REMOTE HEALTH MONITORING FOR ASSET MANAGEMENT

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Master of Science

By

SCOTT EDWARD MORRIS

Dr. Glenn Washer, Graduate Advisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

REMOTE HEALTH MONITORINGS FOR ASSET MANAGEMENT

Presented by Scott Edward Morris,

A candidate for the degree of Master of Science,

And hereby certify that, in their opinion, it is worth of acceptance.

Professor Glenn Washer

Professor Hani Salim

Professor Gregory Triplett

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ABSTRACT

This project explored the development of real-time monitoring technology to be used for effective asset management. There is a critical need to develop technologies to assess and monitor the condition of these bridges over time, to improve the information available to decision-makers such that effective asset management strategies can be employed. This project investigated the development of an instrumented pile that could provide real-time data on bridge scour, allowing for the remote monitoring of bridge conditions by key managers and engineers. The developed technology has the potential to identify hazardous conditions at a bridge site, such that managers and owners can be notified automatically and appropriate actions can be undertaken. The instrumented pile monitors the temperature along its length using an array of semiconductor thermometers embedded in the soil in a river bed. This technology provides a practical means of managing a bridge asset by reporting on potentially dangerous scour conditions such that mitigation strategies can be employed. A prototype pile was designed and constructed that utilized an array of 64 sensors along the length of a 20 ft. HSS 10 x 10 pile. The test pile was installed in Hinkson Creek, Columbia, MO. The test pile was successful in demonstrating the feasibility and operation of the newly developed sensor array technology.

EXECUTIVE SUMMARY

This project explored the development of real-time bridge monitoring technology to be used for effective asset management. The management of the almost 600,000 bridges in the National Bridge Inventory (NBI) provides a significant challenge to bridge owners and engineers. It is estimated that there are more than 90,000 bridges in the NBI that have unknown foundations, complicating decision-making in regards to maintaining the safety and operation of these critical assets. Additionally, there are more than 26,000 bridges in the U.S. identified as scour critical, such that erosion at the foundation of these bridges has the potential to lead to structural instability and bridge failure. As a result, there is a critical need to develop technologies to assess and monitor the condition of these bridges over time, to improve the information available to decision-makers such that effective asset management strategies can be employed.

This project investigated the development of an instrumented pile that could provide real-time data on bridge scour, allowing for the remote monitoring of bridge conditions by key managers and engineers. The developed technology has the potential to identify hazardous conditions at a bridge site, such that managers and owners can be notified automatically and appropriate actions can be undertaken. The instrumented pile monitors the temperature along its length using an array of semiconductor thermometers embedded in the soil in a riverbed. Monitoring the temperature profile along the length of the pile

shows the thermal variations that exist in the water and in the soil, as a means of estimating where the soil / water interface exists. If a scour hole develops in the area of the pile, the depth of the soil / water interface is consequently changed, and this change is detected by thermal variations detected along the length of the pile. This technology provides a practical means of managing a bridge asset by reporting on potentially dangerous scour conditions such that mitigation strategies can be employed.

An innovative new sensor array technology was developed that improves the reliability of field measurements by eliminating the majority of the wires required to make the measurements. A low-cost digital temperature sensor was selected for this application. New manufacturing processes were developed to provide a sensor array that can be integrated into a pile to be embedded at the bridge site. These processes were developed to provide a rugged, fieldable sensor technology that could be applied under a variety of implementation schemes. Laboratory studies of prototype sensor arrays were conducted to determine the adequacy of the sensor for this application. Software was developed and tested that supports long-term monitoring of sensor outputs. A prototype pile was designed and constructed that utilized an array of 64 sensors along the length of the 20 ft. pile. The test pile was installed in Hinkson Creek, Columbia, MO. Software to support monitoring the test pile over the web was developed and implemented. Initial test results from the pile installation are included in the report. The test pile was successful in demonstrating the feasibility and operation of the newly developed sensor array technology.

1 Introduction

A key challenge to managing fixed assets such as bridges and other transportation infrastructure is monitoring their condition over time. Under typical service conditions, deterioration resulting from traffic loading and difficult environmental conditions can result in a reduction or loss of service of a particular asset, or even life threatening and dangerous failures. Extreme events such as earthquakes and floods present a still greater challenge in that the service condition of the asset may change abruptly and without warning, leaving managers without key information they need to respond to the event. The **goal** of this project was to develop remote health monitoring technology that will provide managers and owners with timely information on the condition of civil infrastructure assets. The **objective** of the study was to develop an instrumented pile that could be installed at a bridge either as part of the original construction or installed post-construction to monitor conditions at the bridge. The pile was instrumented using a series the thermal sensors to detect the scour level at a bridge substructure by evaluating which portions of the pile are embedded in soil and which portions of the pile are exposed. This report documents efforts made toward meeting these goals.

During the course of the project, a new method was developed to measure temperature profiles along the length of a pile embedded in the soil adjacent to a highway bridge. A low-cost, rugged and durable temperature sensor array technology was developed. Significant efforts were required to develop the necessary technology to manufacture and assemble the temperature sensor array, and develop supporting instrumentation and software to support remote monitoring of bridge conditions. Progress was made toward developing a unique instrumentation system that would enable the long term monitoring of highway bridges using a unique and highly durable temperature sensor array. A prototype test pile utilizing the newly developed technology was designed, constructed and implemented at a test site in Columbia, MO.

Manufacturing processes were developed to produce a temperature sensor array that could be installed in the difficult environment of a highway bridge and be expected to perform adequately over a long time period. This involved developing a sensor array that would resist corrosion, be durable enough to be driven into the earth during pile-driving operations, and have the necessary sensitivity to detect changes in temperatures associated with developing scour. A design for implementation of the new sensor array technology along the length of a steel H-pile was developed. A field installation site was selected in Columbia, MO. The pile was installed successfully and monitored December 2008 through February 2009.

Project partners included the Missouri Department of Transportation (MoDOT) and the Tennessee Department of Transportation, each of which provided funding to support the project. MoDOT assumed the project lead State status, organizing the team to provide quarterly progress meetings held via teleconference. The project team provided progress overviews to the partner States as a means of technology transfer and to ensure that progress on the project was directed toward meeting the needs of State Departments of

Transportation. The project team prepared detailed slide presentations that documented progress and efforts on the project, and these slides were presented to the project team. Significant input on the direction of the project and specific design assistance was provided by the partner States. In particular, Terry Leatherwood, Tennessee Department of Transportation, provided useful input on past experiences and specific design advice on the development of the instrumented pile.

The primary sponsor for the research was the Midwest Transportation Consortium, a University Transportation Center (UTC) centered at Iowa State University. The University of Missouri also provided matching funds to support the project.

2 Background

The collapse of the Schoharie Creek Bridge in 1987 (shown in Figure 2-1) introduced a new era of concern regarding the structural stability of highway bridges and the stability of the substructure systems supporting them. The tragic collapse and others that followed have focused attention on the need for dependable methods of monitoring the structural stability of highway structures. Bridge scour that results in a loss of structural stability is the most common reason for the collapse of highway bridges, and innovative, cost-effective monitoring methods are urgently needed. Presently there are more than 26,000 bridges in the U.S. identified as scour critical [1, 2]. More than 3,700 bridges were damaged by scour during the period of 1985 to 1995[2].

Figure 2-1. Photograph of the Schoharie Creek Bridge collapse, 1987.

There has been abundant research in methods of analysis of scour. Generally, five scales of scours processes exist [3]. In descending order of size, they are the catchment scale, stream section scale, bridge far-field scale, bridge near-field scale, and local scour scale. The catchment area is the area drained by the river at the point of the bridge. Using this scale, the total amount of flow through the bridge crossing point can be determined, along with what types of debris can be expected. The stream section scale takes into account the meandering and migration effects of the stream. This scale is used to measure long-term scour and stream evolution. The effects of bridge far-field processes are used to determine the elevation of the water surface for smaller scale calculations, and for calculations of short-term scour. Bridge near-field processes include contraction of the flow due to bridge existence. The smallest scale, local scour, is only used to determine what effects the actual structure has on stream erosion, and can be used estimate the scour depths at the abutments using empirical formulas. The type of scour that most of the manufactured sensors detect is the local scour. This is the most important to bridge safety because in a short time, possibly from a single storm event, the piers could become completely undermined and collapse without giving warning to the surface.

A number of technologies have been developed to address the issue of scour in the area surrounding bridge foundations. Many of these technologies, such as fathometers and ground penetrating radar, are aimed at detecting scour holes adjacent and beneath bridge footings. These and similar techniques are based on periodic inspections and may not provide real-time data about sudden events that may occur on a structure. Efforts to use these techniques during extreme events, such as floods, are hampered by high water velocities and increased flow depth.

Conversely, in-place, or fixed, monitoring systems have also been widely applied. These include fixed fathometers, simple depth rods, piezoelectric films, float-out devices buried in the stream bed, and magnetic sliding collar instruments [4]. Dataloggers have been used to collect data electronically during extreme events, and a number of telemetry devices have been used to transmit critical data to State agencies. However, these systems have several disadvantages. First, portions of the systems must be placed in the water flow, such that they are susceptible to debris damage. Second, the scour must occur at the location and in the manner predicted, as these systems make measurements in relatively small areas adjacent to a pier. It is estimated that there are more than 90,000 bridges in the United States with unknown foundations such that the required analysis to predict scour hole locations is simply impossible[5]. Even with known foundation conditions, the behavior of scour under flood conditions may be difficult to fully define. As a result, local scour monitoring devices have practical limitations for effective, widespread installation. The technologies developed during the course of this research have the potential to be implemented within the original construction of bridges, such that actual scour condition affecting a bridge substructure can be monitored. Therefore, it would not be necessary to predict the scour hole locations, as the system could be integral with the bridge and remotely monitor the scour level at the foundation itself.

The National Cooperative Highway Research Program (NCHRP) has done extensive research in scour measuring instruments [6]. In the NCHRP Report 396, a study was conducted on several instruments; sounding rods, magnetic sliding collar devices, and low-cost sonic fathometers. The report broke down each of those instruments and gave a list of pros and cons. They found that the sounding rod was unable to retrieve data remotely. Due to its nature, a worker needs to be on the bridge to operate the instrument. In addition, the sounding device showed the poorest reliability among those tested. The magnetic sliding collar devices performed very well in measuring scour, but needed more caution and care during installation than the other instruments. Another issue is that the collar will only track the maximum depth of scour. After a scour event, the device will lie on the bottom of the scour hole, but during aggradation, or the resettling of sediments, it will be covered back up. This type of behavior is acceptable when the maximum scour depth is needed, but it cannot accurately monitor the current location of the streambed. A main problem with sonic fathometers is the interference of transmission due to air bubbles in the water. This can cause altered readings or complete loss of communication during a turbulent stream event. Also, the design of the mounting system must be well thought out to make sure an even flow is maintained over the transducer. Overall, the research found that the types of instruments focused on in this report were capable of being installed on most pier types, they could generally measure scour accurately within one foot, and only some were operable during flood periods. Essentially, a better instrument needs to be created that can do all of those things well.

In a report by Blue Road Research in Oregon, a system using advanced fiber grating strain sensors is discussed along with its possible uses for measuring bridge scour [7]. Two possible setups are explored, one where the fiber grating sensor is placed in a rod which is driven vertically into the stream bed alongside a pier. This type would measure the strain due to the rod flexing in the water caused by the forces of water flow. As more of the rod is exposed, the bending of the rod would increase, which would be correlated to the amount of scouring. The second setup would have load cells underneath the pier or abutment. As the soil is scoured away, the load on these cells would change and be measured. At this time, there are no solid results from either of these setups, but there is potential for both of the systems to be successful in the field.

A 2005 report published in the Institute of Physics Smart Materials and Structures journal takes the fiber Bragg grating sensor research to the experimental stage [8]. Two types of sensor systems were developed. The first system is similar to the first type used in the research by Blue Road Research above. It consists of a cantilevered mechanism with three sensors along a single optical fiber. The strain at the three locations is used to measure scour. Several of the experiments were reported. The differences were the initial ground line level. The level was first between the highest elevation sensors, while in the second experiment the ground line was initially between the lower elevation sensors. In the final experiment, the ground line was initially below all three sensors. The system was shown to succeed in observing scour and showing an estimated depth in the results. The second sensor system used a tube attached to the side of the pier pointing upstream. The sensors were mounted on this tube using another cantilevered plate attached to the side of the tube. In the experiments on this setup, a scour hole was simulated around the tube. Then, water was released upstream. The sensors above ground show a strain due to the temperature difference, and also due to the bending strain caused by the flow on the cantilevers. As the water continues to flow past the tube, the sensors underground begin to be revealed, and show similar strains. In the final experiment, the flow is released and continued for 30 minutes. Upon the water reaching the exposed sensors, a large strain is read due to the temperature and bending strains. After the scour hole reached equilibrium, sand was poured back into the scour hole over a short time. The exposed sensors were able to respond by showing a diminishing strain over time, until they were completely covered, and read nearly zero strain. When the pouring was ceased and while the water continued to flow, the material was removed again and the sensor read the corresponding strain. This fiber Bragg grating sensor showed promise and warrants more research, due to its ability to measure not only scour, but also deposition, and water level.

A remote scour monitoring system consisting of inclinometers was fielded on a bridge in California in 1999 [9]. This system consisted of a two inclinometers mounted on each face of the pier, wired to a central data acquisition system that collected tilt data from each of the 18 piers on an hourly basis. This data was made available to State personnel from any location by dialing into the system using the program “pc anywhere™”. Initial results from outputs of these sensors indicated that significant diurnal variations in inclinometer output were experienced, making interpretation of data difficult. However, use of this type illustrates the application of targeted monitoring technology for the purpose of asset management, to provide real-time or near real-time data on the conditions in the field at a valuable fixed asset.

This project explored the development of an instrumented pile that could provide real-time data on bridge scour, allowing for the remote monitoring of bridge conditions by key managers and engineers. The developed technology has the potential to identify hazardous conditions at a bridge site, such that managers and owners can be notified automatically and appropriate actions can be undertaken. The instrumented pile monitors the temperature along the length of a pile embedded in the soil in a river bed. Monitoring the temperature profile along the length of the pile shows the thermal variations that exist in the water and in the soil, as a means of estimating where the soil / water interface exists. If a scour hole develops in the area of the pile, the depth of the soil / water interface is consequently changed, and this change is detected by thermal variations detected along the length of the pile. This technology provides a practical means of managing a bridge asset by reporting on potentially dangerous scour conditions such that mitigation strategies can be employed.

A monitoring concept based on thermocouple measurements was previously developed for the State of Tennessee in the 1990's by Camp [10]. This project expanded on Camp's research, and developed a new sensor approach for making measurements along an embedded pile. A digital, semi-conductor based sensor was selected for application on this project. The sensor is a 1-Wire device manufactured by Dallas Semiconductor. The model DS18S20 sensor is a high precision 1-Wire digital thermometer. A data acquisition system for these sensors was developed to read data from the sensors and enable data storage. Two small test piles were constructed and tested in the laboratory. The larger of the test piles used 16 DS18S20 sensors and was connected to a ceramic heater capable of temperatures up to 200 degrees Celsius, to allow adjustments to thermal gradients in the test pile to demonstrate and test the operation of sensor arrays. A prototype test pile with 64 sensors along a 20 ft. length of the pile was designed, constructed and implemented in the field.

Research has been conducted that utilizes the Dallas Semiconductor sensors in underground temperature detection by the National Engineering Research Center for Information Technology in Agriculture in Beijing [11]. This experiment used DS18B20 sensors instead of the DS18S20 sensors used in the research at the University of Missouri. These sensors are very similar, with the main difference being the different types of casings. The DS18S20 comes in a TO92 3-pin casing, while the DS18B20 can come in an 8-pin setup. The research in Beijing was focused on determining temperature at different depths beneath the soil for use in agricultural studies. Subsurface temperature is important to plants for many reasons; the ability for roots to grow and spread, their ability to absorb water and minerals, and the rate of decomposition of organisms. The array used in their research consists of ten DS18B20 sensors along a 50-millimeter length. Through the RS-232 Serial Port, all of the data was sent to a computer for display and storage. Their research proved that the use of semiconductor sensors for underground temperature measurement is both cost effective and can be precise, and is a viable system worthy of more consideration.

The following sections describe the design, development, and testing of the new sensor array technology. Section 3 describes the one-wire sensor used in the research, and describes the manufacturing processes developed to implement the sensors in a rugged, fieldable design. Section 4 presents the results of laboratory testing of the sensor array designs that provided a foundation for the development of a full-sized, field-implementable array. Section 5 describes the design, construction and implementation of the prototype test pile, including initial results of remote monitoring of the test pile installed in the field. Section 6 is the conclusions of this project, along with an implementation plan.

3 Project Instrumentation

A significant portion of the project was dedicated to developing a new method of detecting temperature profiles along the length of a pile. This portion of the report will describe the development of a unique, 1-wire sensor array that was the focus of efforts during the project. First, detailed information about the sensors used will be provided. An overview of the software that was developed will follow, as well as a description of the manufacturing process developed to enable the array to be installed in the field.

3.1 Sensors

The goals of the project required that a suitable temperature sensor device be identified to enable the long-term, stable measurement of thermal conditions in the pile. Thermocouples are a traditional method of measuring temperatures, due to their low cost and durability. Thermocouples operate by measuring the potential difference across a bi-metal interface. Two wires of differing alloy composition are joined together, and the potential difference across the metal interface is a function of the temperature at the interface. These sensor have several advantages, including high temperature sensitivity and low cost. Supporting instrumentation to measure the output of thermocouples is widely available, such that minimal development is required to implement thermocouples as a temperature monitoring device. However, thermocouples also have a number of disadvantages. First, the bi-metal interface is susceptible to corrosion when placed in an environment where water and oxygen are readily available, such as when embedded in a stream. Second, it requires two wires for each individual sensor to provide the bi-metal interface, so that developing an array with a large number of sensors requires a large number of wires. This is a particular challenge for the present project, as each wire provides a potential source of failure such that long-term reliability of a system of thermocouples is problematic. Additionally, the large number of wires that would be required to instrument a pile with a large number of sensors requires an intrusive sensor measurement system to provide a data collection bus and measure each channel individually. Most importantly, the sensor outputs are low-level signals that must be conditioned and measured by an analog circuit, digitized and stored. When installed in an uncontrolled environment such as along a pile embedded in a stream bed, ground loops and other electromagnetic noise provide a significant challenge for the long-term measurement of sensor outputs. As a result, an alternative to thermocouples was sought to provide a suitable sensor for measurement of temperature profiles along the length of the pile.

A literature search and interactions with the project partners led to an alternative to thermocouples for the temperature array designed for this project. The i-button, an automated temperature sensor that can be installed without attached wires and read through a specialized inductive hand-reader, was suggested by the project partners as an alternative to thermocouples. A comprehensive literature search and interactions with the i-button manufacturer led to an alternative, 1-wire temperature sensor based on the same technology as the i-button, but read directly via a hard-wired interface.

The 1-wire sensors are manufactured by Dallas Semiconductor. The sensors provide an alternative to thermocouples. The devices are a semi-conductor based digital temperature sensors. The sensors have been used for many applications, such as timekeepers, current sensors, battery monitors, and for identity verification. The main benefit of these devices is that they need a limited amount of wiring and hardware to be functional. Also, each device has its own unique 64 bit serial number assigned to it when it is fabricated, allowing over 281 trillion different combinations. This feature allows a large number of slave devices to be daisy-chained together along a single wire connection to one microcontroller. The sensors are also connected to a ground wire for reference, but this wire is generally ignored by convention.

