A Compendium of NDE Methods

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Structural Health Monitoring of Civil Infrastructure

Philosophy, technical methods, and projects of the Infrastructure Technology Institute

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SUMMARY

The mission of the Infrastructure Technology Institute is to develop strategies and tools to protect and improve the condition, capacity and performance of the nations highway, railroad, and mass transit infrastructure systems. The Institute does this through the development and deployment of (1) advanced technologies for structural health monitoring, (2) advanced infrastructure materials, analysis and testing techniques, and (3) new tools for integrating infrastructure condition and performance information into system management, investment, and policy decision processes. Development and application of tools and methods for structural health monitoring (SHM) of infrastructure represent core activities for the Institute. Over the past eight years ITI has conducted more than 70 different SHM projects around the US. ITI staff and its research partners (primarily Northwestern University professors) have made significant technical advances in SHM, including measurement techniques, remote monitoring methods, and data analysis. This compendium will discuss SHM in general, review ITIs role in this field, and present a series of case studies that highlight ITIs achievements and capabilities.

INTRODUCTION: WHAT IS STRUCTURAL HEALTH?

Civil infrastructure systems, which include buildings, transportation systems, energy generation and distribution systems, and water delivery and treatment facilities, make possible all other sectors of our modern society, including business, manufacturing, communication and information systems, finance, government, and health care. The safe and effective functioning of modern society is critically dependent on monitoring and managing the health of civil infrastructure systems.

The health of an infrastructure element is a measure of its ability to perform its functions, now and in the future. Those functions can be divided into three categories: utility, serviceability and safety. *Utility* is the value of the functions that the element performs for society. This includes the intended purpose of the infrastructure system, such as a bridges carrying a particular volume of traffic, or the transfer heavy freight at an intermodal terminal. Utility can also be defined to include side effects, positive or negative, such as air pollution emissions, costs (both initial and over the life cycle), and aesthetics. These are effects that must be considered in the design of a structure, and they are also important in evaluating its structural health. A structure that is operating normally in terms of its intended purpose (e.g., load carrying) may still be considered unhealthy if it is negatively impacting the environment (e.g., dropping flakes of lead paint into a water supply), or if its maintenance cost is excessive.

Serviceability is ability of the structure to operate appropriately now and in the future, given normal, and changing, environmental conditions. This aspect of structural health includes the natural deterioration process of a structure as it is assaulted by repeated use and exposure to the environment. Examples of this deterioration include corrosion, cracking, spalling, settling, creep and scour. The ability of a structure to resist these effects over time is its durability, and the total length of time that a structure resists these effects is its life cycle. An aspect of serviceability is *inspectability*—the ease or difficulty of measuring and tracking the physical state of the structure, by visual or other means.

The *limit-state safety* of an infrastructure element is its projected performance under abnormal and extreme stress, either from repeated assaults or a sudden, catastrophic event. Examples of threats include fire, earthquakes, flooding, landslides, repeated excessive loading, and intentional threats, including terrorism. This is different from operational safety (e.g., the risk of crashes at an intersection), which falls under utility. Limit-state safety does not imply continued normal operation after an event, but rather response to an assault that leads to soft failures that protect life and property. For example, in a fire, a building is designed to resist collapse long enough for its occupants to escape. The limit-state safety is a part of the design of a structure, but some aspects of safety can degrade over time and with use and thus must be monitored and maintained (e.g., structural insulation that protects a building against collapse in a fire can deteriorate and lose its effectiveness over time). The distinction between limit-state safety and serviceability is not always clear. Where severe environmental shocks are common enough to be predictable, structures should be designed respond to such events with little or no damage.

STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) is the process of determining the utility, serviceability, and/or limit-state safety of a structure at a specific time. The term SHM is commonly used refer to technology-based approaches, but in fact a full spectrum of techniques, from visual inspection to advanced automated continuous measurement, is included in the arsenal of tools for SHM. State-of-the-art SHM is the ongoing assessment of in-service performance of structures using a variety of measurement techniques, and frequently includes embedding sensors into the structure itself. Because SHM has become so important for ensuring the utility, serviceability and safety of structures, the field has a secure and growing status in the disciplines of civil, mechanical, and aerospace engineering. Regular SHM workshops and conferences have been held since 2000. In the United States, this activity is fueled by growing concerns over the deteriorating state of our national infrastructure, and it is supported by substantial grants from the Department of Transportation (particularly through the Federal Highway Administration) and the National Science Foundation.

The paradigm behind this new field is borrowed from the medical profession: by proactively monitoring health, by discovering problems in their early stages before they become serious, and by responding quickly and effectively to accidents, natural catastrophes, and other incidents, lives can be saved, structural lifetimes can be extended, and money can be saved. This is a diverse field with research and applications in many areas. Advances are especially rapid—and valuable—in several key areas that are particularly relevant to civil infrastructure:

- Development of new technologies for analyzing structures: this falls under the general heading of non-destructive evaluation (NDE), and includes tests of in-service structures and their components. Most recently, applications have been moving toward technologies for remote, automated measurement and interpretation. This usually requires small, rugged, and relatively inexpensive electronic sensors and probes.
- Imbedding SHM sensors permanently into structures to support long term monitoring during normal operation. For example, the new I-35W Mississippi River bridge in Minneapolis is being equipped with built-in sensors to track corrosion and other deterioration pathways.
- Connecting health monitoring technologies to communications channels to gather and transmit large quantities of data, in near-real time, to support continuous, remote evaluation and rapid response to significant changes.
- Automating sensor data analysis and interpretation, bringing different data signals together for integrated analysis and comparison to threshold values to inform the decision process. This may also include numerical simulations of complex structural systems [1].

The following sections elucidate the current state of the field of SHM by reviewing three types, of SHM, in increasing order of technical sophistication, starting with visual inspections, moving to traditional NDE methods, and finally to continuous remote monitoring.

Visual Inspection

Visual inspection is the standard, and most commonly-applied, method of detecting damage and assessing deterioration in most structures, for example, bridges. Indeed, since the beginning of the federal bridge inspection program in 1968, visual inspection has been the primary method for assessing the performance and serviceability of bridges.

By federal law, all structures which carry traffic and have a span greater than 20 feet are subject to comprehensive inspection at least every two years. In a routine biennial inspection, trained bridge inspectors following the guidelines of the FHWA Bridge Inspectors Training Manual [2] check for damage, which may take such varied forms as spalled concrete, corroded steel, and even insect and fungus attack on timber elements; they also examine bearings, deck drains, and expansion joints for proper operation, evaluate the serviceability of bridge substructures, decks, approaches, and appurtenances, and, for waterway crossings, inspect the channel for scour and obstructions to flow.

All of these elements are inspected visually, using basic hand tools where appropriate. The goal of these federally-mandated inspections is to assess and document the condition of essential bridge elements to ensure safety and serviceability and to facilitate the timely programming of maintenance and repairs. This is the essence of structural health monitoring.

Some bridges are also subject to special inspections, in-depth evaluations of the safety and serviceability of particular elements known to have specific problems or present particular risks. For example, special inspections are conducted on fracture-critical bridges: those with non-redundant steel tension components, the fracture of which would likely cause catastrophic failure.

