White Paper: Tiltmeter-Based Bridge Scour Monitoring

David Kosnik, P.E.
Infrastructure Technology Institute
Northwestern University
Evanston, Illinois
dkosnik@northwestern.edu
847-467-6684

Steve Ng, P.E.
Structure Hydraulics & Hydrology
California Department of Transportation
Sacramento, California
steve_ng@dot.ca.gov
916-227-8018

February 17, 2010

EXECUTIVE SUMMARY

Scour is by far the primary cause of bridge failures in the United States. Scour and other hydraulic effects are particularly threatening because the deterioration is often invisible, hidden beneath turbid water. Many scour monitoring methods attempt to measure the development of scour pockets themselves. However, this is difficult due to debris — both floating and submerged — and shifting streambeds. Scour holes develop and backfill with loose sediment as flood discharges peak and recede, misleading the engineer to assess that conditions are good. The newly deposited sediments fail to indicate the true loss of ground stability. To address this issue, the Infrastructure Technology Institute at Northwestern University, in cooperation with the California Department of Transportation, developed a scour monitoring system based on direct measurement of the response of the bridge structure to scour. Using sensitive electronic tilt sensors mounted at the top of each pier, the system measures the movement of each pier cap. Observation of the bridge's response to daily and seasonal temperature cycles reveal the normal structural movement patterns, which are used to construct an envelope of typical safe operation. That is, if pier movement during high water periods differs from the typical pattern, further action — up to and including bridge closure — may be required. However, if pier movement during high water is similar to the historic record, the engineer gains confidence that the bridge substructure is not affected by scour. The tilt sensor-based system is composed of commercial off-the-shelf equipment and is fully scalable; it has been deployed successfully on both short and long bridges — from structures a few hundred feet long with only two or three piers to a quarter-mile-long bridge with eighteen instrumented piers. Remote communication and robust Internet-enabled display technology provide convenient access to both real-time and historical data, enabling quick comparison for decision-making.

INTRODUCTION

Hydraulics, including scour, is by far the primary cause of bridge failures in the United States[1]. Scour and other hydraulic effects are particularly threatening because the deterioration is often invisible, hidden beneath turbid water or obscured by loosely re-deposited material. Evaluation of the stream channel, including probing for scour pockets, has been part of the National Bridge Inspection Standards since 1988[2]. For many bridges, probing about substructure elements with a soil tile probe during biennial inspections may be sufficient. However, some bridges present particular challenges to scour evaluation due to natural or artificial factors. Among these bridges are three structures that were monitored in a cooperative deployment by the Infrastructure Technology Institute (ITI) at Northwestern University and the California Department of Transportation (CalTrans). This white paper will describe the principle and practical aspects of scour monitoring with remotely-accessible tilt sensors, including a case study of one of these locations.

MOTIVATION

Most instrument-based scour monitoring methods — including sonar, magnetic sliding collars, and float-out devices — attempt to measure the development of scour pockets themselves. This is difficult for several reasons. In the case of sonar, water turbidity associated with scour velocities cloud the formation of the hole, while accumulation of debris or re-deposition of loose sediment with little strength will obscure the “view” of the scour hole, creating a false sense of security. Magnetic sliding collars and float-out systems are point measurement devices, designed to detect scour only if it occurs at the instrument location. Unfortunately, the streambeds in some watercourses are highly variable — even snaking around bridge piers in wildly different ways depending on flow conditions — and as such, scour holes may develop at any location around a pier. Figure 1 presents an example of a scour hole along, rather than at the upstream or downstream end, of a pier. Floating debris, such as logs, also may damage or destroy fixed instruments along the streambed. For all these reasons, a more holistic or global approach to scour monitoring is desirable for certain hydraulically-interesting bridges.

MONITORING PRINCIPLE

Rather than attempting to measure scour holes themselves, the ITI-CalTrans approach is to measure the response of the bridge piers to scour. Using sensitive electronic tilt sensors mounted at the top of each pier, the system measures the movement of each pier cap. All bridge structures exhibit movement due to quasi-static loads such as temperature changes as well as much smaller movements due to dynamic loading from traffic, wind, and other factors. Observation of the bridge’s response to daily and seasonal temperature cycles indicates a pattern of normal quasi-static structural movement, which

Figure 1: Scour pocket along, rather than at the upstream or downstream end of, a bridge pier

may be used to construct an envelope of typical safe operation. For structures at scour-prone locations, movement beyond expected norms is assumed to be the result of scour effects on the substructure. If pier movement during high water periods differs from the expected pattern, further action — up to and including bridge closure — may be required. However, if pier movement during high water is similar to the historic record, the engineer gains confidence that the bridge substructure is not affected by scour. This approach requires continuous monitoring with highly sensitive instruments, but provides a global perspective of bridge response, regardless of where or how scour holes develop around the substructure.