The 1-Wire interface is described in many of the Application Notes on the Dallas Semiconductor website, and as such is only briefly summarized here. Information is transferred by the use of high and low voltages present in the line along with the use of "time slots." To read information from a sensor, the micro-controller pulls the bus master voltage to low for 1µs then releases and allows the slave sensor to control the line. A voltage of 2.2V or higher is read as logic 1 and voltages of less than 0.8V is read as logic 0. The voltage must stay in that range for between 60 and 120µs.

The DS2480B is used as a microcontroller for 1-Wire applications. It is described as a "serial bridge to the 1-Wire network protocol." A simplified schematic diagram of the usage of a DS2480B is shown below in Figure 3.1 with two slave devices (DS18S20) attached in a daisy-chain configuration.

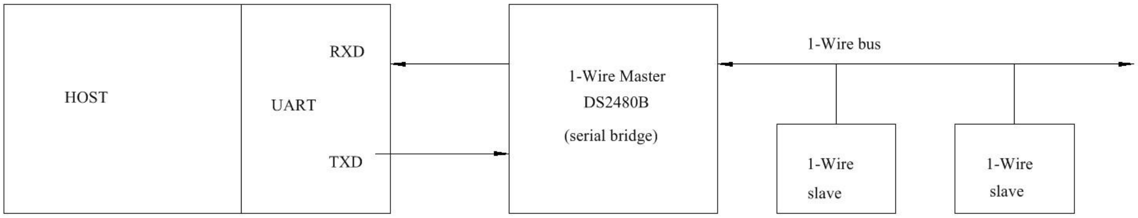


Figure 3-1. DS2480B usage layout.

It is possible to control the 1-Wire devices with a computers IO functions, but the DS2480B relieves the host of this duty and is programmed with the correct timing and waveforms needed. The DS2480B is controlled by 8-bit hexadecimal commands.

The DS18S20 operating temperature ranges from -55°C to +125°C with an accuracy of ±0.5°C between -10°C and +85°C. One microcontroller can regulate many DS18S20 sensors due to the 64-bit serial code given to each sensor during production. The main advantage of the DS18S20 over a basic thermocouple is its direct-to-digital temperature sensor. This reduces the effect of noise on temperature readouts and improves the sensor accuracy. Figure 3.2 below shows a photograph of a DS18S20 and the pin layout.

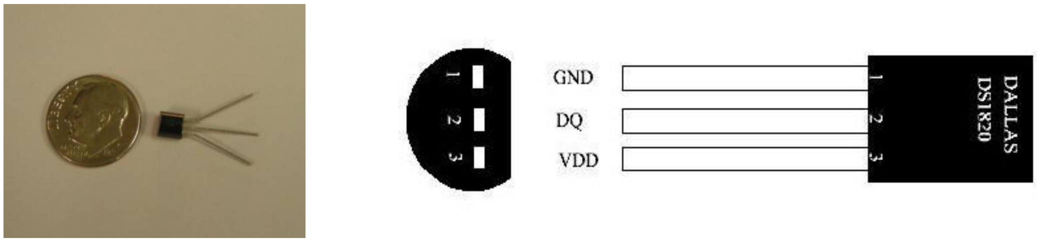


Figure 3-2. Photograph of sensor and pin layout of DS18S20.

The DS18S20 can be powered by a technique called parasite power. In this mode, the sensor is powered by stealing electricity from the DQ line (Figure 3-2) when the bus is high. A capacitor in the sensor is charged during this time to allow the sensor to operate while the bus is low. The simpler way to power the devices is by connecting the V_{DD} pin to a power supply, which is how the sensor is implemented in this project. The manufacturer does not recommend the use of parasite power for temperatures over 100°C due to high leakage currents, and encourages the use of the V_{DD} pin for power connection in applications where the extra wire connection is possible. Using parasite power makes operation much more difficult because the bus must always be held high during any 1-Wire device function. This causes complications with the timing and voltage requirements for reading the data.

For this project, it was decided to use a 3-wire connection to power and read the sensor. This included a ground wire, a data wire and separate power wire. The arrangement was selected to provide long-term durability and to simplify software development. Additionally, there was little disadvantage to using three wires within the instrumentation cable. Developing this technology allowed for a single cable containing three wires to be utilized as the only data acquisition cable, greatly simplifying the system overall and providing improved reliability over a thermocouple system that would require a large number of wire pairs.

One significant advantage of the 1-wire sensors is the low cost of the sensor. In small quantities, the sensor cost ~$2.00 each, but when purchased in large numbers the cost decreases. The low cost of the sensor makes it practical to envision a large number of sensors being implemented in the field. Additionally, the sensors consume very little power, such that a large number of sensors can be powered from a common battery for long periods of time. The low power requirement of the sensor could enable the development of a battery or solar powered system for final implementation of the technology.

3.2 Array Design and Manufacture

To implement these unique sensors within the instrumented pile designed for this project, it was necessary to develop a system by which a multitude of sensors could be connected along a single set of wires, and subsequently installed along the length of a pile. Initial testing utilized individual wires to test the sensors and develop software necessary to read and store data. This requires that the insulation of the wires be breached at each sensor location, and three solder joints applied to connect the sensor to the wire. However, it became apparent that there were several challenges to implementing this design in the field. The primary disadvantage stemmed from the reliability of the wire connections. Attaching a loose wire to the pile, and expecting the high number of individual solder joints to remain reliable over long time periods was unrealistic. Therefore, an alternative to this configuration was sought.

A literature search and discussions with manufacturing experts illuminated an alternative to using a three wire configuration. Printable circuit boards, widely used in a variety of electronic devices, provided an alternative that would enable the sensors to be secured to a rigid polymer backplane, and this rigid backplane can then be connected to a suitable housing for installation in the stream bed. Three “trunk lines” printed onto the polymer backplane would improve the solder connections, simplify manufacturing and provide a more durable long-term solution. However, the disadvantage of this approach is that it required a significant amount of development to manufacture the printed boards. The process for manufacturing a printed circuit board includes the following steps:

- AutoCAD drawing of desired conductor layout
- Development of a photonegative of the conductor layout
- Ultraviolet exposure of board to print pattern onto backplane
- Etching of exposed boards to remove unwanted copper

The AutoCAD drawing of the trunk line design is shown in Figure 3-3. The trunkline design consisted of three conductor lines that run the length of a 24 in. board, a commonly available size for the circuit board materials. Solder tabs are etched at either end of the trunklines to enable the board to be connected by short wires, such that 24 in. modules could be manufactured and then several boards could be connected to create the appropriate length sensor array. The sensors themselves can be soldered to the trunk lines at any spacing interval; a sensor every three or four inches was selected as a suitable spacing for this project. This allows for up to four measurements per foot of pile, adequate for estimating the soil line depth along the pile. This spacing was based on discussions with bridge maintenance engineers that indicated that information on the depth of scour holes to the nearest one foot was adequate for effective decision making and asset management. By placing four sensors per foot, measurement redundancy would exist to provide improved reliability in field applications, and ensure that system resolution met the requirement of determining the depth of a scour hole to the nearest foot.

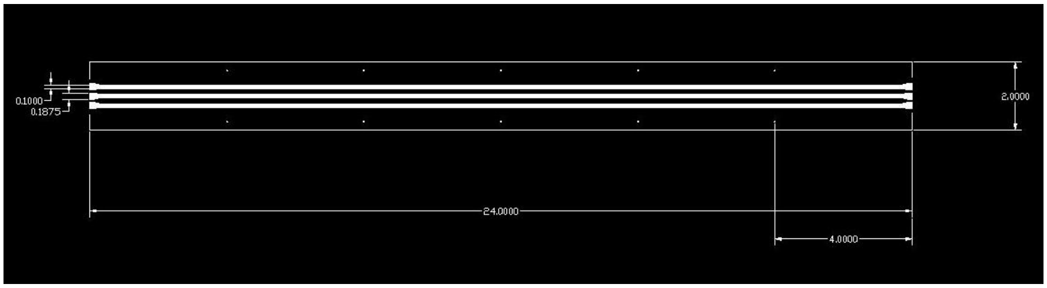


Figure 3-3. AutoCAD drawing used for printing circuit boards.

Figure 3-4 shows the setup used for exposing the circuit boards to UV light. Four fluorescent UV lights were used to maximize the amount of UV light along the entire length of the circuit boards. The large (24 in. long) circuit boards that were required for this project exceeded the size of the exposure beds that were available, and as such a new exposure bed needed to be developed. The exposure bed consisted of a common, 48”

Figure 3-4. Setup for exposing circuit boards.

fluorescent light fixture with a custom-made tempered glass lens. Testing was conducted to determine the optimum exposure times for properly exposing the board such that they could be etched to produce a clear pattern of conductive lines on the surface of the board. Several different commercially available ultraviolet lamps were tested to determine the appropriate wavelength of light to effectively expose the board to generate sharp, clear lines through the etching process.

Figure 3-5 shows the photonegative produced for exposure of the circuit board. This photonegative was produced by a local photography lab based on the AutoCAD drawing of the desired pattern for the board, which is shown in Figure 3-3. The photonegative is used to shield stock board material that is covered with a special UV - sensitive coating. UV light hardens the exposed UV- sensitive coating, such that the exposed areas of the board will not be etched in subsequent acid baths.

To manufacture an individual board, the photonegative is placed on the surface of the rigid polymer backplane. The circuit board was then exposed to UV light. A study was conducted utilizing sample board materials to determine the effective exposure time for the board materials. As a result of this study, the boards were exposed for two minutes and then placed immediately into an acid bath to minimize the amount of ambient light exposure. The exposed board material is shown in Figure 3-6. This Figure shows the purple film that will protect the copper trunk lines during etching processes, leaving only the three conductive strips necessary to provide trunk lines for attaching the sensors. The copper that is visible in Figure 3-6 is removed during the etching process.

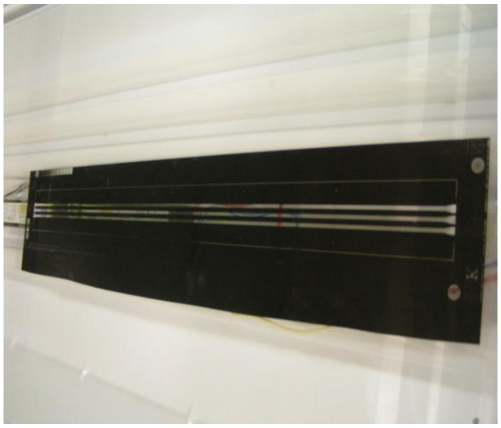


Figure 3-5. Photonegative used for exposure.

Figure 3-6. Exposed boards in the chemical bath.

Figure 3-7 shows the excess copper being removed by the acid solution but leaving the lines that are protected by the hardened film. Once all the unwanted copper is removed the boards are washed to remove the acid. This manufacturing process was developed through an iterative procedure that improved the consistency of the process and ensured that the copper trunk lines remaining on the board had clear edges to improve long term reliability.

Figure 3-7. Excess copper being removed from the printed circuit boards.

Two different sized test arrays were developed in the lab. The goal was to prove that the temperature measurement system worked effectively and expand our knowledge of what to expect from the actual pile deployment. The first test array was six inches long, with only two sensors attached, and the second array was four feet long, with 16 sensors.

A photograph of a small, 2-sensor array can be seen below in Figure 3-8. In this photograph, the two DS18S20 sensors are soldered to the trunk lines along with the attachment cable that leads back to a standard PC. Communication with the sensors is achieved through the serial port of a standard personnel computer. The board material was attached to a polycarbonate frame as shown in the photograph. This frame allowed for the sensors to be potted inside a special epoxy that provides protection from damage to the sensors and supporting trunk lines, and has a high thermal conductivity (close to that of steel). Potting of the sensor array in the special epoxy allows for rapid conduction of changes in the thermal environment of the array in addition to stabilizing the sensors to provide protection from the environment.

After allowing the epoxy to harden for over 24 hours, the sensor was milled to level the surface of the epoxy to the elevation of the polycarbonate walls as shown in Figure 3-9. This provided a machined surface that could then be mounted onto the surface of any type of structure, for example, the side of a steel pile. The flat surface of the sensor array allowed for direct contact with the surface of the steel to ensure effective heat transfer across the interface.

To conduct initial testing, the final milled array was attached to the outside of a two foot long, five inch square HSS member. An infrared heater was used to heat the short test pile to impose temperature changes that could be measured by the sensors. The sensors proved to respond very quickly to thermal changes. To evaluate the response time of the sensor array, a typical thermocouple was mounted to the short test pile. This K type thermocouple was attached to the front of the array as shown in Figure 3-10. This provided a rudimentary comparison of response times for the sensor array for development purposes.

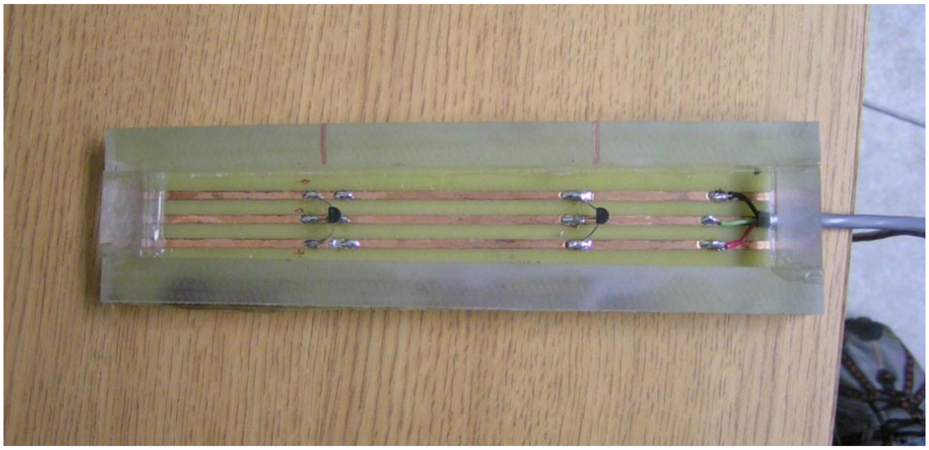


Figure 3-8. Photograph of small test sensor array with 2 sensors.

Figure 3-9. Photograph of the milling operation to level epoxy.

Figure 3-10. Small sensor array test setup.

For the preliminary testing, a small Labview program was developed that read two temperature sensors and controlled the infrared heater. In this Labview program, the unique serial number of each attached sensor is read and shown on the bottom of the panel on the display, along with the temperature reading from the sensor. The results of constructing this prototype array indicated several ways to improve the manufacturing process, as well as confirming several positive design aspects. It was found through testing that the epoxy allowed for rapid conduction of heat to the sensor, such that there was only a small difference in the output of a thermocouple and the output of the sensor array. It also showed that the selected epoxy was machinable such that the sensor modules could be machined once the epoxy was set. The epoxy is expected to play a key role in protecting the sensors and wiring from the surrounding environment.

A larger prototype sensor module was manufactured utilizing the information learned. It consisted of two printed circuit boards attached together, each two feet in length for a total array length of 48 inches. There were 8 sensors on each board, located at three inch intervals. A schematic diagram of the 48 in. sensor array is shown in Figure 3-11. The three least significant bytes of the sensors unique address is shown in the Figure. A polycarbonate frame was constructed to provide a mechanical connection between the separate, 24 in. boards and enclose the epoxy used to pot the sensor array.

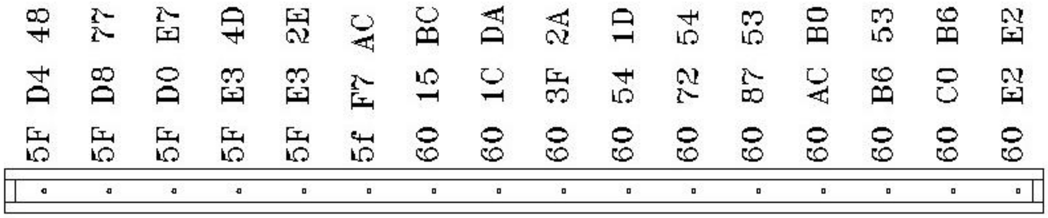


Figure 3-11. Diagram of the 48 in. sensor array, showing individual sensor locations and addresses.

A software program was also developed to record data from each of the 16 sensors included in the array, display the data in real time, and store the data. The array of sensors was again potted in the epoxy to protect the sensors and provide corrosion protection. Figure 3-12 shows the manufacturing of the sensor array, specifically the application of epoxy in the array housing. After curing, the epoxy was again milled plane such that the array sensor could be applied to the surface of a steel pile.

Figure 3-12. Pouring epoxy into large test array.

3.3 Software

Software was developed for displaying and storing data from the temperature arrays. The development of this software was complicated by the complexity of reading data from multiple sensors along a single wire and identifying the spatial location of each sensor. A Labview environment was created to interrogate the large sensor array and provide real-time temperature measurements, as well as to store the data at specified timing intervals. A control switching circuit was implemented in the program to allow for a heating device to be switched on and off based on thermal measurements in the array. The switching circuit was used to establish suitable test parameters in the laboratory such that a thermal gradient could be applied to the test pile to model field conditions, test the sensor array for functionality, evaluate the software developed and demonstrate the utilization of the technology.

4 Laboratory Testing

To evaluate the effectiveness of the sensor array developed, and to demonstrate the technology, a laboratory test set-up was developed. This test set-up included a HSS model pile, heating devices to impose a thermal gradient in the pile, and the data acquisition system to collect and store data from the sensors. This section of the report will provide details of the test set-up and results demonstrating the effectiveness of the sensor array. Measurements from the sensor array are included, as well as a comparison of the behavior of the sensor array and the thermal response of a thermocouple device. Performance of the sensor array in response to impressed thermal gradients is described. Results of a cold water test to demonstrate the anticipated thermal gradients in the pile are also included.

4.1 Test Design

The laboratory set-up included a 6 in. x 6 in. x ½ in. HSS member 48 inches in length to provide a model test pile as shown in Figure 4-1. This test pile was mounted on a 18 in. x 24 in. steel plate by angle clips. A rubber gasket was used to ensure that the HSS would hold water without leaking. The 48" sensor array was attached to the outside of the pile. Inside the test pile, sand was placed in the pile up to a height of approximetely 24 inches, then the pile was filled to the top with water.   During subsequent testing, the sand was replaced with soil. The test setup was intended to model the installation of the pile in the field, with the array and soil/water interface on opposite sides of the pile. In a field installation, the water and soil would be outside the pile and the sensor array would be installed within the pile, to measure the thermal behavior of the pile by attachment to the surface of the steel. This configuration was reversed in laboratory testing for convenience. This enabled the evaluaton and testing of the effect of changing the temperature of the soil and water, and measureing these changes through the ½ in. steel pile wall.