Fracture-critical members (FCMs) are subject to special inspections at least every two years. Bridges containing FCMs of particular concern, such as those with fatigue-prone details, are typically inspected more frequently. FCM inspections often employ special non-destructive testing techniques to detect cracks. Techniques used on accessible surfaces include dye penetrant and magnetic particle testing, which make tiny cracks more visible through the use of brightly-color dyes and patterns of iron particles in a magnetic field, respectively. Some FCMs have details in which only one side of an element is accessible. In these cases, non-visual methods must be used. A common option is ultrasonic testing, in which a highly-trained, certified operator interprets the reflection of high-frequency sound waves projected into the element. Both the visual inspection and instrument-based non-destructive testing methods require up-close access to the elements in question, and thus, FCM inspections are often called “arms length” inspections.

Instrument-based assessment methods can extend the range and depth of hands-on inspection to answer very specific questions about bridge element condition. The most common instrument-based methods deployed on bridges include well-known non-destructive evaluation (NDE) techniques such as ultrasonic testing, eddy-current testing, in which electric signals are used to detect flaws, and radiography, in which high-energy X- or gamma rays create an image of the internal structure of an element on film. These techniques are employed on specific areas of a structure where cracking is suspected. This is for economy, but also because it is simply not practical to conduct these tests on all parts of a bridge. Therefore, thorough knowledge of the theory and practice of bridge design and maintenance is critical to the effective deployment of NDE and SHM technologies on bridges—engineers must know where to look for trouble.

While new sensing techniques suitable for bridges are developing rapidly, visual inspection will remain the foundation of structural health monitoring. Visual inspection provides a synoptic view of bridge condition. Inspectors are able to identify a wide range of threats to bridge safety, including damage in unanticipated areas and issues not intrinsic to the structure, such as stream channel changes; furthermore, inspectors can identify details where the application of advanced inspection and testing techniques might be particularly instructive. No single method or technology can provide the condition information needed to ensure the safety and serviceability of the nations bridges. Consequently, it is important to note that it is the careful integration of sensing technology with traditional inspection techniques that will continue to provide the data that engineers and policymakers need to manage the nations bridges.

Visual bridge inspections have successfully discovered numerous dangerous problems and saved many lives; in extreme cases, bridge inspectors may even coordinate with law enforcement to immediately close a bridge when an unsafe condition exists. Unfortunately, many inspection activities are necessarily qualitative and the inspection and follow-up activities are vulnerable to human errors and omissions. The 2007 collapse of the I-35W Mississippi River bridge in Minneapolis is a notable and tragic example of a case where visual inspection may not have detected signs of an impending failure

Two other issues associated with visual inspections, given that they are subjective assessments performed by people with widely differing experience and training, are their reliability and their consistency. By *reliability* we mean the probability that a serious problem—the type that should be discovered by an inspection—will in fact be noticed and reported as such. By *consistency* we mean the degree to which the condition ratings assigned to the same structure by different inspectors will be in agreement. While the tendency to miss serious problems (reliability) is obviously the more serious issue, the general tendency for the assessments of different inspectors to be in agreement (consistency) also has important ramifications, since these assessments are used to reach general conclusions about the state of the civil infrastructure that in turn affect policy decisions and funding allocation.

In a 2000 study [3] conducted by the Federal Highway Administration's Nondestructive Evaluation Validation Center, a representative group of 49 practicing bridge inspectors from 25 state departments of transportation were subjected to a controlled study. The inspectors were all asked to complete seven routine inspections and three in-depth inspections on the same test bridges while being monitored by the study authors. Information about the inspector and the inspection environment was collected to assess their influence on inspection reliability.

For the study, deficiencies in the test bridges were categorized as either general, recurring deficiencies (for example loss of paint, corrosion over large areas, or section loss in multiple rivet heads) or local deficiencies (for example impact damage at a single location, a single missing rivet, or a few cracked welds). As expected, the inspectors reliably identified the general, recurring deficiencies, as these tended to be quite obvious. However, there was considerable variation in the assignment of rating codes to bridge elements between inspectors. More serious was the issue of the performance of the inspectors in identifying local deficiencies, which was quite poor. For example, the overall accuracy in identifying crack indications was only 3.9%, and the accuracy for bolted connection deficiencies was 24%. All of these indications had been identified prior to the study as being sufficiently apparent such that they should be identified during an inspection.

What can be concluded from this study? Other than the obvious concern that serious problems are routinely missed by visual inspections, we can also point out the related conclusion that SHM techniques that supplement human inspections with remote sensor data do not need to be perfect, or even close to perfect, in order to guarantee that the level of reliability is no lower than what is currently achieved. To be more optimistic, we can project that remote sensor-based monitoring will provide an opportunity to greatly increase the rate of detection of certain types of problems that are difficult to discover from a visual inspection.

Non-destructive Evaluation (traditional)

Non-destructive evaluation (NDE) refers to any method of testing the integrity of an object—here an infrastructure component—that does not reduce the objects future usefulness. The basic principle of NDE is the application of a physical process that interacts with the object being tested without damaging it. With this broad definition, visual inspection is actually a form of NDE. While the term "NDE" is generally reserved to refer to technology-based approaches, the classification of visual inspection as NDE remains quite useful, as it reinforces the fact that data interpretation is another important component of inspection process.

In the case of visual inspection, there is a sophisticated device (the inspector) that receives a signal, makes sense of the data, and enters it into a report that can be used for decision-making.. Of course, based on the study mentioned in the previous section [3], even this process does not work as well as could be desired. When considering the overall utility of a particular NDE method, we need to consider not only how the raw signal is generated and measured, but also how this signal is related to damage or deterioration, and how to decide when the signal has reached a threshold value that warrants action. This assessment must recognize that there are costs associated not only with false negatives (missing damage) but also with false positives (incorrect indications of damage that lead to unnecessary and costly further analysis).

NDE is a broad field with a rapidly expanding role - not only in infrastructure maintenance, but also in manufacturing, power, and construction [4]. This report will not attempt a general review of this complex and dynamic field, except to point out that NDE is most widely used and effective at the start of an objects lifetime, as a method of quality control during manufacturing, and at the end of its lifetime, when it can extend the useful life of an expensive object such as an aircraft by providing an accurate assessment of its physical state. This review focuses on the end-of-lifetime applications, although there are certainly NDE applications for the manufacturing of civil infrastructure materials, such as ultrasonic monitoring of the concrete curing process.

The growth of NDE applications can be attributed, in large measure, to the well-established fact that, if used properly, NDE can have dramatic effects on both infrastructure cost and quality [4]. This has generated significant demand for NDE practitioners and researchers. It is now generally recognized by infrastructure maintenance professionals that NDE, also known as non-destructive testing (NDT), has great potential as an investigative tool for discovering damage and deterioration to civil infrastructure. Also recognized is the potential to reduce the expenditure of time and money associated with visual inspections. This must of course be balanced against the cost of the NDE equipment, which is highly variable but tends to be expensive.

A factor that has slowed the rate of introduction and general acceptance of NDE techniques for civil infrastructure is the degree of expertise required to perform the tests and interpret the data [5]. For example, in 2005, the Florida Department of Transportation commissioned a study [6] aimed at providing the groundwork for increasing the use of NDE to monitor new structures in Florida, motivated in part by newly introduced performance-based specifications for structural health. A general finding of the study was that,

> *Considering the potential gains associated with nondestructive testing, there is a significant lack of expertise available in the State of Florida as well as a lack of knowledge of the fundamental relevance of NDT results* [6].