INSTRUMENTATION

The scour monitoring system is based on commercial off-the-shelf tilt sensors, also known as *tiltmeters* or *clinometers**. Each sensor consists of two parallel curved metal plates with silicone fluid between them. A gas bubble floats in the fluid between the plates. As the bridge structure rotates, the sensor is tilted, and the bubble moves in the fluid, changing the capacitance between the parallel plates — essentially, the tilt sensor is an electronic spirit level, capable of resolving one one-thousandth of a degree of rotation. Unlike tilt sensors based on MEMS accelerometers, capacitive tilt sensors are not subject to long-term drift. The temperature response characteristics of the capacitive tilt sensors are well understood, and thermal drift is easily compensated for through a linear correction.

*Sometimes, the term *inclinometer* is also used, but this can lead to confusion with a geotechnical slope and excavation monitoring device of the same name.

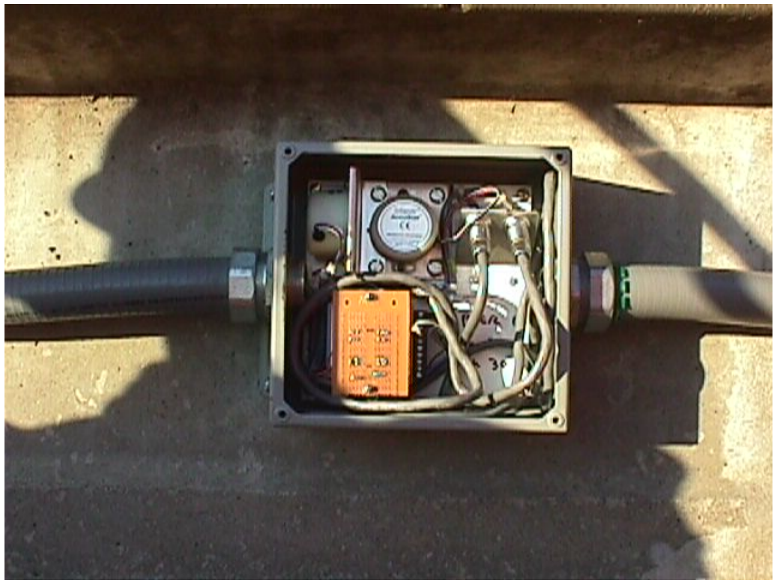

Figure 2: Tilt sensor enclosure deployed on bridge. The lid of the enclosure has been removed to show the contents. The orthogonal pair of tilt sensors is visible on the angle bracket in the upper left corner of the box, and the modular electrical connectors are visible at the upper right.

On-board signal conditioning electronics convert the change in capacitance to a DC voltage output which varies linearly with tilt angle. The sensor and electronics are fully sealed against water and dust. An orthogonal pair of tilt sensors is installed in a small enclosure on each monitored pier to characterize motion along both the longitudinal and transverse axes of the bridge. A thermocouple in each enclosure provides data for temperature correction. Each instrument enclosure features modular jacks for power and communication connections. Each device may then be assembled and tested in the lab and quickly and easily installed in the field.

DATA ACQUISITION, COMMUNICATION, AND POWER

The tilt sensor-based system is composed of commercial off-the-shelf equipment and is fully scalable; it has been deployed successfully on short bridges (a few hundred feet long) with only two or three piers as well as a quarter-mile-long bridge with eighteen instrumented piers. Remote communication and robust Internet-enabled display technology provide convenient access to both real-time and historical data, enabling quick comparison for decision-making.

A base station at one end of the bridge typically includes electrical service, a communication link to the outside — a cellular modem, land-line telephone, point-to-point radio link, or high-speed Internet connection, for example — and a rugged data acquisition computer and support electronics. 120 VAC electrical service to the base station is preferred, but solar-powered installations can be used. Both AC- and solar-powered systems may employ automatic fail-over to battery power.

A four-conductor instrument cable encased in conduit running along each span of the bridge connects provides the power and communication link to each tilt sensor pair. DC power is run along to the cable, and DC-DC converters at each tilt sensor pair provide regulated power to the sensors. On very long bridges, it may be preferable to use AC power on the bridge, with supplemental transformers and DC power supplies at selected intervals.

A two-wire RS-485 serial bus provides a digital communication link along the bridge. RS-485 is a multi-drop protocol, meaning that many devices can share the same physical bus, simplifying wiring. RS-485 is also very resistant to electrical noise and is well suited to very long cable lengths.

