Long term health monitoring of Anthony Wayne Bridge main cable with acoustic emission technique

Rasa Seyedianchoobi

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A Thesis

entitled

Long Term Health Monitoring of Anthony Wayne Bridge Main Cable with Acoustic Emission Technique

by

Rasa Seyedianchoobi

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Degree Master of Science in Civil Engineering

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December 2012
An Abstract of

Long term monitoring of the Main Cables of the Anthony Wayne Suspension Bridge with Acoustic Emission Monitoring

by

Rasa Seyedianchoobi

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The University of Toledo

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The acoustic emission (AE) technique, based on the sudden release of energy within a material generating transient elastic wave propagation, is widely used as a non-destructive technique (NDT). AE events generate a spectrum of stress waves starting at 0 Hz, and typically falling off at several MHz. Based on the characteristics of AE waveforms and wave propagation theory, useful information like source location and the cause of emissions can be obtained. During the course of this research, the background and concepts of AE were studied and utilized. The AE wire breaking detection system on the main cables of the Anthony Wayne Bridge is used as a research laboratory for this thesis.

The acoustic emission (AE) method for nondestructive evaluation of main cables of the Anthony Wayne Bridge predicts the location of future invasive inspection and also is able to prevent disastrous failure of the structure. It will be relatively easy, in comparison with periodic physical inspection, to set up an effective long term high resolution health monitoring system for the main cables of the bridge. This study
investigated the development of the AE monitoring system and the application of AE to detect wire breaks.

The corrosion of metals involves ion transfer between anode and cathode. Electrochemical reactions consist of oxidation and reduction. The oxidation occurs at the anode (releasing electrons to the electrolyte); the reduction, at the cathode. There are several type of corrosion namely pitting, uniform, stress-cracking, and a combination of them.

AE can be used to evaluate and predict damages due to corrosion. Then the applicability of an existing AE system on the bridge for detecting corrosion was explored, including both a field test and laboratory testing. A corrosion test was carried out on a piece of aluminum bar with active pitting corrosion to capture the signature of AE waveforms due to corrosion such as amplitude, intensity of acoustic activity and frequency spectrum. The results of this laboratory test help to filter AE waves from the corrosion source.
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1. Introduction

**Acoustic Emission Method**: This is a versatile, non-destructive method to evaluate the condition of the structure. During the short course at MISTRAS, the concepts and application of this method were acquired. A brief introduction is given in this thesis about what was taught about AE and its application to the Anthony Wayne Bridge (AW).

**Application of AE for cables**: Acoustic emission is increasingly being used for bridge monitoring applications because it can continuously gather data and detect changes in AE activities. 15 sensors are mounted on each cable of the Anthony Wayne Bridge to listen to the AE activities. The cables were monitored for wire break and existence of corrosion in wires.

**Reviewing and interpretation of acquired data**: Based on the reports of AE activities recorded so far, there are no events indicating wire breaks. Data acquired through a day without traffic (October 23, 2011) on the bridge showed AE activities. A classifier must be defined to investigate the level of corrosion in the wires.
**Preliminary investigation into listening for corrosion on the AW:** The sensors mounted on the AW are R.45I with resonant frequency of 45 KHz. To discriminate AE activities due to corrosion, a classifier is needed. This classifier uses amplitude, frequency, power spectrum and other features of AE to pick data related to corrosion process. A corrosion experiment was set up to record emission from the corrosion process. A piece of aluminum bar exposed to the corrosive environment at one end and the AE pocket with its R15I sensor is mounted to the other end. AE activities were acquired successfully so a similar experiment could be done on the steel strands. Comparing collected data on Oct 23, 2011 with obtained data from a laboratory experiment will give a clue about status of corrosion in the cables of the AW.

**1.1 Bridge Description**

AW is a suspension bridge that carries State Route 2 over the Maumee River and nearby streets. The 3,215 ft. bridge has a suspended main span of 1,252 ft., with back spans consisting of trusses supported on concrete bents. The suspension span is connected to the main cables through suspender ropes. The main cables consist of 19 strands of 186 galvanized steel wires each. An elastomeric wrap was applied to the main cables in 1997 and 1998. The main cables anchored to the massive reinforced concrete blocks resisting the pull of the main cables (Burgess & Nipple, 2008).
1.2 Bridge History

1931 – The Anthony Wayne Bridge was opened to traffic.


1978 – Concrete barrier placed on centerline

1984-85 – Painting of structural steel

1987 – Decorative lighting added in the suspension spans

1988 – Sidewalk was replaced in the suspension spans

1989- Substructure concrete, bearing members at the towers, expansion joints, drainage troughs, and curb railing were repaired or rehabilitated.

1991 – First annual inspection of the bridge was performed.

1992- The second annual inspection was carried out.

1993- The third annual inspection was performed.

1995- Rehabilitation plans for various improvements including new cable wrap were prepared.


2003 – The structure was inspected.
1.3 Bridge Condition

ODOT Bridge Inspection Manual (ODOT, 1973) was used to rate the condition of the bridge. The rating chart is provided in the Appendix.

1.3.1 Protective Coating System Condition

Condition rating for protective coating system of suspension components is 6 indicating that “greater than 5 percent and less than 10 percent of the total protective coating system is failed.” (ODOT, 1973) Rusty points cover the surface of the components. As the paint system is not effective, there are exposed metal surfaces. The lowest rating is 0 indicating that less than 50 percent of the protective system is effective and corrosion has occurred and caused section loss. The highest rating is 9 which means there is no corrosion and the protective coating system (PCS) works well. (ODOT, 1973)

1.3.2 Structural Condition of Main Cables

Based on the bridge inspection report the main cable individual rating is 2, inferring fair condition and generally the suspension part of the bridge was rated 6, a satisfactory condition.

1.3.3 Location of the Deficiency of Main Cables

Several deficiencies were seen in the main cables and listed are the locations to be inspected thoroughly.
Water retention was observed at the following locations due to unbonded wrap:

- **Downstream Cable at panels:** 5, 7-11, 14-18, 23, 25, 27, 30, 32-35, 39, 41-46, 48, 49, 51, 55-58, 60, and 63;

- **Upstream Cable at panels:** 5-8, 10, 20, 37, 41, 43, 44-47, 50, 55-60, and 62.
Figure 1-1 Recommended inspection location by physical condition according to 2008 inspection (Burgess & Nipple, 2008)

*= location of cable wrap water retention, Downstream Cable
**= location of cable wrap water retention, Upstream Cable
1.4 Description and Use of AE

Acoustic emission refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material (ASTM E1316, 2011). The AE technique is based on the detection and conversion of elastic waves to electrical signals. This is accomplished by directly coupling piezoelectric transducers on the surface of the object.

AE has application in field inspection, structural integrity evaluation, pressure vessels testing, nuclear components inspection, corrosion detection, and etc.