There is no reason to think that this state of affairs does not apply to the rest of the nation.

The process of NDE can be conceptualized in the following series of steps:

1. A signal is generated and applied to the object of interest.
2. After interacting with the object, the response is measured.
3. The raw data from the response is converted into a usable measurement. This may include converting the signal into to a different, more useful form, normalizing it to a calibration run, removing extraneous noise, etc. We will call the result the measurement.
4. The measurement value is compared to the expected value, or range of values, for this test. This may be as simple as comparing it to yesterdays value to see if there is a change, or it could involve the application of a sophisticated physics-based model to determine the type, extent, and location of damage.
5. Based on the deviation of the measurement from the expected, or acceptable, value, an appropriate response is formulated. As noted above, any response other than "do nothing" involves spending time and money, so there is a cost associated with false positives.

In traditional NDE, steps 1–3 are usually performed by the instrument and its human operator together, while steps 4 and 5 are performed by the human operator alone. One of the goals, and significant challenges, of SHM is to create fully automated systems that can perform steps 1-4 with minimal or no human assistance, and that can even assist human experts in formulating the correct response to the problem (step 5). This will be discussed further in the next section, but first we will briefly review the general types of traditional NDE most often applied to civil infrastructure systems.

Stress-wave propagation

Stress-wave propagation is a broad category that includes a variety of specific NDE techniques that all rely on the same physical principles. Stress waves, which include sound waves, high frequency waves (ultrasound), and impact waves with a single wavefront, can propagate through solid materials, more efficiently, in fact, than they propagate through air. Of equal importance, from an NDE point of view, is the fact that these waves are affected by flaws and heterogeneities within the material. These NDE methods thus consist of generating a pulse and then measuring it again after it has passed through the object. The measurement can be accomplished by putting a second transducer (which converts the deformations resulting from the stress waves into an electrical signal) at a different location on the object, a configuration known as "pitch and catch." However, it is more common to take advantage of the fact that stress waves are reflected by interfaces, such as the outer surfaces of the object (for example a concrete slab or beam), which allows the signal to be measured by the same transducer that generated it, a configuration known as "pulse-echo."

The details of what happens to stress waves inside a solid material are complex, but they can be predicted and described mathematically. These NDE methods can provide a wide variety of information [4]: the wave velocity in the specimen (assuming the depth is known), the location of a flaw (such as a crack, void, or delamination) and even its size and shape, and material properties such as density and elastic modulus.

Probably the most widely used stress-wave type is ultrasound. In this case, the signal is produced by a transducer, which converts an electrical signal to mechanical deformation that is applied to the specimen (the exact reverse of the receiving transducer). This is the same process by which an audio speaker produces sound waves.

When ultrasound pulse-echo is applied to concrete, the signal degrades and attenuates rather quickly, limiting the depth at which flaws can be detected. An alternative method, developed in the 1980s at the National Institute of Standards and Technology specifically for use on large concrete structures [7], is called *impact-echo*. In this case the signal is generated by a single impact, from a hammer blow or dropping weight. This method provides a much stronger signal than ultrasound, and also spreads out through more of the material, interrogating a larger specimen volume. The powerful signal from the impact radiates outward as a spherical wavefront, which is reflected multiple times within the boundaries of the specimen, so the measured signal has the properties of a repeating waveform. A frequency analysis of this waveform will reveal a peak associated with the main reflections at the boundaries. However, if there is a flaw in the specimen, some of the impact signal will be reflected from the flaw, generating a smaller peak at a higher frequency (since the distance of travel will be less, the frequency will be higher).

The impact-echo method has been used successfully to detect a variety of concrete defects, including voids and honeycombed concrete in structural members, cracks in columns, delamination in slabs, corrosion of reinforcing steel, and poor bonding between overlay and base concrete [5]. Impact-echo can also be used to measure the thickness of concrete; an ASTM standard (ASTM C1383) has been developed to do this.

Both the pulse-echo and impulse-echo NDE methods are well established, and portable commercial units are available that consist of handheld transducers and/or impactors (spring-loaded steel balls) connected to a laptop computer interface that acquires and analyzes the data using specialized software. Considerable training and experience is needed to reach a level of proficiency sufficient to detect and identify flaws in concrete accurately.

Eddy Current Testing

One of the most dangerous and common modes of damage in civil infrastructure is cracking of steel components of bridges, because it can cause an apparently sound bridge to collapse suddenly. The collapse of the Silver Bridge in Point Pleasant, West Virginia in 1967 is generally credited[1] as being the catalyst for the development of the national bridge inspection system. It also generated intense interest in developing NDE methods for detecting cracks in steel bridges, as these cracks are often difficult or impossible to identify visually. Bridges are particularly susceptible to fatigue cracking, due to the cyclical nature of loadings—heavy traffic loads, particular trucks, over extended time periods. Cracks in steel components can arise from manufacturing defects, fretting, and stress corrosion, but repeated loading and unloading can cause them to grow.

The most mature and proven NDE method for detecting cracks in metal is *eddy current analysis*, which measures the response of a conductive material to electromagnetic fields over a specific frequency range (usually in the kHz or MHz range). The technique is based on the physical principle of magnetic induction, whereby a magnetic field will induce a current to flow in a conductive material, and, in the exact reverse effect, a current will produce a magnetic field. The basis for an eddy current probe is a pair of wire coils that are maintained at a fixed distance from each other - close, but not touching. An alternating current is applied to one coil (the primary coil). This induces a magnetic field, which interacts with the second coil (the pickup coil) causing a voltage to develop in it. This voltage will have a constant predictable amplitude as long as no other conductive materials are nearby. When the eddy current probe is placed near a conductive material (such as a steel beam) the magnetic field created by the primary coil will induce currents to flow in loops within the conductor—these are the eddy currents. This interaction reduces the voltage induced at the pickup coil, providing a measure of the local resistance of the material . The less resistive the material, the more the voltage will drop at the pickup coil; in fact, if the material is a perfect conductor the voltage will drop to zero.

Because a crack will interrupt the flow of an eddy current, the voltage response at the pickup coil will change when the eddy current probe moves over a crack. The crack essentially causes the material to be locally more resistive. Eddy current technology has been explored for the

[1] Although the proximate cause of failure of the Silver Bridge was a crack in an eyebar, the root cause was poor design; regardless, the crack would not have been identified in a visual inspection.

detection of cracks in the area of welded connections on highway bridges in the field [8]. This required the development of sensors and software designed to adjust for the local spatial variation in properties at the welds. An important advantage of this technique is that it can detect cracks through paint, so existing paint is not disturbed by the inspection.

Eddy current probes are quite portable and are commercially available in a wide variety of configurations. However, as with stress wave NDE, eddy current NDE requires significant training and experience to interpret the results correctly. In general, eddy current analysis is most useful and easy to apply when the geometry of the object and the likely location and orientation of cracks are both well understood, for example in a manufacturing environment. For field inspections this is not always the case. One eddy current study [8] found that of 18 crack indications (i.e., increases in local resistance) on a steel girder, only three were cracks while the others were caused by harmless geometric discontinuities. In this study the trained inspector was fully successful at differentiating these cases, but the likelihood of false positives is likely to hinder the widespread application of this NDE method to infrastructure inspection in the field.

