews the societal needs for bridge scour assessment in real time, introduces a novel scour monitoring system with passive/active smart rocks and wireless communication, and outlines the technical approach and expected outcomes of an on-going study with the U.S. Department of Transportation Research and Innovative Technology Administration. This study will potentially provide a cost-effective evaluation tool for bridge scour, the #1 cause for over 1,500 bridge collapses in the US history. The remote sensing technology with smart rocks is directly transferable to other infrastructure installations such as river banks, dams and levees for their erosion monitoring and mitigation as well as slope stability both during flood events and in normal operations.

SOCIETAL NEEDS FOR REAL TIME SCOUR MONITORING

Fig. 1(a) illustrates the washed-away center pier of a continuous steel-girder bridge over the Thompson River in North Missouri due to the heavy rainfall on September 22, 2010. In the U.S., as indicated in Fig. 1(b), hydraulics (scour) is responsible for 58% of over 1,500 bridge collapses in the past 40 years (Briaud and Hunt, 2006). As clearly illustrated in Fig. 2, it is also a growing problem (Lagasse et al., 1997, Hunt, 2005). The number of scour critical bridges (when their foundations have been determined to be unstable for the calculated or observed scour condition) increases from 2% by 1997 to 5% by 2005. Similarly, the number of scour susceptible bridges over water increases from 29% to 40% over a period of eight years.



(a) Loss of Center Pier



(b) Causes of Bridge Collapse

Fig. 1 Scour-Induced Bridge Damage and Statistics

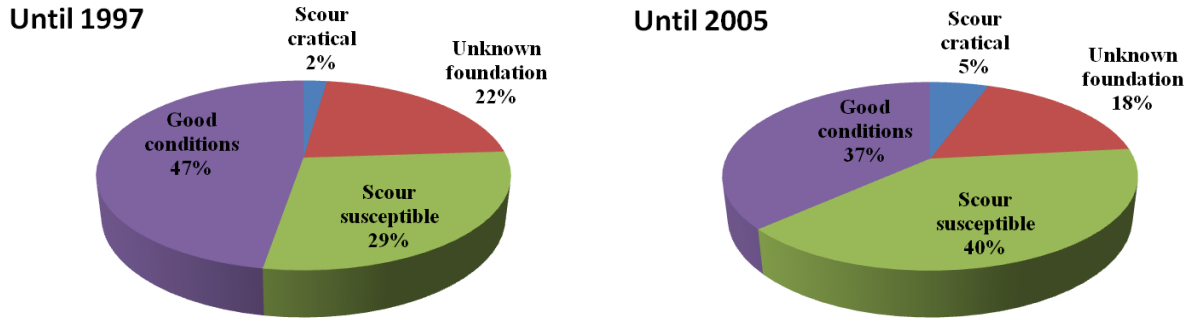


Fig. 2 Growing Problems with Bridge Scour

Due to the criticality of bridge scour, approximately 17 monitoring methods have been developed by 2005 though there were no accepted methods or off-the-shelf equipment for collecting scour data prior to the early 1990s (Mueller and Landers, 1999). According to HEC-23 (Lagasse et al., 2001), the monitoring methods can be classified into three groups as portable instruments, fixed instruments, and others, respectively. Their advantages and disadvantages can be found from Schall and Price (2004) and Ettema et al. (2006). Some of the main technologies are compared in Table 1 in terms of cost, measurement accuracy, durability, ease in installation, and applicability in various environments. They often provide an incomplete set of mission critical data for scour evaluation due to unknown scour locations and refilled scour holes, and cannot survive the harsh environment (debris/ice/muddy/current) during a flood event. Overall, the proposed smart rock technology listed at the bottom of Table 1 expects to be superior to existing methods.