1.5 Problem Statement

The main suspension cables of the Anthony Wayne Bridge are currently being monitored with AE for wire breaks. This helps identify locations where invasive inspection will be most advantageous. As the bridge is projected to be used long in to the future, continuous health monitoring of the main cables will be advantageous. Long term AE monitoring is able to detect and locate wire breaks. Also by ongoing development of AE, it is probable that the system will be able to detect the electrochemical noise directly created by the corrosion process.
1.6 Objectives

This thesis presents:

- A literature review of studies on the applicability of AE in both detection of wire breaks in main cables and corrosion detection was carried out.
- An Introduction to basic principles of AE as well as its nature and mechanics are explained. The structure of a typical AE sensor and the way it works are described. The advantages and disadvantages of this technique are given. Real-time monitoring, detecting active flaws, and passive monitoring are among advantages of this method. Skilled technician and surface contact issues are disadvantages.
- The application of AE on AW main cable wire breaks was shown through the examination of collected AE data by monitoring system. Then a classifier was used to find signals from wire breaks.
- The feasibility of AE for monitoring corrosion was investigated by means of laboratory experiments. An aluminum bar and POCKET AE were used to conduct this test. POCKET AE is a portable data acquisition system with two channels. It can record data and generate graphs while it receives data.
- Future work is suggested.
1.7 Organization

Chapter 1- Introduction: A brief description of the scope of this study.

Chapter 2 - Literature review: Principle of AE and its application in Bridge structures.

Chapter 3 - Field Study: Interpretation of AE data obtained from monitoring system of AW.

Chapter 4- Laboratory Experiment: Feasibility of AE was examined to listen the AE activity of corrosion process.

Chapter 5- Future Work: A guideline for further investigations was proposed.
2. Literature Review

2.1 Acoustic Emission

The early usage of acoustic emission dates back to potters making pottery as early as 6500BC. AE used to assess the quality of products by listening to the audible cracking sounds in cooling process. The first study in engineering filed on acoustic emission was done by Joseph Kaiser in 1950. He recorded the noises generated from within the specimen under tensile force and studied the relation between acoustic emissions and stress-strain curve. The extensive research was done in the United States by Bradford H. Schofield 1954. Clement A. Tatro carried out extensive laboratory tests at Michigan State University with his graduate student. He suggested the use of AE in evaluation the soundness of engineering metals in 1957. The first practical application of AE dates back to 1961 that AE used to verify integrity of the Polaris rocket motor for the US Navy. In 1963, Dunegan used AE to detect defects in the high pressure vessels and in 1969, commercialized AE.

2.1.1 Wire Breaks

Laura et al. in 1969 studied the application of AE in wire break detection. Their work were followed by Harris (1972) into the AE testing of suspension bridge cables. Dunegan (1974) and Harris came to the conclusion that AE techniques can be used to detect and number wire breaks for a given loading of the cable. Bamberger and Reboert
(1978) developed a special routine for detecting and localizing failure of wires. Hanzawa et al. (1982) introduced a wire break detection system that employed time of arrival (TOA) techniques to locate the break. Research in wire break detection by means of AE was carried out extensively at University College, Cardiff during the period 1980-1987. Casey et al. (1985) used Frequency analysis on the signal generated from wire break under both static and cyclic load conditions. Cullington et. Al (2001) used AE to monitor wire breaks in post tensioning tendons of a concrete bridge at UK. They showed continuous AE monitoring leads to the detection of wire breaks due to corrosion. Parmar and Sharp (2010) monitored a cable stayed bridge at I-295 (a bypass of Richmond, VA) by means of AE to assess the condition of the strands in the cables. The results revealed defects in the bridge.

2.1.2 Corrosion

Acoustic emission has been used to monitor corrosion in materials since 1970’s. Okada et. Al. (1974) and Retting and Felsen (1976) first published their result of application of Acoustic Emission in corrosion monitoring. Mansfeld and Stocker (1977) studied AE characteristics of pure corrosion while majority of research focused on special case of stress-corrosion cracking (SCC). The aim of the research was to find a correlation between AE activity and corrosion rate. Then the signal characteristic due to corrosion was investigated. It gave a methodology to discriminate noise signals. Riahi and Khosrowzadeh (2005) examined AE methods if they can detect corrosion rate in steel. They also compared the actual AE amplitude level with the relative ambient noise level. The results of the test showed that the mean amplitude of signal from corrosion is 40dB
and the threshold of 26 dB is well above ambient noise level. They also showed a clear correlation between AE count rate and corrosion rate. Wang et al. (2010) used AE to evaluate the existence of corrosion and cracks in the body of a haul tanker. They used acoustic sensors while the haul was on the operation. Using high speed computers and statistical data, events related to corrosion were reordered successfully despite highly noisy environment of ocean.

2.2 Acoustic Emission

Acoustic Emission differs from most other nondestructive testing (NDT) methods in two key respects. First, the signal has its origin in the material itself, not in an external source. Second, acoustic emission detects movement, while most other methods detect existing geometrical discontinuities.

Often in NDT there is no one method that can provide the whole solution; for cost effectiveness, technical adequacy, or both, it is best to use a combination of methods. Because acoustic emission has features that distinguish it so sharply from other methods, it is particularly useful when used in combination with them.

Main advantage of AE inspection is that it allows the whole volume of the structure to be inspected by the nonintrusive. It is not necessary to scan the structure looking for local defects; it only needs to connect a number of fixed sensors; which are typically placed 4 to 20 ft apart. This leads to major savings in testing large structures, for which other methods require removal of insulation, or scanning of very large areas.
Typically, the global AE inspection is used to identify areas with structural problems, and then other NDT methods are used to identify more precisely the nature of the emitting defects.

2.2.1 Other Non-Destructive Testing Methods Often Used in Conjunction with AE

2.2.1.1 Radiographic Testing (RT)

X or Gamma Rays and Neutron beams are used to find defects in the body of the material. Radiation is emitted to the material under inspection. These rays are able to pass through the body of the material and be projected on the sensitive film. The resulting shadowgraph shows the internal features and soundness of the inspected material. Material thickness and density changes are indicated as lighter or darker areas on the film or detector. The practical limitations are the safety concerns and its local applicability.

2.2.1.2 Magnetic Particle Testing (MT)

The magnetic field is applied to a ferromagnetic material. Surface and near-surface flaws disrupt the flow of the magnetic field and allow the magnetic flux to leak; a sound ferromagnetic material does not disrupt the flow of the magnetic field. Ferrous iron particles are then applied to the surface of the part. If an area of flux leakage is present the iron particles will be attracted to this area. This produces is a visible indication of defect on the surface of the material. This testing is qualitative and might need special equipment for access. It is not applicable in the case of corrosion monitoring.
2.2.1.3 Ultrasonic Testing (UT)

In ultrasonic testing, high-frequency sound waves with center frequencies ranging from 0.1-15 MHz are delivered into a material to detect internal imperfections or to characterize materials. A sensor generates a pulse and delivers it to a test object and echoes from internal imperfections or the part's geometrical surfaces are returned to a receiver sensor. Based on the received signal, the soundness of the object is examined. It is active form of NDT which make this method costly for long term monitoring.

