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16. Abstract

The research performed in this project focuses on the application of instruments including accelerometers and tiltmeters to monitor bridge scour. First, two large scale laboratory experiments were performed. One experiment is the simulation of a bridge with a shallow foundation, and the other is the simulation of a bridge with a deep foundation. A series of instruments were installed on the simulated bridge to monitor the performance of the bridge due to scour. Both the shallow foundation experiment and deep foundation experiment show that accelerometers and tiltmeters can be used in scour monitoring events since both give warning of bridge failure successfully. Subsequently, two individual monitoring systems were designed and installed on two bridges: US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge in Texas. Realtime data are collected and transmitted to a computer server at Texas A&M University, which can be accessed remotely. The instrumentation on the two bridges does not show great hope of application of accelerometers to monitor bridge scour because of a lack of sufficient excitation from traffic. Another issue with the accelerometers is the high power consumption during the transmission of accelerometer data, which cannot be satisfied with a typical solar panel and battery. Tiltmeters can provide the integral behavior of the bridge, and therefore are very useful devices for scour monitoring. Guidelines and protocols for scour monitoring based on the US59 over Guadalupe River Bridge and the SH80 over San Antonio River Bridge are provided in the study.

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REALTIME MONITORING OF BRIDGE SCOUR USING REMOTE MONITORING TECHNOLOGY

by

Jean-Louis Briaud
Research Engineer, Texas A&M University

Stefan Hurlebaus
Assistant Professor, Texas A&M University

Kuang-An Chang
Associate Professor, Texas A&M University

Congpu Yao, Hrishikesh Sharma, Ok-Youn Yu and Colin Darby
Graduate Students, Texas A&M University

Beatrice E. Hunt,
STV Incorporated

and

Gerald R. Price
ETI Instrument Systems, Inc.

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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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EXECUTIVE SUMMARY

BACKGROUND

Bridge scour is recognized as the number one cause of bridge failure in the country and accounts for about 60 percent of all failures. There are several options to prevent failure of bridges subjected to scour and the associated loss of life. They are replacement of the bridge and scour countermeasures. Three main types of scour countermeasures are used nowadays: structural, hydraulic, and monitoring countermeasures. Monitoring is usually the least expensive of the three options. It is particularly helpful if the predictions appear to be very conservative but little evidence beyond common sense and engineering judgment exists to prove it. There are three types of scour monitoring: visual monitoring, portable, and fixed instrumentation. Fixed scour monitoring consists of placing an instrument close to the bridge and close to the river bed to record some data for the purpose of warning the engineer when the scour depth becomes excessive. Scour monitors have evolved over the years yet they are still relatively expensive. There is a need to make scour monitors less expensive and more convenient so they can be used on more bridges than is currently the case.

At present, there are approximately 700 scour critical bridges in Texas and 26,000 in the U.S. It is urgent for researchers to find an inexpensive and easy way to monitor bridges in Texas. This project is aimed at choosing the proper scour monitors for a bridge and warning the owner of an imminent failure so that appropriate action can be taken before exposing the public to undue risk.

APPROACH TAKEN TO SOLVE THE PROBLEM

The approach selected to solve the problem is based on a combination of a review of existing scour technology, development of new technology, laboratory proof of functioning, and field installation and demonstration. The review of existing scour technology helps establish a solid foundation. The development of new technology helps progress on the field of bridge scour monitoring. The laboratory proof of functioning provides valuable experience for instrumentation on bridges, and leads thorough research on scour monitors. The field installation and demonstration provides a validation of the scour monitoring technology.

OUTCOME OF THE STUDY

The outcome of the study is the results of the laboratory experiments, the bridge instrumentation in the field, and associated guidelines and protocols. Two large scale laboratory experiments were performed at the Coastal Haynes Engineering Laboratory at Texas A&M University. One experiment is the simulation of a bridge with a shallow foundation, and the other is the simulation of a bridge with a deep foundation. A series of scour monitors were installed on the simulated bridge to monitor the performance of the bridge during scour. Both the shallow foundation experiment and deep foundation experiment show that the accelerometer and tiltmeter can be used in scour monitoring events since both gave proper warning of bridge failure. Another product of the project is the instrumentation of two bridges in Texas: US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge. Individual monitoring systems were designed and installed on the two bridges. Realtime data are collected and transmitted to a computer server at Texas A&M University, which can be accessed remotely. The instrumentation on the two bridges does not show great hope of application of accelerometers to monitor bridges during scour events because of the lack of efficient excitation from traffic. Another issue with accelerometers is the high power consumption during transmission of the data, which cannot be satisfied with a typical solar panel and battery. Tiltmeters can provide the integral behavior of the bridge and are recommended for use in scour monitoring projects. Guidelines for selecting scour monitors and protocols for US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge are provided in the study.

CHAPTER 1:
INTRODUCTION

WHY THE PROBLEM WAS ADDRESSED

Figure 1-1 shows the possible causes of bridge failure based on data collected from 1966 to 2005. Figure 1-1 shows that bridge scour is the number one cause of bridge failure in the country and accounts for about 60 percent of all failures. The second most common cause is ship impact with 12 percent of all failures. Earthquake is fairly far behind with 2 percent of all failures.

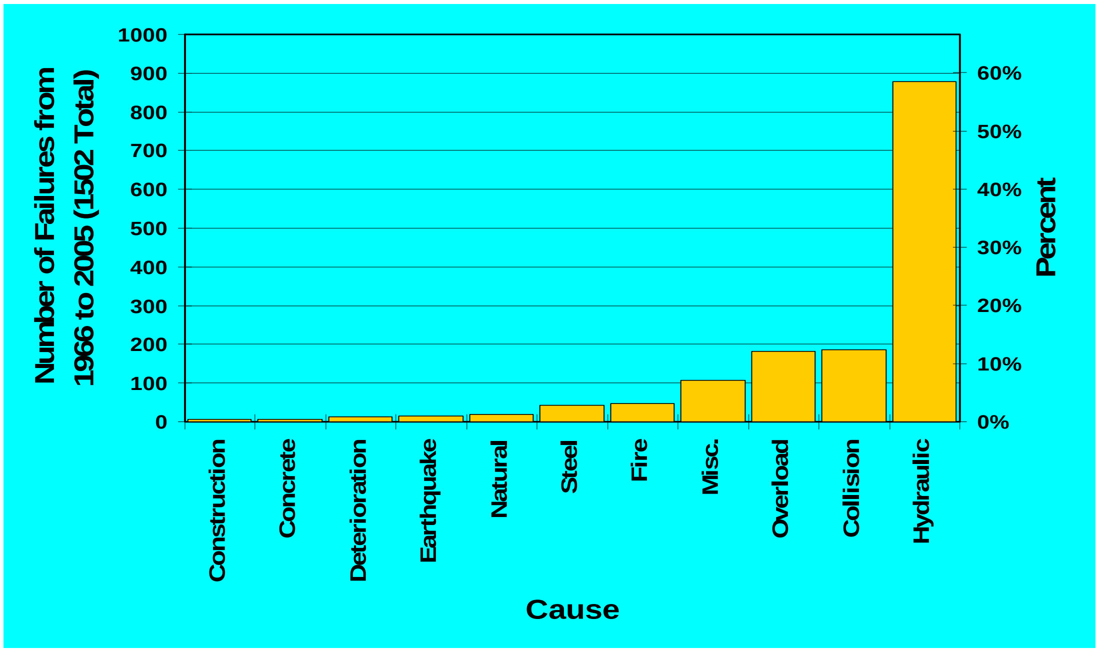


Figure 1-1. Causes of Bridge Failure (1966–2005).

Since hydraulic failure is the number one cause of bridge failure, it is important to predict or monitor scour at bridges before it causes casualties. There are several options to prevent failure of bridges subjected to scour and associated loss of life. They are replacement of the bridge and scour countermeasures. Three main types of scour countermeasures exist: structural, hydraulic, and monitoring countermeasures. Monitoring is usually the least expensive of the three options. It is particularly helpful if the predictions appear to be very conservative but little evidence beyond common sense and engineering judgment exists to prove it. There are three types of scour monitoring: visual monitoring, portable, and fixed instrumentation. Fixed scour monitoring consists of placing an instrument close to the bridge and close to the river bed to record some data for the purpose of warning the engineer when the scour depth becomes excessive. Scour monitors have evolved over the years, yet they are still relatively expensive. There is a need to make scour monitors less expensive and more convenient so monitors can be used on more bridges than is currently the case. At present, there are approximately 700 scour critical bridges in Texas and 26,000 in the U.S. The project is aimed at optimizing monitor selection for bridges for scour and warning the owner of imminent failure so that appropriate action can be taken before exposing the public to undue risk.

APPROACH SELECTED TO SOLVE THE PROBLEM

First, a thorough literature review was conducted by the research team. The existing scour monitoring technology was reviewed and evaluated. The scour monitoring progress in different states was studied and is documented in Chapters 2 and 3.

Second, two large scale laboratory experiments were performed at Texas A&M University. The aim of the laboratory experiments was to study existing scour monitoring methods, develop and test new technologies. The laboratory had the advantage of controlled conditions, so that a desired response of the bridge could be generated and its effect on the designed scour monitoring system could be studied. Chapter 4 presents a detailed description of the two experiments as well as data analysis.

Third, two bridges in Texas were chosen to be instrumented with scour monitoring system as a validation of the findings in the laboratory. US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge were chosen due to scour issue they are facing. The instrumentation, data collection, and monitoring information for both bridges are presented in Chapters 5 and 6.

Fourth, the mechanism of bridge failure was studied and general recommendations on the threshold for a tiltmeter reading was given in Chapter 7. Specific threshold values for tiltmeters are proposed.

Fifth, guidelines for instrument selection and specific protocols for the US59 over Guadalupe River Bridge and the SH80 over San Antonio River Bridge were established and are documented in Chapters 8 and 9. Finally, Chapter 10 presents conclusions and recommendations.

CHAPTER 2:
LITERATURE REVIEW

According to the FHWA guidelines, existing bridges found to be vulnerable to scour, should be monitored and/or have scour countermeasures installed. FHWA's HEC-18 (Richardson and Davis, 2001) first recommended the use of fixed instrumentation and sonic fathometers (depth finders) as scour monitoring countermeasures in their Second Edition (1993). The TRB NCHRP Project 21-3, *Instrumentation for Measuring Scour at Bridge Piers and Abutments* (Lagasse et al., 1997) developed, tested, and evaluated fixed scour monitoring methods both in the laboratory and in the field. The purpose of this project was to study devices that measure and monitor maximum scour at bridges. The NCHRP project extensively tested and recommended two systems—the sonic fathometer and the magnetic sliding collar devices. Each of these fixed instruments measures and monitors scour. Additional fixed scour monitoring systems that were tested under this project included sounding rods and other buried devices. Subsequent to the NCHRP project, additional fixed monitors have been developed and installed—float-out devices, tilt sensors, and Time Domain Reflectometers.