Acoustic emission

Acoustic emission is the generation of elastic waves within a material due to a sudden redistribution of stress. The name arises from the fact that these waves are of the same form as sound waves, and often occur in the frequency range that can be heard by the human ear. This phenomenon has been recognized for thousands years; for example, plastic deformation of tin during the smelting process causes mechanical twinning which generates an audible sound known since ancient times as “tin cry” [9]. The use of acoustic emission as an NDE technique arises from the emission of elastic waves from a source such as crack propagation or fretting of connections, among others. These emissions are measured by placing transducers on the surface of the object to convert the elastic waves into an electrical signal. In addition to cracking, acoustic emission can also detect other events, including slip between concrete and steel reinforcement and failure of individual strands in wire cables.

Acoustic emission differs from most other NDE techniques in that it is passive, meaning that a signal is not generated by the probe, but rather the instrument simply listens for the energy released by the object. Acoustic emission does not normally detect the crack itself, but only the propagation of the crack, though fretting around a stable crack can be detected with AE. In general, however, the object being examined must be under a load sufficient to cause crack activity during the test, or even a large and potentially dangerous crack may be missed. Acoustic emission is thus typically applied to objects in service—for example, a bridge under live traffic or a test load.

For the purpose of monitoring structural health, acoustic emission has some important advantages. Foremost of these is the fact that, because the signal is not just associated with damage but is in fact damage itself, the method provides a direct indication of the current risk of failure. (Note that this does not disqualify the technique from being "non-destructive" since the technique is not causing the damage). Because the elastic waves propagate well through concrete and steel, acoustic emission can be used to locate cracks and other discontinuities. Once a crack or other defect has been located, statistical analysis or in-depth analysis of the acoustic emission waveforms can provide important insight into the nature of the defect. In particular, these analyses can be used to determine whether a crack is actively propagating.

Acoustic emission has been successfully deployed to locate and characterize defects on a wide variety of civil structures, especially steel bridges. The technique has proven to be especially useful in determining levels of crack activity on bridge details subject to fatigue cracking; it has also been successfully used to evaluate the performance of retrofits to fatigue-prone details.

Acoustic emission also holds promise for monitoring of structural cables and tendons, such as the catenary cables of a suspension bridge and the tendons of a post-tensioned concrete bridge. Should any strands of these cables or tendons fail, it will produce a very strong acoustic signature.

Continuous remote monitoring

The concept of continuous remote monitoring continues the evolution of SHM from a low-tech, labor intensive process based on visual, on-site inspections toward a fully automated and autonomous process of monitoring that only requires human intervention when serious problems are detected. As discussed in the previous section, technology-based NDE methods provide significant advantages for health monitoring by providing information about the structure that is not visible to the eye. However, the basic inspection process is not really changed: a trained inspector would still need to go on site to perform the test, and then the results would need to be analyzed and interpreted so that a decision could be made.

The fundamental concept of continuous remote monitoring is that there is a one-time installation process, after which data gathering and initial data processing are done automatically without on-site human operators. The data is uploaded to a central location to be interpreted. With this approach, a relatively small number of trained experts could monitor areas of concern on a large number of structures without extensive travel, providing significant cost savings over time that would offset the initial cost of setting up the system.

Ideally, the cost of installation would be part of the capital budget, installation would occur during initial construction (allowing for embedded sensors), and then continuous monitoring would be performed throughout the life cycle. At present this is rarely the case. More often, continuous monitoring is employed only after the structure starts to degrade significantly, allowing the inter-inspection interval to be maintained or even extended, allowing scarce inspection resources to be used elsewhere. In other cases, specific problems are be identified by periodic inspection, and continuous monitoring is applied until repairs can be made.

Some characteristics of continuous remote monitoring, including both technical requirements and potential benefits, are:

- Sensors are left permanently in place, so that measurements can be performed at any time, or at regular specified intervals. This means that sensors must cover all areas of the structure that are to be monitored (instead of moving a single sensor over the structure).
- Sensors must be reliable, as frequent replacing, repairing, or recalibrating of sensors through on-site visits will reduce any cost savings and possible reduce the safety margin provided by sensor data.
- Individual sensors must be relatively inexpensive, since multiple sensors must be dedicated to a single structure; however, the advantages of continuous remote monitoring may justify a considerable initial cost.
- Sensors must be robust, since they will often be exposed to the elements and must operate over long periods of time without degrading.
- A reliable communication system is needed to send the data. Where wired communication is not practical, wireless communication can be used.
- A source of power must be available for the sensors, data acquisition, and communications equipment. In remote locations this may require the use of solar panels.

The present trend in the field of continuous remote monitoring is to develop larger scale and much more complex systems with a large number of sensors of different types, some of which may be specially designed for a specific structure. The amount of raw data that is generated by such applications can become extremely large, and an important aspect of the SHM process is developing and deploying the data handling software so to support informed infrastructure management. The types of information generated by remote continuous infrastructure monitoring can be classified into three types, based on the user [10]:

- Web information: For the general public and the media, a simple overview of operations that describes whether various aspects of the system are operating normally, abnormally, or not at all..
- Viewer information: For infrastructure managers, much more detailed information for interpretation by technical experts to diagnose what is happening and what it means for the structure. For example, following an alarm condition or a sudden change in a signal, this information would guide emergency inspections or repair efforts and decisions about closing the structure.
- Expert information: Researchers can use raw data from infrastructure sensors to to identify long-term trends and build predictive models of future performance.

In addition to providing all these levels of information reliably and securely, the monitoring system must also safely archive the data and ensure that the system is secure. These are significant software requirements, and designing data-handling software for continuous remote monitoring systems is an important technical challenge that must be considered in tandem with the instrumentation and communication systems.

OVERVIEW OF SHM ACTIVITIES OF THE INFRASTRUCTURE TECHNOLOGY INSTITUTE

The Infrastructure Technology Institute (ITI) at Northwestern University was established in 1992 with a mission of research, technology transfer, education, and management and policy studies related to Americas surface transportation infrastructure. ITI is an interdisciplinary center within Northwestern's Robert R. McCormick School of Engineering and Applied Science supported by Northwestern and a grant from the U. S. Department of Transportation. ITI has a full time engineering staff and close collaborations with Northwestern engineering professors and their graduate students.

A primary focus of the work of ITI is structural health monitoring (SHM). In collaboration with deployment partners (typically infrastructure owners such as state departments of transportation), ITI researchers have used elements of the nations civil infrastructure as a field laboratory to develop, deploy, and test advanced SHM technologies around the U.S. These research and development efforts gather data at different points in the life of a structure—from construction through long-term utilization and life extension. Using periodic static measurements or real-time dynamic measurements, their engineers deploy powerful tools to capture, transmit, store and display infrastructure data, often in challenging environments and over great distances. The data are typically presented via a secure web site to provide timely support for evaluation and decision making. These projects have helped partner agencies identify and understand significant problems in their transportation infrastructure and have provided unique and challenging settings for research and exceptional learning opportunities for students.

In this section we discuss some of the particular SHM problems that ITI addresses, including an overview of the particular techniques that are used. Then in the next section we will present selected case studies of ITI SHM projects of interest.

Evaluating and monitoring cracks in steel bridges

The danger associated with cracking of steel bridges has been stressed in previous sections. ITI is a pioneer in the application of strain gauges, acoustic emission, and other sensors to determine the location and character of cracks, and particularly to determine if the crack is active (growing), or if the stress already relieved itself (stable).