2.2.1.4 Electromagnetic Testing (ET)

In this testing method, electrical currents are generated in a conductive material by an altering magnetic field. The currents induced in the material are measured. Material defects cause interruptions in the flow currents. Changes in the flow currents indicate the presence of flaws and imperfection inside the test object. The interpretation of the results is difficult and usually the size of equipment is large and hard to handle.
2.2.2 Principles of AE

Acoustic emissions are transient elastic waves generated by the rapid release of energy from localized sources within a material or structure. These elastic waves propagate throughout the structure. AE is a global non-destructive evaluation (NDE) and structural integrity monitoring technique. A key advantage of the method is its ability to detect and locate only active flaws, making it a prime candidate for real-time continuous health monitoring of highway bridges. This method is also able to direct local NDT straight to potential problem areas, while ignoring inactive flaws that are not a threat to integrity. The working frequency of AE depends on the kind of triggering events. In the field of non-destructive tests (NDT) the frequency range of AE is 20 KHz to 1.0 MHz. AE is a passive form of NDT that makes AE a method for long term monitoring (Casey & Laura, 1997).
2.2.3 AE Sensors

When AE wave reaches the surface of a test object, minute movements on the surface occur. AE sensors detect these mechanical movements and transform them to electrical signal. AE sensors use piezoelectric elements for transducers. The signals are recorded in a narrow band frequency to enhance the sensitivity of detection of AE signals. The other type of PZT sensors are damped sensors performing in broad band frequency (high fidelity sensors) while they are less sensitive to the surface movements.

![Figure 2-2 Typical parts of a PZT sensor](image)

Figure 2-2 illustrates the general components of a PZT sensor used in AE. Recently most of the PZT sensors come with internal amplifier.

2.2.3.1 Sensor Type

Sensors are of variety of type with different working frequency. The nature of each AE activity requires specific type of sensors. For example, as corrosion is a high frequency AE activity with low amplitudes, a sensor with high working frequency and sensitivity is needed.
2.2.3.1.1 Physical Acoustic Sensor R15α

This general purpose sensor provides a good combination of high sensitivity and low-frequency rejection (Mistras sensor catalog, 2010). This sensor is very suitable for monitoring common structures such as pipelines, vessels, bridges, and storage tanks in petroleum, refineries, chemical plants, or offshore platforms.

![R15α PZT sensor](image)

Figure 2-3 R15α PZT sensor

Its resonant frequency is 150 kHz. This sensor comes with internal pre-amplifier of 40dB gain. Its weight is 34 grams and its dimensions are 0.75” diameter and 0.88” height.

Figure 2-4 illustrates the frequency response of the R15α. This diagram shows the frequency range in which the sensor has the highest sensitivity (Mistras sensor catalog, 2010).
2.2.3.1.2 Physical Acoustic Sensor R.45I

The R.45I is very low frequency and high sensitivity, internally amplified AE sensor with a 20 kHz resonance frequency, 124 dB peak sensitivity and useful bandwidth from 1 to 30 kHz. The cavity is made from stainless steel. It is approximately 2.0 inches high.

Figure 2-5 Physical acoustic sensor R. 45I – installed on Anthony Wayne Bridge
The integral preamp sensors were specifically engineered to attain high sensitivity and have the capability to drive long cables without the need for a separate preamplifier. Incorporating a low-noise input, 40dB preamplifier and a filter all inside the sensor housing, these transducers are completely enclosed in stainless steel.

This sensor is used on AW because:

1. The lower the frequency, the longer distance possible between sensors
2. The sensor is less sensitive. So the ambient noise does not affect acquired data terribly.

### 2.2.3.2 Coupling

An essential requirement in mounting a sensor is sufficient acoustic coupling between the sensor’s surface and the structure surface. A thin layer of couplant applies to the surface to fill gaps caused by surface roughness and eliminate air gaps to ensure good acoustic transmission. Air bubbles and thick couplant layers must be avoided to prevent
Commonly used couplants are Ultrasonic gel, hot glue, Vaseline, and vacuum grease (Theobald, Zeqiri, & Avison, 2008).

![Figure 2-7 Couplant used with a transducer](image)

Couplant should be applied in a thin uniform coating to ensure a consistent inspection. In choosing a couplant, one should consider the surface finish of the part, temperature of the part, cleaning requirements, and the chemical reaction between the part and the couplant, particularly corrosion effects.

The effectiveness of a given couplant is dependent on its acoustic impedance, acoustic absorption, application thickness and viscosity. Each of these can have a strong influence on the sensitivity response of the sensor and can ultimately change the way the sensor responds to different wave modes (Theobald, Zeqiri, & Avison, 2008).
2.2.3.3 Signal Conditioning

Signal conditioning comprises amplification, filtering, and any other processes required to make sensor output suitable for data acquisition device after conditioning. Sensor signals must be normalized and filtered to levels suitable to convert analog signal to digital for computerized devices.

2.2.3.3.1 Amplification

The very small voltage generated across the piezoelectric transducer generates very small signals. Signals are normally amplified both by a pre-amplifier and by a main-amplifier, and are filtered. The gain of the amplifier is given in dB (decibels), which is the ratio between input voltage \( V_i \) and output voltage \( V_o \) as \( dB_{dc} = 20 \log_{10}(V_o/V_i) \). The preamplifier must be located close to the sensor and is usually integrated into the sensor case (Fig. 2-8). Integral preamplifiers lessen the effect of unwanted noise including electromagnetic interference picked up on the AE system cabling, coming from radio stations, navigation systems etc.

![Amplified Signal](image-url)

Figure 2-8 Amplified signal (Pollock A., 2011)
2.2.3.2 Filtering

Filtering in the preamplifier is the primary means of defining the monitoring frequency range of an AE test. In practice, the lower frequency limit is set to eliminate the background noise such as traffic and ambient noises. Wave attenuation of signal determines the upper frequency limit in order to maintain the accuracy of AE test. The most common frequency range for AE testing is 100–300 kHz.

2.2.4 AE waveform parameters

2.2.4.1 Waveform

Figure 2-9 shows a general AE signal. In order to determine the cause of the signal, characteristic features are defined. When a useful transient, or burst signal is correctly obtained, parameters like amplitude, counts, duration, and rise time can be extracted. For example AE of wire break has specific parameters which distinguish it from other AE sources, say corrosion.
2.2.4.1 Amplitude

In AE testing, amplitude is the largest voltage present in the signal waveform. A typical AE sensor of PZT element transforms elastic motions of 1 pico-meter displacement into electrical signals of 1 μV voltage. Amplitude is usually measured in $dB_{ae}$, a decibel scale running from 0 to 100. $0 dB_{ae}$ is defined as 1 μV at the preamplifier input.

$$A = 20 \log_{10} \left( \frac{V_s}{V_{ref}} \right)$$

$V_s = \text{The signal amplitude at the preamplifier input}$

$V_{ref} = \text{The reference voltage depending on calibration}$
2.2.4.2 **Duration**

Duration refers to the length of time from the first threshold crossing to the last, measured in μSec (Fig. 3-7).