NCHRP Synthesis 396 entitled *Monitoring Scour Critical Bridges* (Hunt, 2009) assessed the state of knowledge and practice for fixed scour monitoring of scour critical bridges. It included a review of the literature and research, and a survey monitoring systems. Table 2-1 summarizes the types of fixed scour monitor instrumentation that are being used in the United States as found in the synthesis survey, as well as advantages and limitations of the devices.

Table 2-1. Fixed Instrumentation Summary.

Type of fixed instrumentation	Best application	Advantages	Limitations
Sonar	Coastal regions	Records infilling; time history; can be built with off the shelf components	Debris, high sediment loading, and air entrainment can interfere with readings
Magnetic sliding collar	Fine bed channels	Simple, mechanical device	Vulnerable to ice and debris impact; only measures maximum scour; unsupported length, binding
Tiltmeters	All	May be installed on the bridge structure and not in the stream-bed and/or underwater	Provides bridge movement data that may or may not be related to scour
Float-out device	Ephemeral channels	Lower cost; ease of installation; buried portions are low maintenance and not affected by debris, ice or vandalism	Does not provide continuous monitoring of scour; battery life
Sounding rods	Coarse bed channels	Simple, mechanical device	Unsupported length, binding, augering
Time domain reflectometers	Riverine ice channels	Robust; resistance to ice, debris, and high flows	Limit on maximum lengths for signal reliability of both cable and scour probe

The different types of fixed scour monitoring instruments are described in the sections that follow. A scour monitoring system at a bridge may be comprised of one or more of these types of devices. Scour monitoring systems are configured uniquely for each bridge under consideration. This occurs because of differences in bridge construction and in hydraulic and environmental influences peculiar to each site.

The various devices are either mounted on the bridge or installed in the streambed or on the banks in the vicinity of the bridge. The scour monitoring device transmits data to a datalogger at its remote unit. The data from any of these fixed instruments may be downloaded manually at the sight, or it can be telemetered to another location. The early scour monitoring devices measured streambed elevations using simple units mounted on-site and read manually. Almost all of the more recent installations use remote technology. Each bridge may have one or more remote sensor units that transmit data to a master unit on or near the bridge. The scour monitoring data are then transmitted from the master unit to a central office and/or posted on the Internet.

The study found that 30 of the 50 states use, or have employed, fixed scour monitoring instrumentation for their highway bridges. A total of 120 bridge sites were identified that have been instrumented with fixed monitors. The five types of fixed instruments being used in 2007 included sonars, float-outs, tilt meters, magnetic sliding collars, and time domain reflectometers.

The site conditions and the types of bridges that were monitored with fixed scour instrumentation varied in many aspects. There were small to long span bridges with lengths ranging from 12.5 m (41 ft) to 3,921 m (12,865 ft). The Average Daily Traffic ranged from 400 to 175,000 vehicles per day, and the bridges were constructed between 1920 and 1986. The site conditions included both riverine and tidal waterways, intermittent to perennial flows, and water depths ranging from less than 3 m (10 ft) to 22.5 m (75 ft). The soil conditions ranged from clay to gravel, and some had riprap protection.

The scour monitors were installed between 1992 and 2007. The earlier installations included sounding rods, magnetic sliding collars, and sonars. More recent installations also include float-outs, tilt sensors, and TDRs. The sonar scour monitoring system is the most commonly used device, installed at 70 of the 120 bridge sites. This was followed by the magnetic sliding collar at 21 sites. The bridge owners reported that 90 percent of the structures monitored with fixed instruments were piers. The remaining devices were on abutments or in the vicinity of the bridge on bulkheads or downstream countermeasure protection.

The survey respondents indicated that high velocity flows, debris, ice forces, sediment loading, and/or low water temperatures were extreme conditions that were present at the monitored bridge sites. The debris and ice forces caused the majority of damage and interference to the scour monitoring systems. They noted that the extent and frequency of the damage was often not anticipated by the bridge owner and this resulted in much higher maintenance and repair costs than anticipated.

The bridge owners provided information on their future needs for improved scour monitoring technology, which include:

- More robust devices – increased reliability and longevity.
- Decreased costs.

- Less maintenance.
- Devices more suitable for larger bridges.
- Devices that measure additional hydraulic variables and/or structural health.

CHAPTER 3:
INSTRUMENT DESCRIPTION

INTRODUCTION

According to the FHWA guidelines, existing bridges found to be vulnerable to scour, should be monitored and/or have scour countermeasures installed. The scour countermeasures are categorized into three general groups: hydraulic, structural, and monitoring. Hydraulic countermeasures include both river training structures that modify the flow and armoring countermeasures that resist erosive flow. Structural countermeasures consist of modifications of the bridge foundation. These may be classified as foundation strengthening or pier geometry modification. Monitoring countermeasures may be fixed instrumentation, portable instrumentation, or visual monitoring. A bridge may have one or more types of scour monitoring techniques that also can be used in combination with other hydraulic or structural scour countermeasures. The fixed instrumentation is the most common countermeasure during the scour monitoring. The fixed instrumentation scour monitors are placed on a bridge structure and take readings that can provide information on scour in the vicinity of the bridge. These instruments either measure streambed elevations or bridge movement in order to detect scour.

This research is the application of fixed instrumentation to monitor bridge scour. In this chapter, all fixed instrumentation applied in the research is introduced. The chapter is organized into 10 sections. Following the introduction, seven instruments are introduced one by one: float-out device, tiltmeter, water stage sensor, sonar sensor, tethered buried switch, accelerometer, and acoustic doppler velocimeter (ADV). For each instrument, the general description is presented, followed by the advantages and disadvantages of the instrument. The product manufacturer and specification is also described. After the eight sections, the data acquisition system and communication system for the bridge scour monitoring during the research is presented respectively. Finally, a summary of the fixed instrumentation is presented.

FLOAT-OUT DEVICE

Description

A float-out device is a cylindrical device to monitor the bridge scour. A typical float-out device is 11.43 cm (4.5 inches) in diameter at the ends and 0.3 m (12 inches) long. The one used in the large scale laboratory experiment is a typical float-out device (Figure 3-1a). The one used in US59 Bridge over Guadalupe River is specifically designed for the project. It is 0.6 m (2 ft) long and 8.9 cm (3.5 inches) in diameter (Figure 3-1b).

The device is installed by burying it vertically into the soil. The internal radio transmitter triggers a signal when the device is in horizontal position. It is an indication that the scour depth has reached a level at which the instrument is buried and now the instrument is in float-out state. The device gives output in the form of two discrete values 0 and 1. The internal radio transmitter will send a value of 0 to the data acquisition system if the float-out device is vertical. The radio transmitter will send a value of 1 to the data acquisition system if the float-out device floats out.

(a) **(b)**

Figure 3-1. Float-Out Device: (a) Used in Laboratory and (b) Used on US59 over Guadalupe River Bridge.

Advantages and Disadvantages

The float-out is easy to operate and is self-contained. This also implies that it has a limited lifespan due to battery life. Its internal battery can stay in standby mode for seven years.

Recent developments have been made to improve the battery life of the float-out to increase its life span. The float-out device gives an estimate of the local scour only. It can show the scour depth only at the location where the device is installed. It does not provide any intermediate indication of the scour depth between the float-out installation depths. The installation process in field requires coring and drilling, which is expensive and not simple.

Product Manufacturer and Specification

Product manufacturer:	ETI
Spread spectrum type:	FHSS (Frequency Hopping Spread Spectrum)
Power output:	100 mW (20 dBm)
Outdoor/RF line-of-sight range:	Up to 20 miles (32 km)
Receiver sensitivity:	−110 dBm (@ 9600 bps)
RF data rate:	9.6 or 19.2 kbps
Interface data rate:	Up to 57.6 kbps
Size (typical):	0.3 m (1 ft) long cylinder with 11.43 cm (4.5 inches) diameter
Output:	Single number: 0,1
Position:	Activated when scoured out

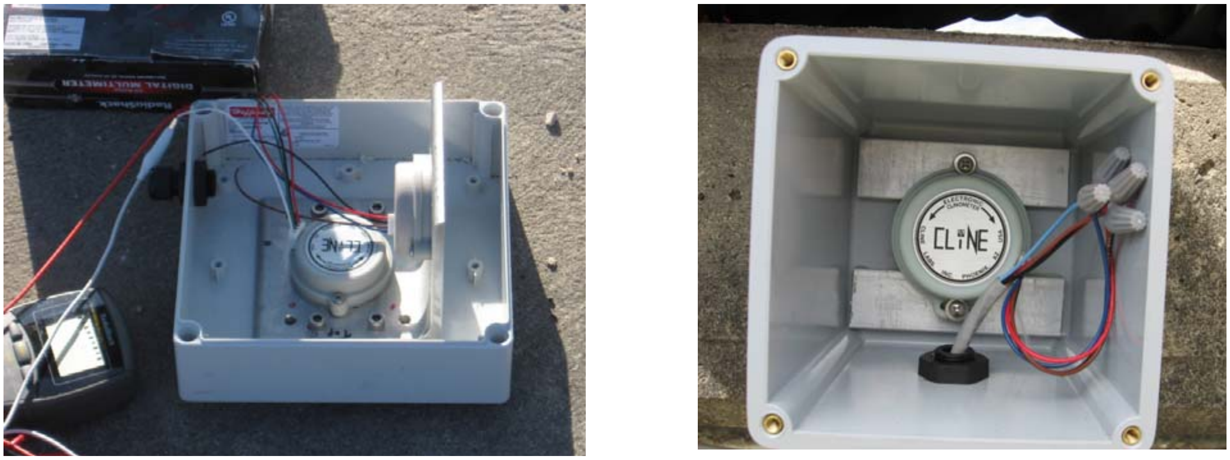
TILTMETER

Description

Tiltmeter, also known as inclinometer or tilt sensor, is used to measure the change in angle of the member it is attached to with respect to a level or an axis. It is hardwired to the data acquisition system. The output is positive if the tiltmeter rotates clockwise (facing the tiltmeter).

Two single-axis tiltmeters are mounted together along the perpendicular axis to form a dual-axis tiltmeter. Figure 3-2 shows the dual-axis tiltmeter used in the laboratory experiment, which measures the tilt angle of the deck around the axis in the two directions (flow direction and traffic direction). Figure 3-3 shows the single-axis and dual-axis tiltmeter installed on the bridges in the field. When the tiltmeter is installed in field, it is important to put the sensor in an enclosure to protect against environmental conditions.

Figure 3-2. Tiltmeter Used in the Laboratory Experiment.



(a)

(b)

Figure 3-3. Tiltmeter Used on SH80 over San Antonio River Bridge: (a) Dual-Axis Tiltmeter and (b) Single-Axis Tiltmeter.

Advantages and Disadvantages

The output of the tiltmeter is simple and easy to interpret. It shows the tilt angle readings directly. The operation of the instrument is reliable and it has low power consumption. The tiltmeter is compact, rugged, lightweight, and is easy to integrate mechanically. The key issue during the installation is to make sure that the tiltmeter is set to a level reading with respect to which the change in angle is measured. The disadvantage is that it does not give a direct measure of the scour depth.