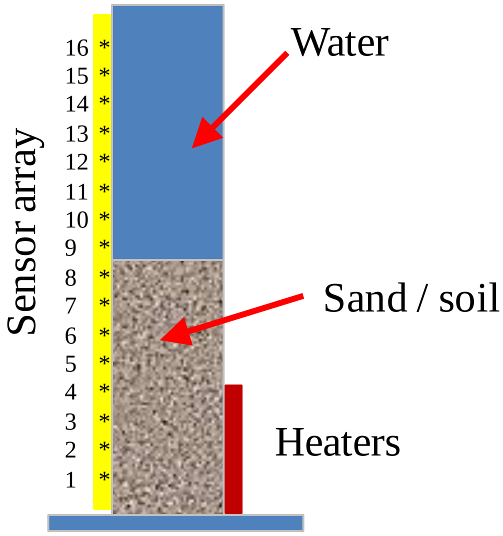


Figure 4-1. Schematic diagram of test set-up showing heaters, sensor array and sand/water interface.

Two ceramic heatplates were used to heat the test pile. The ceremic heaters were attached to the pile near the base as shown in Figure 4-1. These ceramic heaters were attached to a switch (120 V AC) that was under software control in a loop circuit that included one of the temperature sensors in the array. Using this configuration, a target temperature for the control sensor was selected, and the heaters were switched to maintain a certain temperature at the sensor location. Since the sensor location was on the opposite side of the pile from the heaters, the thermal inertia of the pile was expected to provide some variation in the thermal behavior of the test pile. Using this test set-up, a thermal gradient could be imposed on the pile and subsequently quantified using the 16 element sensor array.

Figure 4-2 shows a photograph of the test pile from two angles. The 16-sensor temperature array is attached to the side of the pile, extending from the base to the top of the test pile as shown in the Figure. A single 3-conducter wire is used to connect the array to the data acquisition computer. The ceramic heaters, attached near the base plate of the test pile, were concealed by a polycarbonate plate to ensure that the heater connections were not inadvertently contacted during the testing. A fan was also used during the testing to speed the cooling of the pile by convection.

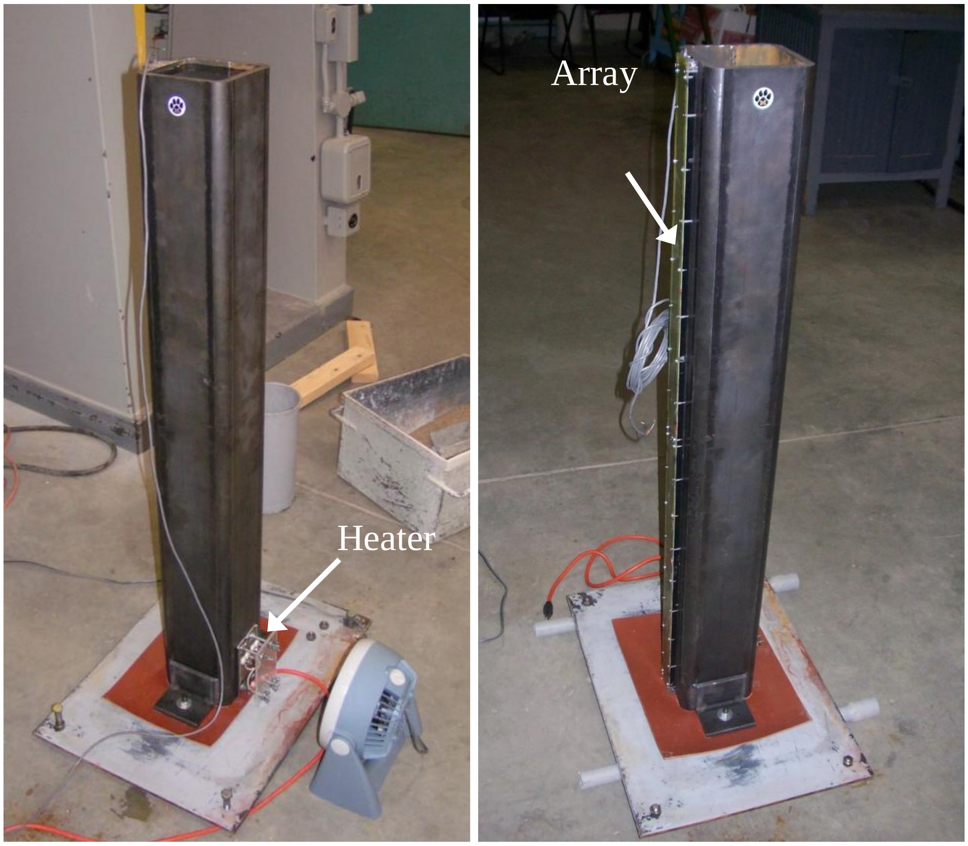


Figure 4-2. Both sides of large test pile, showing heater and array locations.

A closer photograph of the test pile is shown in Figure 4-3. The outside of the 16-sensor array can be seen. The three copper trunk lines are visible through the back of the circuit board, along with the black epoxy. The gray 3- conductor wire attaches all of the sensors to the serial port of the test computer through an adapter. Also, the water that fills the inside of the pile can be seen. The combination of water and sand/soil within the test pile was expected to allow for thermal gradient changes such as would be expected in the field.

Figure 4-3. Image of sensor array and water filled test pile.

4.2 Results

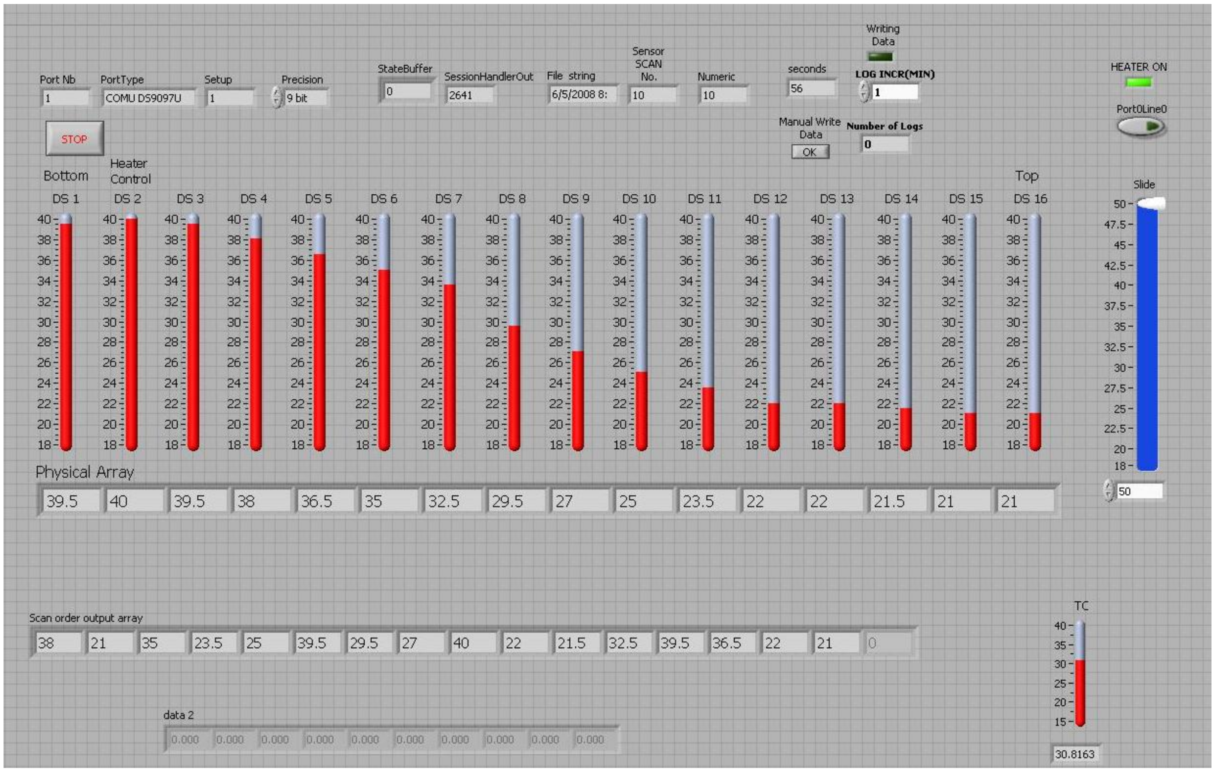
A number of tests were conducted using the test pile. The objectives of these tests included:

- Evaluate the software developed
- Demonstrate that the 16-sensor array can operate reliably
- Evaluate the resolution of the thermal measurement

- Determine if the soil/water interface can be detected
- Determine the response time of the sensor array relative to a thermocouple

To achieve these objectives, the ceramic heaters were used to impress a thermal gradient in the pile. Typically, the target temperature was set in the range of 30 to 50 ºC and maintained at a constant temperature. Testing intervals ranged from a few hours to more than two weeks to evaluate the longer term performance of the array and the data acquisition system reliability.

The software suite that was developed was capable of detecting and measuring the outputs from the 16 temperature sensors and controlling the heating circuit. A screen shot of the software front panel is shown in Figure 4-4. This front panel displays the temperature measurements from each of the sensors in the array, provides a bar-type graphic of the sensor temperatures, and stores the data at a specified rate. A slide control on the front panel allows the user to set the target temperature for the heaters.



Port Nb	1
PortType	COMU DS9097U
Setup	1
Precision	9 bit
StateBuffer	0
SessionHandlerOut	2641
File string	6/5/2008 8:
Sensor SCAN No.	10
Numeric	10
seconds	56
LOG INCR(MIN)	1
Number of Logs	0
Slide	50
TC	30.8163

Physical Array

39.5	40	39.5	38	36.5	35	32.5	29.5	27	25	23.5	22	22	21.5	21	21

Scan order output array

38	21	35	23.5	25	39.5	29.5	27	40	22	21.5	32.5	39.5	36.5	22	21	0

data 2

0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Figure 4-4. Front panel of Labview program.

The testing of the 48 in. sensor array demonstrated the effectiveness of the new measurement technology. Figure 4-5 shows the results of one test where the pile started at room temperature and was heated. When the sensors nearest the heater reached 50 degrees Celsius the heater was turned off. From the start of the test to the peak temperature took about three hours, and from there back to equilibrium took about seven hours. The seventh sensor, which was just less than two feet from the heater, was the furthest away from the heat source that registered a significant differential from the adjacent sensor. The test illustrated that the gradient measured along the pile was detected by the sensors in their complete array configuration, and the data was successfully stored for later processing. The test also illustrated that the sensor array responded in a timely manner to impressed thermal changes.

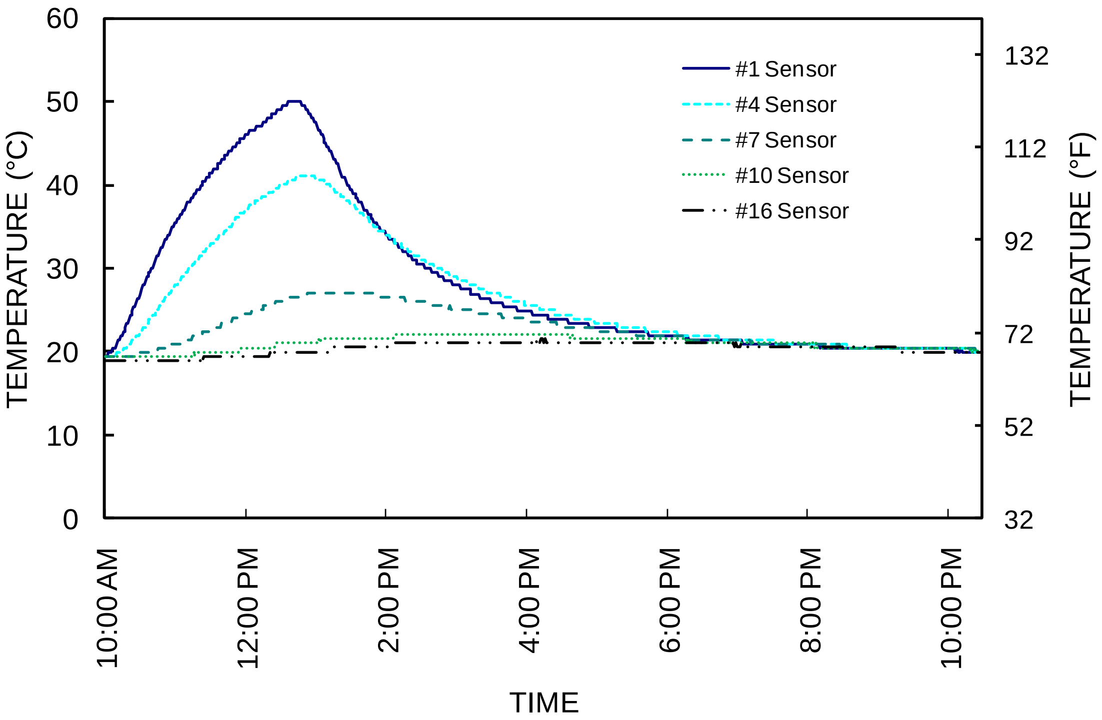


Figure 4-5. Sensor array measurement during heating to50°C and cooling.

Figure 4-6 shows temperature measurements for a test where the target temperature of 55 ºC was established for the heaters and this target temperature is maintained for about 18 hours. During this test, it took about the same amount of time for the pile to heat and cool as in the initial test, and the ninth and tenth sensors registered a significant differential from adjacent sensors. This was due to the longer time period of the test. The Figure illustrates that sensor 1 responded rapidly to the application of heat from the ceramic heaters mounted on the test pile. The control system for these ceramic heaters turned the heaters on and off as a result of temperature measurements received from sensor 2. As a result of thermal inertia of the steel pile filled with soil and water, there is a delay in the response of the system to applied heat. This delay manifests in the variations in the temperature measurements (cycles) in time shown in the Figure.

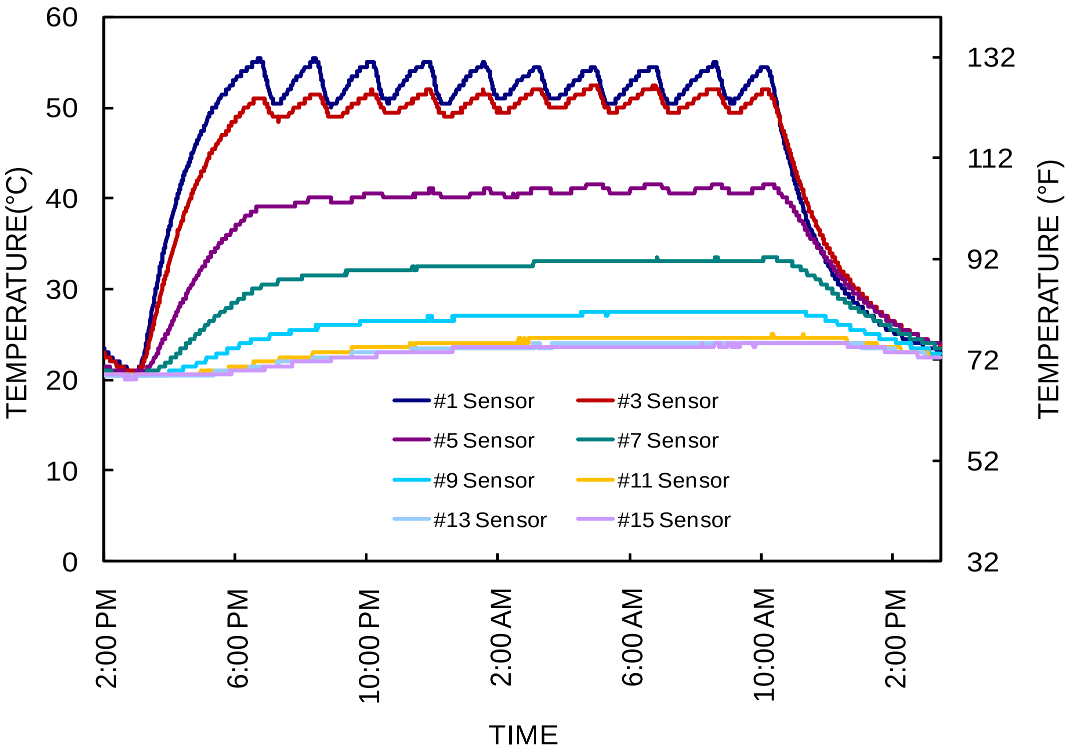


Figure 4-6. Sensor array output during 1-day, 55 degree Celsius test.

It is useful to examine data from the test pile as the thermal profile along the pile. Figure 4-7 shows the thermal output of the sensors along the length of the pile, starting with sensor 1 located nearest the heaters and ending with sensor 16, which is the furthest sensor from the heaters located at the top of the pile. The vertical axis is temperature. The figure shows the development of the thermal gradient in the pile as heat is applied by the ceramic heaters. Individual scans of the sensor array at times of 5, 10 and 30 minutes after a change in the control temperature for the heaters is shown. As shown in the figure, the sensors nearest the heaters respond to applied heat, and a thermal gradient is developed in the pile as intended. Sensors farthest from the pile do not respond to the applied heat. The change in temperature during the test for each sensor can be observed in the Figure, for example the output of sensor 1 changes significantly in the final 20 minutes of the test. Graphing data as the gradient or profile along the length of the pile is expected to improve the ability to identify where the soil/water interface exists and how this interface changes over time.

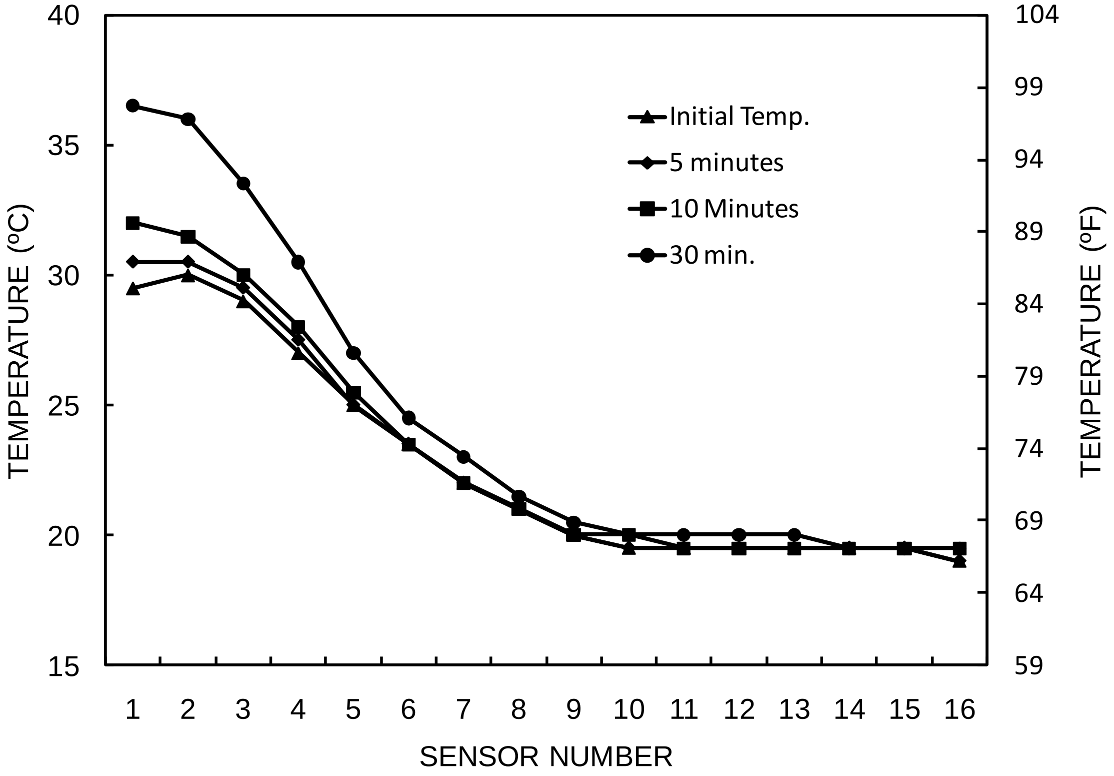


Figure 4-7. Temperature gradient in the test pile during heating.