2.2.4.3 **Signal Energy**

The area under the voltage-time envelope is signal energy.

\[ E = \int_0^t |V| \, dt \]

This feature has been used as the most successful quantitative description for AE.

![Voltage-time envelope](image)

Figure 2-10 Voltage-time envelope (Pollock A., 2011)
2.2.4.4 Counts

Count is the number of threshold crossings from the first to the last. Both positive threshold and negative threshold crossings are measured but the result is divided by two.

2.2.4.5 Rise time

The time from the first threshold crossing to the signal's greatest amplitude is rise time and recorded in $\mu$Sec.

2.2.5 AE Wave Propagation

The short pulse from the source is the beginning of the AE process. The motion at the sensor is quite unlike the original shock at the source. This the part played by wave propagation in the signal shaping chain.

The typical AE source motion is finished in a few millionths of a second. The wave takes a thousandth of a second to reach the sensor and it may take a hundredth of a second for motion to die away.

Three factors play significant role in AE wave propagation:

- Attenuation: The loss of amplitude as the wave travels through the material. This is important for the detection of distant sources.
- Wave velocity: The speed with which the wave travels
Signal shape: The shape of the signals emitted and detected by sensor

2.2.5.1 Attenuation

The reduction in AE signal amplitude as a wave propagates is termed attenuation (Pollock, 1986). Followings are four major factors:

- Geometric spreading of the wave front
- Internal friction
- Dissipation of the wave into adjacent media
- Dispersion of signal components

In the region close to the source, the dominant attenuation mechanism is geometric spreading of the wave front. Further away from the source where the majority of structural AE monitoring measurements are made, attenuation becomes dominated by absorption or conversion of sound energy into heat (internal friction). Absorption has a relationship with distance and it can be calculated as an attenuation coefficient in dB per unit. Dissipation attenuation can be caused by inhomogeneities in the propagation medium which scatter the sound wave in the same material. For example this is prevalent in wrapped cables that waves can propagate into surrounding media around steel cable.
2.2.5.1.1 Pencil lead break test

The breaking of the lead creates very short duration impulse similar to a natural acoustic emission source.

This test is used to develop attenuation curves. The lead is broken several times at each of several different distances from a sensor, recording the amplitude for each break. The amplitude for each distance are averaged, and the the average amplitudes are plotted against distance. Attenuation curve is an important aid to determine the sensor placements. The test also gives the wave velocity in the specific medium.

The Hsu pencil and the accessory Nielsen shoe are convenient, inexpensive aids that have been used in practical AE testing.
2.2.5.2 Wave velocity

Source location calculations are based on the times that the waves at the sensors are detected. These arrival times depend on the velocity with which the waves travel from source to sensor. The wave velocity depends on the geometry of the structure as well as the material from which it is made.

Waves consist of combination of wave modes which are patterns of oscillatory motion that can propagate in a stable way, maintaining their shape as they travel. For example in plates, there are four sets of wave modes; namely, longitudinal, transverse, surface, and plate wave modes. Wave modes travel at different velocities. Theory of elastic wave modes determines the velocity of wave modes as well as the wave.

In practice, pencil lead break test is used to find the equivalent wave velocity.

2.2.5.3 Signal shape

Wave propagation is a tremendously important stage in the signal shaping chain. It is wave propagation that largely determines the signal's size, shape, and shape-dependent signal features such as rise time and duration. The interpretive techniques are mainly based on signal shape.

Figure 2-12 shows how a short impulse at source is changed to a complex signal in the sensor.
2.2.6 Source Location

Source location techniques may be classified by the type of AE source mechanism (continuous or discrete) and include amplitude measurement techniques, such as the zone and attenuation measurement methods, and timing techniques, such as the cross-correlation, coherence and Time of Arrival (TOA) approaches.

Linear location is a computed location technique based on the assumption that the source is in line with the sensors. Two sensors are required as a minimum. With just two sensors, the calculation is very simple. There are some variants of the technique involving more than two sensors.
Referring to figure 2-13 if the first-hit occurs at sensor 2, then the source lies in the area from a point half-way between sensor 1 and sensor 2 to a point half way between sensor 2 and sensor 3. This area can be reduced somewhat by also noting the second-hit sensor. If the second-hit sensor is sensor 1, then the source lies between sensor 2 and a point halfway between sensor 1 and sensor 2. For evenly spaced sensors, this halves the potential location region (figure 2-13, b). This procedure is termed zonal source location, since it only allows identification of the covered zone rather than a more exact specification of the source position. However, if not only the hit sequence, but the time difference (arrival delay) between hits is measured (figure 3-10, c) more precise location
can be achieved. If the arrival delay of a signal between sensor 1 and sensor 2 is zero, it would indicate a source sited precisely midway between the two sensors. If the hit sequence is sensor 2, sensor 1 and the arrival delay is equal to the time taken to cross the entire sensor spacing, then the source is located at sensor 2. In general the linear source location is given by:

\[ d = 0.5(D - \Delta t \cdot V) \]

Where \( d \) is the source location (measured from first-hit sensor), \( D \) is the sensor spacing, \( V \) is the wave velocity and \( \Delta t \) is the arrival delay.

### 2.3 Comprehensive Cable Deterioration Study

To understand better the mechanisms of cable deterioration, a specially fabricated cable was installed in a test cell at Columbia University (New York City), in a joint project with MISTRAS Group and Parsons, the well-known bridge engineering company. They developed an integrated methodology that utilizes sensing capabilities and NDT direct and indirect technologies to assess the cable condition. A network of 76 sensors were implanted inside a suspension bridge cable for measuring environmental conditions (temperature, humidity, and pH) as well as corrosion vulnerability using some promising NDT technologies for direct detection of the corrosion damage (Main Flux method,
Magnetostrictive technology together with Acoustic Emission technology). This is the only accurate method for reliably assessing the condition of suspension bridge cables.

A full-scale mock-up of a suspension bridge cable was built in the Carleton Laboratory at Columbia University. This cable mock-up is 35ft long, and has more than 9,000 five-mm diameter high-strength steel wires. Subjected to 1,200 kips tension force, it is placed inside a corrosion chamber that can create cyclic aggressive environments.

The purpose of this study was to understand the environment and the dependence of corrosion on external challenges and maintenance variables. Information was collected for input to predictive models that could tell the degradation of a cable’s strength over long periods of time as a function of environment and cable condition.
3. Field Study

3.1 Introduction

The applicability of AE on AW was investigated. A monitoring system including is used to collect AE. A classifier embedded in AEwin™ discriminated signals and assigned a numeric label to each of them. These labels are defined on the severity of the received signal from 0 to 7.

3.2 Monitoring System

3.2.1 Sensor Highway II Smart Remote System

Two Mistras Sensor Highway II (SH-II) AE systems are mounted on the Anthony Wayne Bridge (1 system/main cable) and the AEwin Sensor Highway Smart Monitor (SHSM) software application package is used for the collection of AE data. Each system contains a total of 16 AE channels (15 channels installed). The sensor highway case size is approximately 20” x 16” x 6” deep.