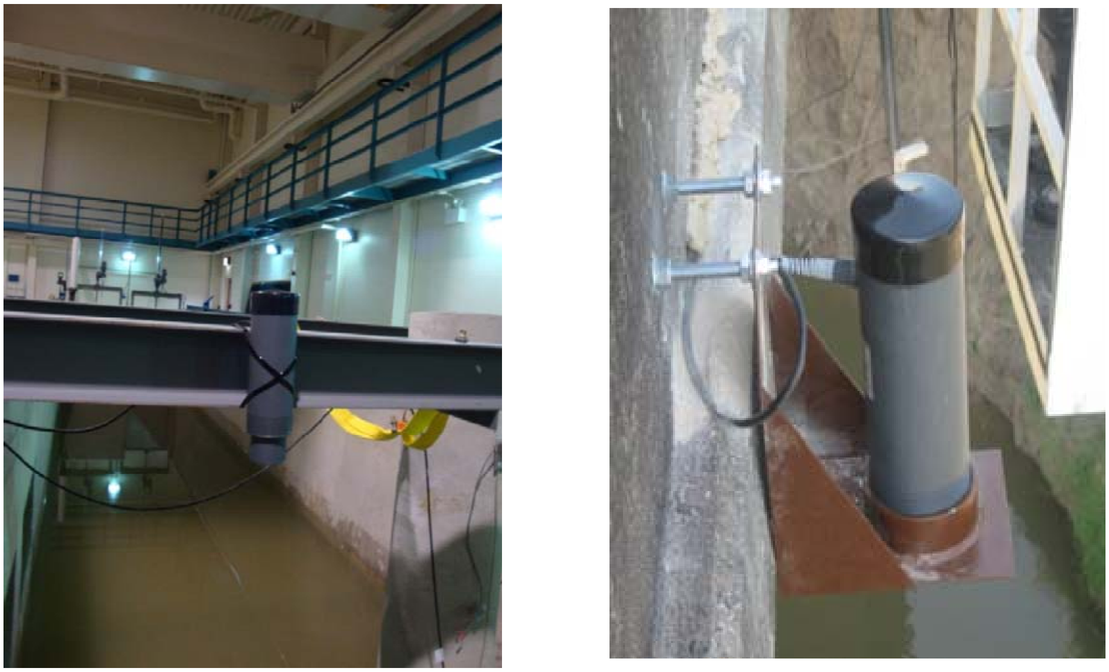
Product Manufacturer and Specification

Product manufacturer:	Cline Labs Inc.
Range:	±60°
Resolution:	0.001°
Linearity:	From 0 to 10°, is ±0.1°
	From 10 to 45°, is ±1% of angle
	From 45 to 60°, is monotonic
Operating temperature:	−40°C to +85°C (−40°F to +185°F)
Outer diameter:	67.92 mm (2.674 inches)
Thickness:	19.69 mm (0.775 inches)
Unit:	°

WATER STAGE SENSOR

Description

A water stage sensor is an ultrasonic distance finder, aimed from a fixed reference (e.g., from the side of the bridge deck) to the water surface. The water stage sensor is hardwired to the data acquisition system and measures the distance from its mounting on the bridge to the water surface. Occasionally in the field, the water stage sensor is used to directly indicate the water surface elevation by subtracting the measured distance of the sensor transducer to the water surface from the known elevation of the transducer. The water stage sensor is installed so that it has a minimum deviation from vertical axis. Figure 3-4a shows the water stage sensor used in the laboratory. In field, the stage sensor is mounted using a fixing bracket (Figure 3-4b).



(a) (b)

Figure 3-4. Water Stage Sensor: (a) Used in Laboratory and (b) Used on US59 over Guadalupe River Bridge.

Advantages and Disadvantages

The water stage sensor gives the indication of the water level. It requires initial leveling for installation because any tilt in the instrument will affect the readings. Frequent checks are required during the monitoring process since the sensor can easily be affected by the environment.

Product Manufacturer and Specification

Product manufacturer:	APG
Model:	APG Model DCU-1104
Operating range:	0.6 m to 15 m (2 ft to 50 ft)
Outputs:	4 to 20 mA
Resolution:	2.54 mm (0.1 inch)
Accuracy:	0.25% of range with no temperature gradient
Beam Pattern:	9° off axis
Sample rate:	Programmable 0.120 to 1 second

Size: 89 mm (3.5 inches) diameter by 330 mm (13 inches) in length

Unit: ft

SONAR SENSOR

Description

The sonar sensor operates by releasing a sonic pulse from an emitter, which then travels until it is reflected back due to the change in medium such as at the interfaces of air/water, soil/water, etc. It then reflects back to a receiver, which is usually mounted alongside the emitter. The time taken for the signal to propagate from the emitter to the receiver in combination with the material properties gives an estimate of the distance from the emitter to the interface of the two mediums. Sonar is manufactured in both portable and fixed forms. Figure 3-5 shows the sonar sensor used in the laboratory.

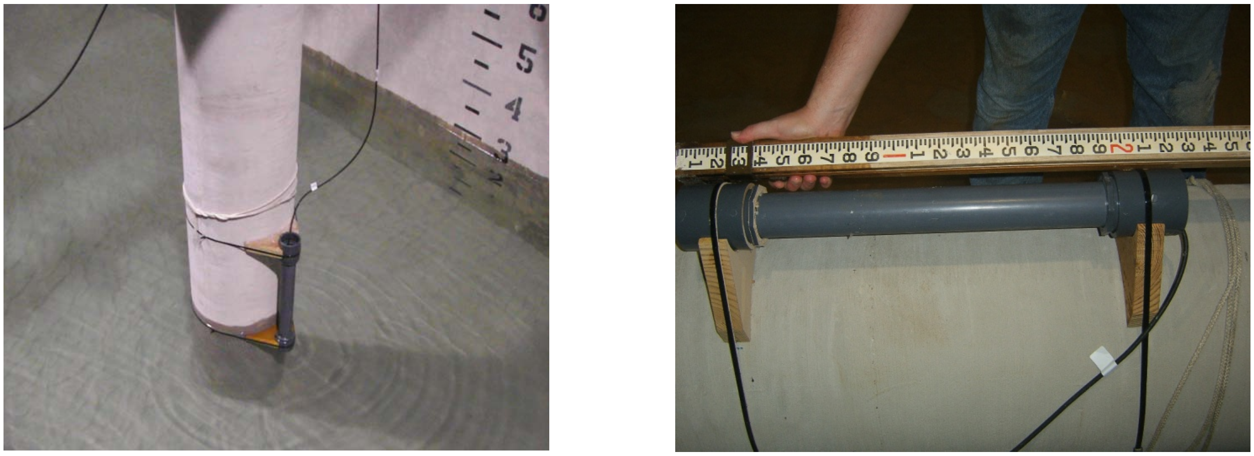

(a) (b)

Figure 3-5. Sonar Sensor Used in Laboratory: (a) Sonar Sensor Is Working and (b) Measure of Sonar Sensor.

Advantages and Disadvantages

Portable sonar is a useful bridge inspection tool. It does not provide a continuous data record for the soil erosion. Fixed sonar sensor can provide continuous data record for the soil erosion, so fixed sonar sensor is used in this project. Even though the fixed sonar sensor has an advantage of providing complete data record, it also has some limitations. First, it is accurate only within given depth tolerances. Too shallow installation of a sonar unit or too short resolution distance between sonar head and medium interface will result in useless data. Second, sonar is generally accurate only within a narrow area. Side scan sonar can be used to build a complete channel profile, but it is expensive and thus unsuited for long periods of installation. If a sonar unit is not mounted properly above the deepest point at which the scour hole is developing, it will give a false sense of security about the development of scour. Third, sonar is a below waterline instrument; if the channel is subject to debris loading, the sonar will be exposed to debris and can be destroyed. The sonar instruments are nontrivial purchases, so their destruction should be avoided if possible.

Product Manufacturer and Specification

Product manufacturer:	ETI
Type:	Piezzoflex ultrasonic
Electronics:	Embedded signal processing
Transducer beam:	8°
Signal output:	NMEA-0183@4800 baud Sentence – DDBT
Data rate:	1 Hz
Operating frequency:	235 kHz
Minimum depth:	0.6 m (2 ft)
Max depth:	100 m (333 ft)
Supply voltage:	11.8 to 28 volts DC
Supply current:	45 mA
Cable length:	20 m (66 ft)
Housing:	Stainless steel with threaded stem
Size:	69.85 mm × 82.55 mm (2.75 inches × 3.25 inches) including threaded stem
Cable connection:	Shield – ground Blue – + 12 volts Black – signal output

TETHERED BURIED SWITCH

Description

The tethered buried switch (TBS) is a type of float-out device, which is buried into the soil vertically in order to give an indication of the development of the scour around the bridge foundation. It consists of one 0.3 m (1 ft) long hollow aluminum rod containing an electrical switch (Figure 3-6). It is hardwired to the data acquisition system. The electrical switch triggers when the rod turns from the vertical to the horizontal position. It is caused by the hydraulic drag during the flood as the scour depth reaches the instrument buried level. It has three discrete values of 1, 2, and 3, corresponding to the three working states of the instrument. If the TBS is in the vertical position and the trigger has not been launched, the sensor will transmit a value of 1. If the switch is triggered and the scour reaches the buried level of the instrument, the sensor will transmit a value of 2. If the wire of the switch is broken, the sensor will transmit a value of 3. Figure 3-6 shows the TBS used in the laboratory, while Figure 3-7 shows the TBS used on US59 over Guadalupe River Bridge. The TBS used in the field is covered by a PVC pipe.

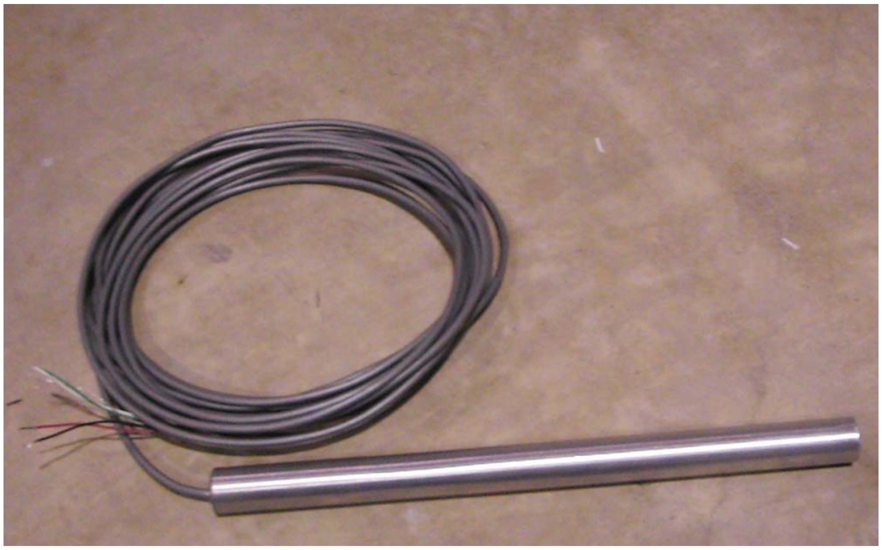


Figure 3-6. TBS Used in the Laboratory.