Table 1 Existing Technologies versus the Proposed Technology

Method	Cost (×\$1,000)	Accuracy	Durability	Ease in installation	Applicability		
					Current	Debris/ice	Mitigation
Diver	0.5-1	Poor	NA	Good	NA	NA	NA
Probing rods	2	Fair	Poor	Fair	NA	NA	NA
Ground penetration radar	3-10	Good	Fair	Poor	NA	NA	NA
Boats	0.5-1	Fair	NA	Poor	NA	NA	NA
Sonar	5-15	Good	Fair	Good	Good	NA	NA
Float-out	3	Fair	Poor	Fair	Poor	NA	NA
Magnetic collars	5-10	Good	Good	Good	Good	NA	NA
Optical sensors	5-10	Good	Fair	Fair	Good	NA	NA
Global positioning	5-20	Good	NA	Good	Good	Good	NA
Smart rocks	0.5-5	Good	Good	Good	Good	Good	Good

However, by 2005 the available technologies were only deployed on approximately 100 bridges in the U.S. due to their limitations and associated costs. At that time, fixed instruments were installed on 90% of the monitored bridges. The sonar scour system was the most popular device used at 51 bridge sites, followed by magnetic sliding collar at 23 sites and float-out device at 13 sites (Hunt, 2005). To date, little or no real time scour data exists from historic flood events.

On the other hand, real time monitoring of bridge scour is not only critical to maintain ground transportation services, but also a safety issue in a time window of hours or days during high flood seasons (NITS, 1988). Therefore, it is imperative to

develop a new monitoring system for scour evaluation in real time. To be more cost effective and robust in harsh environments, it is even desirable to combine the function of scour monitoring with scour mitigation strategies such as commonly-used riprap or armoring techniques with rocks (Chiew, 1992; Delatte, 2009). Riprap makes use of the increased weight of rocks to resist the increased turbulence caused by the presence of an abutment or pier (Maynard, 1988). Armoring produces a barrier with heavy rock units to withstand the eroding power of the local flow field formed around the bridge pier (Melville, 1997).

GOAL AND SPECIFIC OBJECTIVES

The current practice in bridge maintenance is to visually inspect bridge foundation scour by divers every five years unless a problem is detected. This practice is both uneconomical when a bridge is in good condition and risky missing occurrence of bridge scour in between two inspections. Under strong current situations, it is dangerous to have a special inspection of bridge scour condition with divers. Furthermore, visual inspections are qualitative and subjective, particularly in muddy water during a flood event when riverbed profiles are not visible to divers. Foundation scour has also been monitored with instruments but mostly in normal operations of bridges. During floods, neither visual inspection by divers nor existing instrumentation provide useful foundation scour data in real time, which is critical for a timely warning, response, and prevention of scour-induced collapsing of bridges in a time window of hours or days during a flood event.

This study is focused on two application scenarios for real time bridge scour monitoring: (1) determining the maximum scour depth around a bridge pier and (2) monitoring a riprap scour countermeasure with rocks. As illustrated in Fig. 3, Scenario 1 involves several smart rocks distributed against the side faces and around the perimeter of a footing or foundation cap of an existing (or new) pier. As it is undermined during a flood event, a properly-designed smart rock (slightly larger than the natural rocks near the foundation) falls and always stays at the bottom of a developing scour hole so that the maximum scour depth can be monitored and determined. To facilitate the monitoring of smart rock positions, a master (heavy, square, tied to the pier as needed) smart rock can be placed on top of the footing or foundation cap to serve as a reference point, collect data from nearby small smart rocks, and transmit data to a remote station.

As shown in Fig. 4, Scenario 2 involves smart rocks and natural rocks placed in an existing scour hole around a pier so that the effectiveness of the scour countermeasure can be evaluated over time. As it moves, a smart rock or its group with other smart rocks changes its position. The following discussions are mainly based on Scenario 2 for brevity and clarity.