3.2.2 Acoustic Emission Sensors

The sensors used for collection of AE data are the Mistras R0.45I-LP-SC-AST sensors. The “R” designation indicates that the sensor is a “resonant” transducer with a resonant frequency of 45 kHz and peak sensitivity over an operating frequency range of 5-30 kHz with a roll off to either side of the range. This sensor is typically used for AE inspection of suspension/cable-stay structures. The “I” designation indicates that the sensor has a built-
in, low power 12dB preamplifier, which allows the capability to drive long cables without the need for separate preamplifiers. A total of 15 sensors have been installed on each of the main cables with a spacing of approximately 100 feet between each sensor.

Figure 3-1 Sensor map location

3.2.3 Wireless Communication

For communication, each system contains a Sierra Wireless PinPoint X broadband mobile device figure 3-3, the systems and data can be accessed either
through the internet or directly through the built-in Ethernet 10/100 interface with a laptop.

![Airlink PinPoint X broadband](image)

**Figure 3-2 Airlink PinPoint X broadband**

### 3.2.4 Monitoring System Setup

Each SH-II system is located at mid span near to Sensor 8 for each main cable. This location was chosen because:

- Easy access to system for future maintenance
- Access to power (using the navigational lighting power source)

Once all sensors were mounted, a center punch test (equivalent to pencil lead break test) was carried out to verify the response of each sensor, system and location detection. The center punch is a standard test which generates a known (and repeatable) AE signal into the material in order to evaluate the system performance and verify its functionality.
Final system setup and verification was completed on July 14, 2011 and both systems brought online for the collection of data.

3.3 AEwin software

AEwin is a 32 bit WINDOWS, data acquisition and replay program capable of running acquisition boards and loading recorded data. AEwin uses full WINDOWS resources including: Setting of any WINDOWS available screen resolutions, printing, networking, and multi-tasking, multi-threading. AEwin allows user to replay and analyze all previously collected AE files. The software has all the acquisition, graphing and analysis capabilities that are expected in AE technique.

![AEwin software graphical user interface](image)

Figure 3-3 AEwin software graphical user interface
Each data acquisition board is controlled by AEwin software. Built in to the software is a series of different location algorithms. For the Anthony Wayne Bridge, the linear location algorithm is used. To use the algorithm, the location of each sensor (in relation to one another) is entered into the system along with the sensor spacing and the calculated wave velocity along the cable. For linear location, an AE source must be strong enough to propagate through the cable and be detected by a minimum of 2 sensors. Then using the location and wave velocity information, the time difference is calculated and the location of the AE event is displayed.

3.4 Anthony Wayne Bridge Recorded Data

3.4.1 Merging Data

The AE data are recorded up to a limited size because of:

- Avoid huge data files resulting in slower replay
- Easy system backup

To review AE data in a long period like a month, split data files are to be merged. AEwin is capable to merge split files which are continuous data (in terms of time). Merge is the utility that allows the user to merge multiple continued files into one larger data file. The user has to provide the input file names and order for merging them.
3.4.2 Source Type and Wire Break Classifier

Each system uses a built-in classifier that was specifically developed for wire break detection. In the case of the classifier, a set of 7 user defined AE values is entered in to the algorithm, so that if an AE source is strong enough to be located, the collected parameters, such as the amplitude of the signal, energy of the signal, frequency centroid, etc. are compared. For each feature that meets or exceeds the value of the classification, it is assigned a source type. Thus for a wire break, the AE signal would meet or exceed all 7 criterion and would receive a Source Type classification of 7.

3.4.3 Analysis of Data from April - Jun 2012

Figure 3-4 shows the classification of each of the located events detected from April 27th 2012 thru June 15th 2012. As it can be seen in figure 4-7, majority of located events have a source classification of 1, 2, and 3. This means that none of the AE events have met the criterion for a wire break. There are 4 events of source type 6. These events are strong and close to source type 7. Further investigation is needed for the location of these events.
Figure 3-4 Source type classification vs. linear location (North Cable)

North Cable:

5 events with Source Type 6 classification:

- Sensors [10, 9]: 1 event; March 15, 9:26PM
- Sensors [11, 12]: 2 events; May 9, 5:40PM & 5:42PM
- Sensors [10, 9]: 1 event; May 9, 5:42PM
- Sensors [8, 9]: 1 event; May 21, 3:31PM

South Cable:

7 events with Source Type 6 classification:

- Sensors [10, 9]: 2 events; April 28, 11:38AM
- Sensors [10, 11]: 1 event; April 28, 11:40PM
- Sensors [4, 5]: 1 event; May 9, 5:42PM
- Sensors [6, 5]: 2 events; May 9, 5:42PM & 5:44PM
- Sensors [11, 12]: 1 event; May 29, 7:31AM
Table 1 Events with classifier of 6 - North Cable April 27th 2012 thru June 15th

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<th>AMP(dB.ae)</th>
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GP# | x(ft) | y(ft) | Source Type | dT(µS) | Src Amplitude(dB.ae) |
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1 [11, 12] | 1026.8 | 0.625 | 6 | 5468 | 103 |

5/9/2012 5:42PM

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GP# | x(ft) | y(ft) | Source Type | dT(µS) | Src Amplitude(dB.ae) |
---|-------|-------|--------------|--------|----------------------|
1 [10, 9] | 877.21 | 0.625 | 6 | 1354 | 93 |

5/9/2012 5:42PM

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1 [12, 11] | 1074 | 0.625 | 6 | 656 | 93 |

5/21/2012 3:31PM

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<td>33</td>
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</tbody>
</table>

GP# | x(ft) | y(ft) | Source Type | dT(µS) | Src Amplitude(dB.ae) |
---|-------|-------|--------------|--------|----------------------|
1 [9, 8] | 753.34 | 0.625 | 6 | 1732 | 91 |

CH: Channel Number  RISE: See Section 3.4.5  ENER: The area under the signal waveform
AMP: See Section 3.4.1  A-FRQ: Average Frequency of detected waveform
SIG STRENGTH: Area under rectified waveform and reported in pV.S  ABS-ENERFY: Area under squared waveform
FREQPP1: First peak frequency in the waveform’s spectrum  FREQPP#: #th peak frequency in the waveform’s spectrum
C-FRQ: Central frequency of the spectrum  P-FRQ: Peak frequency of the spectrum
Some of this AE activity is related to friction between the cable band and main cable, personnel walking along the cable, etc. This information still provides useful information for trending over time for significant changes. For a wire break, the energy and amplitude of the wire break signal is several orders of magnitude above this type of AE activity.

### 3.3 Results and Conclusion of AE analysis

An acoustic monitoring system has been installed on the main cables of the Anthony Wayne Bridge. It is designed to aid in assessing the health of the entire cable volume of the cable by detecting wire breaks, helping to identify areas with potentially active corrosion, and integrated with other information can be useful in selecting areas to be opened for internal inspection.