A rugged field computer at the base station serves as the communication and control hub. At prescribed intervals — typically once an hour — the field computer reads each tilt sensor several times, averages the readings to eliminate any electrical noise artifacts, and records the average on its hard drive. The field computer may then “push” the data to a central location or wait for data to be “pulled” automatically or manually. Storage on the local hard drive prevents loss of data in the event of communications disruption. In that case, the field computer will continue to collect and store data until communications are restored and all data are downloaded.

MONITORING

Typically, measurements are taken every hour and saved on the on-site field computer. Engineers may connect to the field computer on demand to download data; however, it is preferable to configure automatic data downloads. Software and methods developed at ITI facilitate autonomous transmission of data from a field computer to a password-protected Web site, where data are easily shared among stakeholders. Figure 3 is a schematic of that process.

The ITI-CalTrans method of tiltmeter-based scour monitoring depends on creation and maintenance of a record of historical response of the bridge to daily and seasonal thermal cycles as a baseline for comparison. In many cases, it is sufficient to qualitatively examine the data by eye to determine whether current pier motions are typical or atypical — and therefore cause for further investigation. Quantitative analyses which account for daily and seasonal effects on bridge response are also available. Among these approaches are the time-series analysis methods described by Washington et al. [4].

Time-series plots of each pier’s longitudinal and transverse response provide a basic sense of normal behavior, as shown in Figure 4. However, it can be more useful to plot the longitudinal response against the transverse response, generating a graph similar to Figure 5. This method reveals a clear elliptical envelope of normal behavior.

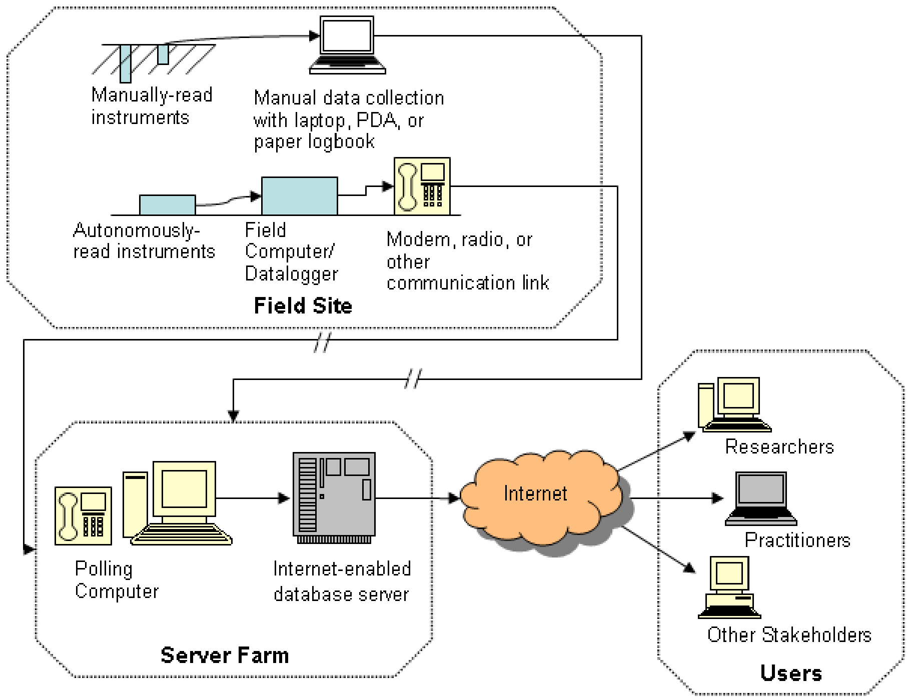

Figure 3: Autonomous transmission of data from field to password-protected Web site (after Kosnik [3])