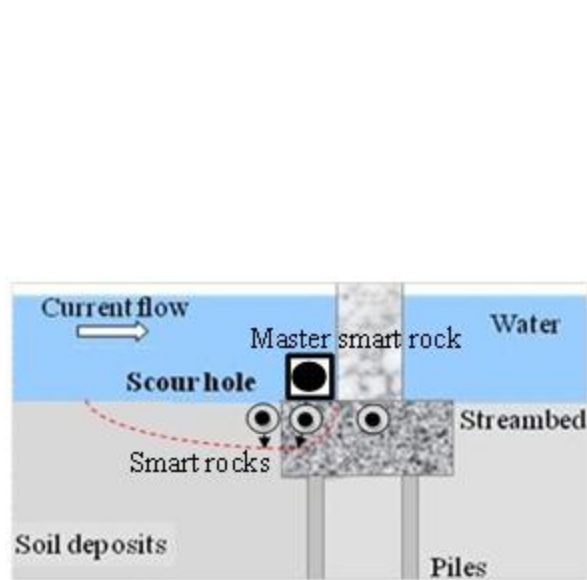


Fig. 3 Maximum Scour Depth Monitoring

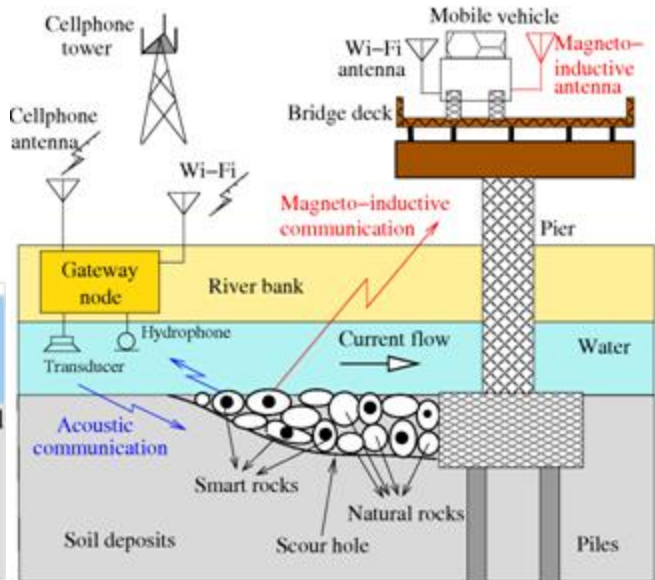


Fig. 4 Scour Countermeasure Monitoring

The long-term goal of this study is to develop a pragmatic but highly innovative, real-time bridge scour management system with remote sensing and communication technologies for integrated monitoring and mitigation of foundation scour. The specific objectives of this study are (1) to integrate several alternative commercial measurement and communication technologies into a scour monitoring system with passive and active sensors embedded in smart rocks, (2) evaluate the comparative effectiveness of these communication technologies in laboratory and field conditions and improve them for better performances and/or reduced costs in bridge applications, and (3) analyze the movement of smart rocks during testing for the determination of scour depth or the change in smart rock group, which directly correspond to the two application scenarios in Figs. 3 and 4.

TECHNICAL APPROACH

Each smart rock enables the tracking of its position over time through wireless coordination by an acquisition device at a remote station. Together, a group of smart rocks and the acquisition device form a wireless rock positioning system that potentially gives critical spatial information about bridge scour in real time. Smart rocks can be developed in two versions: passive and active. The passive smart rocks are rocks with embedded magnets for magnetic field measurements at distance while the active smart rocks with embedded electronics can be connected to a remote station with wireless magneto-inductive and acoustic communications. As spatially-distributed field agents, smart rocks can be deployed around a bridge foundation to register both temporal and spatial information of scour process and transmit critical data for an engineering evaluation of foundation scour in real time, particularly for the maximum scour depth and riprap mitigation strategy effectiveness. Scour vulnerability of multiple bridges affected by a flood event can then be reported anytime to engineer-in-charge and first responders through a cellular network as needed.

Details of the Scour Monitoring System

The remote sensing technology under development involves passive and/or active sensors embedded in rocks or reinforced concrete blocks, both referred to as smart rocks in this study, and magneto-inductive or acoustic communications for a real-time engineering evaluation of bridge scour. Together with natural rocks, smart rocks are not only distributed around a bridge foundation as shown in Fig. 4 for scour mitigation but also represent the process of bridge scour as they are washed away.

Passive smart rocks with embedded ferrous objects or magnets can locally alter the Earth's magnetic field and, once measured with a magnetometer equipped with a Global Positioning System (GPS), provide spatial information on the onset and process of bridge scour. Active smart rocks with embedded, battery-powered electronics or controllable magnets function as spatially-distributed field agents, register their locations, receive commands from a remote station near the bridge, and transmit mission-critical data that leads to an engineering interpretation of the spatial information (e.g. scour depth and area) of bridge scour. Specifically, active smart rocks are equipped with sensing and wireless communication systems. Sensors such as timers, 3-axis accelerometers and mini 3-axis magnetometers can provide temporal and spatial information about the rocks.