Figure 4-8 shows the thermal gradient along the length of the pile for three conditions. The steady-state condition is the thermal gradient in the pile after a test temperature of 30°C has been established and maintained for several days. This is an established, steady thermal gradient along the length of the pile. The test temperature was then raised to

40°C, resulting in the increased thermal gradient along the length of the pile as expected. The test temperature was subsequently adjusted to 20°C. During the cooling of the pile, the thermal gradient is reduced as sensors respond to the pile reaching toward thermal equilibrium. This is illustrated by the increased temperatures of sensors 5-16 during the cooling phase, as the thermal wave resulting from the increased test temperature propagates through the pile. This testing illustrated that the sensor array was sensitive to changing thermal conditions and was capable of determining the thermal profile along the test pile under a variety of thermal conditions.

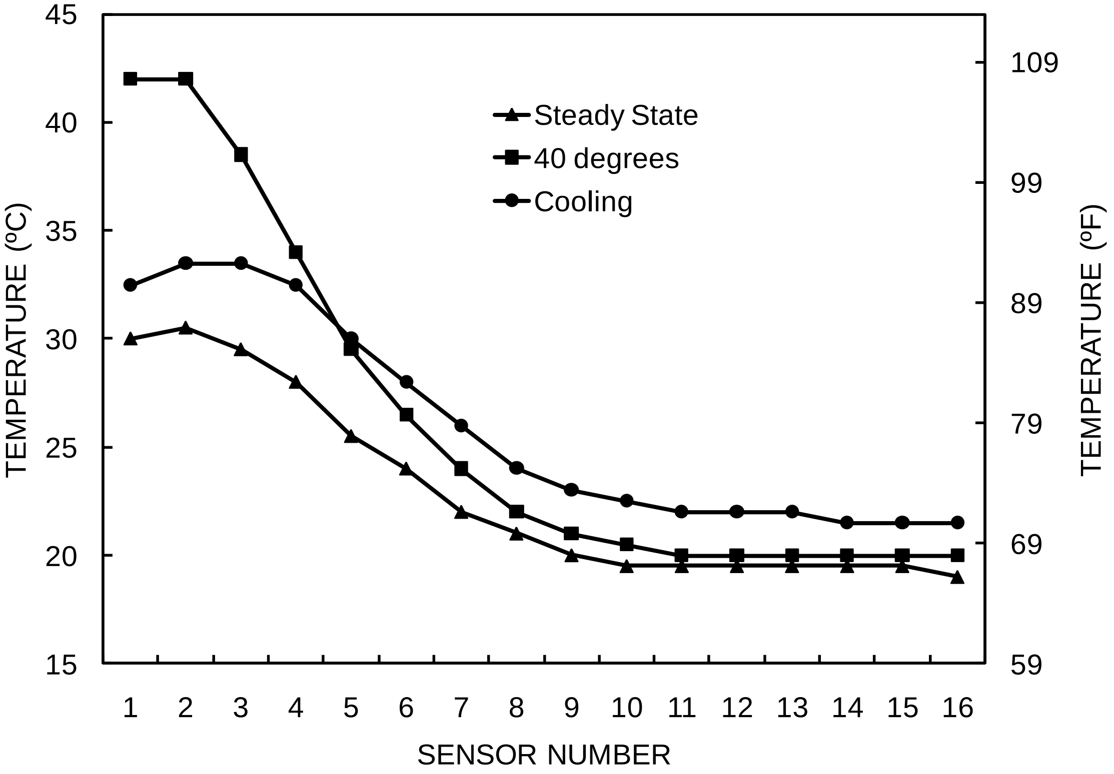


Figure 4-8. Temperature gradient in the test pile during heating and cooling.

It was also necessary to establish the time delay for the sensor array to respond to a thermal change relative to the thermocouple, to determine if system performance would be negatively impacted by the array design. Because the sensors are embedded in epoxy, it is expected that some delay will exist between changing thermal conditions outside the array and the actual array response. Figure 4-9 shows the results of testing to determine how much lag exists from the sensor array relative to a basic K type thermocouple. The thermocouple was placed directly along the side of the large array in-line with sensor 5. All other sensors have been removed from the graph for simplicity. At the outset of the test, the thermocouple read 42.4 degrees Celsius, while the DS18S20 was reading 41.5 degrees. They both cooled for almost 18 hours, after which the thermocouple read 19 degrees and the DS18S20 read 20. The heater was turned on, and the thermocouple first showed a temperature increase at 8:57am. The DS18S20 showed its first increase at 9:03am, 6 minutes later. Note that the DS18S20 only has a resolution of 0.5°C; such that the output will not change until 0.5°C temperature variation is experienced. At 12:15 the sensors reached the highest temperature in the test, the thermocouple read 36.5 degrees while the DS18S20 on the array read 37. Finally, at the end of cooling, the thermocouple showed 19.1 degrees while the DS18S20 was at 20 degrees Celsius. In this test, the sensor array and the thermocouple reacted very similarly to the heating being applied, and there was only a small lag (<6 minutes) in the response of the sensor array relative to a thermocouple device. The DS18S20 sensor also registered a slightly higher temperature than the thermocouple throughout the test, possibly due to calibration differences between the sensors.

To better demonstrate how the pile is expected to perform in the field, a test was conducted to illustrate the detection of the soil/water interface. To achieve this objective, it was necessary to fill the test pile with cool water during the testing to model the behavior of running water in a streambed. This was done by using two siphons, one deep in the pile to remove the ambient temperature water and another pouring cool water into the pile. The results of this test are shown in Figure 4-10, which shows a number of thermal profiles of the pile at different times after the initiation of the water exchange in the test pile. The Figure shows the thermal profile in the pile at the initiation of the test (existing conditions), and 5, 45 and 90 minutes after the test initiation. The large difference in temperature of the water and dirt created results that clearly showed the transition area to be between the 5th and the 11th sensor, corresponding to 13 and 31 inches from the bottom of the test pile. The actual interface is locating at approximately 24 inches from the bottom of the pile. As illustrated in the figure, the interface results in a significant change in the thermal gradient along the pile. By the 90th minute, the ice had melted, which is why there was an increase in temperature between the 45th and 90th minutes. This test illustrates that the sensor array prototype is capable of making the desired measurements to monitor changes in thermal profile along the length of the pile. A total temperature difference of 8.5ºC existed between the hottest and coldest sensor.

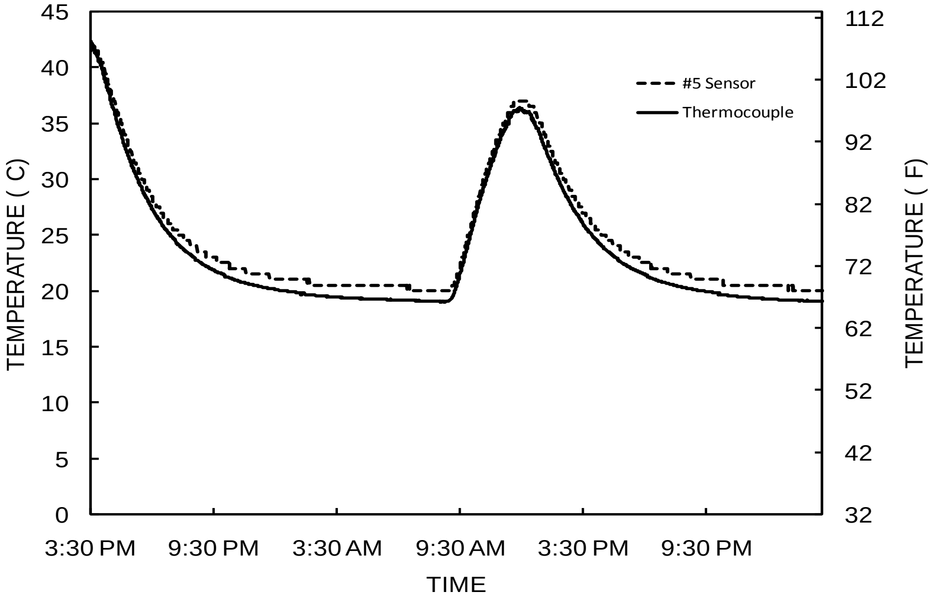


Figure 4-9. Thermocouple and DS18S20 readings during cooling and heating.

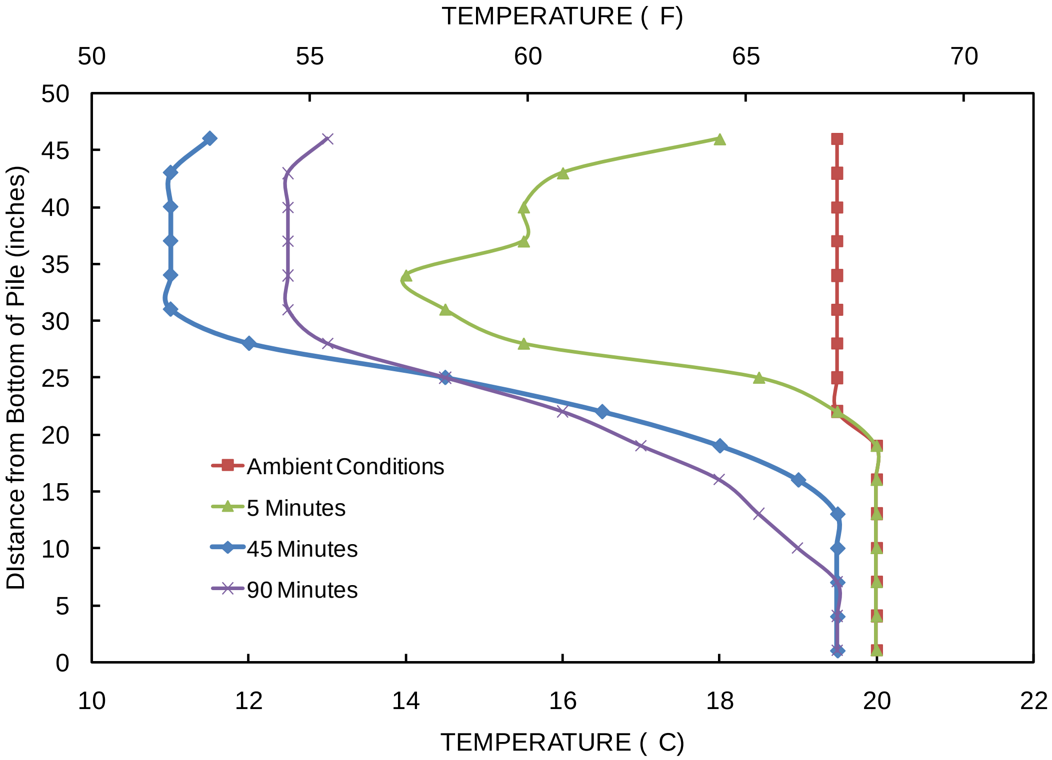


Figure 4-10. Thermal gradient along the length of the test pile during cold water test.

Figure 4-11 shows the output of the sensor array mounted on the test pile over a time period of 5 days. Several changes in thermal conditions were impressed on the pile by the ceramic heaters. During this particular test, the temperatures ranged from 18.5 to 56.5ºC. Room temperature remained just below 20 degrees for the duration. When the test began, the whole pile was at room temperature. The heater control temperature was set to 45 degrees for over 24 hours. The control temperature was then raised to 60 degrees and returned back to 45 degrees as it approached this control temperature. The control temperature was again raised to 55 degrees and allowed to stay there for almost 48 hours. The heater was then shut off to allow the pile to return to room temperature. This test and previous tests run in the lab illustrate that the software developed is capable of storing data over long time periods and that the sensor array performs as expected. The array responded effectively to temperature changes, illustrated very little noise, exhibited no electronic drift over time, and consistently registered data.

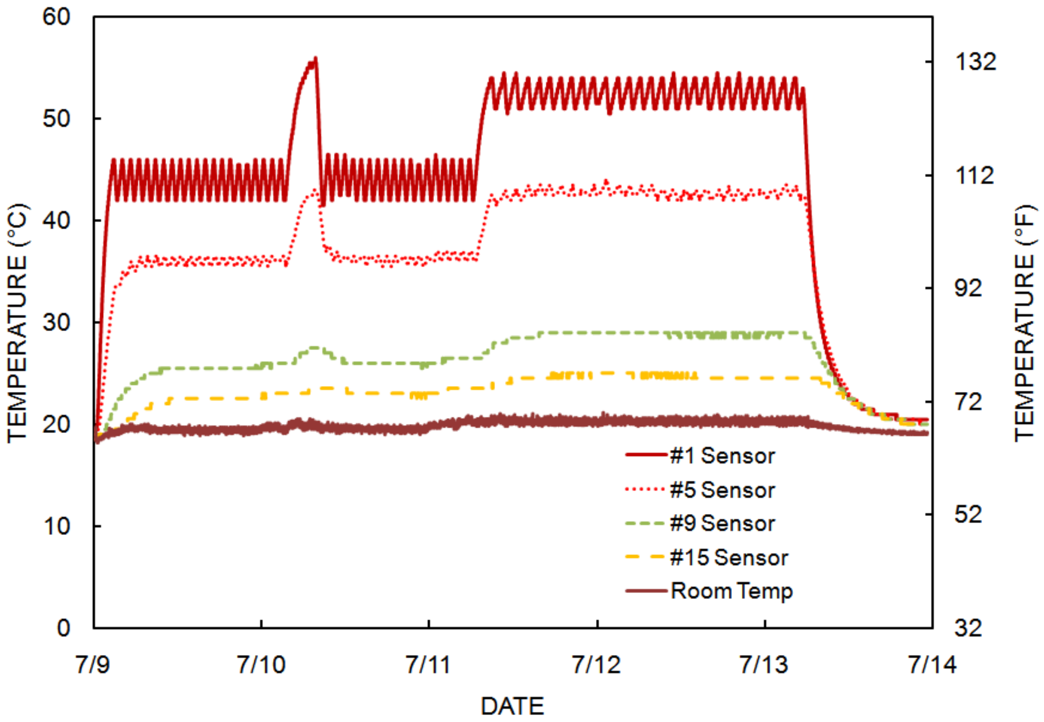


Figure 4-11. Results of monitoring the sensor array over a 5 day period.

The laboratory testing of the prototype 16 sensor array demonstrated the feasibility and effectiveness of the design approach. Specifically, the testing showed that

- The sensors were capable of measuring accurately when potted in epoxy
- The sensor were capable of measuring a thermal gradient along a test pile
- The response time of the sensor array was minimal (<6 min.)
- The array and supporting software were capable of logging data over long time periods
- Temperature measurement from the array were consistent with thermocouple readings

Based on the findings from the laboratory testing, a design for a prototype pile to be installed in the field was developed. A 10 inch H-pile that is 20 ft. in length was selected to install in the field. A total of 64 sensors were utilized along the length of the pile. The following section describes the field implementation of the technology, including the manufacturing of a full-size armored array, development of software for remote monitoring, laboratory testing of the sensor array, and installation of the test pile along Hinkson Creek, Columbia, MO.

5 Field Implementation of Technology

The final step of the project was to prepare and deploy the full size test pile at a field test location. The site that was chosen is on Hinkson Creek, near A.L. Gustin golf course in Columbia, MO. It was selected for several reasons. First, there was enough access to the side of the creek to drive up a small backhoe for driving the pile. Second, the location is on MU property, near another MU research project that has available electricity. Finally, the creek is known to rise and fall several feet during storms, such that changes in the conditions at the pile can be effectively detected and monitored by the sensor array. This section of the report details the construction, testing and installation of the test pile.

5.1 Sensor Array Manufacturing

The field test pile consisted of 64 DS18S20 one-wire sensors mounted along the length of a 20 ft. H-pile. To effectively implement the sensors in the field, the sensor array needed to be armored and mounted in such a fashion that it could be driven into the ground, operate over a long time period while submerged in water, and survive in the rugged environment of a bridge. To support these goals, a design was developed in which the sensors were mounted on the rigid circuit board material, and this rigid circuit board was then mounted onto stand-offs welded onto a 3/8 in. steel channel. The final configuration of the sensor within the armor channel is shown in Figure 5-1. Angles welded periodically onto the sides of the armor channel provide a positive mechanical connection for the completed thermal array for installation onto the web of the pile.

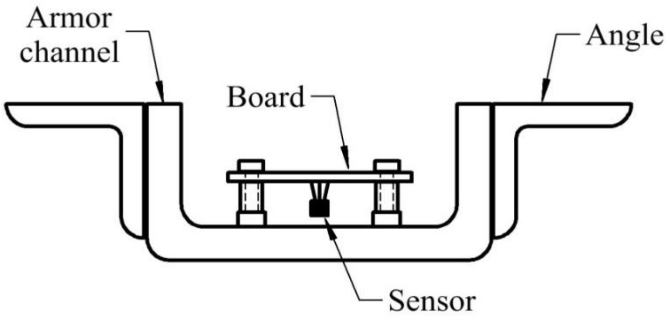


Figure 5-1. Schematic diagram of sensor configuration in armor channel.

The rigid circuit boards were produced in the laboratory at MU to have three conductive trunk lines extending over the 24 in. length of the board. Each 24 in. board had 8 sensors mounted on the board, at a separation of 3 inches. Each sensor was mounted in a through-hole fashion on the rigid circuit board to provide some mechanical support to the soldered joint between the sensor and the circuit board. When mounted in this fashion, the sensors are mounted on the opposite side of the circuit board from the conductive trunk line. Once this board and associated sensors are potted in the epoxy, the sensors are fixed and will not move. The sensors were placed such that they are close to the armor channel in which the array is mounted. Figure 5-2 shows the armored sensor housing during the construction of the sensor array. The Figure shows the threaded studs that are welded to the steel channel, plastic stand-offs used to set the sensor array at a constant elevation in the cross-section, and the rigid circuit board with the sensors attached. As noted earlier, the sensors are mounted in a through-hole fashion such that the sensor leads project through the circuit board and are actually soldered to the board on the opposite side of the circuit board.

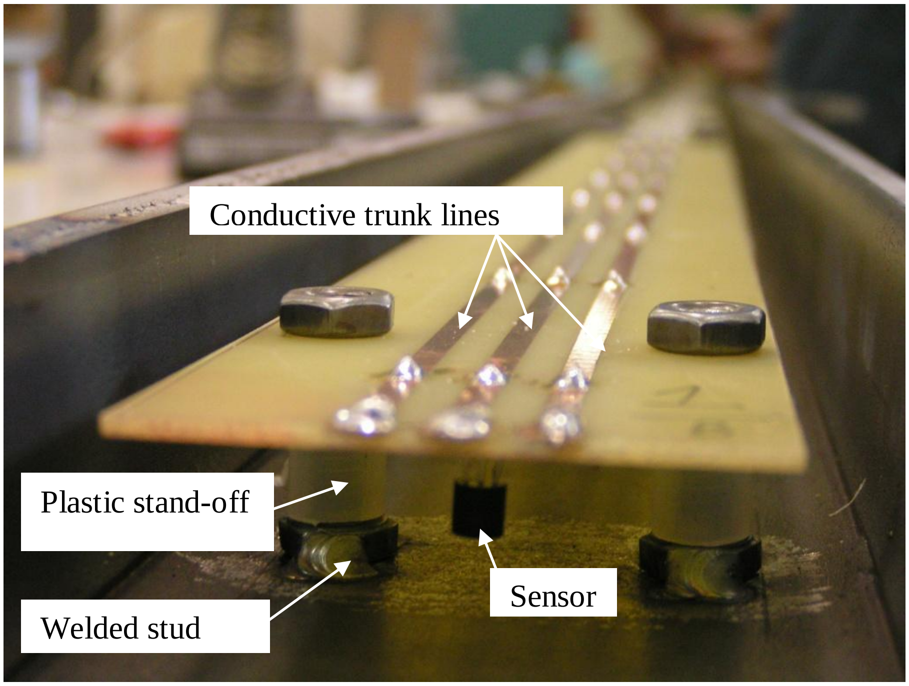


Figure 5-2. Photograph of the assembled sensor array showing plastic stand-offs, welded studs, sensors and conductive trunk lines.