Figure 3-7. TBS Used on US59 over Guadalupe River Bridge.

Advantages and Disadvantages

The TBS gives a direct and simple indication of the scour depth. TBS is simple, easy to install, inexpensive, and has an infinite lifespan as it is connected to the data acquisition system through a wire. The wire, however, is a drawback as the specific protection should be taken to avoid vandalism or damage due to debris. Another limitation is that the TBS sensor is only able to give an output for the scour up to the depth of embedment of the instrument. It only provides localized information about the scour.

Product Manufacturer and Specification

Product manufacture:	ETI
Size:	0.3 m (1 ft) long
Output:	Single number: 1, 2, 3
Position:	Activated when scoured out

ACCELEROMETER

Description

The accelerometer, also known as motion sensor, is used to measure the acceleration of the member it is attached to in three directions. In the field, the sampling rate of accelerometer is 80 Hz. The data are transmitted to the data acquisition system through RS232 connection or a wireless connection. In this project, both hardwired accelerometer and wireless accelerometer are used. The accelerometer data can be analyzed by a Fast Fourier Transform (FFT) to obtain the natural frequency of the bridge system, which shows great potential in the prediction of bridge scour. Figure 3-8 shows the circuit board of accelerometer. Figure 3-9 shows the hardwired accelerometer installed on US59 over Guadalupe River Bridge.

Figure 3-8. Circuit Board of Accelerometer.

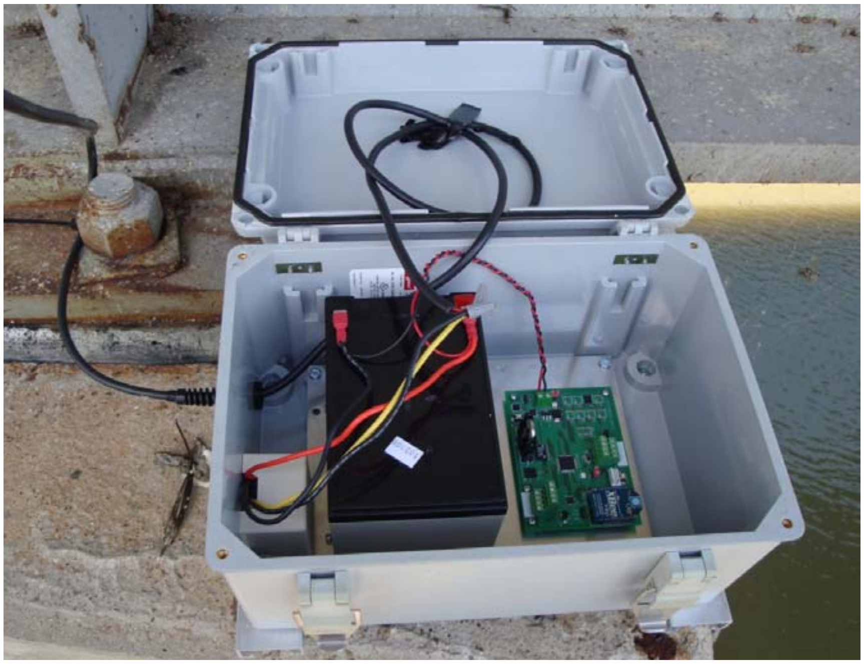


Figure 3-9. Hardwired Accelerometer on US59 over Guadalupe River Bridge.

Advantages and Disadvantages

The accelerometer gives the integrated response of the bridge. It is easy to install. The deflection and rotation of the bridge can be obtained by integrating the measured acceleration data. The shortcoming is that it requires a lot of power to transmit the required large volume of data from the master station via cellular modem.

Product Manufacturer and Specification

Product manufacturer:	ST Microelectronics
Model:	ST Microelectronics Model LIS3LV02DQ
Description:	The LIS3LV02DQ is a three-axis digital output linear accelerometer that includes a sensing element and an IC interface able to take the information from the sensing element and to provide the measured acceleration signals to the external world through an I2C/SPI serial interface.
Range:	$\pm 2g$
Operating temperature:	−40°C to +85°C (−40°F to +185°F)
Calibration factor:	2/32768
Unit:	Acceleration of gravity (g)

ACOUSTIC DOPPLER VELOCIMETER

Description

An acoustic doppler velocimeter device is designed to record instantaneous velocity components at a single point. It has three acoustic receivers and can measure the velocity in three dimensions in remote sampling volume with 6 mm (0.24 inch) diameter and 9 mm (0.35 inch) height. The ADV used in the laboratory (Figure 3-10) is provided by Haynes Coastal Engineering Laboratory and has a sampling rate of 1 Hz. In the laboratory, a two-dimensional ADV is used to record the water velocity flowing in the flume as well as across the channel during the experiment. It provides the hydrograph for the test flume during the experiment.

Figure 3-10. Acoustic Doppler Velocimeter Used in Laboratory.

Advantages and Disadvantages

ADV is easy to install, but it is easily affected by the installation position. It is unsuitable for field use, because it is a delicate instrument that can be damaged by negligent handling or debris flowing in a river.

Product Manufacturer and Specification

Product manufacturer:	SonTek/YSI Incorporated
Sampling Rate	0.1 to 50 Hz
Distance to Sampling Volume	50 mm (2 inches)
Resolution	0.1 mm/s (3.93×10^{-3} inch/s)
Programmed Velocity Range	30, 100, 300, 1000, 2500 mm/s (1.18, 3.94, 11.8, 39.4, 98.4 inch/s)
Accuracy	1% of measured velocity, 2.5 mm/s (0.1 inch/s)
Maximum Depth	60 m (200 ft)
Input Power	12–24 VDC
Typical Power Consumption	2.5 to 4.0 W Operating | <1mW Sleep

DATA ACQUISITION SYSTEM

Description

The data acquisition system receives the readings from the instruments and then stores and transmits the data via communication or data storage peripherals. The data acquisition system used in this project is a CR1000 datalogger from Campbell Scientific Inc. (Figure 3-11). It is designed for standalone operation in harsh, remote environments. The CR1000 is compatible with nearly every available sensor. In the field, solar panels are used to power the data acquisition system (Figure 3-12).

All the sensors transmit the data to the datalogger through a cable or wireless connection in a fixed time interval. After the data are stored in the datalogger, the data can be retrieved through software such as LoggerNet using remote connection.

Figure 3-11. CR1000 Datalogger from Campbell Scientific Inc.

Figure 3-12. Solar Panel near the Data Acquisition System on the Bridge.

Advantages and Disadvantages

The datalogger is a reliable system. It is rugged so that it can sustain the extreme environmental conditions and be operational. It is also robust for complex configurations required by the current project. The CR1000's low power consumption allows it to operate for extended time periods on a battery charged with a solar panel, thus eliminating the need for AC power supply. This datalogger suspends execution when the primary voltage drops below 9.6 V, reducing the possibility of inaccurate measurements.

Product Manufacturer and Specification

Product manufacturer:	Campbell Scientific Inc.
Mode:	Campbell Scientific CR 1000
Current Drain:	~0.6 mA (sleep mode), 1 to 16 mA (w/o RS-232 communications), 17 to 28 mA (w/RS-232 communications)
A/D Bits:	13
Scan Rate:	100 Hz
Analog Channels:	16 single-ended (8 differential), individually configured
Analog Voltage Range:	± 5000 mV

Analog Voltage Accuracy: ± (0.06% of reading + offset), 0°C to 40°C (32°F to +104°F)
Measurement Resolution: to 0.33 µV
Switched Excitation Channels: 3 voltage
Pulse Counters: 2
Control Ports: 8
Memory: 2 MB Flash (operating system), 4 MB (CPU usage, program storage, and data storage)
Communication Ports: 1 RS-232, 1 CS I/O, 1 Parallel Peripheral
Protocols Supported: PakBus, Modbus, DNP3, FTP, HTTP, XML, POP3, SMTP, Telnet, NTCIP, NTP, SDI-12, SDM
Weight: 0.945 kg (2.1 lb)
Dimensions: 215 mm × 100 mm × 22 mm (8.5 inches × 3.9 inches × 0.85 inches)
Operating Temperature Range: −25°C to +50°C (−13°F to +122°F), Standard
−55°C to +85°C (−67°F to +185°F), Extended

COMMUNICATION SYSTEM

Description

The communication system in this project refers to the cell phone modem, LoggerNet Software, and the computer server. The aim is to set up the connection between the instruments located either in the laboratory or on the bridge with the computer server.

In the field, the system is equipped with a Raven X Airlink digital cellular data modem that is accessed through its IP address (Figure 3-13). Campbell Scientific LoggerNet software provides the required interface to communicate with the system to download the sensor data.

Figure 3-13. Raven X Airlink Cellular Modem.

The server at Texas A&M University hosts a webpage to show the real-time monitored data for the two bridges, which allows a view of the data by typing the link in the internet browser: http://scour.civil.tamu.edu.

Advantages and Disadvantages

The Raven X Airlink cellular modem is rugged and reliable for use in the extreme environmental conditions. The data stream relies on the service of the carrier.

Product Manufacturer and Specification

For Raven X Airlink cellular modem:

Product manufacturer:	Campbell Scientific Inc.
Band:	800 MHz Cellular, 1900 MHz PCS
Transmit Power:	200 mW max
RS-232 Data Rates:	1200 bps to 230.4 kbps
Input Voltage:	9 to 28 Vdc
Input Current:	85 to 270 mA
Operating Temperature Range:	−30°C to +70°C (−22°F to +158°F) (10% duty cycle limit above 60°C (140°F)
Operating Humidity:	5% to 95% non-condensing

Serial Interface:	RS-232, DB9-F
Ethernet Interface:	10/100 Mbps RJ-45
Dimensions:	116 mm × 35 mm × 63 mm (4.6 inches × 1.4 inches × 2.5 inches)
Weight:	<0.5 kg (<1 lb)

CONCLUSION

The fixed instrumentation is the most commonly used countermeasure in scour monitoring. Each monitor has its advantages and disadvantages, therefore, the proper instruments have to be selected for the scour monitoring. The proper working environment is very crucial for instruments under harsh conditions.

CHAPTER 4:
LARGE SCALE LABORATORY EXPERIMENTS

INTRODUCTION

The aim of this research is to develop a scour monitoring system for bridges facing scour problem. Therefore, laboratory experiments are designed to study the existing technology and to develop and test new technology. The laboratory experiment under controlled conditions allows a simulation of a bridge failure due to scour and a test of the scour monitoring system.

The goal for the large scale laboratory experiment was to (1) evaluate existing technology, (2) identify improvements in the existing technology, (3) explore potential problems that might be encountered in field, (4) develop and evaluate new scour monitoring technology, (5) obtain guidelines for the field test, and (6) evaluate scour prediction methods based on the scour monitoring system.

The large scale laboratory experiments were performed in the Haynes Coastal Engineering Laboratory located at Texas A&M University. The scour primarily affects the foundation and abutments of the bridge. Shallow and deep foundations are the most widely used foundation types for bridges. The effect of scour on these two foundation types was studied in the laboratory experiments.