As illustrated in Fig. 4, magneto-inductive and acoustic communication systems can exchange critical sensing data and control commands between smart rocks and gateway nodes mounted in river bank or mobile vehicles. In addition, their signal strength and timing information can be exploited to estimate the location of the smart rocks. Magneto-inductive communication, often called radio-frequency (RF) communication, represents the near-field electromagnetic field coupling between transmitting and receiving antennas that penetrates well through both air and water over 50 m distance. Alternatively, a wireless acoustic communication network consists of underwater acoustic communication between smart rocks and gateway nodes installed on river banks, air Wi-Fi communication between the gateway nodes and a mobile vehicle, and air cellular communication between the gateway nodes and the office of engineer-in-charge. Utilizing the ultrasonic wave propagation in water, mud, and soil, the acoustic system provides robust communication over 100 m range among smart rocks and between smart rocks and gateway nodes.

Both wireless communication systems can continuously or periodically request, receive, process, and transmit mission-critical data to a mobile vehicle parked near a bridge or the office of engineer-in-charge. The multi-sensor data sets (e.g., rolls, tilts, headings, and centroid positions of smart rocks both individually and in group) and engineering and environmental information at the bridge site can then be fused together to improve the accuracy, reliability and completeness of real-time scour evaluation.

The Overall Project Activities

The operation environment for the scour monitoring system is extremely harsh, particularly during a flood event. To minimize the environmental effects on real-time scour monitoring, remote magnetic field measurements are investigated with passive smart rocks that encase ferrous objects or magnets. Both magneto-inductive and

acoustic systems are applied into wireless communications with active smart rocks that include battery-powered electronics for receiving, processing, and transmitting signals.

To achieve the project objectives, smart rocks and wireless communication systems will first be designed and built with commercial parts, and individually tested in the laboratory until their component performances are satisfied to pre-determined design criteria that will be developed in consultation with an External Advisory Committee. The tested components will then be integrated into an initial set of prototypes (multiple smart rocks, one magnetometer system, one water/air magneto-inductive modem system, and one underwater acoustic modem system) and tested in underwater conditions in laboratories or nearby lakes. The initial prototypes will next be field tested with two in-service bridges and, based on the test results, will be reviewed for performance improvement and cost reduction so that a trade-off will be sensitively made against the predetermined design criteria.

The individual prototypes will be re-designed to arrive at an integrated smart rock system consisting of smart rocks and remote measurements, which has the best performance within a certain budget restraint to meet the predetermined design criteria. The more integrated prototypes will be the final set of prototypes in this study. They will be extensively tested in the laboratory and finally field validated with two in-service bridges. Throughout the project, potential end users, manufacturers, and engineers through their service on the External Advisory Committee will participate in various tasks to ensure that practical solutions are derived and that commercialization paths are identified for the field validated technology upon completion of the current study.

Potential Technical Obstacles and Strategies to Overcome Them

Due to its harsh operation environment during a flood event, real-time scour monitoring at a bridge foundation must be operated at a remote station near the bridge or in the office of engineer-in-charge. It has two main obstacles for technological development: (1) relatively long distance between scour location and its monitoring station (e.g. 5 m ~ 30 m) and (2) multi-phase, multi-layer media with potential unknown objects in between (e.g. air/water/mud/deposit, metals carried at riverbed with water current). The scour monitoring system is promising to overcome these obstacles. Its advantages and disadvantages as well as potential mitigation strategies for all disadvantages are summarized below.

Bridge scour monitoring with passive smart rocks has the advantages of cost effectiveness, ease of deployment, and robustness to harsh environment. The technical challenges of this approach include (1) rapid attenuation of signals over distance, (2) potential signal interference from nearby ferrous objects and steel reinforcement of bridges, and (3) difficulty to locate individual rocks. The mitigation strategies for passive smart rocks include (1) maximizing magnetic field strength of the rocks by properly selecting the type of magnetization, material, volume, and shape of ferrous objects within the physical constraint of rocks, (2) improving the sensitivity of magnetometer detections, and (3) taking advantage of the background knowledge about the deployment site to fuse the change of measured magnetic field into scour signatures.