The channel armor was assembled in the laboratory with studs welded along the armor channel to secure the circuit board materials in the channel. The 24 in. sensor assemblies were fabricated in the electronics shop to ensure secure solder connections for each of the sensors in order to provide long-term durability of the connection. Following the assembly and initial testing to ensure that all of the sensors were functional and operating as anticipated, the entire array of 64 sensors was potted in epoxy to secure the sensors. The two part epoxy was mixed in the lab and poured into the channel to submerge the sensor array and the circuit board entirely in epoxy. Figure 5-3 shows the process of placing the epoxy in the channel sections to pot the sensor array. Figure 5-3 A shows the soldering of the connections between the 24 in. circuit board units, Figure 5-3B shows mixing the epoxy in the laboratory in preparation of placing the epoxy in the armored channel. Figure 5-3C shows a photograph of the epoxy placement in the armored channel with part of the board already submerged in epoxy. Figure 5-3D show a photograph of the array after the epoxy has been placed, showing a view from one end of the 18 ft. armored channel.

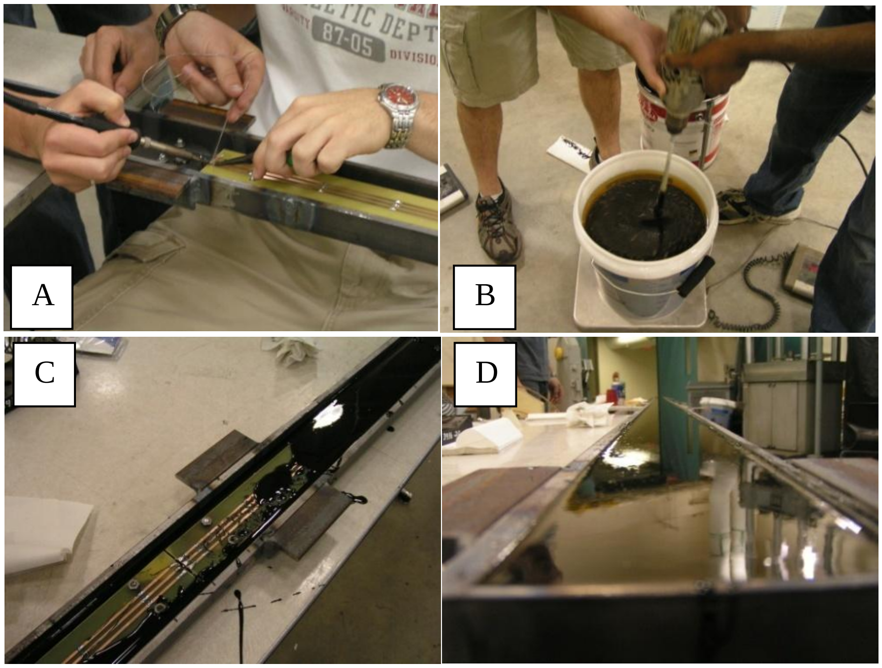


Figure 5-3. Photographs of the array construction showing A) soldering connections in the armored channel, B) mixing the epoxy, C) placing the epoxy in armored channel and D) completed array.

5.2 Laboratory Testing of Sensor Array

The array of 64 temperature sensors was tested in the laboratory to ensure that all of the sensors were functioning, to develop and test the supporting software, and to establish an estimate of the delay time for the sensor array in its as-built condition. This section describes the laboratory testing conducted and the results of that testing for the 64 sensor array in-place in the armored channel, potted in epoxy.

An infrared lamp was utilized to impose a thermal gradient in the sensor array. The lamp provides an intense heat source that performs consistently and can be easily moved to different portions of the array to establish the operation of all 64 sensors. Numerous tests were conducted during the development of the software needed to read and log the output of all 64 sensors. The results of two tests are focused on here: first, the response time of the array was evaluated by placing the lamp at one end of the pile and collecting sensor outputs over several hours, shown as location 1 in Figure 5-4. Second, the lamp was placed at different locations along the test pile to establish that all of the sensors were operational, and that the sensor locations were correctly identified (locations 2 – 4). The test setup is shown schematically in Figure 5-4. The sensor array was mounted horizontally in the laboratory with the infrared lamp directed at the array from a distance of approximately 18 inches for a typical test.

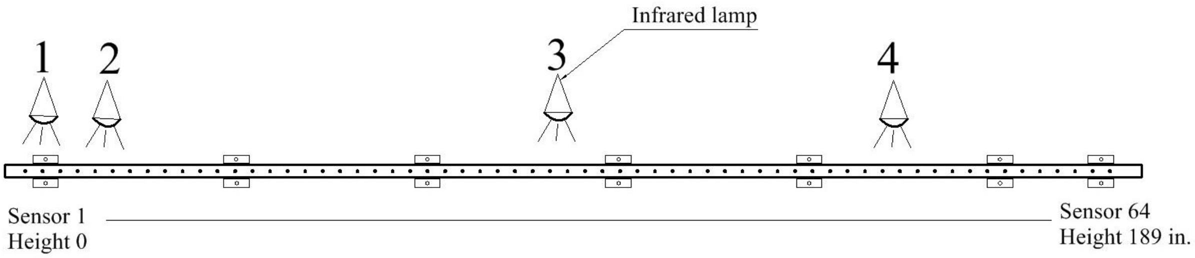


Figure 5-4. Schematic diagram of laboratory test set-up.

To establish the response time of the sensor array, the lamp was placed adjacent to sensor 2, approximately 10 inches from the end of the sensor array as shown in Figure 5-4, location 1. The output of the sensor array was monitored at 1-minute intervals. Figure 5-5 shows the initial temperature along the sensor array and the array output for various time periods following the application of heat. As shown in the figure, the array begins to respond at the 7-minute mark of the test, when sensor 1 changes its output by 0.5ºC, the minimum resolution interval for the digital sensors. The figure shows the output of the array at time intervals ranging from 7 minutes after test initiation up to 4 hrs after test initiation. Sensor 1 reached maximum ~4 hours after the test initiation, and maintained that temperature.

Figure 5-6 shows the performance of sensors 1, 6, 11 and 30 during the test. As shown in the figure, when the test is initiated (the heating lamp is turned on) the sensor responds to the external heat application and measures the heating of the sensor array up to a maximum temperature of 33.0ºC approximately 4 hrs later. The temperature distribution along the length of the pile measured by the remaining sensors in the array was expected to show a thermal gradient as the distance from the heat source to the individual sensor increased. Figure 5-6 shows that a sensor located 87 inches from the heat source (sensor 30) showed no reaction to the application of heat at the end of the pile, while sensor 6 (15 in. from the heat source) and sensor 11 (30 in. from the heat source) responded to the application of heat in an expected manner, increasing less rapidly over the course of the testing.

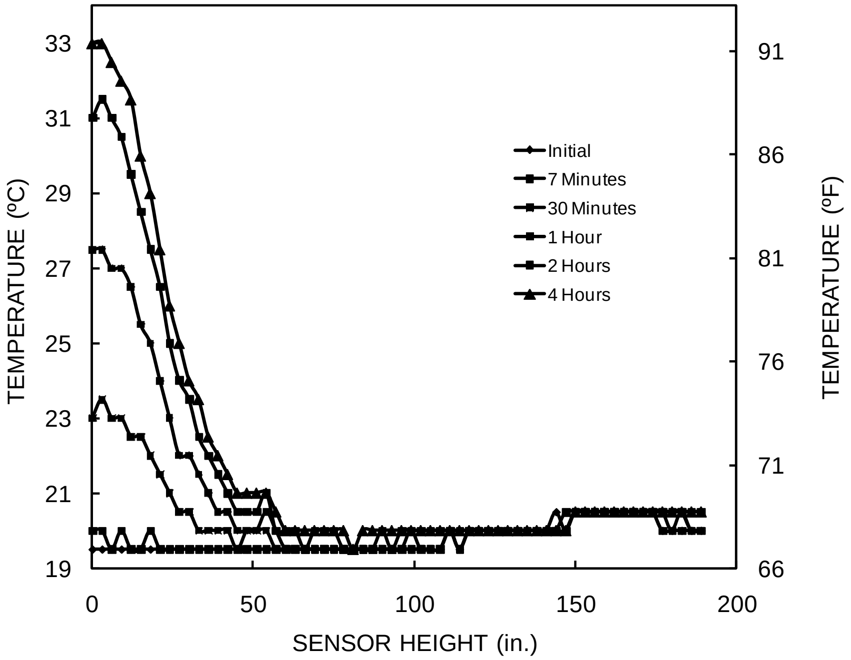


Figure 5-5. Sensor array output during heating test.

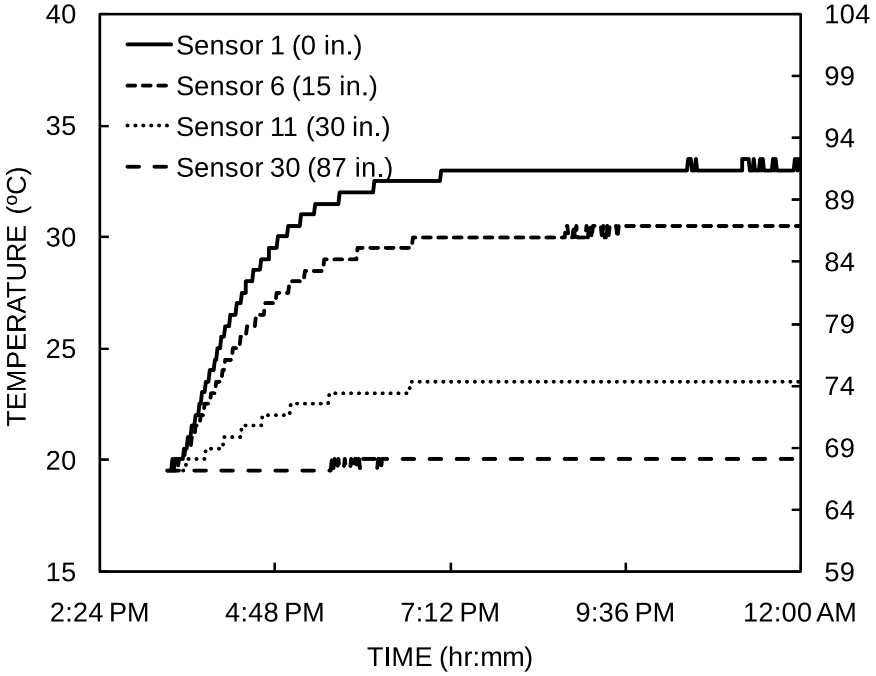


Figure 5-6. Response of sensor 1, 6, 11, and 30 to applied heat from an infrared heater at location 1.

To evaluate the functionality of all sensors in the array, and evaluate and develop the necessary software to scan the sensor array and store the data, the infrared lamp was relocated to different locations on the array. For this test, the infrared lamp was located at three different locations as shown in Figure 5-4, locations 2-4. The heat lamp was initially placed at location 4, then location 2 and finally placed at location 3. Heating was applied in location 4 for approximately 45 minutes, location 2 for approximately 60 minutes, and left at location 3 for 21 hours at a distance of 24 inches, relocated to 18 in. from the array for 47 hours, and then shut off. This allowed for the heating of the array in different sections, and to evaluate the response of the array. The distribution of heat along the length of the array during the testing is shown in Figure 5-7. This Figure shows time intervals of maximum temperatures at each location for the array. This test demonstrated that all of the sensors were operational, had approximately equivalent response to external stimuli, and there were no latent effects on the sensors.

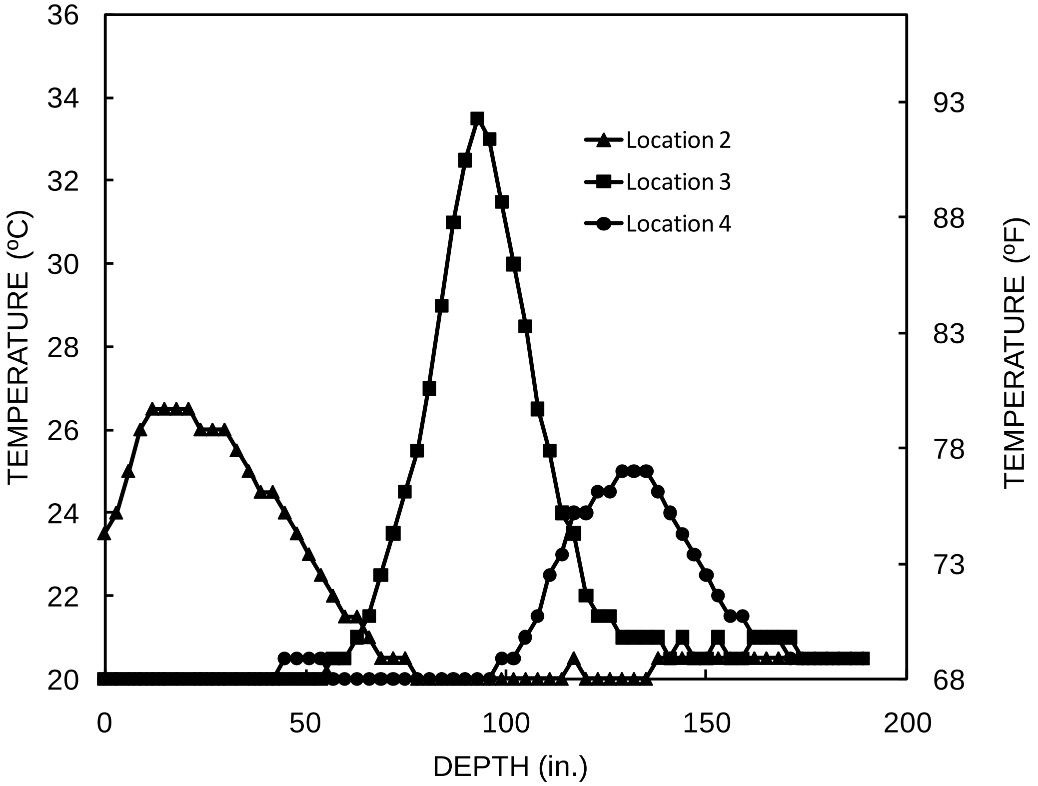


Figure 5-7. Temperature distribution along the length of the array during laboratory testing.

Data from this test is also shown in Figure 5-8, which illustrates the 3-dimensional graphing of the array data that will be useful in the post-processing of data from the pile when it is installed. The data for each sensor, for each time interval (15 minutes in this case) is shown in this Figure. When installed in the field, it is expected that the variation of temperatures in portions of the pile installed in sound earth will be much smaller than the temperature variations in the portion of the pile exposed to diurnal temperature variations of either the ambient environment or water in the stream bed. As shown in the Figure, the variation in temperatures as a function of height along the pile and time is displayed as a color-coded surface. Color is added to the Figure to assist in the visual interpretation of the data. Such a graphing approach was utilized in the installed pile to evaluate if changes in the thermal behavior of the pile have occurred.

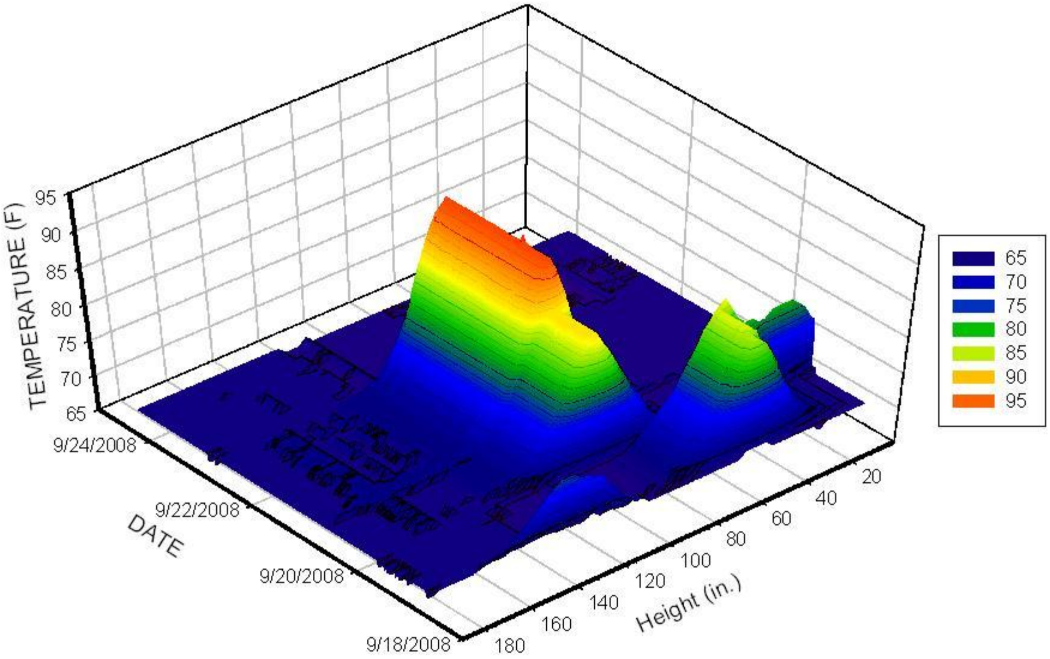


Figure 5-8. 3-D graph showing sensor array behavior in the laboratory.

The laboratory testing established the operation of the sensor array and served as a platform for developing the necessary software to monitor the sensor array. Following the laboratory testing, field installation of the test pile was initiated. The following sections describe the elements of the field installation process.

5.3 Site Selection

To test the functional operation and installation of the test pile, a field test site was selected to install the pile for monitoring. Following discussions with the technical panel, it was decided that the installation of the pile in a nearby stream would be a suitable demonstration of the functionality of the array. A field test site in close proximity to the University of Missouri was explored to provide convenient access for researchers. This was necessary because of the prototype nature of the sensor system and to enable troubleshooting and allow for modifications to be made rapidly. The characteristics of the test site that was sought were as follows:

- 120 volt AC power
- Easy access for equipment to install the pile
- Sufficient water level to demonstrate the operation of the pile
- Close proximity to the University

After surveying the local area and meeting with campus facilities personnel, it was determined that a USDA research station located adjacent to the University campus met the requirements for installing the test pile. The test location area is shown in Figure 5-9. The location includes access to 120 V power on-site at the buildings housing various farm-related equipment. Hinkson Creek passes through the site, and there is access to the creek for the machinery necessary to install the test pile.