Based on the channel by channel analysis of the wire break and corrosion data presented, potential areas of interest for future inspection of the north side of the bridge (based on AE activity classification) as are noted in figure 3-5.
Figure 3-5 Potential areas of interest: [NORTH] middle section between sensors 14 & 15, any panel between 8 & 9

The data was reviewed to illustrate how the wire break data is categorized and processed. Events, such as a wire break, which have high energy, can be detected by two or more sensors. Additionally, during a period when there was no traffic on the bridge the AE thresholds were lowered and the sensors were used to listen for active corrosion. As of July 2011 – the systems and sensors on both the North and South cables have been continuously recording and monitoring the cable.
4. Laboratory Experiment

The objective of AE application for corrosion analysis is to evaluate and predict damage. This experiment relates AE signal to corrosive damage mechanisms. Signal conditioning methods were used to increase efficiency. Also identification of AE sources in corrosion processes is presented. Retting and Felsen (1976), and Mansfeld and Stocker (1979) demonstrated the potential usefulness of AE for detecting and monitoring of active corrosion.

4.1 Chemistry of Corrosion

At the anode, the metal’s atoms go into solution as cations, this constituting the anodic reaction. Oxidation of metal atoms releases electrons (oxidation) whose negative charge would quickly build up in the metal and prevent further anodic reaction, or corrosion.

\[ M \rightarrow M^{2+} + 2e \quad \text{anodic reaction} \]

Thus this dissolution of cations will only continue if the electrons released can pass to a site on the metal surface where a cathodic reaction is possible. At the cathodic site the electrons react with some reducible component of the electrolyte and are themselves removed from the metal. Based on the availability of the oxygen, there are two types of cathodic reactions:
When pH is lower than two the hydrogen bubbling is the dominant case, on the other hand, at pH higher than eight the second reaction happens. In the field, the combination of reactions occurs.

The rust that eventually forms is the reaction of metal ions with hydroxide ions and oxygen:

\[ M^{2+} + 2OH^- \rightarrow M(OH)_2 \]

\[ 2M(OH)_2 + H_2O + \frac{1}{2}O_2 \rightarrow 2M(OH)_3 \]

The precipitation of rusts makes a porous media on the surface of the metal which absorbs the electrolyte and encourages further corrosion.

If solid corrosion products are produced directly on the surface of the metal as the first result of anodic oxidation these may provide a protective film retarding further corrosion, and the surface is then said to be passive. The production of an oxide film on aluminum in water is an example of such a process.

\[ 2M + 3H_2O \rightarrow M_2O_3 + 6H^+ + 6e \quad \text{passive film formation} \]

Other factors are involved in the corrosion process. In practice all steel surfaces are coated in order to retard corrosion. One method is using zinc as a coating. This is
called galvanization. Zinc sacrifices itself and saves steel. This is because of the nature of electrochemistry. According to metals' electrochemistry table, metals with less potential save the metal with higher potential. For example zinc is able to protect steel.

4.2 AE sources in Corrosion

Significant AE signals are generated by the evolution of hydrogen ($H_2$) gas via cathodic reaction in solutions of pH lower than 4 (acid solutions) and the breakdown of thick surface oxide film. In addition, the fracture of precipitates, second-phase particles are expected to produce detectable AE. In the presence of external loading, which is called stress-cracking corrosion (SCC), AE signals are mainly emitted by crack initiation and growth induced by SCC or HE (hydrogen embrittlement). On the other hand, dissolution of metals is not easy to detect by AE techniques. These mechanisms that can produce AE are schematically illustrated in figure 4-1.

As illustrated in Fig 4-1, there are several sources for AE during the corrosion process. Based on the sensitivity of the sensor and strength of the emitted signal, some of
them are easy to catch and some not. Both anodic and cathodic reactions produce AE, however the signals are very weak and hard to detect. Decohesion and dissolution of metal and its precipitation cause weak AE in addition to cathodic and anodic reactions. Other sources of AE which are detectable signals mainly come from SCC crack propagation, hydrogen bubbling, and passive film breakage.

4.2.1 Frequency of Gas Bubbling Breakage Waveform

The resonant frequency of bubble break-up in a fluid can be found by standard wave equation. The radial vibration of a gas bubble in a fluid is modeled as a simple harmonic oscillator, the stiffness and mass parameters relate to the properties of the gas and fluid (Leighton, 1994).

\[ f_0 \approx \frac{1}{\pi D_{\text{max}}} \sqrt{\frac{3\gamma P_0}{\rho_0}} \]

\( f_0 \): Resonant frequency of gas bubbles \( \approx 125 \) KHz

\( D_{\text{max}} \): Max. bubble diameter \( = 0.9 \)mm

\( P_0 \): Static pressure in the incompressible fluid \( = 3.110 \times 10^7 \text{ Kg/m}^2 \)

\( \gamma \): Specific heat for the ideal gas \( = 1.4 \text{ J/kg.K} \)

\( \rho_0 \): Newtonian fluid density \( = 1000 \text{ Kg/m}^3 \)
Bubble diameter of less than 0.9mm makes higher resonant frequency. As a result, it can be concluded that waveforms with frequency of 125 KHz or higher come from hydrogen bubble break-up. This frequency is used to discriminate AE source of bubbling from the rest. Also the AE amplitude of these waves is small in comparison with other AE sources.

4.2.2 Duration feature of passive film rupture and pit growth waveforms

Jirarungsatian & Prateepasen (2010) studied the AE activity of pitting corrosion. The results showed duration feature (µSec) can be classified into rupture of passive films and pit growth signal sources. AE waveforms with duration of 65µSec and less are emitted by passive film rupture, otherwise, by pit growth.

4.3 Aluminum Bar Test

Figure 4-2 Pocket AE and test fixture
The experimental set-up used for monitoring AE is shown in figure 4-2. R15α

Physical Acoustic resonant transducer with a band characteristic from 50 to 200 kHz, and 150 kHz resonant frequency is used to detect the acoustic signals. Signals are then filtered and amplified by an internal amplifier. The acquisition system is POCKET AE™. For each detected AE signal, the following acoustic parameters are studied:

- Hit Number
- Amplitude and peak frequency
- Duration

The testing solution is tap water. The duration of the test was set to 12hrs. The AE sensor was mounted using vacuum grease and duct tape on the surface of the aluminum bar. A plastic wrap was used to isolate the corrosion cell in order to prevent oxygen feeding. The sensor connects to POCKET AE™ through a co-axial cable.

4.3.1 POCKET AE™

The POCKET AE™ is a high performance, computerized, two channel AE system. It is useful in the laboratory that the system carries out lab tests by utilizing its two channels of AE and one channel parametric input for collecting load or stress data along with AE activity. It can perform AE feature extraction signal processing as well as advanced waveform acquisition and processing.
Results are displayed on an integrated color LCD touch screen. AE data files are saved in DTA files and can be transferred to the computer via compact flash cards and/or USB, for full data analysis, using AEwin™ software.