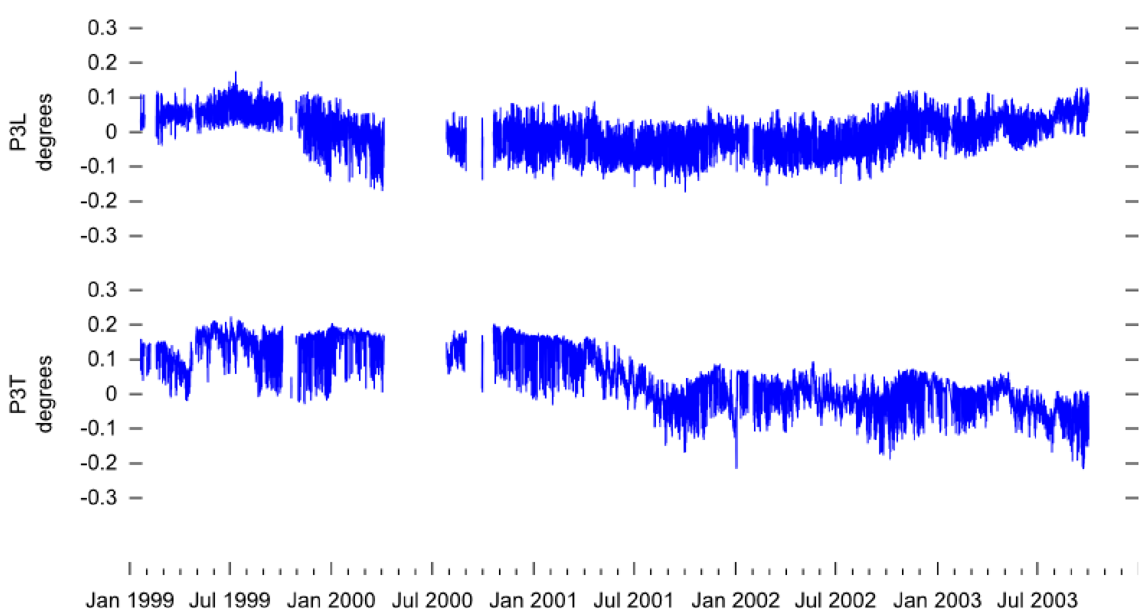

Figure 4: Time history of typical longitudinal and transverse response of a pier

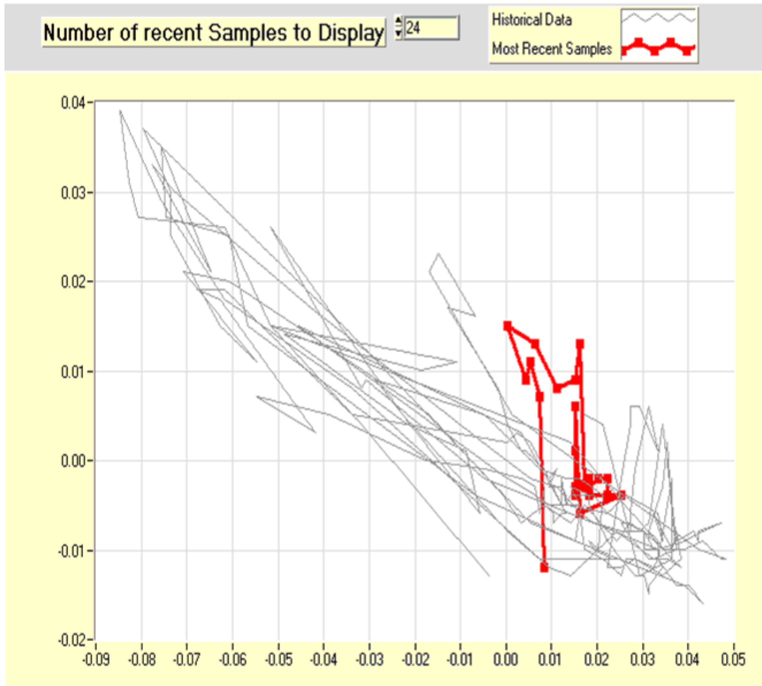

Figure 5: Typical longitudinal response plotted against transverse response. The most recent data are highlighted for easy comparison to the historical record.

CASE STUDY: STATE ROUTE 32 OVER STONY CREEK, GLENN COUNTY, CALIFORNIA

The Stony Creek Bridge (CalTrans Bridge Number 11-92), completed in 1976, was a two-lane 1492 foot continuous concrete box structure over a tributary of the Sacramento River subject to highly variable flows. The river discharges from the Black Butte Reservoir, approximately 15 miles upstream from the bridge. While Stony Creek is only a few feet wide during summer low water, winter storms cause it to swell into a torrent nearly a quarter-mile wide, capable of moving significant amounts of sediment. Appreciable active in-stream gravel mining operations occur within a few hundred feet of the bridge in both the upstream and downstream channel reaches, increasing channel degradation at this location. Material was lost quickly from the streambed under these conditions, and the bridge foundations were partially exposed by 1992. Though riprap and other countermeasures were installed, the bridge was rated scour critical again within eight years due to ongoing degradation of the streambed[5].