During the laboratory experiments, the water velocity varied to develop scour. The response was monitored using instruments such as accelerometer, tiltmeter, sonar sensor, water stage sensor, and float-out device. The monitored response of the bridge systems was evaluated to study the variation in response with the scour development.

This chapter is organized into seven sections. Following the introduction, the details of the large scale experiment facility at Haynes Coastal Engineering Laboratory are presented. Second, various experiments performed to obtain the soil properties are given. Third, the shallow foundation experiment is discussed. The fourth section details the deep foundation experiment. The fifth section discusses the finite element simulations of the shallow and deep foundation experiments. In the sixth section, the online data monitoring system using the website is presented. Finally, conclusions obtained from the large scale laboratory experiments are presented.

Laboratory Facility

The experiments were performed at the Haynes Coastal Engineering Laboratory, which houses one of the largest and most modern flumes as well as a towing tank and a three-dimensional wave basin. The towing tank has dimensions of 45 m (150 ft) long, 3.6 m (12 ft) wide, and 3.3 m (11 ft) deep with a designed flow rate of 2.2 m^3/s (35,000 gallon per minute). In the towing tank, there is a sediment pit that is 9 m (30 ft) long, 3.6 m (12 ft) wide, and 1.5 m (5 ft) deep. It is located about two thirds of the way down the tank from the flow inlet end to allow scour studies. The pit can be open or closed by steel plates. A carriage on the top of the flume is used to mount instruments and setup experiments. The carriage is controlled by a computer so the position and speed can be precisely controlled. Figure 4-1 shows the schematic of the towing tank. Figure 4-2 shows the tank and the carriage.

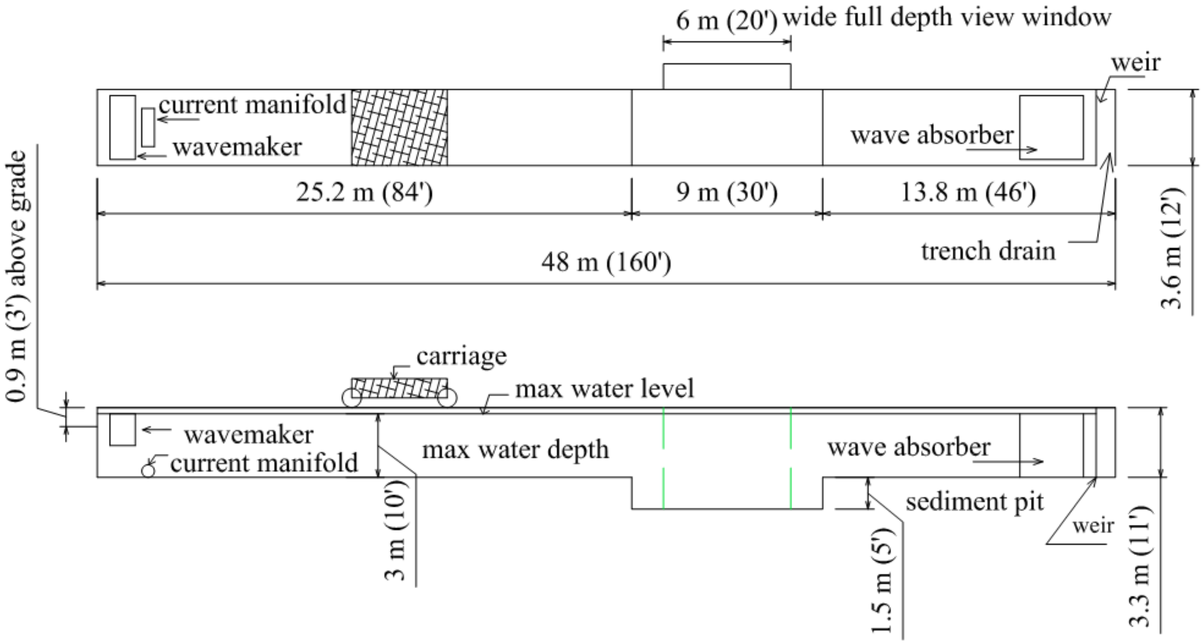


Figure 4-1. Schematic of the Towing Tank.

(a) (b)

Figure 4-2. Haynes Coastal Engineering Laboratory: (a) the Carriage and (b) View of the Tank.

SOIL PROPERTY

The soil used in the laboratory experiments is fine, clean, and uniform silica sand. A series of soil property tests were conducted to estimate the various properties of the sand. These properties are required for the soil prediction and numerical simulation.

Sieve Analysis

Sieve analysis on the sand was performed as per ASTM standards on October 8, 2008. The total mass of the sand was 748.79 g (1.65 lb), passing through a set of sieves (No. 4, No. 10, No. 40, No. 80, No. 200) and the pan. The mass of the bowl was 277.47 g (0.61 lb), and the combined mass of the bowl and the sand was 1026.26 g (2.26 lb). The sieve analysis result is shown in Table 4-1. Figure 4-3 shows the gradation curve.

Table 4-1. Sieve Analysis Result of the Sand.

Sieve no.	Sieve opening	Mass of sieve	Mass of sieve and sand remaining	Sand remaining	Percentage of remaining sand	Percentage passed
	(mm) (inch)	(g) (lb)	(g) (lb)	(g) (lb)	(%)	(%)
4	4.750 (0.187)	514.93 (1.135)	514.94 (1.135)	0.01 (2.2×10^{-5})	0.001	99.990
10	2.000 (0.0787)	484.45 (1.068)	484.64 (1.068)	0.19 (0.0042)	0.025	99.970
40	0.425 (0.0167)	381.22 (0.840)	433.22 (0.955)	52.00 (0.115)	6.940	93.030
80	0.180 (0.0071)	351.26 (0.774)	938.56 (2.069)	587.30 (1.295)	78.400	14.760
200	0.075 (0.003)	341.73 (0.753)	449.99 (0.992)	108.26 (0.239)	14.460	0.520
Pan	0.000 (0.000)	377.33 (0.832)	381.24 (0.840)	3.91 (0.0086)	0.520	0.000

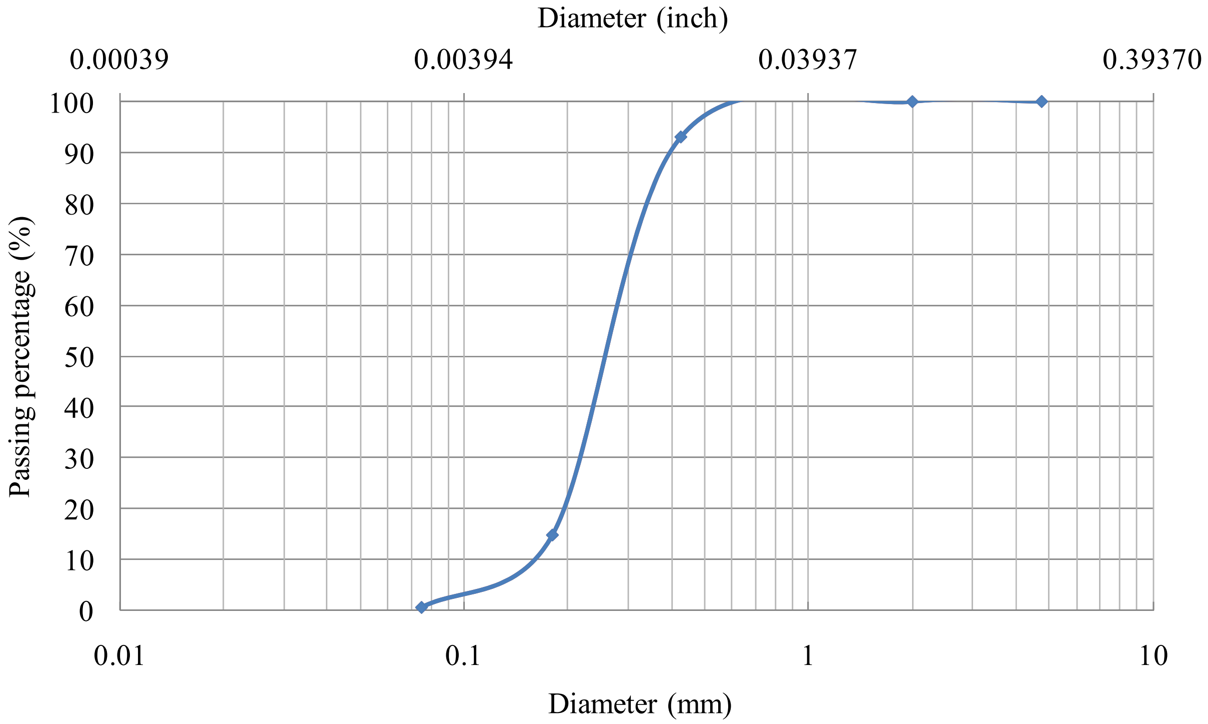
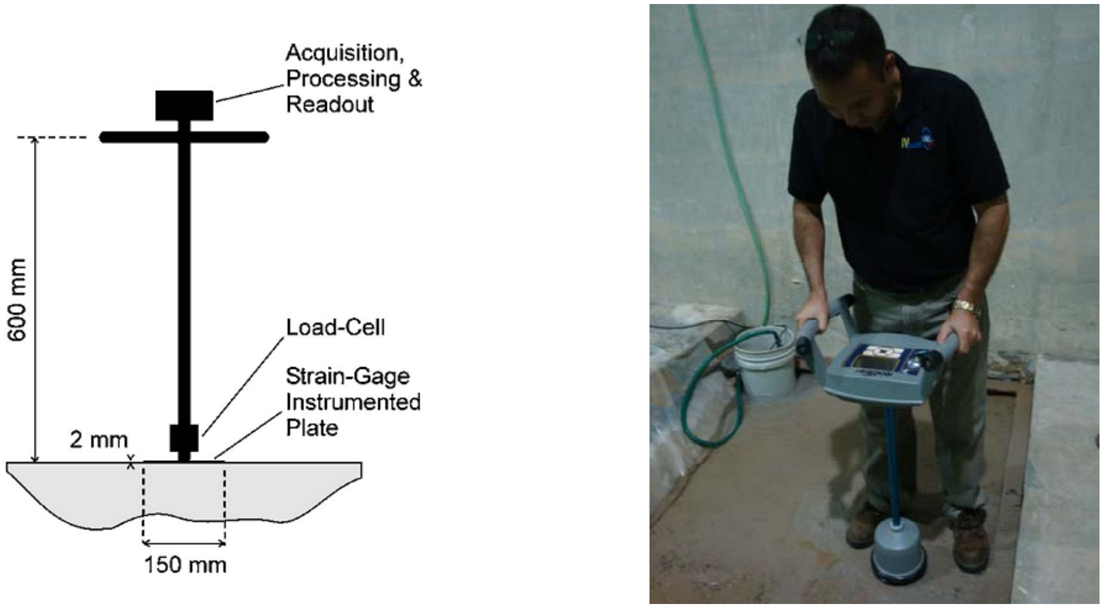


Figure 4-3. Gradation Curve of the Sand.