Monitoring bridge movement caused by scour

Bridge scour is the removal of sediment surrounding the piers or abutments of a bridge by the action of flowing water. In its most serious form, rapidly flowing water (such as a flash flood) will scoop out a deep scour hole next to one or more piers, causing the bridge to destabilize and fail. Directly monitoring the scour hole itself is quite difficult. ITI has developed a method that uses clinometers (tiltmeters) to monitor continuously the tilting of the piers at locations above the waterline. Comparison of current data with past trends provides a reliable early warning against destabilization and failure.

Monitoring earth movement during excavation

Underground construction, including foundations for buildings and subway stations, can pose a threat to adjacent structure, particularly in the close quarters of urban areas. While it is important to develop design and construction methods to preclude destructive impacts on nearby structures, in critical circumstances it may be necessary to monitor unintended earth and foundation movements to guard against these spillover effects. ITI researchers have deployed a variety of ground monitoring technologies at active construction sites around the U.S. both for real time monitoring and to gather data that provides a basis for developing advanced models to predict construction-driven ground movements. ITI has engaged in similar applications where transportation infrastructure is at risk due to natural or anthropogenic threats, including the effect on highways of underground coal mining.

Monitoring response of structures to blast/construction vibrations

Blasting for infrastructure construction, or for mining infrastructure materials such as at gravel quarries, presents risks—real or perceived—to nearby structures. This naturally generates public resistance to these activities. ITI researchers have developed and deployed methods for continuous wired and wireless monitoring of cracks in structures to understand and isolate the effects of construction activities from the consequences of normal environmental changes, e.g., variations in temperature and humidity.

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MICHIGAN STREET BRIDGE, STURGEON BAY, WISCONSIN (1995–PRESENT)

Continuous remote monitoring of a historic and badly degraded steel lift bridge using a variety of sensors including strain gauges, clinometers, and weather monitoring equipment.

Overview: The Michigan Street Bridge, located in the central business district of the city of Sturgeon Bay, Wisconsin, spans the Sturgeon Bay Ship Canal, a waterway that bisects the Door Peninsula and is a major shipping route between Lake Michigan and Green Bay. For many years, it was one of only two bridges that connect the northern portion of Door County with the mainland. A third bridge is scheduled to open in late 2008. The Michigan Street Bridge was built in 1930 and since that time has been operated and maintained by the Wisconsin Department of Transportation. The bridge is 1420 feet long, consisting of 12 overhead steel truss spans and one rolling-lift bascule movable span to allow for the passage of ships. With this design, the bascule spans rotate upward as their lower ends roll along a track, a process driven by electric motors and assisted by counterweights, both of which are located above the structure. The bridge is one of the busiest in the state in terms of lifts, opening about 3600 times per year. The bridge has historic value due to its age and relatively rare design, and it has been placed on the National Register of Historic Places.

The Problem

In June, 1994, an inspection noted movement in the rolling plate where it is attached to the segmental girder during lift operations (see Figure 2). Closer inspection performed by Wisconsin DOT revealed serious cracking throughout the segmental girder. A majority of the cracks initiated from field repair welds that were made in the mid-1960s. All rivets connecting the rolling plate to the connection angles were inspected ultrasonically and determined to have failed. In fact, in several places, the only mechanism holding the rolling plate in place was corrosion in the rivet holes. Emergency repairs were performed by placing bolts in failed rivet locations. The bridge was placed on a schedule of monthly inspections and the number of openings was reduced as much as possible.

In September, 1994, a new area of concern was discovered. The bascule span had settled due to the wear of many years of use. This was having a negative effect on the rack-and-pinion gearing system used to connect the drive motors to the bascule. In the original design, the pinion gear (drive gear) teeth had of clearance as they meshed with the rack teeth. However, due to the settling the pinion teeth were bearing directly on the rack teeth. This places additional loads on structural elements for which they were not designed and causes binding that increases the power requirement from the drive motors. The potential ramifications of these problems were quite serious. If the drive system failed and was unable to lift the bascule, shipping traffic would be unable to pass through the canal. This would likely require the Coast Guard to demolish the

Figure 1: The Michigan Street bridge, with the bascule spans in the upright position to allow a ship to pass through the Sturgeon Bay Ship Canal.

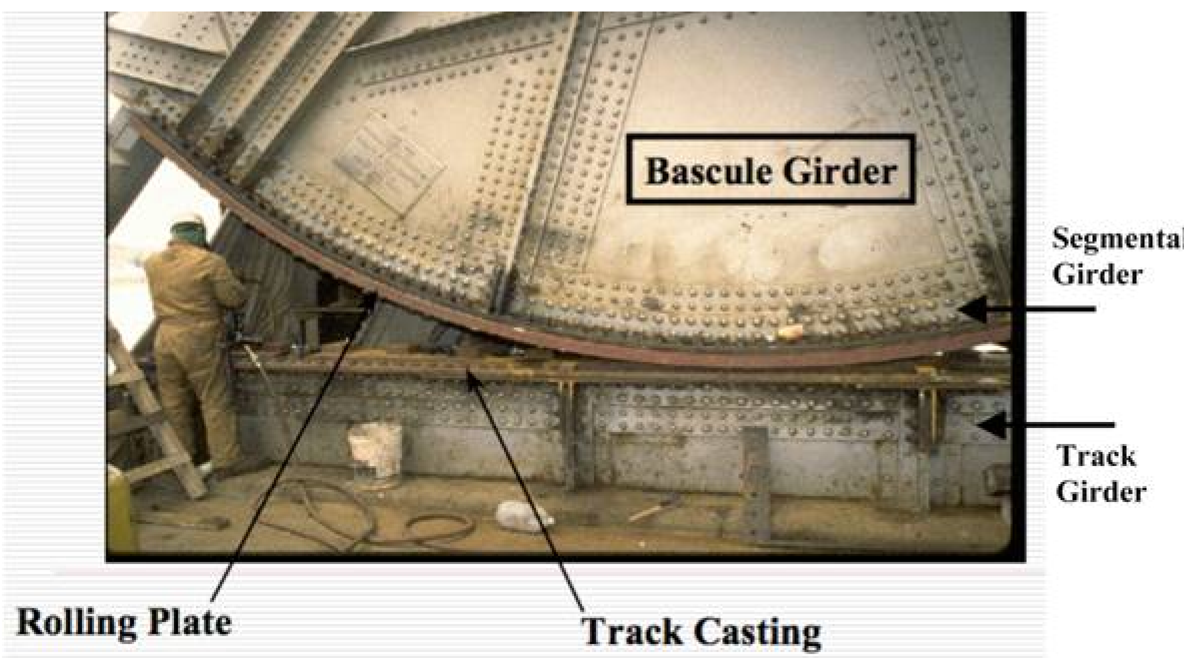

Figure 2: Closeup of the base of one bascule. The segmental girder connects the rolling plate (made of rolled steel) to the bascule girder. This assembly rotates as the bascule span lifts. The track girder supports the track plate, which is a steel casting. The rolling plate has holes that match the teeth in the track plate.

bascule span as a barrier to navigation. Due to the generally poor condition of many of the steel components of the bascule span, there was also serious concern that the system could fail completely during a lift, resulting in a catastrophic collapse of the bascule span.