CalTrans engineers considered the threat of scour at this vulnerable structure during high water periods to be severe enough to warrant stationing personnel with survey equipment at the bridge 24 hours a day during high water. The field observer checked the bridge hourly and had authority to close the bridge to traffic if excessive tilt was observed. As the name suggests, the stream bed consists primarily of loose stones, and constantly shifts with changes in flow. The bridge was supported by 19 piers (numbered

2–20, with abutments numbered 1 and 21); each pier was built on concrete pile caps over either steel or concrete pilings. At low water, Stony Creek flows parallel to the bridge on the upstream side and make a right-angle turn to flow beneath the bridge between Piers 19 and 20, leaving the remainder of the streambed dry. During high flow, however, all piers were in the water. Piers 3–20 were instrumented with tiltmeters. The installation and early monitoring of the system at Stony Creek was described in detail by Marron [6].

Figure 6: Overall view of the downstream side of the Stony Creek Bridge, looking east. At low flow, the stream passes under the far end of the bridge in this view.

The Stony Creek Bridge was eventually replaced by a new structure built on high-capacity piles[5]. The new structure was built alongside the old; ITI and CalTrans monitored the old bridge until it was taken out of service. Monitoring was continuous with the exception of interruptions due to lightning strikes. Tiltmeter-based scour monitoring increased CalTrans engineers' confidence in the Stony Creek Bridge during high water, helping keep the bridge open until it could be replaced as scheduled.

COMPARISON WITH OTHER SCOUR MONITORING METHODS

CalTrans has experience with a wide variety of instruments for scour monitoring. These include float-out devices, magnetic sliding collars, sonar, stage gages, time-domain reflectometry (TDR), and a Brisco monitor. Each of these devices attempts to measure the formation of scour holes. With the exception of sonar, each device must be installed in the streambed (sonar devices must be installed with the transducer submerged). In general, these systems provide "point measurements" — an indication of changes in the streambed at the particular location of the instrument only. The ITI-CalTrans tiltmeter-based system, by contrast, provides an overall indication of the structure's response to scour, no matter where the scour occurs. Several additional advantages are gained by instrumentation of the bridge rather than the streambed. Most importantly, the system is not susceptible to misleading reports due to turbidity or accumulation of debris. The instruments are not vulnerable to damage from floating or submerged debris, and are easier to install and maintain since no entry into the water is required. Furthermore, elimination of the need to mount devices in-stream may provide environmental benefits.

CONCLUSION

The ITI-CalTrans tiltmeter-based scour system at Stony Creek worked well from installation through replacement of the bridge. The hard-wired system proved to be robust, with reliable data downloads. With the monitoring system in place, CalTrans engineers no longer considered it necessary to post a field observer on-site during high water. Ultimately, no excessive movement of the piers was recorded while the instruments were in place.

While the tiltmeter-based system is a powerful monitoring tool, it cannot replace engineering judgment regarding the safety and serviceability of a bridge. The system is designed to track the movement of the piers and provide an indication if the bridge is subject to excessive movement. Tilt data should not be considered as the sole trigger for activation of scour emergency plans. However, careful and timely analysis of tilt data by an experienced engineer may provide sufficiently early warning of possible failure to enable a proactive response.

ACKNOWLEDGMENTS

The Infrastructure Technology Institute is a National University Transportation Center funded by the US Department of Transportation Research and Innovative Technology Administration. This work was conducted in partnership with CalTrans Structures Maintenance and Investigations.

REFERENCES

[1] Hunt, B. E., *NCHRP Synthesis 396: Monitoring Scour Critical Bridges*. Transportation Research Board, Washington, D.C., 2009, http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_396.pdf.

[2] Lagasse, P., P. Clopper, J. Pagán-Ortiz, L. Zevenbergen, L. Arneson, J. Schall, and L. Girard, *Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance (Hydraulic Engineering Circular No. 23)*. Federal Highway Administration, US Department of Transportation, Washington, D.C., 2009, http://www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=23&id=142.

[3] Kosnik, D. E., Internet-enabled geotechnical data exchange. In *Proc. 7th Int'l Symposium on Field Measurements in Geomechanics*, American Society of Civil Engineers, Boston, Massachusetts, 2007.

[4] Washington, S., J. Leonard, D. G. Manning, C. Roberts, B. Williams, A. R. Bacchus, A. Devanhalli, J. Ogle, and D. Melcher, *NCHRP 20-45 final report: Scientific Approaches to Transportation Research*. Transportation Research Board, Washington, D.C., 2001, http://onlinepubs.trb.org/onlinepubs/nchrp/cd-22/start.htm.

[5] Liebich, B. A., High-Capacity Piles at the Stony Creek Bridge Project. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2116, 2009, pp. 41–46.

[6] Marron, D. R., Remote monitoring of structural stability using electronic clinometers. In *Proceedings, Structural Materials Technology IV — An NDT Conference* (S. Alampalli, ed.), Technomic Publishing Co., Lancaster, Pennsylvania, 2000, pp. 233–239.