The advantages of active smart rocks include multiple sensing abilities, accurate identification and local measurement of individual rocks, ease of control and networking of multiple rocks. The challenges, however, include (1) need of power in deployed rocks

for long life time, (2) localization ambiguity due to multi-path propagations or low signal strength, and (3) high cost of current commercial communication products. The strategies to overcome the barriers include: (1) reducing transmission power while maintaining robust communication using well designed digital transceivers and brief data burst of less than 1 sec., (2) selecting quality batteries to target 20 years of operation life span, (3) possibly utilizing both magneto-inductive and acoustic wave propagation means to mitigate the localization ambiguity, (4) combining information from low-cost passive smart rocks and background site knowledge to improve scour monitoring, and (5) designing and integrating lower cost transceivers and their networking protocols.

EXPECTED OUTCOMES AND SIGNIFICANCE

The deliverables of this study include a prototype scour monitoring system (hardware), a scour depth evaluation model with measured data, and a real-time bridge scour management methodology. The results and outcomes will dramatically change the state-of-the-art and state-of-practice of sensing technologies, and potentially revolutionize the current management system of scour susceptible bridges. The technical approach taken in this study will reinforce/increase engineers' interests in structural health monitoring by collecting only mission-critical data and relating data to the ratings of existing bridges based on foundation susceptibility to scour.

In the U.S., over 1,500 bridges have collapsed in the past 40 years, making scour the #1 cause of catastrophic bridge failure. The smart rock technology is a cost-effective way to provide a timely warning and solution for bridge scour issues. In addition, the smart rock technology is directly transferable to other infrastructure installations such as water mains and wastewater collection systems. For example, smart rocks are equally applicable to river banks, dams and levees for their erosion monitoring and mitigation as well as slope stability both during flood events and in normal operations.

ACKNOWLEDGEMENTS

Financial supports for this study are provided by the U.S. Department of Transportation Research and Innovative Technology Administration (USDOT/RITA) under Cooperative Agreement No. RITARS-11-H-MST with Mr. Caesar Singh as Program Manager and by the Missouri Department of Transportation. The views, opinions, findings and conclusions reflected in this article are the responsibility of the author only and do not represent the official policy or position of the USDOT/RITA or any State or other entity.

REFERENCES

- Briaud, J.L., and B.E. Hunt, "Bridge Scour & the Structural Engineer," *Structures Magazine*, December 2006, pp.58-61.
- Chiew, Y. M., "Scour Protection at Bridge Piers," *Journal of Hydraulic Engineering*, ASCE, 118(9), 1992, pp.1260.
- Delatte, N. J., *Beyond Failure: Forensic Case Studies for Civil Engineers*, Reston, VA, ASCE Press, 2009.

- Ettema, R., T. Nakato, and M. Muste, "An Illustrated Guide for Monitoring and Protecting Bridge Waterways against Scour," Iowa Department of Transportation Project TR-515, 2006, pp.53-94.
- Hunt, B. E., "Practices for Monitoring Scour Critical Bridge," *NCHRP Report 205*, Transportation Research Board, 2005, 8p.
- Lagasse, P.F., E.V. Richardson, and J.D. Schall, "Instrumentation for Monitoring Scour at Bridge Piers and Abutments," *NCHRP Report 396*, Transportation Research Board, National Research Council, Washington, DC, 1997, 109p.
- Lagasse, P.F., L.W. Zevenbergen, J.D. Schall, and P.E. Clopper, "Bridge Scour and Stream Instability Countermeasures," *FHWA-NHI-01-003 Hydraulic Engineering Circular No. 23*, 2001, 402 p.
- Maynard, S. T., J.F. Ruff, and S.R. Abt, "Riprap Design," *Journal of Hydraulic Engineering*, ASCE, 115(7), 1988, pp.937.
- Melville, B. W., "Pier and Abutment Scour: Integrated Approach," *Journal of Hydraulic Engineering*, ASCE, 123(2), 1997, pp.125-136.
- Mueller, D.S., and M.N. Landers, "Portable Instrumentation for Real-time Measurement of Scour at Bridges," *Report FHWA-RD-99-085*, Federal Highway Administration, McLean, VA, 1999, pp.12-46.
- NTSB, "Collapse of New York Thruway (I-90) Bridge over the Schoharie Creek, near Amsterdam, New York, April 5, 1987," *Highway Accident Report: NTSB/HAR-88/02*, National Transportation Safety Board, Washington, D.C., 1988.
- Schall, J.D., and G.R. Price, "Portable Scour Monitoring Equipment," *NCHRP Report 515*, National Research Council, Washington, D.C. 2004, pp.4-36.