4.4 Results and Discussion

4.4.1 Hit Number

![Graph of Hits vs. time (Sec) and 3 periods of aluminum pitting corrosion](image)

Figure 4-3 Hits vs. time (Sec) and 3 periods of aluminum pitting corrosion

The number of cumulative counts vs. time curve (figure 4-3) clearly shows the process of pitting corrosion.

Period 1: The first period is pit nucleation which leads to the formation of a small area of bare, un-filmed passive surface of metal. During this period, oxygen is abundant. The presence of oxygen accelerates the corrosion. Sharp slope of the curve at this period shows very high AE activity at the beginning of the test.
Period 2: This period is called metastable. The development of a metastable pit leads to local dissolution of underlying metal. During this period the formation of either a stable pit or re-passivation is possible. The dissolved oxygen in the tap water is almost consumed by corrosion development.

Period 3: The damaged metal is formed and can be observed. The pitting process is continued by passive film rupture (AE source) and results in hydrogen bubbling (AE source). At this stage, the solution becomes acidic and pH is less than 7. Addition of table salt or lemon juice accelerates the corrosion and can increase the slope of the curve in this period.

4.4.2 Signal Conditioning

AE sources in corrosion processes can help evaluate metal damage. Signal conditioning based on frequency and duration features discriminates different phases of pitting corrosion. AEwin™ uses FFT to extract the frequency spectrum of a waveform.
4.4.3 High Frequency Waveforms

Hydrogen bubbling waveforms have frequency of 125 KHz or higher shown in figure 4-4.

Figure 4-4 Amplitude (dB) vs. duration (μSec) - for hydrogen bubbling

Figure 4-4 helps define a more refined classifier for hydrogen bubbling by limiting the AE wave signature of amplitude that ranges from 30dB to 60dB and duration higher than 150μSec.
Figure 4-5 Amplitude (dB) vs. time (Sec) - The distribution of hydrogen bubbling over the time of test

The shaded area with fewer signals in Figure 4-5 shows the presence of the passive film. This passive film retards the process of corrosion and leads to a period with few AE activities.

4.4.4 Low Frequency Waveforms

Duration feature classifies low frequency waveforms into two categories:

- Passive film break-up with duration of 65μSec and shorter
- Pit growth with duration longer than 65μSec (Jirarungsatian & Prateepasen (2010) and Fregonese et. al. (2001)).
Figure 4-6 Amplitude (dB) vs. time (Sec) of passive film breakage obtained by duration and frequency filters.

Figure 4-6 is divided to 5 zones in order to show the correlation between AE activity, film breakage, and the general corrosion process. There 5 zones are:

- Zone A: Pitting and film formation
- Zone B: Few film breaks
- Zone C: Pitting and film formation
- Zone D: Scattered film breaks
- Zone E: Several successive film breaks

Passive film breakage starts after 5000 seconds of the test. Comparing figure 4-6 with figure 4-5 reveals that between zone B to zone D there are few AE activities due to film break-up, then formation of passive film leads to less AE activities due to bubbling. AE activities in figure 4-5 after 22000 sec show revival after many passive film break-up which leads to higher AE due to bubbling.
Figure 4-7 Duration (µSec) vs. time (Sec) of passive film breakage

Figure 4-7 shows that most of the low frequency emissions were occurred at E zone. This led to pit-growth (phase 3).

Figure 4-8 Amplitude (dB) vs. time (sec) – AE with frequency less than 125 KHz and duration higher than 65µSec - Pit growth
Figure 4-8 proves that no pit growth found at the second phase (metastable) because of existence of passive film.

High duration of low frequency waveforms is based on how these types of waveforms travel through solid materials. There is less attenuation in the case of low frequency waveforms so these waveforms bounce back whenever they hit the boundary and produce longer activity at the location of the sensor. This could be avoided by setting appropriate HLT and HDT.

![Data Lookup Display: Hit/Wave 18 of 22](image)

Figure 4-9 typical low frequency AE waveform

Figure 4-9 shows a typical low frequency waveform. The features of the wave shown in the table beneath the signal shows characteristic of this kind of signal like
relatively low energy, and short rise time. However regression analysis is needed to find reliable relationship between these features.
5. Summary

Throughout this thesis, a comprehensive literature review on the application of AE on main cables of suspension bridges as well as applicability of AE to corrosion has been done. History of application of AE in engineering, wire break detection, and corrosion was presented.

Basic principles of AE were presented in chapter. The concept of AE was explained in order to show the advantages like detecting active flaws and real-time monitoring system and disadvantages of this method such as requiring skilled operator and weakness with regard to the defects currently not active.

AE data from the Anthony Wayne Bridge were examined. A classifier was to examine acoustic emissions exceeding the threshold. The classifier analyzed amplitude of the signal, energy of the signal, frequency centroid. The events were ranked on severity scale from 1 to 7 depending on how many characteristic of a wire break the event had. No wire breaks were detected. 5 events on the north cable and 7 on the south cable were ranked 6 from April to June 2012. Then the time and location of these events were investigated. All results were tabulated and shown.

AE of corrosion processes on the aluminum bar were caught by POCKET AETM. POCKET AE is a hand held device for detecting AE activity. It consists of internal data acquisition board and two channel with AE sensors. Recorded data were analyzed. The
results showed the clear correlation between AE activity and three steps of the corrosion process. Analyzing data gave a way to define a special signature for signals due to pitting corrosion.

The work done thus far in this research leads further work in several directions.

First of all, the performance of different types of sensors is different. Each resonant sensor responds with respect to its natural frequency, thus the waveform features change due to effect of attenuation. The present study was carried out with high frequency resonant sensor (R15) meanwhile; sensors on the bridge are low frequency sensors with less sensitivity toward attenuation. As a result, further study is required with different resonant frequency.

Moreover, the material used in the lab test was aluminum because aluminum corrodes fast. Investigation on AE of corrosion process in the steel strands will strengthen the findings in the present study.
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Appendix

A. Rating Chart of ODOT Bridge Inspection Manual:

A.1 Structural Condition

<table>
<thead>
<tr>
<th>Code</th>
<th>Condition</th>
<th>Definition</th>
<th>Summery and General Appraisal Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Good</td>
<td>No repairs needed</td>
<td>9 As Built</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 Very Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 Good</td>
</tr>
<tr>
<td>2</td>
<td>Fair</td>
<td>Minor deficiency, still functioning as designed</td>
<td>6 Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 Fair</td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>Major deficiency, item in need of repair to continue functioning as designed</td>
<td>4 Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 Serious</td>
</tr>
<tr>
<td>4</td>
<td>Critical</td>
<td>Item no longer functioning as designed</td>
<td>2 Critical</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 Imminent Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 Failed</td>
</tr>
</tbody>
</table>
## A.2 Protective Coating System Condition