ITI activities

Initial repairs: In conjunction with the Wisconsin DOT, a plan was formulated to make immediate emergency repairs and install continuous monitoring equipment. In February, 1995 the bridge was closed and the bascules locked into the open position, and then the track plates and rolling plates (see Figure 2) were removed. Deterioration was more severe than expected. The cast steel track plates had considerable cracking on the bottom side. Where the cast steel track plates connected to the angles, there was heavy wear (up to $\frac{1}{8}$" and severe corrosion with deep pitting. On the rolling plates, up to $\frac{1}{8}$" of wear had taken place where they bear on the web plates of the segmental girder, and there was also wear and deep pitting corrosion at the connection angles. Additional cracking was found in the connection angles along the rivet lines. After determining that fabrication of replacement track plates would delay the bridge reopening by an unacceptable period of several weeks, the decision was made to repair them by welding. These repairs were performed under supervision by a commercial fabrication shop. Deterioration from wear and original casting flaws made it impossible to weld repair two of the cast steel track castings completely. Because of the fracture critical nature of these castings, Northwestern Universitys industrial research laboratory was contracted to develop a strain gauging system to allow continuous monitoring of these plates from a remote location. While they were in the fabrication shop, a total of 16 strain gauges were installed on the two plates between the two web plates of the box girder that are inaccessible when track plates are in position on the bridge. These gauges were required to measure strains arising both from bridge lifting and from live traffic loads. To provide redundancy, a second pair was added at each location (see Figure 3). The gauges were protected from the elements with multiple layers of protective tape and neoprene rubber with specially formulated adhesives. Other repairs to the plates included cleaning to remove deep pitting corrosion, drilling of crack tips to halt crack growth, and priming and painting. In addition, the rack and pinion teeth were machined to regain the originally specified clearance. . Finally the plates were reassembled with new clamping plates, titanium putty, and bolts; the bridge then resumed operation.

During early operation some bridge movement was felt during lifts. Therefore an additional installation of clinometers was performed to monitor the tilting of the main bridge piers. The clinometers were installed in orthogonal pairs to allow measurement of both longitudinal and transverse components of tilt. The piers were found to tilt by about 0.1 degree longitudinal away from the shipping channel as the bridge opens, with no measurable transverse component. These readings have remained consistent throughout the tests.

Initial monitoring: Data from the strain gauges were downloaded to Somat S-2100 data loggers. For the first few weeks of bridge operation following the shutdown, the data were uploaded manually from the data loggers to a laptop computer. With the exception of the first two

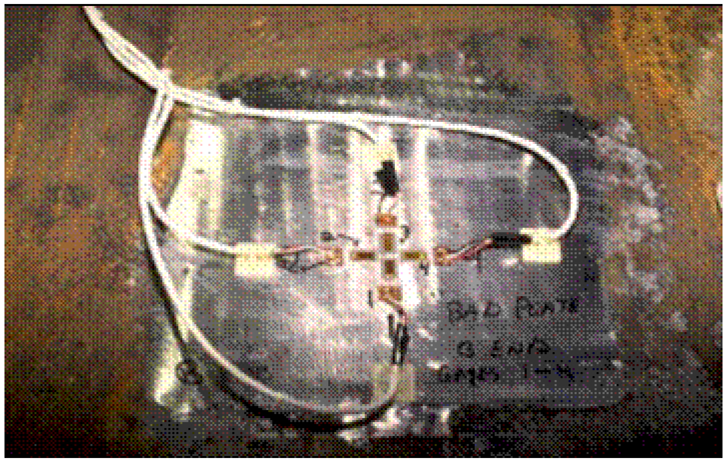

Figure 3: Installation pattern of 4 strain gauges at a single location on one of the badly damaged track plates. Photo taken prior to application of weatherproofing layers.

loading cycles (when one area exhibited some strain offset) the readings from the strain gauges followed a standard pattern that remained very constant with time as the bridge underwent about 25 openings per day during the summer months (see Figure 4a).

Following the initial shakedown testing, the system was upgraded to allow continuous remote monitoring. The data logging equipment was installed in permanent protective enclosures and the two test sites were networked by means of a spread spectrum radio link to a host computer installed in the bridge tender's office. All of the signal conditioning and data logging functions were performed by SoMat S-2100 field computer systems. All data was stored on the host computer and could also be viewed in real time from a remote site over a modem connection.

Later that summer, radical changes began to be occasionally observed in the data from the strain gauge mounted at the most severely damaged site on the south west track casting. These abnormal readings increased in frequency over a period of a few days. The abnormalities consisted of large amounts of drift in the strain gauge zero and large discontinuous excursions of the strain readings during a cycle (see Figure 4b). ITI personnel who were monitoring the data alerted Wisconsin DOT. ITI engineers felt that crack propagation in the vicinity of the strain gauge was responsible for both the discontinuous strain profile and the change in the baseline value. This was verified by a visual inspection conducted with a boroscope. The damage was monitored closely, allowing the bridge to safely remain in operation until the winter, when it was repaired again.

Continued Developments

The remote monitoring system on the Michigan Street bridge has been in continuous oper-

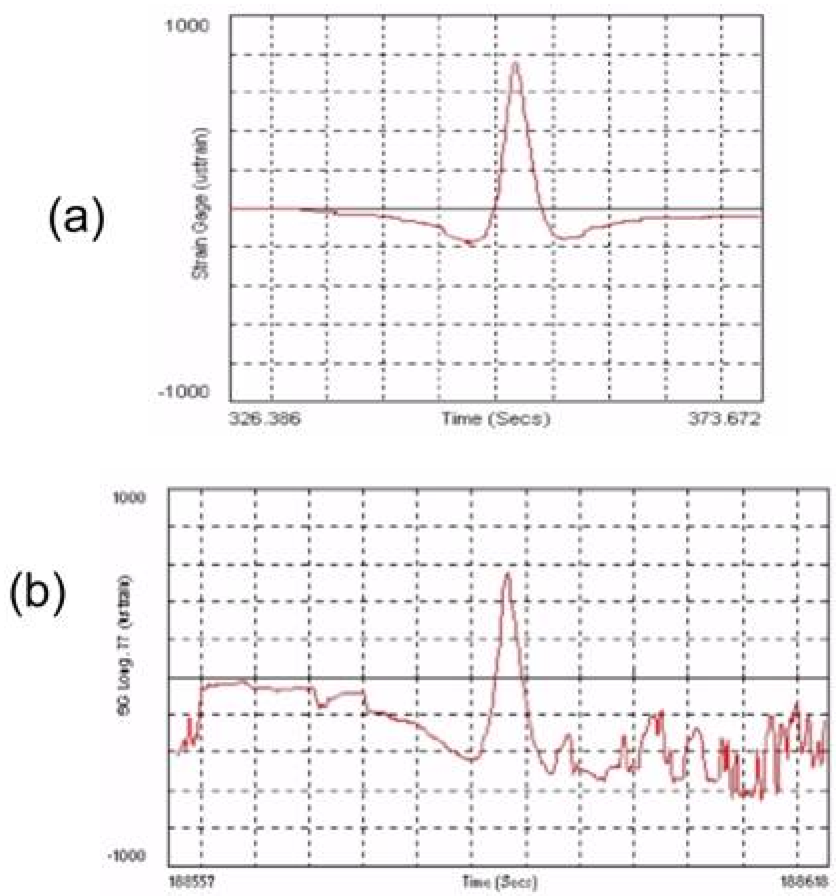

Figure 4: Figure 4: a) Normal data from a strain gauge during a bridge lift. A sharp strain peak is induced as the rolling bascule passes over the gauge location, but there is no change in the baseline strain reading following the lift. b) Abnormal data from one strain gauge after a few months of operation. The large offset of the baseline value indicates permanent deformation induced by the lift.

ation since July 1995. Over time the system has continued to evolve. Since the settling of the bascules onto the tracks continues, motor current meters were added in 2002 to measure any increase in the loads on the drive motors that would indicate binding of the rack and pinion gears. Wind speed and direction monitors were added in 2003, because, when it is open, the bascule spans present an enormous cross-section to the prevailing winds in the area, and this can affect strains in the bridge components. Wind data is collected periodically between lift cycles and continuously during lift cycles.