The test results showed that the D50 of the silica sand was 0.26 mm (0.01 inch), and the sand was uniform. The percent passing No. 200 sieve was 0.5 percent, and the largest particles were less than 0.6 mm (0.024 inch) in diameter.

Briaud Compaction Device Test

The Briaud Compaction Device (BCD) test was performed on the sand to obtain Young's Modulus. The BCD is a new instrument used to measure the Young's Modulus of the soil in only a few seconds. The working principle of the BCD is as follows. The load is applied on a rod by pressuring it downwards. The end of the rod is equipped with a thin circular metal plate, where eight electrical strain gages are installed to measure the bending of the plate. Young's Modulus of soil is obtained by applying a standard load of 223 N (50 lb) to the plate slowly and measuring the bending of the plate. Figure 4-4a shows the schematic of the BCD, while Figure 4-4b shows the BCD test performed on silica sand in Haynes Coastal Engineering Laboratory.



(a) **(b)**

Figure 4-4. Briaud Compaction Device: (a) Schematic of BCD and (b) BCD Test on Silica Sand in Laboratory.

In the experiment, five points were selected on the soil bed, and three readings were taken at each of these points using the BCD. The readings at each point were averaged to obtain the value of Young's Modulus of the sand. Figure 4-5 shows the profile of the measured Young's Modulus of the soil over the bed. An average performed on the entire results gave a value of 12 MPa (1740 psi). This value was used as an overall estimate of the Young's Modulus of the sand. The result was used in the numerical simulations to generate an accurate model of the sand used in the laboratory.

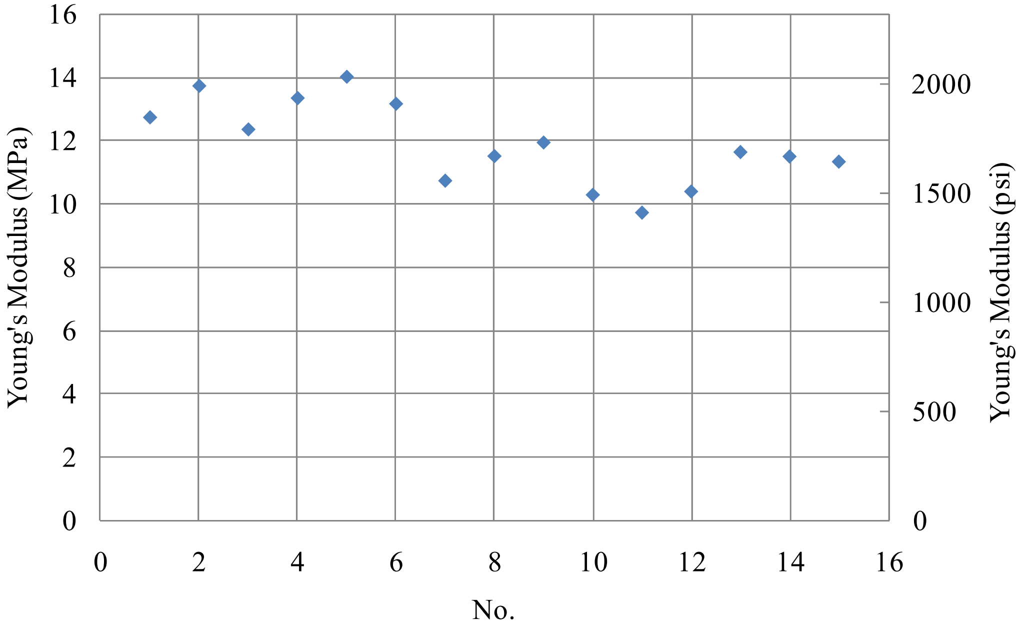


Figure 4-5. Young's Modulus of Silica Sand.

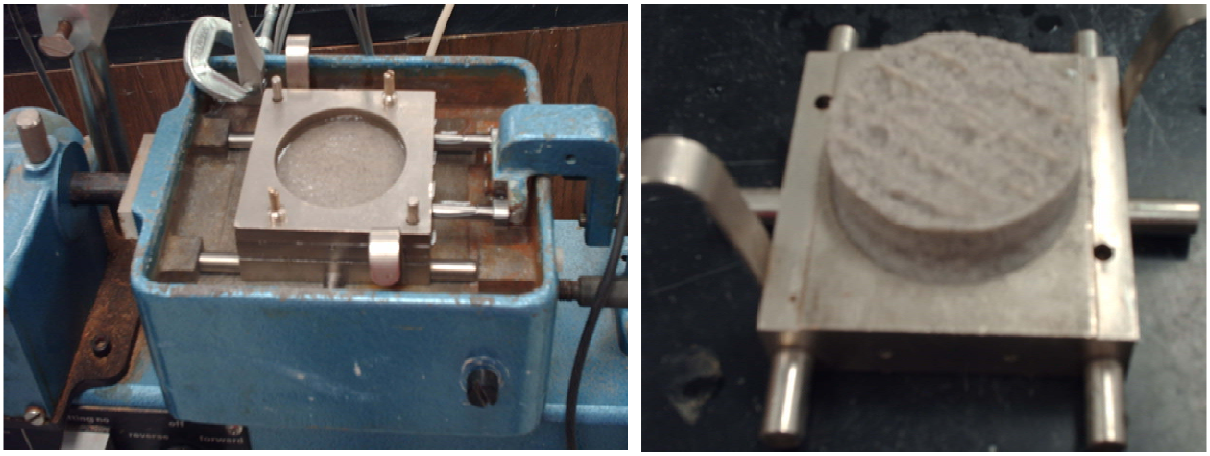
A standard mold was used to obtain the unit weight of the sand. The unit weight of the sand was 18.9 kN/m^3 (3,690 lb/ft^3). The standard test to obtain the water content of the sand gave the value of 23.9 percent. Figure 4-6 shows the sand before and after oven drying.

(a) **(b)**

Figure 4-6. Soil Sample: (a) before Oven Drying and (b) after Oven Drying.

Direct Shear Test

The direct shear test as per ASTM D3080-04 standard was performed to find the friction angle and dilation properties of the sand based on an assumed natural deposition. The direct shear test gave a friction angle of 32.62 degrees for the silica sand. Figure 4-7 shows the soil sample before and after direct shear test was performed.



(a) **(b)**

Figure 4-7. Saturated Sand: (a) in the Shear Box and (b) after Shearing.

Erosion Function Apparatus Test

The Erosion Function Apparatus (EFA) was designed by Dr. Jean-Louis Briaud to estimate the erodibility of soil. Figure 4-8 shows a picture of the EFA. EFA test results for the silica sand are presented in Figure 4-9 and Figure 4-10. Figure 4-9 shows the relationship between erosion rate and shear stress of the sand, while Figure 4-10 shows the relationship between erosion rate and water velocity during the test. The critical velocity for the sand obtained from the EFA was 0.2 m/s (0.65 ft/s). The critical velocity was used in the SRICOS-EFA, which was developed by Dr. Jean-Louis Briaud, to simulate and predict the scour for the laboratory experiments.

Figure 4-8. Erosion Function Apparatus.

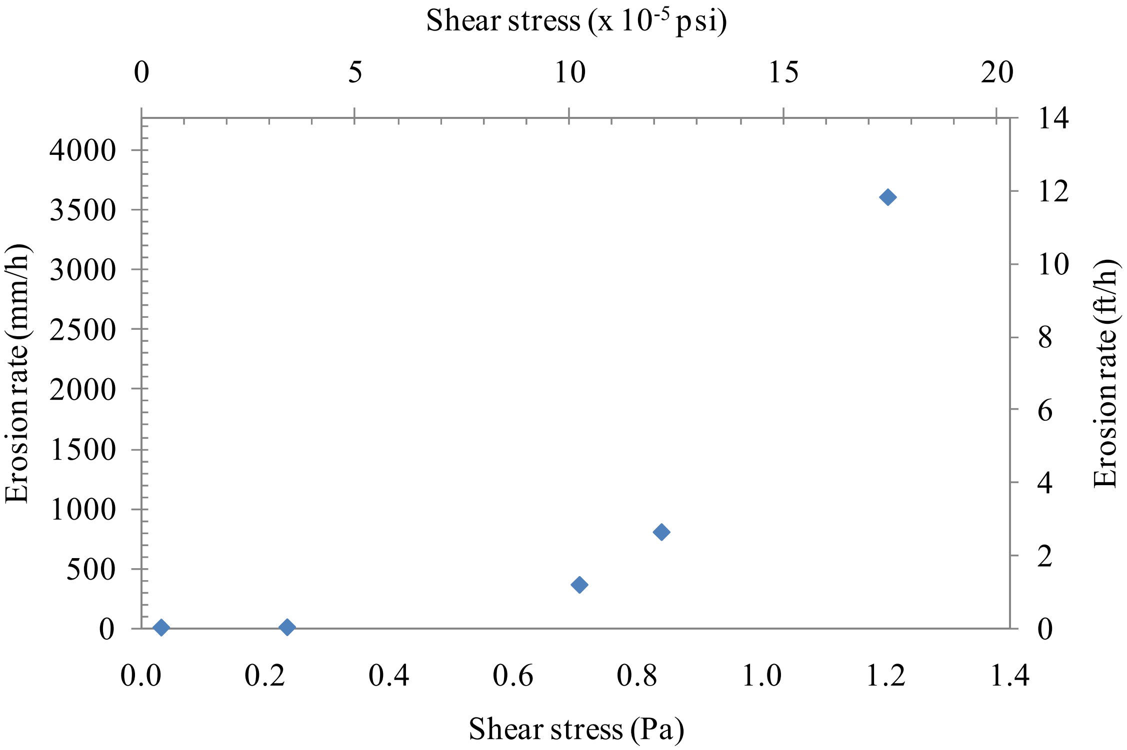


Figure 4-9. Erosion Rate vs. Shear Stress for the Sand.