Following the selection of the test site, an application to the U.S Corps of Engineers was prepared to ensure that the installation of the pile was not in conflict with relevant rules and regulations governing work conducted within waterways. This included preparing and submitting the form ENG FORM 4345 to the army Corps of Engineers, submitted in July, 2008. The Army Corps responded on August 11, 2008 that the installation of the pile would not require a permit.

Figure 5-9. Satellite photograph of the location of the test site where the prototype pile was installed.

5.4 Software

To read the output of the sensors, the commercial software Labview was used to develop a program that could read and log the data from each individual sensor. Key elements of the software developed included the ability to link the sensor numbers, which are 64 bit unique numbers stored in the ROM of each individual sensor, to the spatial position of each sensor along the test pile. The software also allows for the user to determine the time interval between data collection. This value has been set at 15 minute intervals, such that the sensor data is logged four times each hour. The software also provides a display screen that shows the current temperatures reported by each sensor, as well as other operational data, such as the number of scans collected, time to the next scan, and operational status of the program. The software stores the data from each scan to a database file for further processing.

A separate program operates a cell-phone based link to a server in the engineering building at MU. This program uses a Sprint cell phone modem to transmit data to the server at the set time interval. A time interval of 15 minutes between data transmission was selected, to couple with the scan interval for the temperature sensors. This software is embedded in the system, and does not interact with the user. The wireless connection is shown schematically in Figure 5-10. Data is collected on-site, transmitted over the cellular modem to a server at MU, and subsequently made available over the World Wide Web.

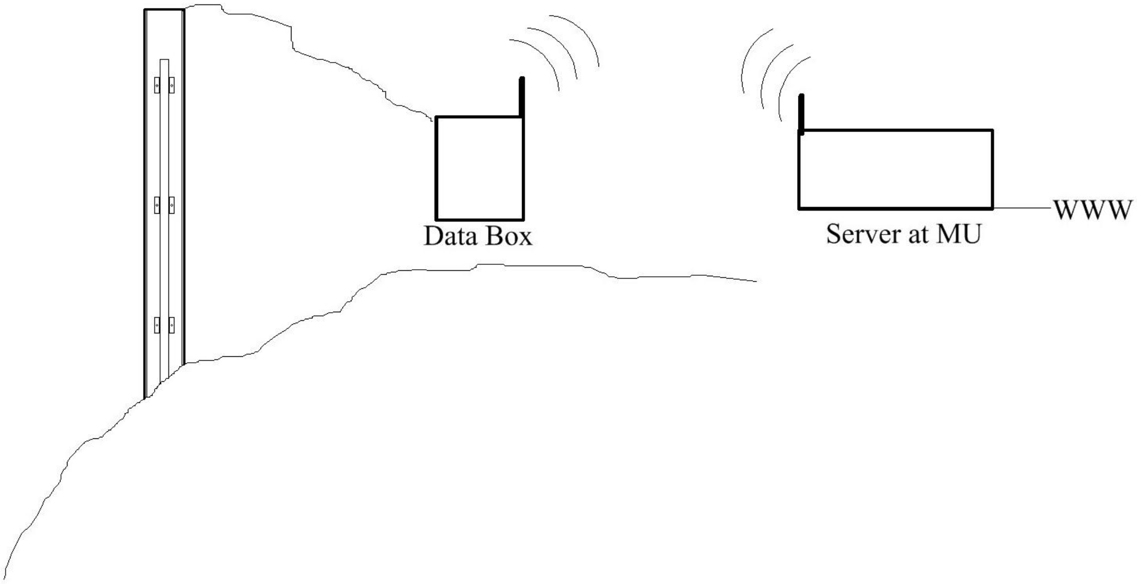


Figure 5-10. Schematic diagram of wireless data connection for remote monitoring of test pile.

A third program operates on the web server at MU. This program allows for the database files transmitted from the test pile to be displayed on the World Wide Web. This program allows a user to observe the current status and previous behavior of the test pile. A series of drop-down menus allow the user to select a previous time period, for example, the previous 14 days, to observe the temperature data from the test pile. The user can also download the previous data for further post-processing.

5.5 Prototype Pile

This section describes the final construction and installation of the test pile. The final construction of the test pile included affixing the sensor array to the web of the test pile, installing the test pile adjacent to the creek bed, and establishing an on-site data acquisition system to collect sensor array data. The H-pile selected for the prototype pile was an H10 steel pile with yield strength of 50 ksi. This pile was selected as a typical, representative full-scale pile for demonstration of the technology. The pile was delivered to the test location from the steel fabricator, such that the installation of the sensor array onto the web of the pile was completed in the field. The thermal array was positively connected to the web of the pile using ½” steel bolts, bolted through the angles on the sensor array to the web, as shown schematically in Figure 5-11. A coating of epoxy was applied to the sensor array immediately prior to installing the array onto the web of the pile, such that there was effective thermal coupling and the connection would be waterproof. All web holes needed to support the installation of the thermal array were made in the field using a common magnetic drill. Two angles were connected to the web in front of the array to deflect debris during the installation of the pile and to protect the array from direct impact on the nose of the array during the driving procedure.

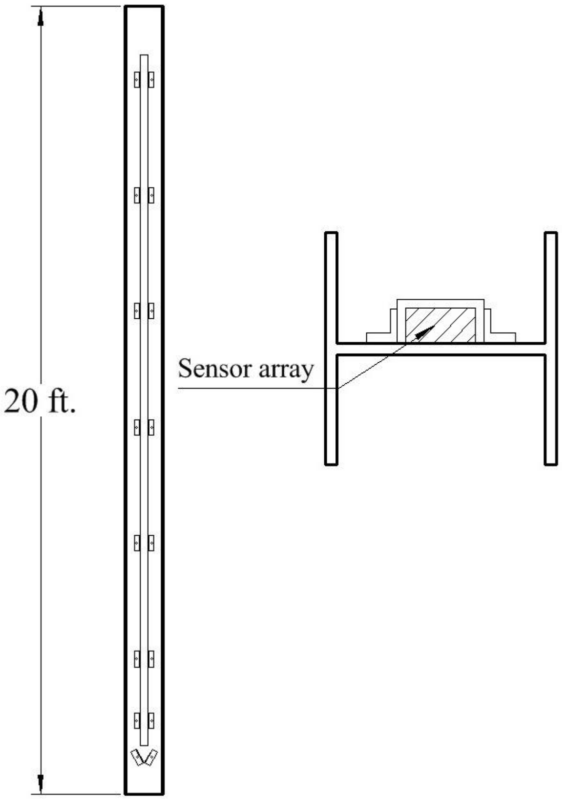


Figure 5-11. Schematic diagram of prototype test pile.

An LPC-350 Mini PC from Stealth Computer Corporation was purchased for the on-site data collection. It was selected due to its small footprint and because it has a serial connection, which was needed for data acquisition through our setup. Figure 5-12 shows the front panel of the mini PC. An on-site enclosure (data box) houses the computer data acquisition system. This data box includes the Mini PC, keyboard, mouse, monitor, and a small thermoelectric cooler. The system is power by typical 120 V AC power. Communication with the field data acquisition system is achieved using a cellular modem attached to the USB port of the stealth computer. The installation of the test pile was completed using a back-hoe to lift the pile and drive (push) it into the bed of Hinkson

Creek. Initial installation of the pile in the creek bed revealed that bedrock was located at a depth of only about 18 inches in this portion of the creek. As a result, the creek bed was determined to not be a suitable location for the test pile. The test pile was removed from the creek bed and re-installed along the bank of the creek. In this configuration, shown in Figure 5-13, a portion of the pile is installed in sound soil, and the rest of the pile is exposed to ambient air conditions. This represents an installation scheme along a normally dry bank of a river that is only submerged during flood conditions.

Figure 5-12. Photograph of Stealth computer used for data acquisition from temperature sensors.

The pile was driven to refusal at this location. Approximately 18 in. of loose soil was placed around the top of the pile to level the bank and extend the portion of the test pile installed in the soil. This area of the creek is expected to flood regularly during high water events because the creek has steep, narrow banks, such that high water will occur with modest amounts of rainfall. The test pile was connected to the computer in the data box, and data stored on site as well as at a server on the MU campus.

Figure 5-13. Photograph of the test pile installation at Hinkson Creek.

5.6 Results of Pile Installation

The installation of the test pile was completed on November 19, 2008. After trouble shooting the data acquisition system, data collection was started in continuous fashion on December 3, 2008. This section reviews data and results from the initial installation of the test pile.

Figure 5-14 shows typical results from the test pile over the first week of installation. The pile is installed with approximately 80 in. embedded in the soil, and approximately the first 27 sensors being at or below the soil line. Figure 5-14 shows typical profiles of the temperature along the height of the pile. The Figure shows three different temperature profiles from the first week of continuous data collections; when air temperatures is highest, when the air temperature is lowest, and the initial air temperature when data collection was started. The Figure shows that there is an area of transition from the air temperature to the sound soil temperature. In this transition area, the temperatures measured along the pile are in transition from the external air temperatures to the sound soil temperature. This transition area includes the loose soil that was placed along the pile at the time of pile installation which has a low density relative to the soil that was intact at the time of installation. As shown in the Figure, there is a consistent height along the pile at which the temperatures remain the same, regardless of the external air temperature. The movement of this sound earth point along the pile would be indicative of scour occurring at the pile. This height (~52 in., or between sensors 17 and 18) along the pile has remained consistent throughout the initial testing, with the exception of the some slight changes (+/- 2 ºC) that occur over long time periods of several days. Temperatures increase slightly into the sound soil, as the pile is not driven very deep due to the bedrock present at the site.

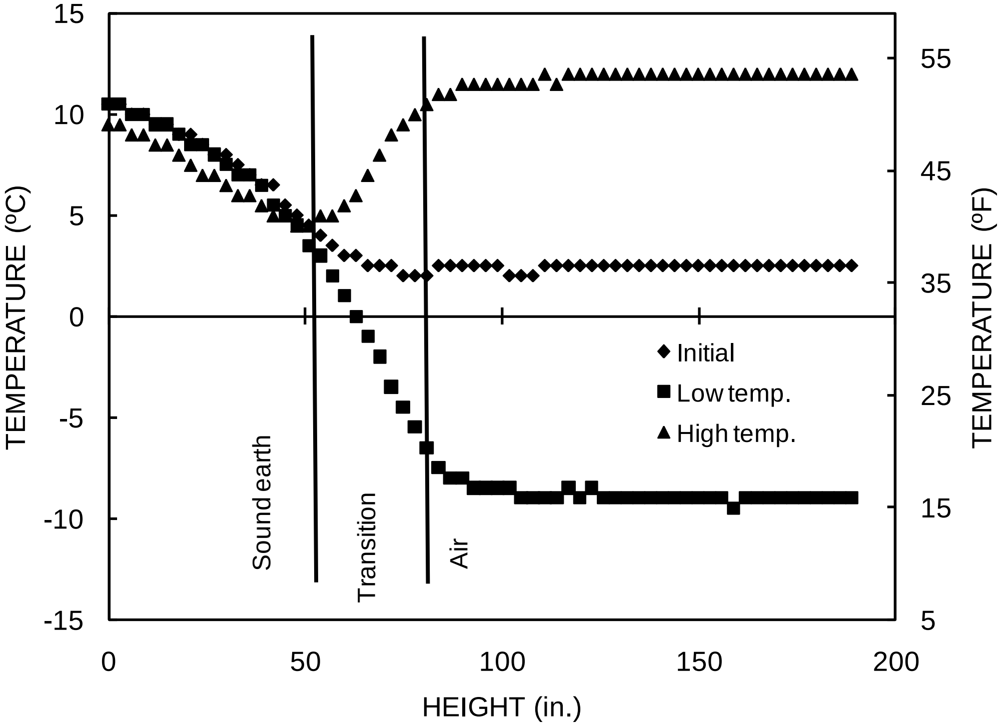


Figure 5-14. Temperature profile along the test pile for high, low and initial air temperatures.

To further investigate the location of the air/soil interface on the installed pile, the pile was locally heated with a torch at the air/soil interface. The pile is installed along an inclined bank, such that the air/soil interface is different on opposing sides of the pile as shown in Figure 5-15. Heat was applied to the pile at the down – hill location (location A) to heat the pile locally, such that the sensor that responded to the applied heat could be identified. The distribution of heat along the length of the pile is shown in Figure 5-15. Heat was also applied, though for a shorter time, to the up-hill side of the pile (location B), directly heating the armor channel holding the sensor. A smaller amount of heat was applied at location B to avoid damaging the epoxy in which the sensors are embedded. The spike in temperatures at location A and B can be clearly seen in the pile profile in

Figure 5-15. The data indicated that sensor 24, located at a height of 69 in., was closest to applied heat at location A. At location B, sensor 27, at height of 78 in along the pile, was closest to the applied heat.

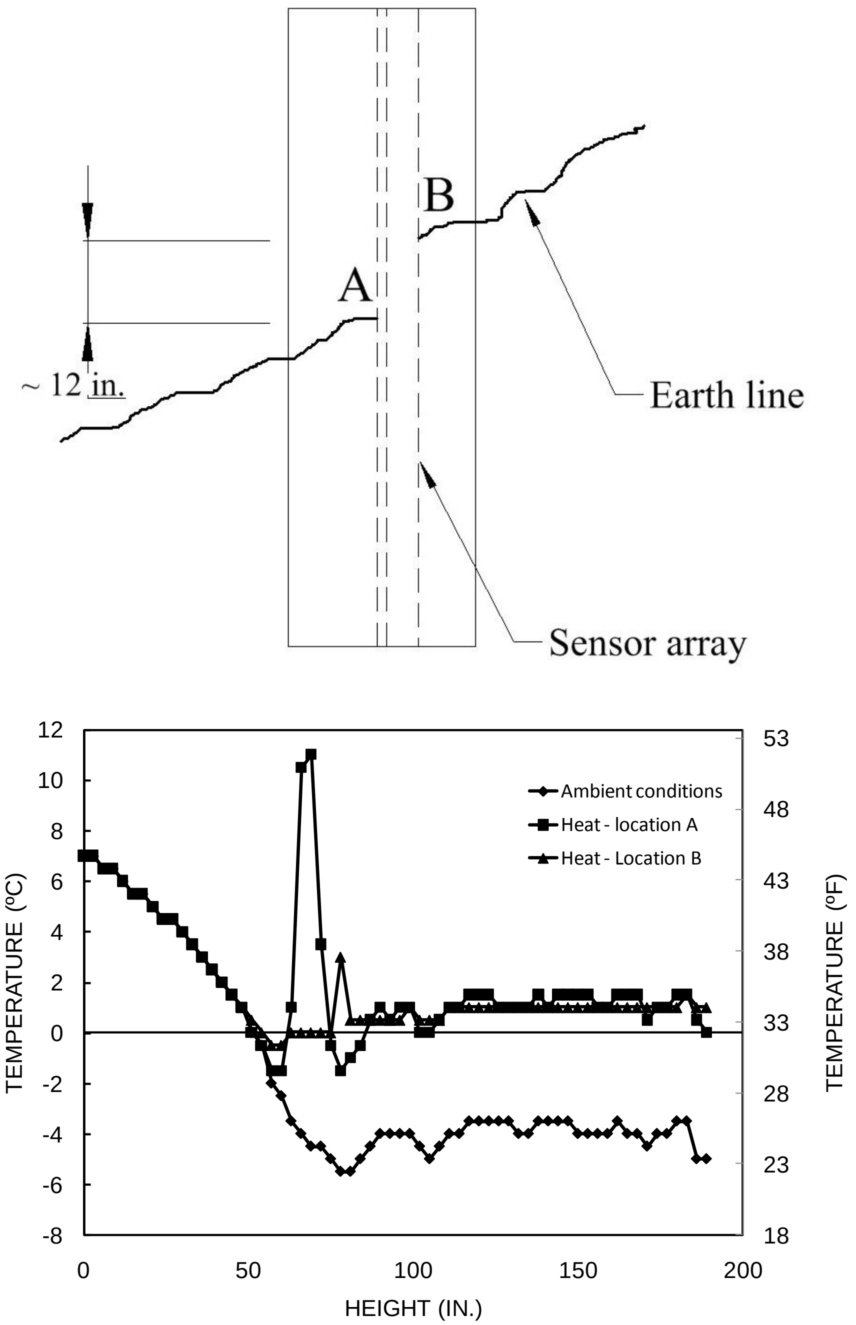


Figure 5-15. Schematic diagram of test pile showing locations where heat was applied (top) and resulting temperature measurements along sensor array.

The sound earth point and the transition area were further investigated by determining the standard deviation of the data measured from each sensor. The standard deviation is determined from the equation:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$$

Where $\bar{x}$ is the sample mean and n is the sample size. The standard deviation is a measure of how widely dispersed values are from the average. For sensors exposed to air, the measurements vary with the diurnal temperature variations, and as such the standard deviation is high. For sensors in sound earth, the temperature varies very little over time, such that the standard deviation would be expected to be low. To evaluate the behavior of the sensor array, data was examined under three conditions; the standard deviation over a 24 hour period, the average of 24 hr standard deviations over 1 week, and the standard deviations for 1 week of data. Figure 5-16 shows the standard deviation from the sensor array under each of the three conditions. Analysis of data in this manner reveals if such data analysis would be adequate over a short time period (24 hours), when ambient temperature variations may be small, as well as over a longer time period (1 week) when ambient temperature variations would be expected to be larger. For evaluation of the effects of scour, a shorter time period is desired, such that rapid notification of a change in condition at the pile site would be feasible.

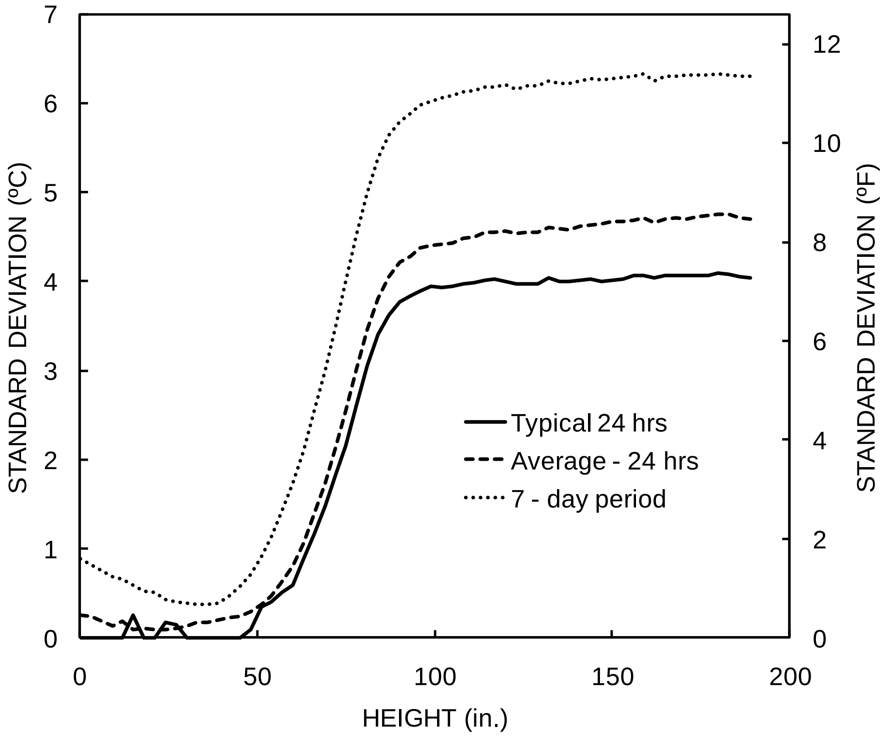


Figure 5-16. Standard deviation of temperature outputs for three time intervals: 24 hr. period, average of 24 hr. periods for 7 days, and standard deviation over a 7 day period.