Data handling and access has evolved considerably into a user-friendly internet display. Data from the field computers is automatically downloaded nightly over a telephone line to the ITI lab in Evanston, Illinois. There, a computer program automatically parses the data and makes it available on a secure web site that serves as a clearinghouse for all sensor data from the bridge (see Figure 5). Another program compares the new data to preset alert thresholds configured by individual engineers. If the sensor readings exceed the thresholds, an e-mail alert is sent to researchers at the Institute. The maximum strain, tilt, and motor current values for each lift cycle can be viewed over a customizable time span to show how each lift compares to the historical norms. Data for each individual lift is also available. The web site facilitates easy comparison of the current data to historical norms and provides at-a-glance information on how quickly the bridge is deteriorating.

Resolution

Following the severe problems first discovered in 1994, Wisconsin DOT originally requested that the bridge be replaced. This proved to be unacceptable to the community of Sturgeon Bay due to the bridges landmark status. In 2000, an intensive study was launched to investigate alternatives. In 2002, the decision was announced to rehabilitate the bridge to allow at least 25 more years of operation. Money was earmarked for this project in 2005, and the work is scheduled to finally begin in 2008. The remote monitoring system installed by ITI, which has allowed this severely deteriorated structure to remain operational for more than 12 years since the discovery of serious problems, is a major factor in the survival of this bridge.

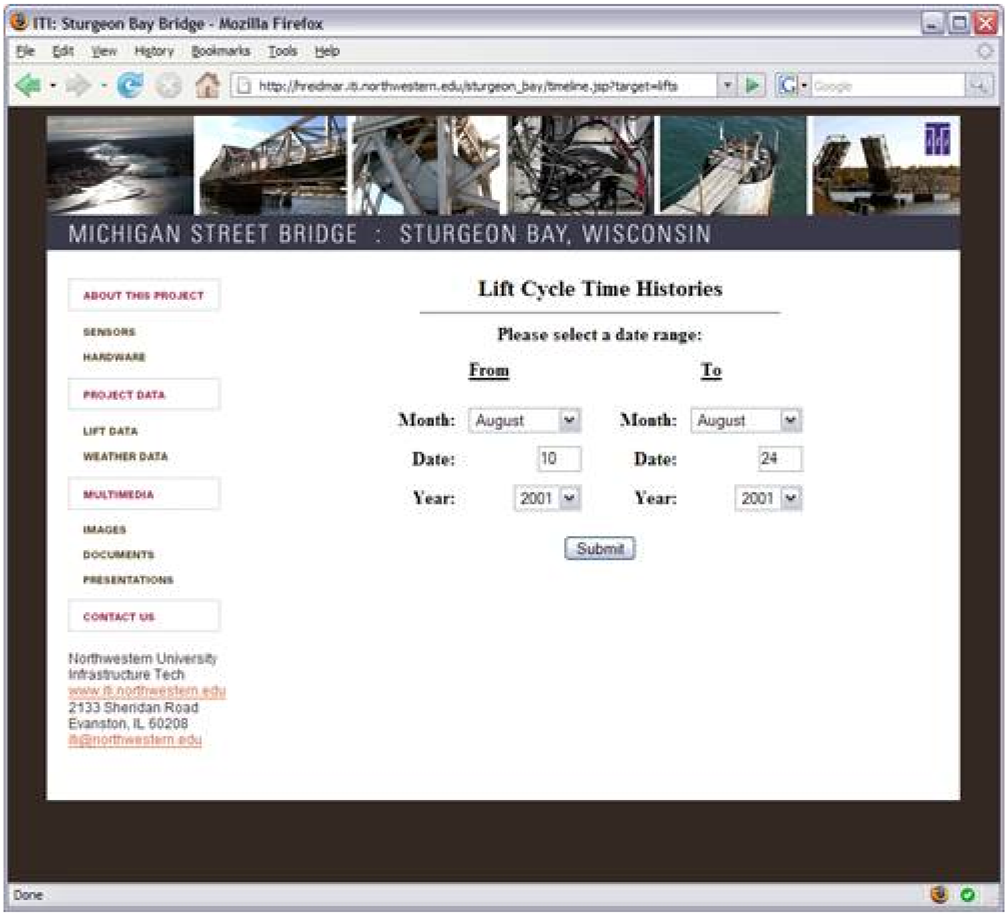

Figure 5: Michigan Street Bridge remote monitoring web site

STONY CREEK BRIDGE, GLENN COUNTY, CALIFORNIA (1998–2005)

Continuous remote monitoring of a concrete highway bridge for tilting of the piers caused by bridge scour.

Overview: The Stony Creek Bridge is located on State Route 32 between Chico and Orland and is maintained by the California Department of Transportation (Caltrans). This bridge was completed in 1980 and replaced in 2005. It was a reinforced concrete box bridge with 19 piers and a total length of 1492 feet (see Figure 6). The piers ran the full width of the deck, but were relatively narrow and were angled with respect to the roadway. All piers had concrete footings over either steel or concrete 70-ton pilings. Stony Creek itself experiences intermittent, high flows. During installation of the monitoring system, the water ran parallel to the bridge upstream, then turned at a right angle under the bridge to flow between piers 19 and 20. The remainder of the streambed was dry. Historically, this bridge has experienced, and remains susceptible to, local bridge scour next to its concrete piers.

Figure 6: Stony Creek Bridge. The bridge passes over a wide creek bed, supported by 19 piers. The location, direction, and strength of the Stony Creek are variable and erratic within this creek bed.

The Problem

Since its completion in 1980, the Stony Creek Bridge was found to be susceptible to scour that could undermine its piers. This scouring action is believed to be due in part to in-stream gravel mining operations conducted both upstream and downstream of the bridge, which added suspended solids to the water flow. This was a significant concern to Caltrans, which was responsible for its safe operation. Because bridge scour can progress very quickly during high water periods, it was necessary to have a surveyor and an engineer on site to conduct nearly continuous visual inspection of the bridge during the most dangerous stream conditions. Therefore, Caltrans was eager to install a continuous remote monitoring system that would provide early warning of scour activity.

Most scour monitoring methods attempt to measure the scour pocket itself in some way. This is very difficult due to changing water levels, debris, turbulent water, re-deposition of material, etc. (See Figure 7). In the case of the Stony Creek Bridge, scour could occur anywhere in the vicinity of its 19 piers, making the monitoring of individual scour pockets particularly impractical.