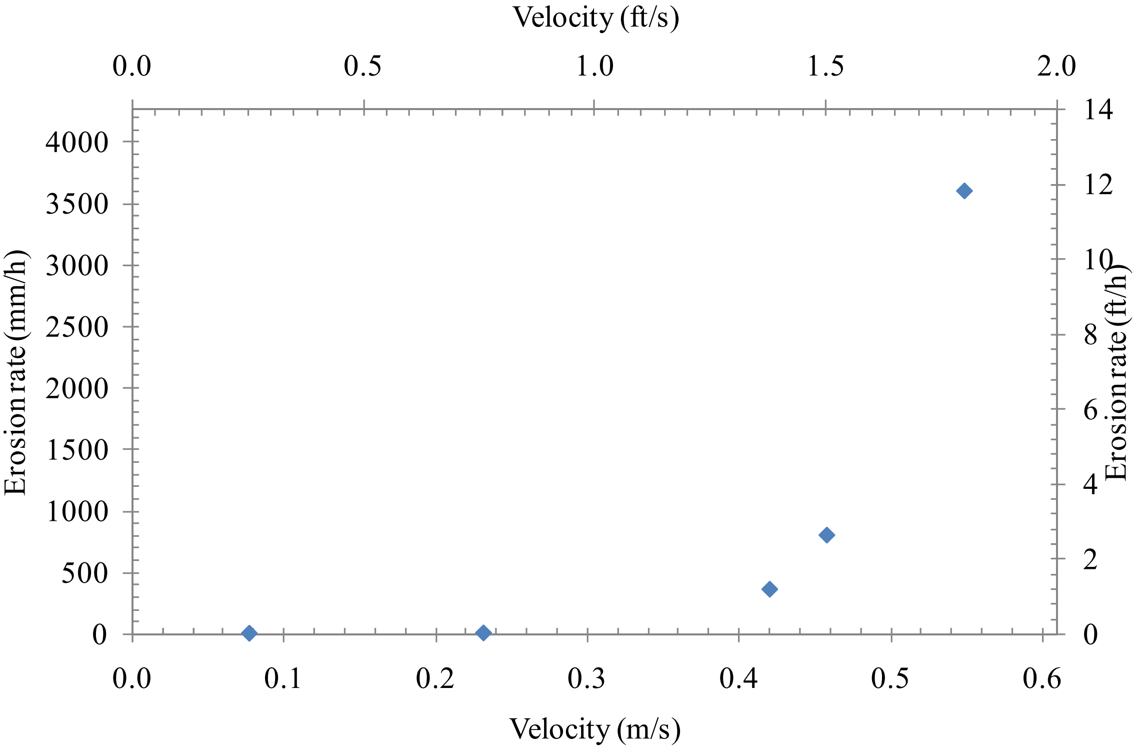


Figure 4-10. Erosion Rate vs. Velocity for the Sand.

SHALLOW FOUNDATION EXPERIMENT

The bridges susceptible to scour have different types of foundations. The most widely used foundations are shallow and deep foundations. The laboratory experiments are designed to study the effect of scour on these two foundation types. A model of the bridge with a shallow foundation was used for the first laboratory experiment. The laboratory experiment on the shallow foundation was performed on November 7, 2008. The model bridge was subjected to growth of progressive scour by increasing the water velocity in the flume. The installed instruments measured the response of the model bridge. The data were analyzed to study the change in response of the model bridge with the shallow foundation to indicate the growth of scour. The following sections describe the prefabrication of the model bridge, the experimental setup, installation of the instruments, and experimental procedure. After that the data analysis of the obtained result and discussion of the results are presented.

Prefabrication of the Model Bridge with Shallow Foundation

The column (pier) and the two slabs (decks) for the model bridge with the shallow foundation were prefabricated. The dimensions of the model bridge were selected to be as large as possible considering the geometry of the flume in the laboratory. The column was 4 m (13.1 ft) long, with a diameter of 0.45 m (1.5 ft). The slab was 2.03 m (6.75 ft) long, 0.53 m (1.75 ft) wide, and 0.10 m (4 inches) thick. During the experiment, the slab was hit by an impact hammer to simulate the effect of the moving traffic. Five excitation points were marked on one of the slabs as shown in Figure 4-11. Figure 4-12 shows the top view and the elevation of the model bridge with the shallow foundation used in the laboratory experiment.

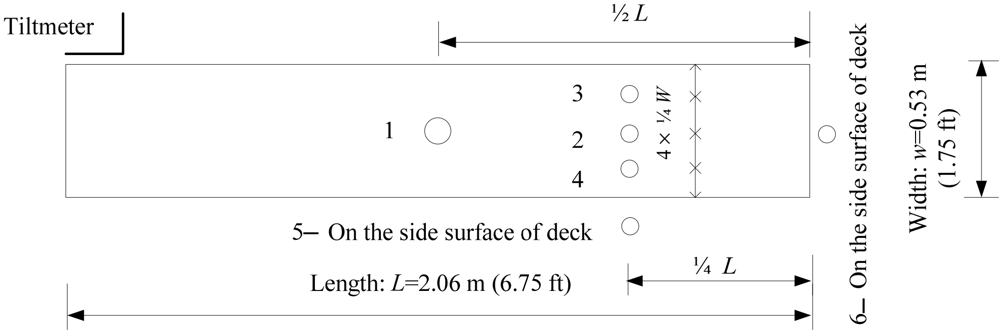


Figure 4-11. Plan View of Bridge Deck and Excitation Points.

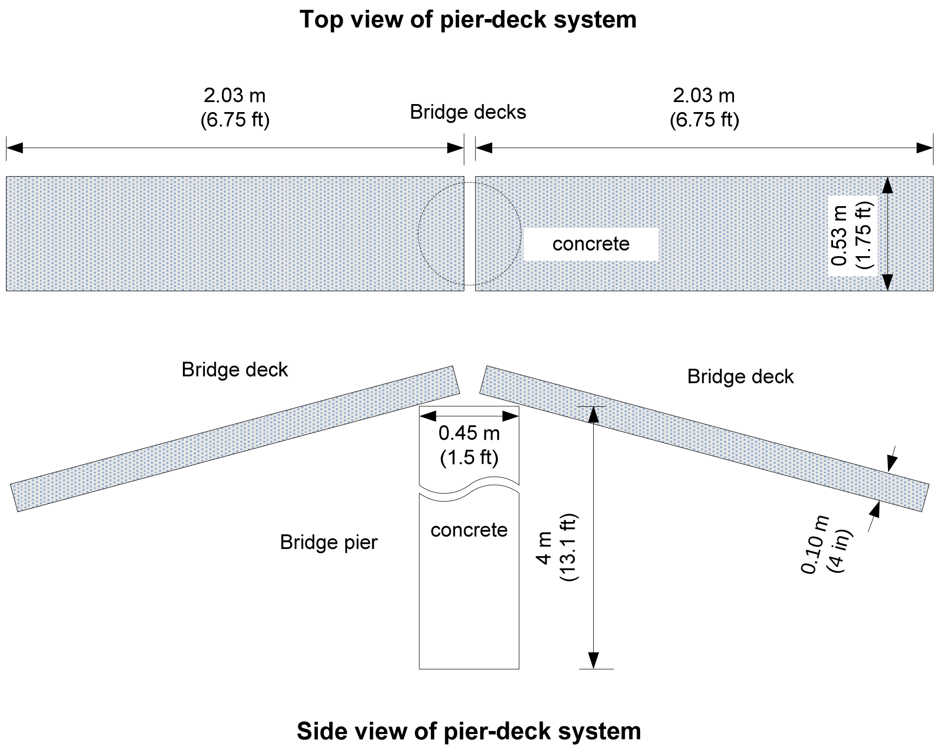


Figure 4-12. Model Bridge with Shallow Foundation.

Experimental Setup

The soil consisting of fine, clean, and uniform silica was placed and compacted in the pit of the flume. Then the concrete column was embedded to a depth of 0.3 m (1 ft) in the sand. After that, the two prefabricated concrete slabs were placed end to end on top of the column. This placement was followed to model a bridge with a shallow foundation. Figure 4-13 shows the step by step installation of the model bridge in the flume of the laboratory.

(a) **(b)** **(c)**

Figure 4-13. Experiment Setup: (a) Dig a Hole in the Sand, (b) Bury the Column 0.3 m, (1 ft) Deep, and (c) Place the Slabs.

Installation of the Instruments

The scour monitoring system installed on the model bridge consisted of instruments to collect the response of the model bridge with the shallow foundation. The instruments installed in the laboratory experiment were: (1) accelerometer, (2) dual-axis tiltmeter, (3) float-out device, (4) sonar sensor, (5) water stage, and (6) ADV.

A datalogger (CR1000) was used to collect the data and transfer it through a RS232 interface to a server located at Texas A&M University. The installation of the instruments on the model bridge and data collection was as follows:

- Mounted on the side of the column, the accelerometer measured the acceleration in three directions at a sampling rate of 124 Hz.
- The dual-axis tiltmeter was fixed on the side of slab and measured the tilt angle of the slab around the flow direction axis and the tilt angle of the slab around the traffic direction axis.
- The float-out device was installed just beneath the sand and had a dimension of 0.3 m (1 ft) length and 0.11 m (4.5 inches) diameter. It gave direct estimation of the scour hole and was wireless. The data were directly collected in the datalogger. The device would float out when the scour hole was 0.3 m (1ft) deep during the experiment.

- The sonar sensor was mounted on the column at a distance of 0.75 m (2.5 ft) from the bottom of the sensor to the top of sand. The performance of the sensor can be affected by water turbulence and soil suspension.
- The water stage sensor was attached to the steel beam that rested on the rail at the top of the flume.
- The two-dimensional ADV was installed in the upstream side of the flow and was located at a height of 0.4 m (1.3 ft) above the flume bottom. It monitored the water velocity in the flume. The water velocity data measured by the ADV was transmitted to a local computer.

Figure 4-14 shows the installed instrument on the model bridge with shallow foundation, while Figure 4-15 shows the schematic of the installed instruments.

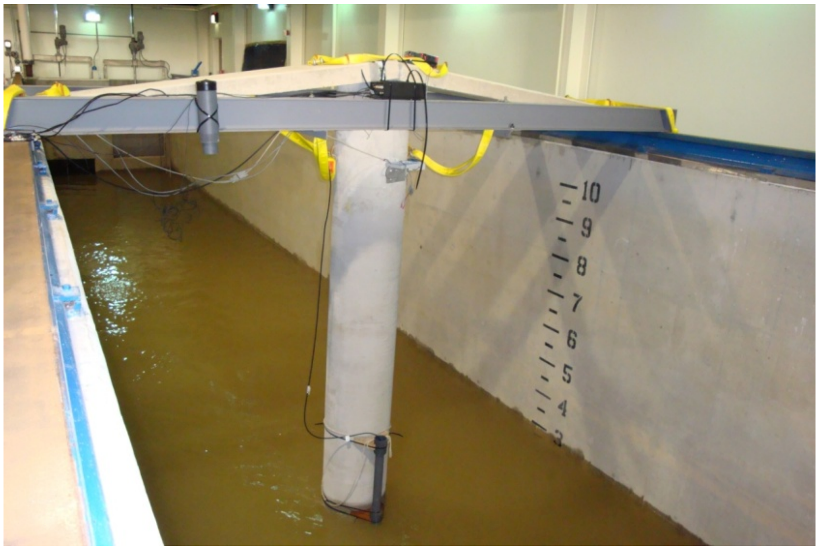


Figure 4-14. Experimental Setup.