Figure 5-17 shows the average standard deviations for the 24 hr periods, as well as the standard deviation of those results, to indicate the scatter between separate 24 hr periods. As the figure indicates, the dispersion of standard deviations is higher for the sensor in air and in the transition region relative to those sensors in sound earth. The results shown in this figure indicate that examining the standard deviations may provide a robust tool for estimating the height of sound earth along the pile. The standard deviations for three sensors are shown in Table 1. This includes a sensor in sound earth at a height of 3 in., a sensor in the transition region (75 in.) and in air (150 in.).

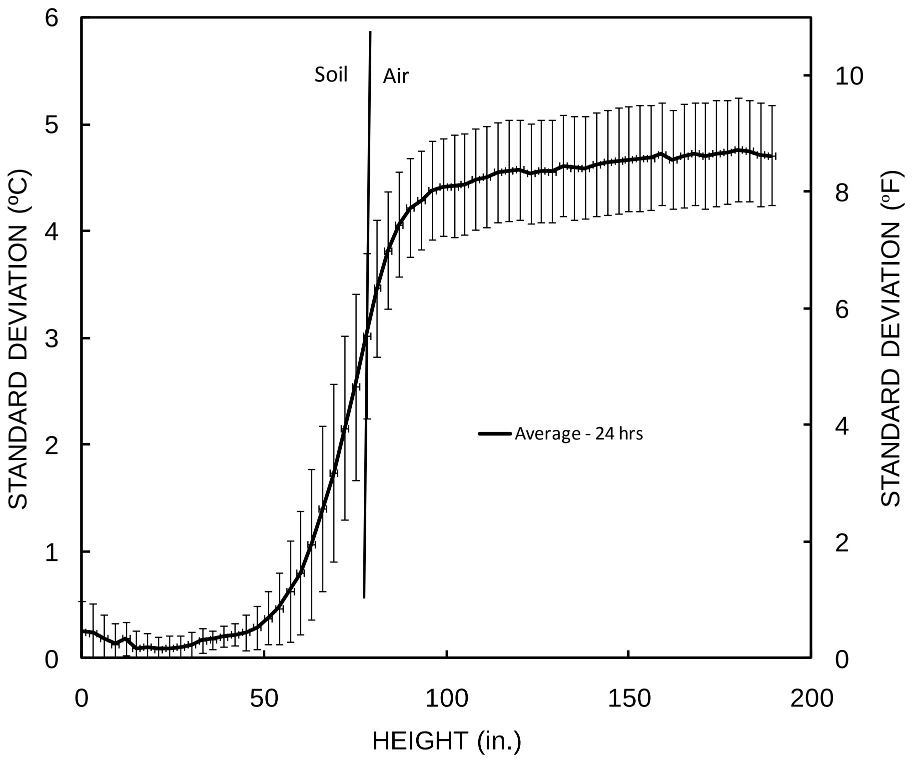


Figure 5-17. Standard deviation of temperature data from sensors along the height of the pile. Plot shows the average 24 hr. standard deviation for 7 days, and error bars showing the dispersion (standard deviation) of the results.

Table 5-1. Standard deviation of temperature measurements for sensors at height of 3, 75 and 150 inches.

Sensor Height (in.)	**Standard Deviation 24 hr., 7 day average ºC (ºF)**	**Standard Deviation Over 7 Days ºC (ºF)**
3	0.24 (0.43)	0.82 (1.5)
75	2.5 (4.5)	4.0 (7.2)
150	4.7 (8.5)	6.3 (11.3)

This data indicates that quantitative measurements of the location of sound soil can be easily determined based on the scatter of temperature measurements along the height of the pile. This data provides a uniform and quantitative evaluation of the portions of the pile exposed to thermal variations typical of being exposed to ambient temperature variations of the air, or variations in the water temperatures, on a daily basis. The evaluation of the standard deviation also allows for the computer algorithms to be developed to automate the process of monitoring the air/soil interface. This may be useful in future research efforts to develop an autonomous remote monitoring system.

The data can also be observed as a three-dimensional plot that shows the daily variation in air temperatures, and the consistent behavior of the sensors that are embedded in sound soil. Such a plot is shown in Figure 5-18, which shows a color-coded plot of the sensor response over a 15 day period (Dec. 3 – 21, 2008). In this Figure, the temperature measurements are shown on the vertical axis, and the height along the pile and time of measurements shown on the base plane. Such a presentation of data provides a visual representation of where the sound earth exists along the pile, as well as showing the transition range and the sensor in air, which vary significantly over the course of each day. As shown in the Figure, the sound earth sensors are very stable over the two-week period. The data also shows that there is a slight increase in the temperatures as the embedment of the pile increases. This result is consistent with previous research results by Camp [10].

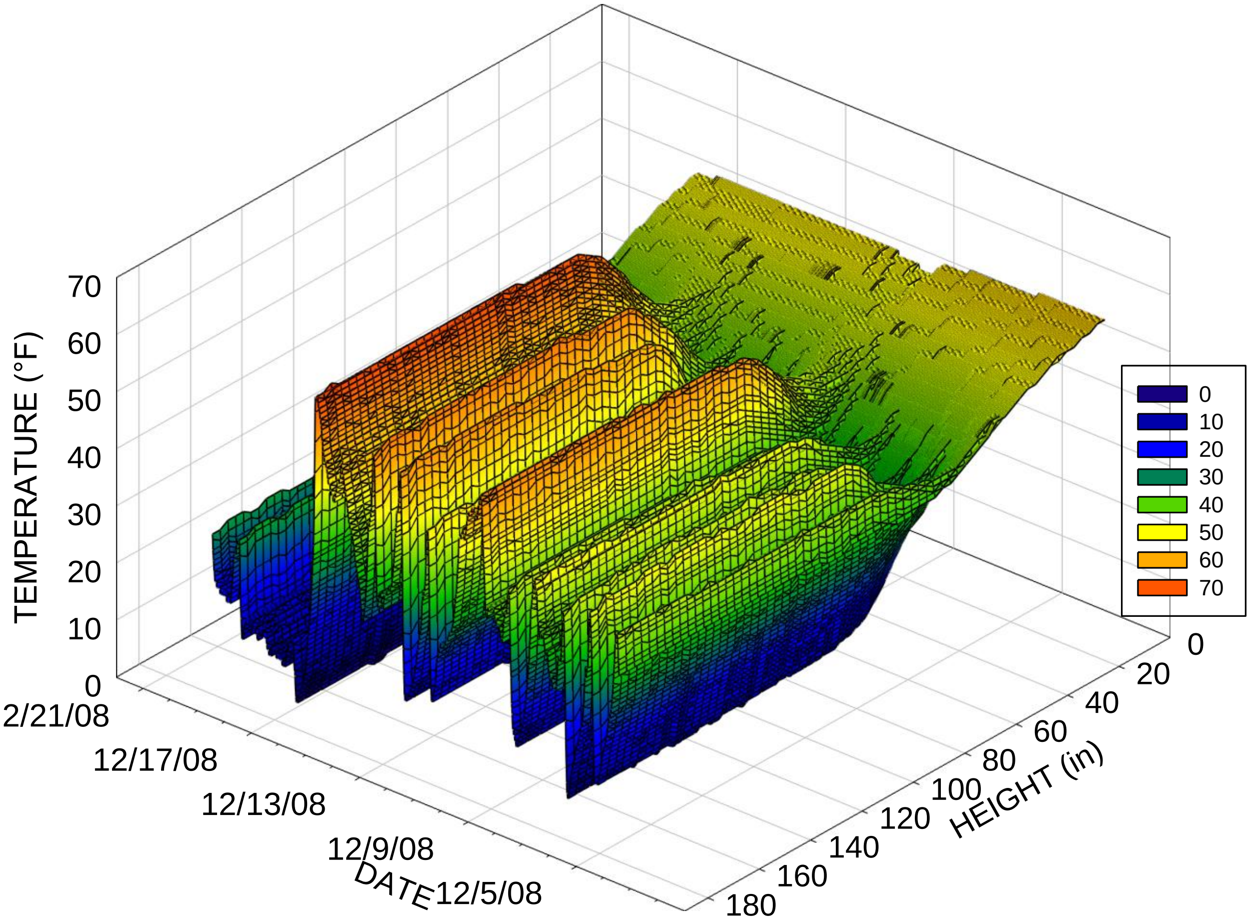


Figure 5-18. Plot showing temperature variations along the pile as a function of time over 15 days.

A 3-dimensional plot was also created showing the application of the heat at the air/soil interface. Figure 5-19 shows the output of the sensor array during testing, and clearly shows the spikes in temperature that occurred at the air/soil interface. The arrow in the figure points to the increase in temperature as a result of heating the pile with a propane torch, as previously discussed. This data was collected as part of the ongoing data collection at the test site, transmitted over the cellular phone link and collected at the server on-campus at MU.

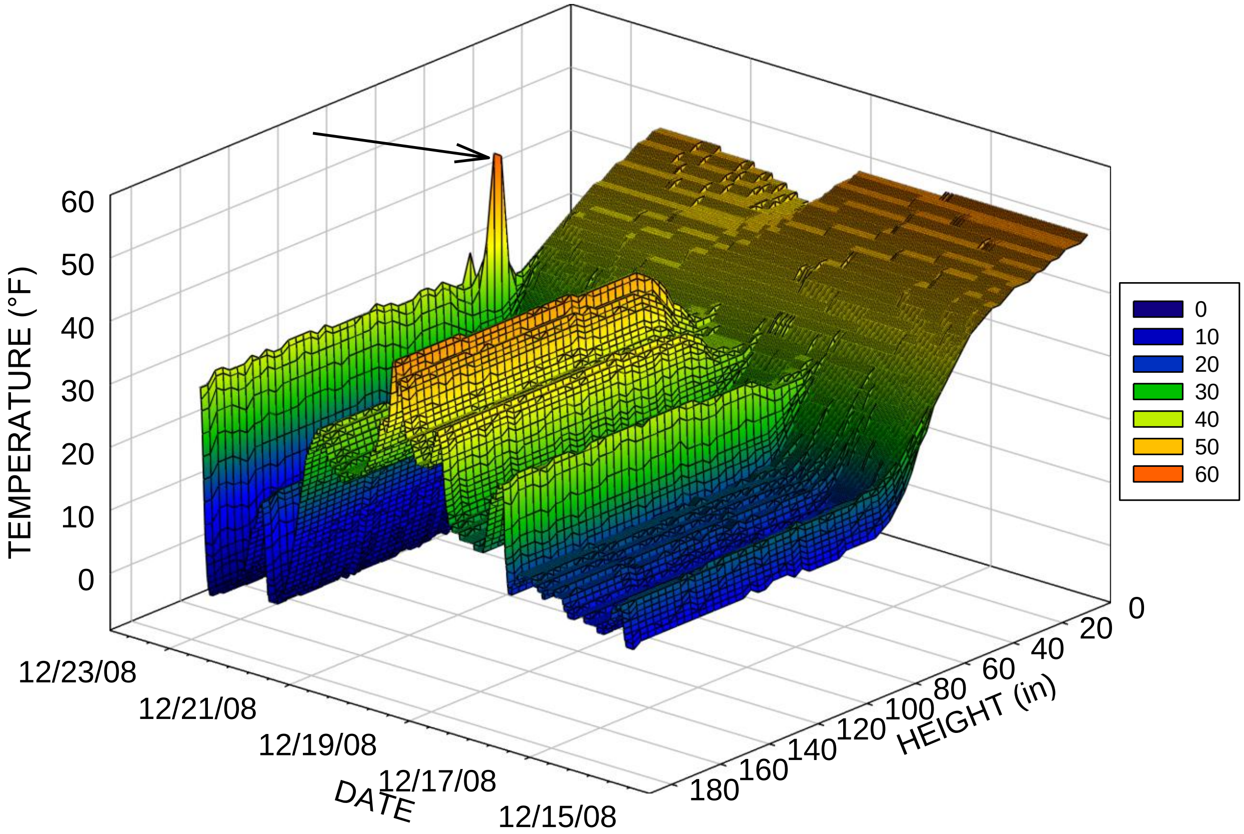


Figure 5-19. 3-D plots of plots of pile temperature profiles showing local heating at air/soil interface.

5.7 Flood Event

This section describes the response of the prototype pile to flooding conditions that occurred. During this flood, the flow level of Hinkson Creek increased to the level of the ground/pile interface on December 27, 2008, as shown in Figure 5-20. Using the data measured before, during, and after this flood event, an investigation was conducted to determine if scour was detected in the area of the pile. No significant scour was observed as a result of the flood. The data analysis described in this section indicated there was not clear evidence of a change in earth level, though there was some evidence that suggest the earth line may have moved.

Figure 5-20. Photo of Pile during High Water Event, December 27, 2008.

Typical temperature profiles along the length of the pile before and after the flood event are shown in Figure 5-21. Four days were selected for the graph, two from exceptionally warmer days, and two from colder days. The days were selected such that one of each is before the flood and one after the flood. Similar to Figure 5-14, the inflection point is clearly visible, near a height of 50 inches. After the storm, the inflection point did not change noticeably. If the inflection point were to move lower on the pile, it would be an indication that scour occurred.

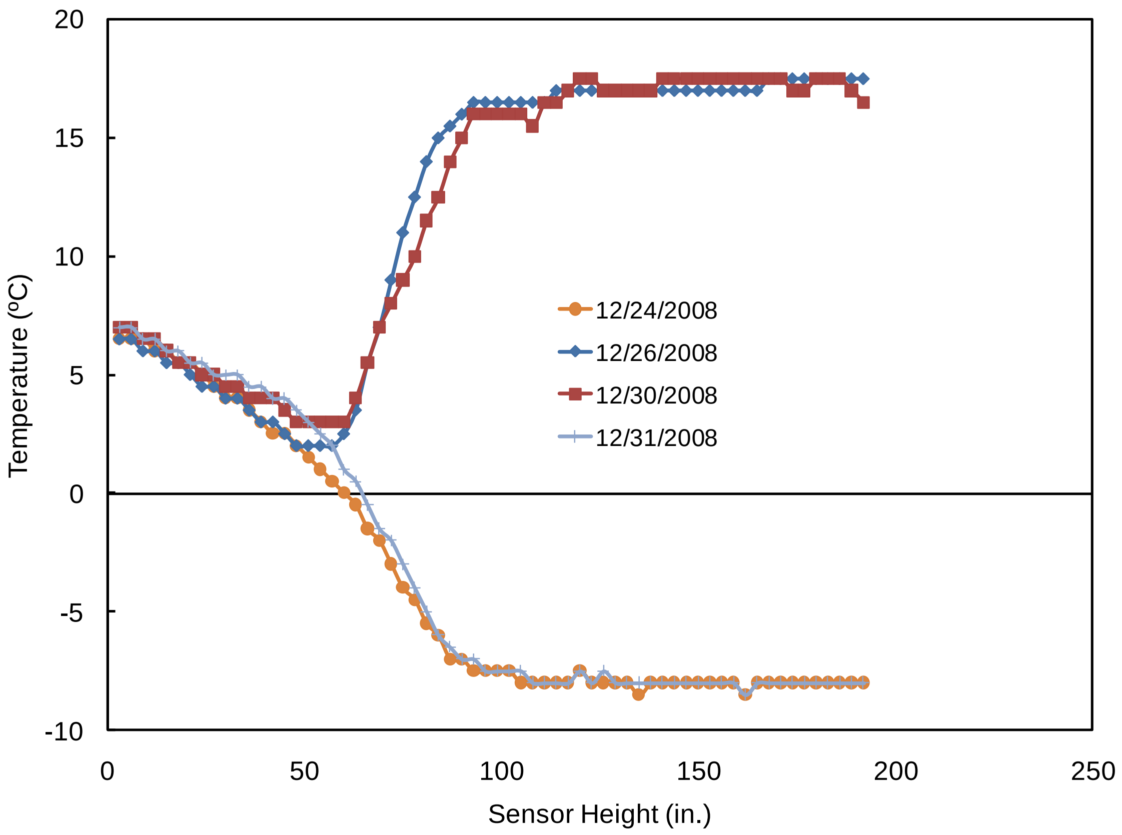


Figure 5-21. Typical temperature data profiles.

It was previously shown in Figure 5-14 that the sound earth line was nearest to sensor 17, at a height of 52 inches. In addition, from the earth line exploration test (Figure 5-15) the ground level of the loose soil surrounding the pile was nearest to sensor 24 on the creek side, and sensor 27 on the bank side. Due to those important locations, the data analysis was focused on the sensors near that range.

Taking advantage of the temperature data captured by the pile, each day was reduced to two data points, one for the minimum and one for the maximum temperature, to illustrate the range of temperatures being experienced at individual sensors. To eliminate the data that did not pertain to the time of the storm, only the week before and the week after the storm were analyzed. In Table 5-2, a summary of the sensor data is shown, which includes only the even numbered sensors between #16 and #28. For clarity, rows in the Table corresponding to the date of December 27th , the date of the flooding, is shown in bold text in the Table. Sensors 16 and 18, the two sensors deepest underground on the pile, have average temperature ranges of 0.5°C and 0.64°C respectively. For sensors that were exposed to the ambient environment (sensors 24-28), the average range of daily temperature was between 5.9°C and 10.7°C. This is an indication that those sensors are exposed to the ambient environment, and thus affected by diurnal temperature variations. It is seen from this Table sensors 16-22 had smaller temperature variations than sensors 24-28 prior to the flooding. In the week following the flooding temperature ranges were increased, due to increased range of ambient temperatures during that time period.

Table 5-2. Maximum and Minimum Data for Even Sensors 16 through 28.