ITI Activities

Caltrans contacted ITI for consultation on this problem, and a remote monitoring approach was developed to measure the orientation of each pier using tilt sensors. These sensors will detect any slight change in the angle of the pier caused by scour, providing an early warning of destabilization. This approach requires highly sensitive and continuous monitoring.

The tiltmeters used for this project are commercially available capacitive clinometers, which operate on the same basic principle as a carpenters bubble level. They consist of a container of silicone fluid with a gas bubble that floats between two curved metal plates. Any rotation of the sensor causes the bubble to move, changing the capacitance between the plates. This is converted to a small output voltage that constitutes the signal. The resolution of these sensors is 1/1000 of a degree. For each pier sensor, two clinometers were used, oriented at 90 to each other and bolted to a piece of aluminum angle and enclosed within a watertight panel box connected to a cable that provides the communication link and power (see Figure 8).

Eighteen of the piers were instrumented in this way. The data acquisition system was completely assembled in the ITI lab in Evanston, Illinois, and was fully functional before shipment to the bridge. The sensor enclosures and pre-measured lengths of cable with connectors attached were shipped to HSH Construction, which performed the bulk of the installation, including placing the main computer enclosure on the abutment, connecting power and telephone service, attaching all sensor enclosures, installing conduit, and pulling the communications cables. ITI then completed the installation of the panels and PC in November 1998.

The network of sensors was powered by and communicated with a PC-104 based controller located in a weatherproof enclosure located on the southwest abutment of the bridge. This enclosure also contains a backup battery for the system in case of a power interruption. All components of the system were designed to operate on 12-volt DC power so that batteries or even solar cells could be used. A second, higher voltage power circuit was needed on this bridge

Figure 7: Bridge scour at the Stony Creek Bridge. Top: Stony Creek flowing past one of the concrete piers. Bottom: A scour pocket partially refilled with debris. The piling has been partially exposed, dangerously destabilizing the pier.

Figure 8: Panel box containing a pair of capacitive clinometers for measuring tilt of a pier resulting from scour. Eighteen such boxes were connected to an on-site computer.

due to the long length of cable required.

The on-site computer continuously ran a simple executable program written by ITI. The program displayed a table with the current inclination of each clinometer expressed in degrees. It also saved a date and time stamped snapshot of the readings from every sensor to a text file once an hour. The PC was accessed by means of a commercial software package called PC-Anywhere. This software enabled a remote user to connect with the bridge PC using a modem. In addition to downloading stored tilt data, a remote user could also control the system in the same way as if he were on site using the bridge PC.

The tilt measurements recorded by this system change over time as the bridge undergoes a range of normal motions due to temperature changes. These motions are unique to this bridge, and the normal behavior pattern over time can be learned by studying the baseline data recorded over a period of at least several days. Plotting the data from the two clinometers located at a pier against each other reveals that the temperature-induced movement is not random but consists of a regular oscillation around a point (See Figure 9). This system was operated continuously for period of over six years, allowing the Stony Creek Bridge to operate safely until it was replaced as scheduled in 2005.

Resolution

Due to the ongoing degradation of the existing bridge, it was finally replaced with a new bridge at the same location. Work on this $9.2 million project began in March of 2003. After the installation of the ITI scour monitoring system, the bridge never had to be closed due to deformation from scour.

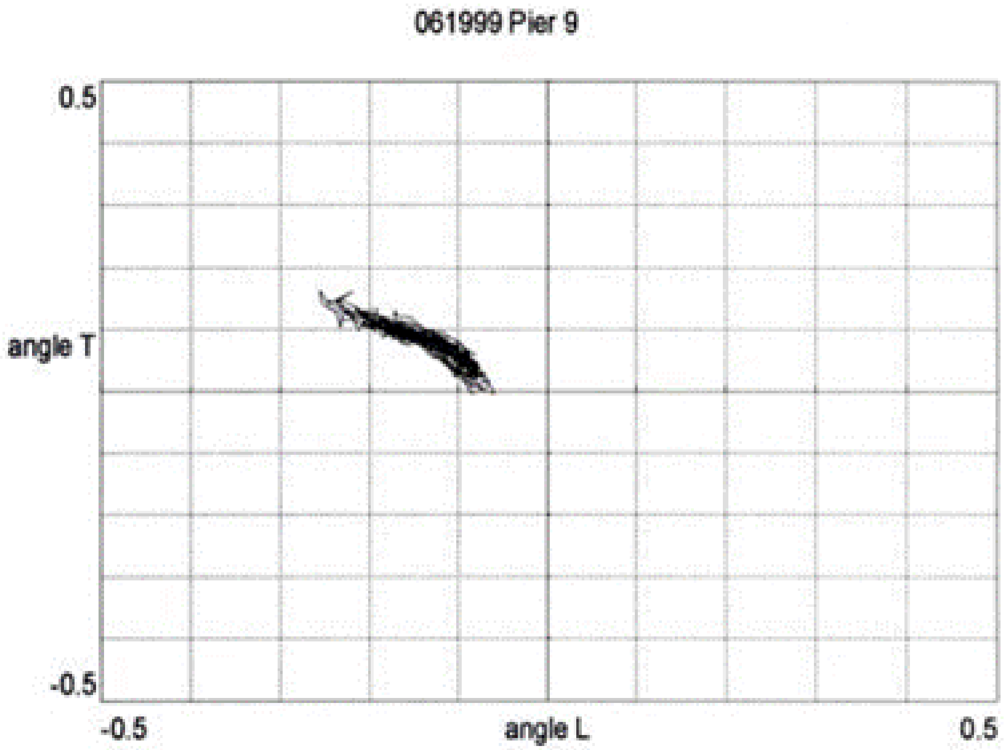

Figure 9: Data from two perpendicularly oriented tilt meters at the same pier location plotted against each other, revealing regular temperature-induced oscillation over time. Deviation from this pattern during a high-water period would provide a warning of possible bridge scour at this location.

CLOSURE: THE FUTURE OF SHM FOR CIVIL INFRASTRUCTURE

A variety of factors will amplify the pressure on the management of U.S. surface transportation infrastructure. These including aging of the physical plant, growing demand measured in terms of vehicle weights as well as traffic volumes, funding shortfalls, rapidly rising costs of materials, and attrition of trained professionals in transportation agencies. Together these will increase our reliance on high quality, detailed, and timely information on the condition of key infrastructure components, and they will make it even more important to utilize this information to make good decisions about preservation, rehabilitation and replacement.

Structural health monitoring will play a key role in this process. The opportunities for and the feasibility of substantial advances in the state of the art are at hand. Among the advances being implemented now, or expected in the near term, are these:

- Use of embedded sensors built into new or substantially rehabilitated structures, e.g., the new Minneapolis I-35W bridge[2].
- Applications of nanotechnology in sensor design to develop low-powered, area wide sensors
- Advances in wireless applications that reduce or eliminate dependence on physical connection of sensors or continuous sources of power
- Application of new, renewable power sources to support long -term sensor operations
- Advances in field devices to support arms-length inspection of infrastructure components.

These technologies and applications, and the wise use of the data gathered by them, will serve to make transportation infrastructure safer from deterioration, accidents, and intentional threats.

[2] http://content.asce.org/I35WcollapseMinnesotaDeptofTransportation.html