<table>
<thead>
<tr>
<th>Code</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>There is no evidence of corrosion; the protective coating system (PCS) is sound, fully intact, and functioning as intended to protect the metal or concrete surfaces. No workmanship related issues.</td>
</tr>
<tr>
<td>8</td>
<td>Less than 1 percent of total surface area of the protective coating system is failed. Isolated light surface or freckled rusting along flange edges, cross frame members, end cross frames, bearings, phase or lap marks, or at bolted splices. Isolated chalking or fading or other early evidence of paint system distress. Isolated workmanship issues (painted surfaces only), surface defects less than 5 percent of total surface area. Workmanship defects include painted over grit, rust, mill scale, heavy paint drips, mud cracking in paint, or other related workmanship issues. No finish coat separation from intermediate coat.</td>
</tr>
<tr>
<td>7</td>
<td>Greater than 1 percent and less than 5 percent of the total protective coating system is failed. Light surface rusting along flange edges, cross frame members, end cross frames, bearings, phase or lap marks, or at bolted splices. Multiple workmanship issues (painted surfaces only), surface defects less than 10 percent of total surface area. Workmanship defects include painted over old paint, grit, rust, mill scale, heavy paint drips, mud cracking in paint, or other related workmanship issues. Finish coat separation from intermediate coat less than 10 percent. Chalking or fading or other early evidence of paint system distress.</td>
</tr>
<tr>
<td>6</td>
<td>Greater than 5 percent and less than 10 percent of the total protective coating system is failed. Surface or freckled rust is prevalent throughout. The paint system is no longer effective at beam ends beneath joints. There may be exposed metal but there is no corrosion, which is causing loss of section. Peeling, cracking, or separation of any caulking material. Workmanship issues (painted surfaces only), surface defects less than 15 percent of total surface area. Workmanship defects include painted over old paint, grit, rust, mill scale, heavy paint drips, mud cracking in paint, or other related workmanship issues. Finish coat separation from intermediate coat greater than 10 percent.</td>
</tr>
<tr>
<td>5</td>
<td>Greater than 10 percent and less than 15 percent of the total protective coating system is failed. Surface or freckled rust is prevalent. The paint system is no longer effective at steel bridge bearings, beam ends near joints at abutments and piers and along outside face of fascia beams. There is exposed metal with active corrosion causing light loss of section or pitting, typically less than 1/8-inch. Peeling, cracking, or separation of any caulking material with rust staining. Workmanship issues (painted surfaces only), surface defects greater than 20 percent of total surface area.</td>
</tr>
<tr>
<td>4</td>
<td>Greater than 15 percent and less than 20 percent of the total protective coating system is failed. Surface or freckled rust is prevalent. The PCS system is no longer effective. There is exposed steel throughout the</td>
</tr>
</tbody>
</table>
structure with active corrosion. Failure of caulking on crevice corrosion. Old paint system was painted over.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Greater than 20 percent and less than 30 percent of the total protective coating system is failed. The paint system is no longer effective. There is exposed steel throughout the structure with active corrosion.</td>
</tr>
<tr>
<td>2</td>
<td>Greater than 30 percent and less than 40 percent of the total protective coating system is failed.</td>
</tr>
<tr>
<td>1</td>
<td>Greater than 40 percent and less than 50 percent of the total protective coating system is failed.</td>
</tr>
<tr>
<td>0</td>
<td>Greater than 50 percent of the protective coating system has failed. Corrosion has caused section losses.</td>
</tr>
</tbody>
</table>
B. Bridge Shutdown Data Analysis (MISTRAS report)

On Sunday, October 23, 2011, the Anthony Wayne Bridge was shut down to traffic from between 7:30-8:00AM through around 6AM Monday, October 24, 2011. This date was chosen because it had followed several rainy days and it was the intent of the authorities to try and use the acoustic emission monitoring system to identify areas of potential corrosion. During this time, sensitivity of the acoustic monitoring system was increased in order to try and locate areas along both cables that may be experiencing or is susceptible to ongoing corrosion activities.

For this installation, there is a limitation in corrosion monitoring in that AE activity will be limited to the local areas in which the sensors are installed. The reason for this limitation is that AE generated by the corrosion process is in high frequencies and attenuates in a couple of feet. AE signals of corrosion are not strong enough to reach the next nearest sensor which is approximately 100 feet away. Typically for corrosion monitoring, sensor spacing is less than 5 feet. As such, analysis of the AE data was performed on a channel by channel basis.
Figure B-1 shows the AE hit rate (from all channels) before and during the time when the bridge was closed to traffic for the north and south side of the bridge. During the time of bridge shutdown, there were 2 distinct periods of changes noted in the data. The first was a period in which wind speed had changed from a calm period to high winds with gusts up to 21.9 mph (SSW-S) for approximately 3.5 hours. The next period occurred in the evening in which the relative humidity rose from 45% to 70% and began increasing until around 4:30AM when the next rain band moved through the area. Figure 4-4 shows the overall hit rate decreased after the bridge closure to traffic. However, the hit rate for the South side of the bridge increased around 9AM and was sustained throughout the day until around 7PM as compared to the North side of the bridge during this same period. By increasing the sensitivity of the system, and removing the live load...
from the bridge, it is expected that if there are active corrosion sources in the area, the increase in activity will be due to corrosion. However, due to the increased wind loading during this time period, trying to decouple AE generated just from corrosion and AE generated by bridge movement is extremely difficult. Typically, localized corrosion will produce AE events that are relatively low in amplitude, energy, and duration.

![Figure B-2 AE hit distribution by channel for North (top) and South (bottom) sides of the bridge.](image)

**Figure B-2** shows the channel by channel breakdown for the total number of hits detected for all sensors mounted on the North side of the bridge. Just looking at the cumulative number of hits for each channel, the north side of the bridge shows more of a distribution of AE hits with the highest channels at 1, 9 and 14.
Figure B-3 shows the amplitude of each AE hit recorded and time when the AE activity was recorded for channel 14 on the north cable. It is expected that for active corrosion, AE will be constantly recorded during this time period. The graphs have been divided into periods that show changes external loading on the bridge. Period 1 shows activity caused by traffic loading on the bridge. Period 2 shows the start of the shutdown of the bridge and during the time when the wind was relatively calm. Period 3 highlights the start of the period when there was a significant increase in the wind with gusts up to 21.9 mph. Period 4 shows the time when the wind decreased to around 5-6 mph (and the start of increasing relatively humidity) and Period 5 shows the time when there was a continuous increase in the relative humidity and start of a period of rain that lasted approximately 3.5-4 hours.

As such, at the beginning of Period 2, right after the bridge was closed to traffic; there is a significant drop in the hit rate. There is then a hit increase during Period 3 and the high wind loading event. While there is likely to be some AE due to corrosion during
Period 3, it is masked by the increase in AE hits due increased wind loading on the bridge. Once the high winds died down in Period 4, again, the majority of the AE channels returned to very little AE activity. Several channels, including channel 14, were exceptions to this general trend. Also, during period 4 the relative humidity began to increase from around 45% to 70% and then on to 90+% in Period 5 when a new rain event moved through the area. Typically in corrosion monitoring, it has been observed that corrosion will not typically activate until relative humidity levels reach at least 55% and above. Thus looking at the transition from Period 4 into Period 5, observation in the change of AE activity is may be indicative of areas that are potentially susceptible to corrosion.