Date	Sensor 16			Sensor 18			Sensor 20			Sensor 22			Sensor 24			Sensor 26			Sensor 28		
	Max	Min	Range	Max	Min	Range	Max	Min	Range	Max	Min	Range	Max	Min	Range	Max	Min	Range	Max	Min	Range
12/20/2008	3	2.5	0.5	2	1.5	0.5	1	0.5	0.5	0.5	-1	1.5	0	-4.5	4.5	0	-8	8	0	-10.5	10.5
12/21/2008	2.5	2	0.5	1.5	0.5	1	0.5	-1.5	2	-1.5	-4.5	3	-3	-8.5	5.5	-4.5	-11.5	7	-6	-14	8
12/22/2008	2	1.5	0.5	0.5	0	0.5	-0.5	-2	1.5	1	-5.5	6.5	0	-9	9	0.5	-12.5	13	1	-14.5	15.5
12/23/2008	1.5	1.5	0	1	0.5	0.5	0	-1	1	0	-2	2	0	-3	3	0.5	-4	4.5	1.5	-4	5.5
12/24/2008	2	1.5	0.5	1	1	0	0	0	0	0	-1.5	1.5	0.5	-3	3.5	0.5	-5	5.5	1.5	-6.5	8
12/25/2008	2	1.5	0.5	1	0.5	0.5	0	-1	1	0	-3	3	1	-5	6	2.5	-7	9.5	5.5	-8.5	14
12/26/2008	2.5	1.5	1.0	2.5	1.0	1.5	4.0	0.0	4.0	6.5	0.0	6.5	10.5	1.0	9.5	14.0	2.0	12.0	16.5	3.0	13.5
Average	2.21	1.71	0.50	1.36	0.71	0.64	0.71	-0.71	1.43	0.93	-2.50	3.43	1.29	-4.57	5.86	1.93	-6.57	8.50	2.86	-7.86	10.71
12/27/2008	**5.0**	**2.5**	**2.5**	**5.5**	**2.5**	**3.0**	**6.0**	**3.0**	**3.0**	**8.5**	**1.5**	**7.0**	**12.0**	**0.5**	**11.5**	**14.5**	**0.0**	**14.5**	**16.5**	**-1.0**	**17.5**
12/28/2008	4.5	3.5	1.0	4.0	2.5	1.5	4.0	1.5	2.5	5.0	0.5	4.5	6.5	-0.5	7.0	7.5	-1.0	8.5	9.5	-2.5	12.0
12/29/2008	4.0	3.0	1.0	4.0	2.0	2.0	4.5	1.0	3.5	6.0	0.5	5.5	8.0	-0.5	8.5	10.0	-1.5	11.5	12.5	-2.5	15.0
12/30/2008	4.0	3.0	1.0	4.5	2.5	2.0	5.5	1.5	4.0	8.5	0.5	8.0	11.5	0.0	11.5	14.5	-0.5	15.0	17.0	-1.5	18.5
12/31/2008	4.0	3.0	1.0	3.5	2.0	1.5	3.0	0.5	2.5	2.5	-0.5	3.0	3.0	-2.0	5.0	4.0	-4.0	8.0	6.0	-6.0	12.0
1/1/2009	3.0	2.5	0.5	2.5	1.5	1.0	2.0	0.5	1.5	2.5	-1.0	3.5	4.0	-3.0	7.0	5.5	-4.5	10.0	8.0	-6.0	14.0
1/2/2009	3.0	2.5	0.5	3.0	1.5	1.5	3.0	0.5	2.5	4.0	-0.5	4.5	6.0	-1.0	7.0	7.5	-2.5	10.0	11.0	-3.5	14.5
1/3/2009	5.0	3.0	2.0	5.5	2.5	3.0	7.0	2.0	5.0	9.5	2.0	7.5	12.5	2.0	10.5	14.5	2.0	12.5	16.5	2.5	14.0
Average	3.72	2.62	1.10	3.64	1.87	1.76	3.97	0.98	2.99	5.39	0.05	5.34	7.53	-0.81	8.34	9.39	-1.66	11.05	11.64	-2.54	14.17

Table 5-3. Standard Deviation Averages for Sensors 15 through 28.

Sensor Number	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Average Before	0.19	0.17	0.18	0.24	0.32	0.47	0.72	1.11	1.57	2.01	2.48	2.90	3.31	3.60
Average After	0.30	0.35	0.48	0.59	0.77	1.07	1.38	1.84	2.32	2.73	3.17	3.59	4.15	4.67

Standard deviation is similar to range, but it gives more importance to values that are far from the mean. The standard deviation of each individual sensor was calculated for each day by the formula given in section 5-6. As discussed earlier, and similar to the discussions on range, it can help determine where the soil interface resides. Table 5-5 was made by averaging the daily standard deviations for the week before and after the storm. From the Table, it can be seen that the standard deviation is very low on the underground side of the pile, less than 1°C for all sensors beneath #21. The standard deviation increases with increasing height along the pile, and reaches values above 4°C by sensor 28.

Figures 5-22 and 5-23 are both graphical representations of the standard deviation data, and include data from all of the sensors on the pile. The standard deviation increased with increased elevation along the pile as would be expected based on the previous (see Figures 5-16 and 5-17.) In the week before the storm, sensor 17 (~52 inches) was the approximate location where standard deviations began to increase. After the flood, the standard deviation begins to increase approximately 12 inches lower, at sensor 13. This could be a sign that scour occurred, and the earth line has moved lower on the pile. However, the ambient temperature ranges that occurred during the time period after the flood were also much greater, such that there is uncertainty regarding whether this measurement is indicative of scour, or an artifact of the measurement conditions.

Figure 5-23 graphs data from sensors 1 through 32 only. Sensor 33 through 64 are exposed to the ambient environment, and there is little variation in the standard deviation between separate sensors. The data shown in the figure is a normalized standard deviation, which was calculated by dividing all of the sensors by the standard deviation at sensor 32. This normalized the standard deviation of the temperatures measured before the flood event to those measured after the flood event in terms of deviation magnitudes. The week after the storm had larger diurnal temperature ranges. With the normalized standard deviations, the normalized deviations for the time period before and after the flood are approximately equal at sensor 14. From that point, the normalized deviations increase more rapidly for the time period following the flood than for the period prior to the flood. This may be a sign of scour occurring.

These example methods of data analysis may need to be improved looking forward to operational implementation of such a scour device. Since this project focused on the development of innovative sensor technology to enable the measurements, rather than methods of data analysis that might be used to assess the data, further analysis of this data was not developed within this report.

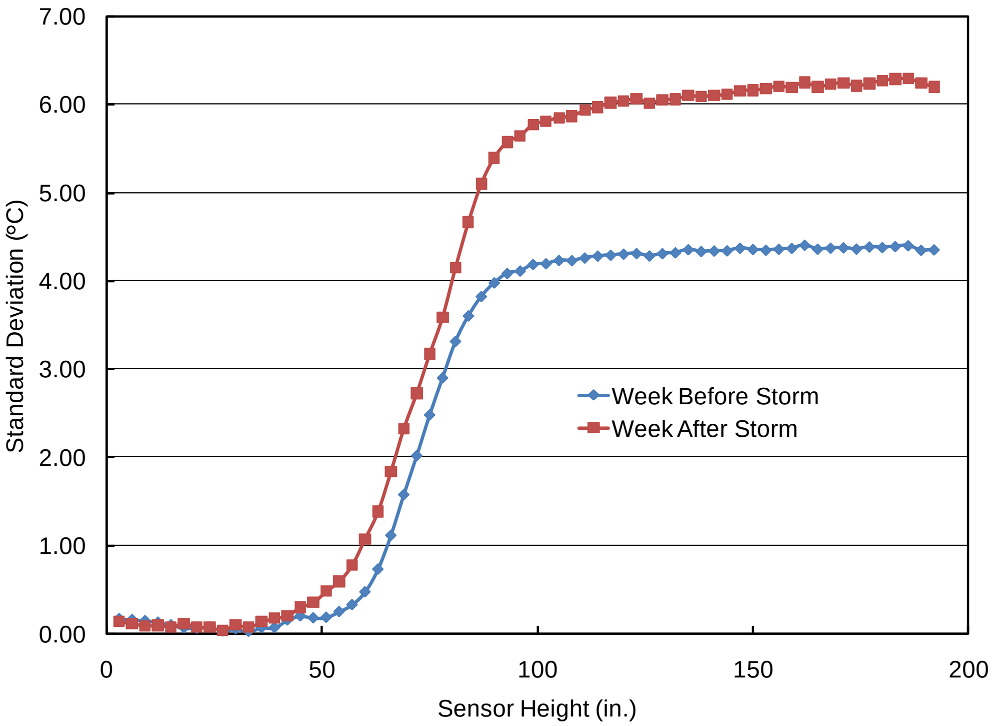


Figure 5-22. Standard deviations in week before and after flood event.

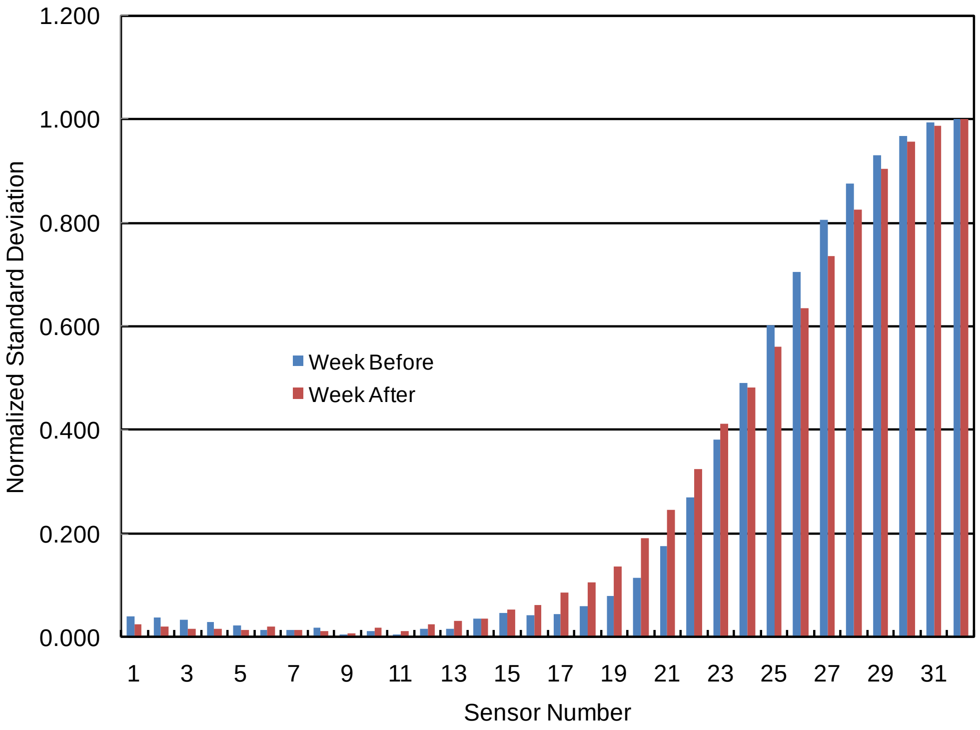
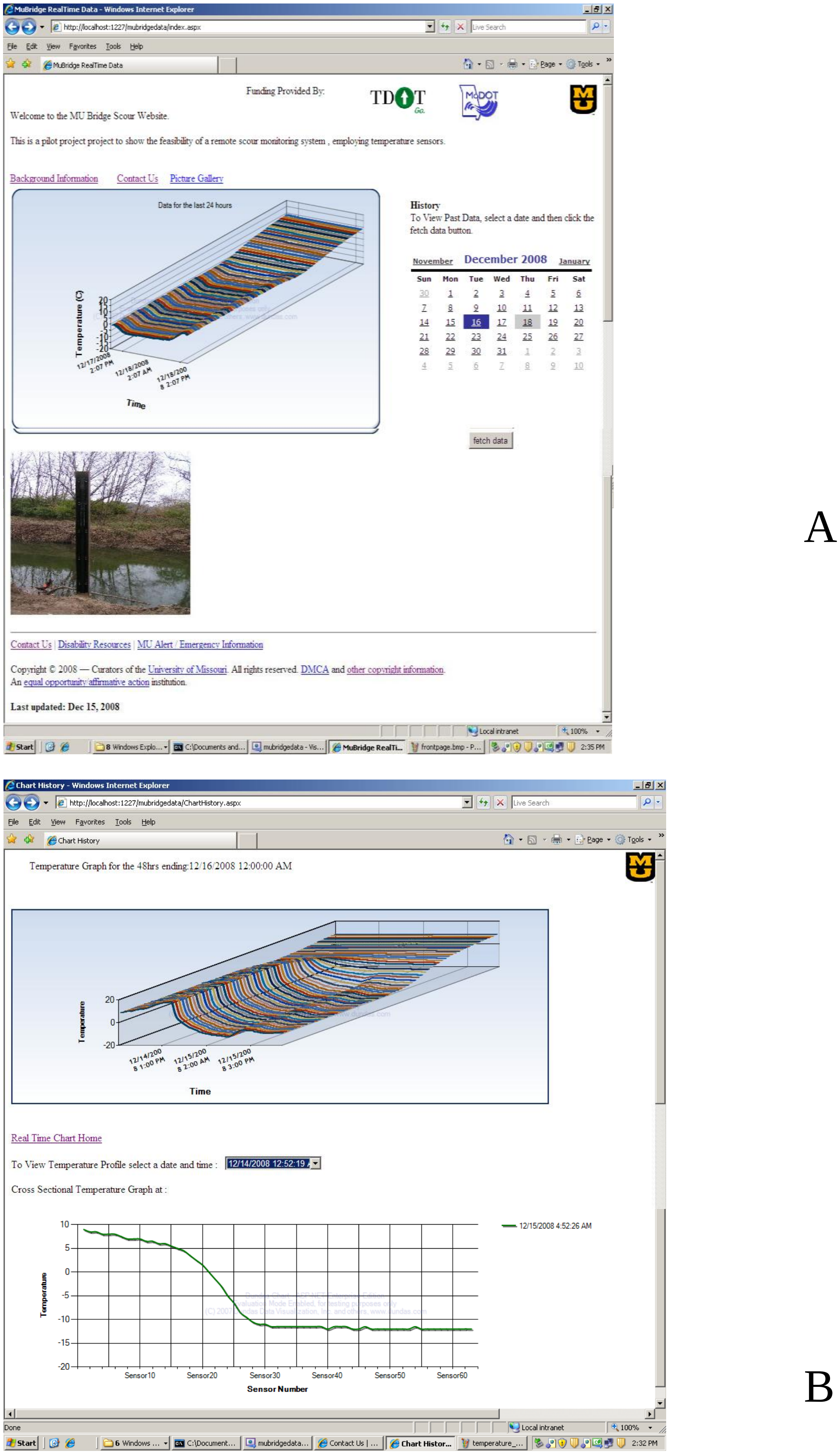


Figure 5-23. Normalized standard deviations in week before and after flood event.

5.8 Web Data

A web site was developed to monitor the behavior of the test pile from a remote location. This web site allows for a user to check the status of the test pile from anywhere that web access exists. The software to provide web access to the data from the test pile was developed over the course of the project to provide some rudimentary capability to observe the behavior of the test pile from a remote location. This section briefly describes the data available from the web site.

Data from the test pile is transmitted to a server at MU each time a sensor scan occurs. Presently, data is collected from the test pile every 15 minutes, stored in the on-site computer and then transmitted to a server database at MU. Once transmitted, the data is integrated into a live 3-dimensional graph that shows the most recent 24 hr. test period. This graph shows the measurements for each sensor at 15 minute intervals. A screen capture of the front page of the web site is shown in Figure 5-20A. This figure shows a 3-dimensional plot of the test pile data over the last 24 hrs, a photograph of the test pile, and other ancillary data such as contact information, project sponsors, etc. A calendar on the front page of the web site enables the user to select a different time period for the test pile to create a graph that shows the 48 hrs leading up to the selected time. This function queries the database of past data to develop a plot showing the specific 48-hour test period of interest. This function could be used, for example, to observe the behavior of the pile during a recent high water event. When historical data is selected, the user has the further option to generate a temperature profile of the pile at any point in time desired within that 48 hr. period. This enables the user to observe changes in the temperature profile of the pile that may have occurred. The historical representation of data is shown in Figure 5-20B. The Figure shows the three-dimensional plot of the test pile output over a 48-hour period leading up to the date selected by the user for review, and an associated temperature profile along the length of the pile at a user-selected time interval.



Funding Provided By:

Welcome to the MU Bridge Scour Website.

This is a pilot project project to show the feasibility of a remote scour monitoring system , employing temperature sensors.

Background Information Contact Us Picture Gallery

History
To View Past Data, select a date and then click the fetch data button.

Contact Us | Disability Resources | MU Alert / Emergency Information

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Last updated: Dec 15, 2008

Temperature Graph for the 48hrs ending:12/16/2008 12:00:00 AM

Real Time Chart Home

To View Temperature Profile select a date and time : 12/14/2008 12:52:19

Cross Sectional Temperature Graph at :

Figure 5-24. Screen capture from the test pile web site showing A) homepage and B) historical data.

6 Conclusions

This research has explored the development of an instrumented pile for monitoring the scour conditions at a bridge. This monitoring technology is intended to improve the tools available for asset management by providing real-time data to owners and engineers on the site conditions at a bridge. An innovative new design for a fieldable temperature array that can be mounted on a pile has been developed and tested in the laboratory. This sensor array consists of a series of 1-wire digital temperature sensors that are mounted on a polymer substrate of a printed circuit board. The technology for manufacturing printed circuit boards that provides a durable trunkline system for assembling the sensor array has been developed as part of the project.

Laboratory testing showed that the sensor array responded effectively to changing thermal conditions, and that software and data acquisition hardware performed reliably over long time periods. The laboratory testing also showed that the temperature array responded with only a slight delay relative to thermocouples, which are commonly applied for temperature measurements in the field. The time lag for detecting thermal changes was on the order of a few minutes, which is not expected to affect the effectiveness of the system in the field.

A prototype test pile integrating 64 temperature sensors along 16 ft. of the pile was designed, constructed and implemented in the field. This test pile was installed along Hinkson Creek in Columbia, MO. Initial monitoring of the test pile indicated that the thermal response of the test pile was able to clearly delineate portions of the pile embedded in soil and portions of the pile in air, with a transition region surrounding the air/soil interface. Analysis of data from the pile demonstrated that the standard deviation of temperature measurements over a 24 hour period were indicative of the location of the air/soil interface. For sensors located in sound soil, standard deviations on the order of 0.25ºC were typical, while sensors in air had standard deviations on the order of 4ºC.

6.1 Recommendations

The field demonstration indicated that the unique sensor array design could be practically implemented in the field for monitoring scour conditions at a bridge. The sensor array was sufficiently durable to be installed using normal construction equipment, and was not negatively affected by installation. Monitoring of the array performance in the field is ongoing. The installation in the field also demonstrated the use of a cellular modem for transmitting data to a host server for presentation on the World Wide Web. This enables the real-time monitoring of the pile behavior from remote locations. All data from the pile is currently being collected remotely over the cellular modem link.

Based on the findings of the research, it is recommended that a second-generation device be developed based on the successful concepts demonstrated through the project. The use of small, semi-conductor based temperature sensors developed through the research open a broad range of possibilities for implementation of the technology. Specifics of the recommended design parameters for such a system are included in the following section. It is anticipated that these additional developmental steps will result in a fully implementable system for implementation within Missouri and all other States.

6.2 Implementation Plan

The project developed a prototype instrumented pile and demonstrated the functionality of that pile under field conditions. The technologies that were developed include a semi-conductor based sensor array that is very low in power requirements, low cost and durable enough for field implementation. Software was also developed to collect data from the array, and transmit that data to a centralized database for presentation on the web. To implement this technology in the field, the following is recommended:

- Develop a low power, small footprint data acquisition system that could be widely implemented in the field, having the following characteristics:
    - Single board computer
    - Solar and/or battery power
    - On-site web server to provide direct-to-the-web data
    - Autonomous operation in the field
    - Simple field installation by contractors
- Implement the printed circuit board technology through a commercial resource to provide a sensor array on a flexible substrate
    - Technology is commercially available with some customization
    - Low cost sensors with flexible design characteristics
    - Flexible sensors could be implemented in a wide variety of scenarios with minimal development required
- Develop necessary software to provide processed data to users that reports on the earth level of the pile, and reports changes to the earth level automatically
- Implement the technology through one or more demonstration projects

  - Include embedding the sensors in a concrete pile and implementation on steel piles as demonstrated in this project

The technical challenges/risks associated with the recommended implementation plan are minimal, since the concepts and procedures necessary for implementation have been developed and tested through this project.

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