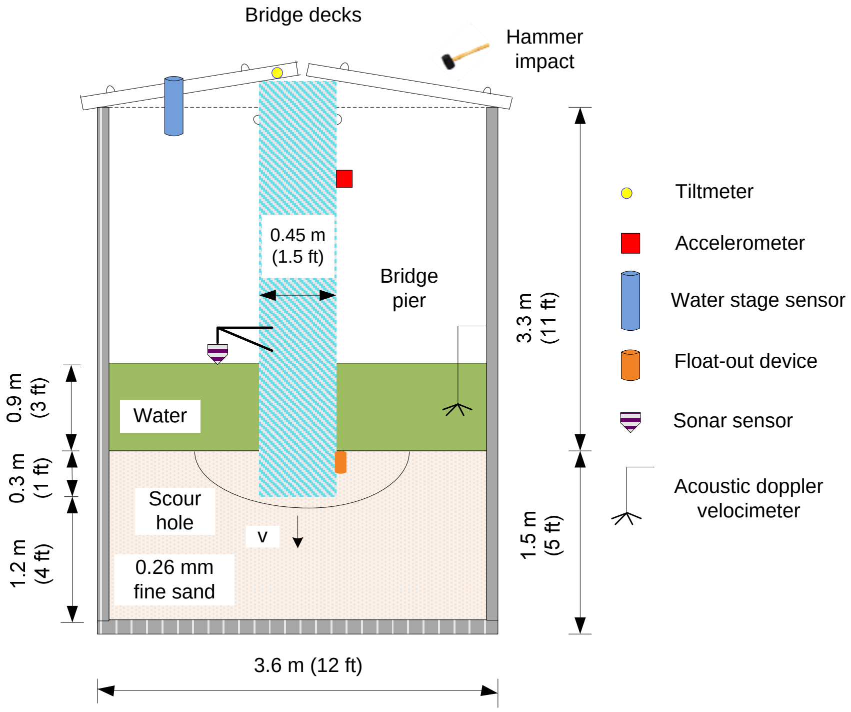


Figure 4-15. Schematic of the Installed Instruments.

Experimental Procedure

In the laboratory experiment, the water velocity was increased in controlled steps to induce progressive scour around the shallow foundation. The model bridge was excited by striking with the impact hammer, and the response was recorded by the instruments. The data were transmitted to the datalogger and then stored in the server at Texas A&M University. The experiment started at 11:48 a.m. on November 7, 2008. The total duration of the experiment was 6 hours and 45 minutes. The experiment was performed in several steps as follows:

1. At the beginning, the flume contained no water. The slab was hit with a 0.45 kg (1 lb) rubber hammer at the five excitation points as shown in Figure 4-11. It followed by a 1 minute series of random impacts.
2. The flume was filled until the water reached a level of 0.9 m (3 ft). The slab was again impacted as in the previous step with standing water (hydrostatic condition).
3. The impact test was repeated under increasing water velocities. The set of water velocity at which the impact test was done were 0.15 m/s (0.5 ft/s), 0.3 m/s (1 ft/s), and 0.45 m/s (1.5 ft/s).

The data were continuously collected for the entire duration of the experiment. As the water velocity reached 0.6 m/s (2 ft/s), the column began to settle due to the scour, undermining the foundation. The final depth of the scour hole was about 0.42 m (1.4 ft). It had a conical shape with a top diameter of 1.91 m (6.35 ft). The depth of the hole was measured at four points and the width of the hole in two directions. Figure 4-16 shows the schematic of the measured scour hole after the completion of the experiment.

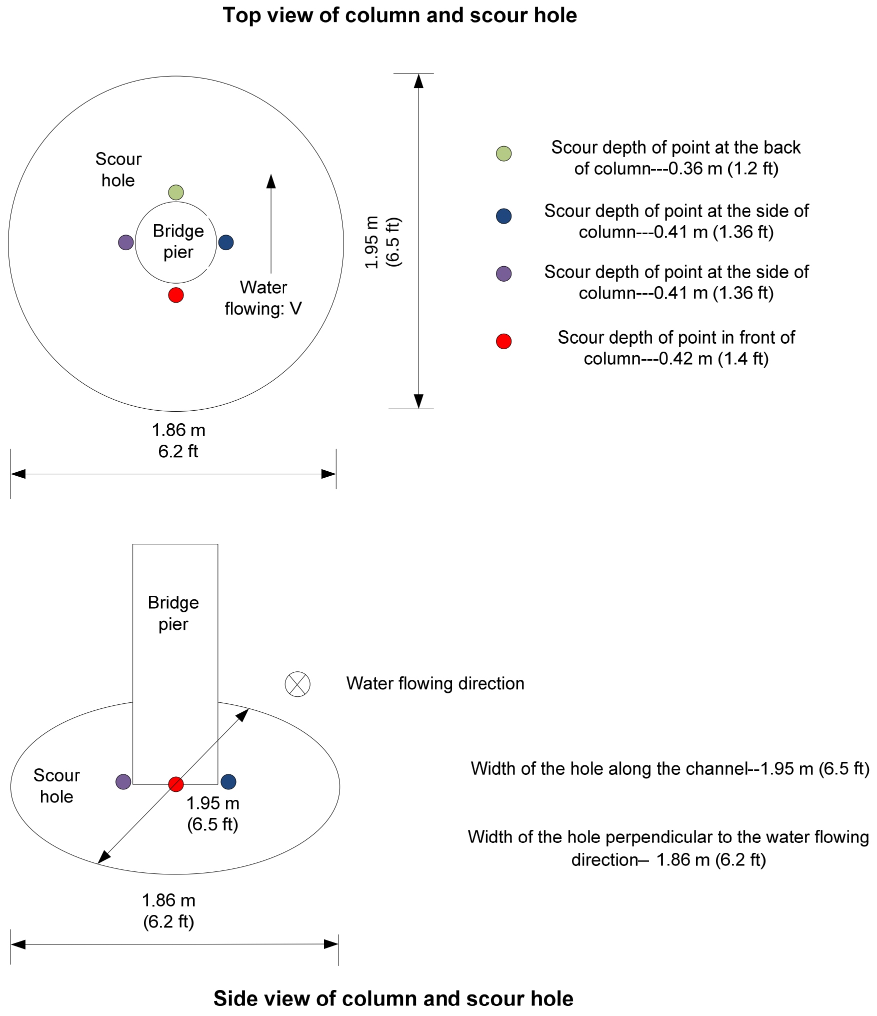


Figure 4-16. Schematic of the Scour Hole.

Data Analysis

The data were collected from the instruments for the entire duration of the experiment. The sampling rate of the accelerometer was 124 Hz. The sampling rate of the other sensors was 1 Hz.

Accelerometer

Figure 4-17 shows the time history of the acceleration of the column in three directions at the location of the instrument for the entire duration of the experiment. The acceleration was converted to the units of *g* (acceleration due to gravity). In the analysis below, *x* represents flow direction, *y* represents traffic direction, and *z* represents vertical direction. The impact tests on the slab can be seen clearly as groups of peaks. Approximately after 4.5 h, the acceleration in the flow direction (*x*) started to deviate significantly from the mean value. This corresponds to the time when the scour hole reached the bottom of the embedded portion of the column. After that, the column started to settle and rock with the farther deepening of the scour hole. So the acceleration in the flow direction (*x*) clearly indicates the change in the response of the column with the progress of the scour.

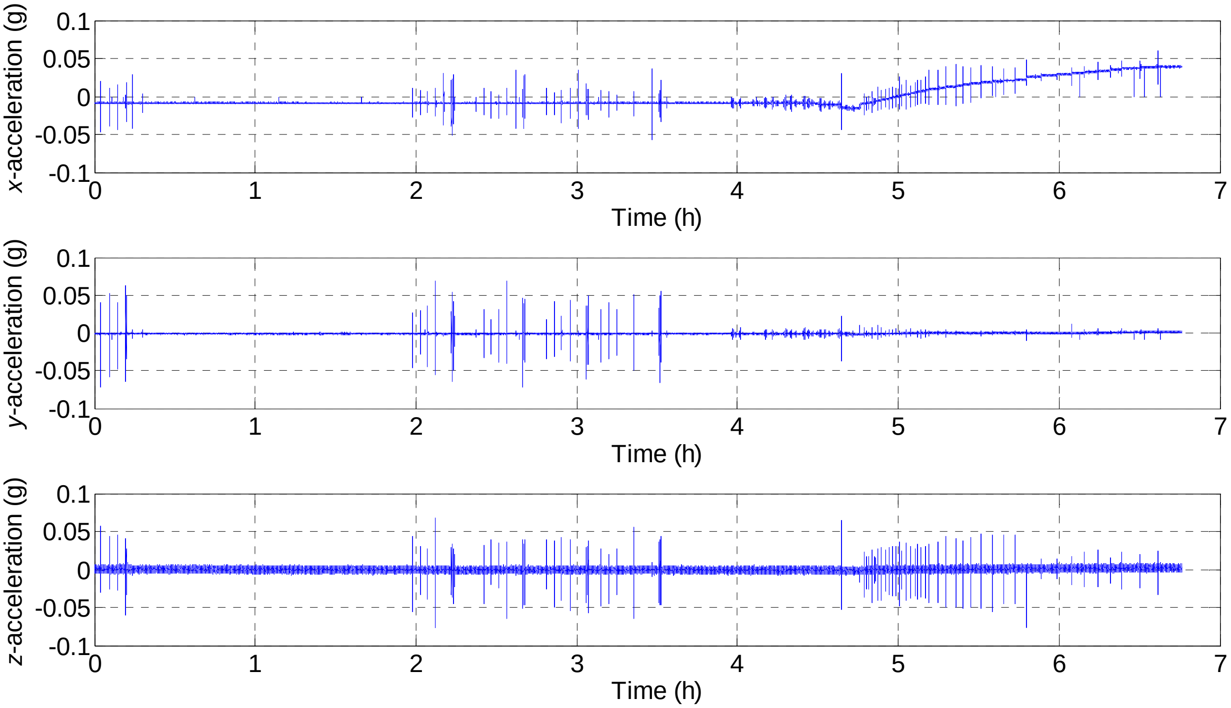


Figure 4-17. Time History of Acceleration in Three Directions.

The acceleration time history is studied in the frequency domain to get further insight of the response of the column. An FFT is performed on the signals to study the variation in response with the changing water velocity and growth of the scour hole. In order to study the signal in the frequency domain, the acceleration time history is divided into time intervals. Eleven time intervals are chosen based on the impact tests:

- 0–0.25 h (dry WAK test).
- 0.25–2 h (fill the tank, no test).
- 2–2.25 h (no flow, wet WAK test).
- 2.25–2.4 h (v = 0.15 m/s [0.5 ft/s], no test).
- 2.4–2.7 h (v = 0.15 m/s [0.5 ft/s], WAK test).
- 2.7–2.87 h (v = 0.3 m/s [1 ft/s], no test).
- 2.87–3.1 h (v = 0.3 m/s [1 ft/s], WAK test).
- 3.1–3.2 h (v = 0.45 m/s [1.5 ft/s], no test).
- 3.2–3.6 h (v = 0.45 m/s [1.5 ft/s], WAK test).
- 3.6–4.5 h (v = 0.45 m/s [1.5 ft/s], no test).
- 4.5–6.75 h (v = 0.6 m/s [2 ft/s], no test).

The FFT of the accelerations versus time plot for each time interval is plotted. The FFT is done for all the three directions: flow, traffic, and vertical. Figures 4-18 to 4-19 show the FFT plots for the flow and traffic directions because they give a clear indication of the change in frequency with the varying conditions and progress of scour.

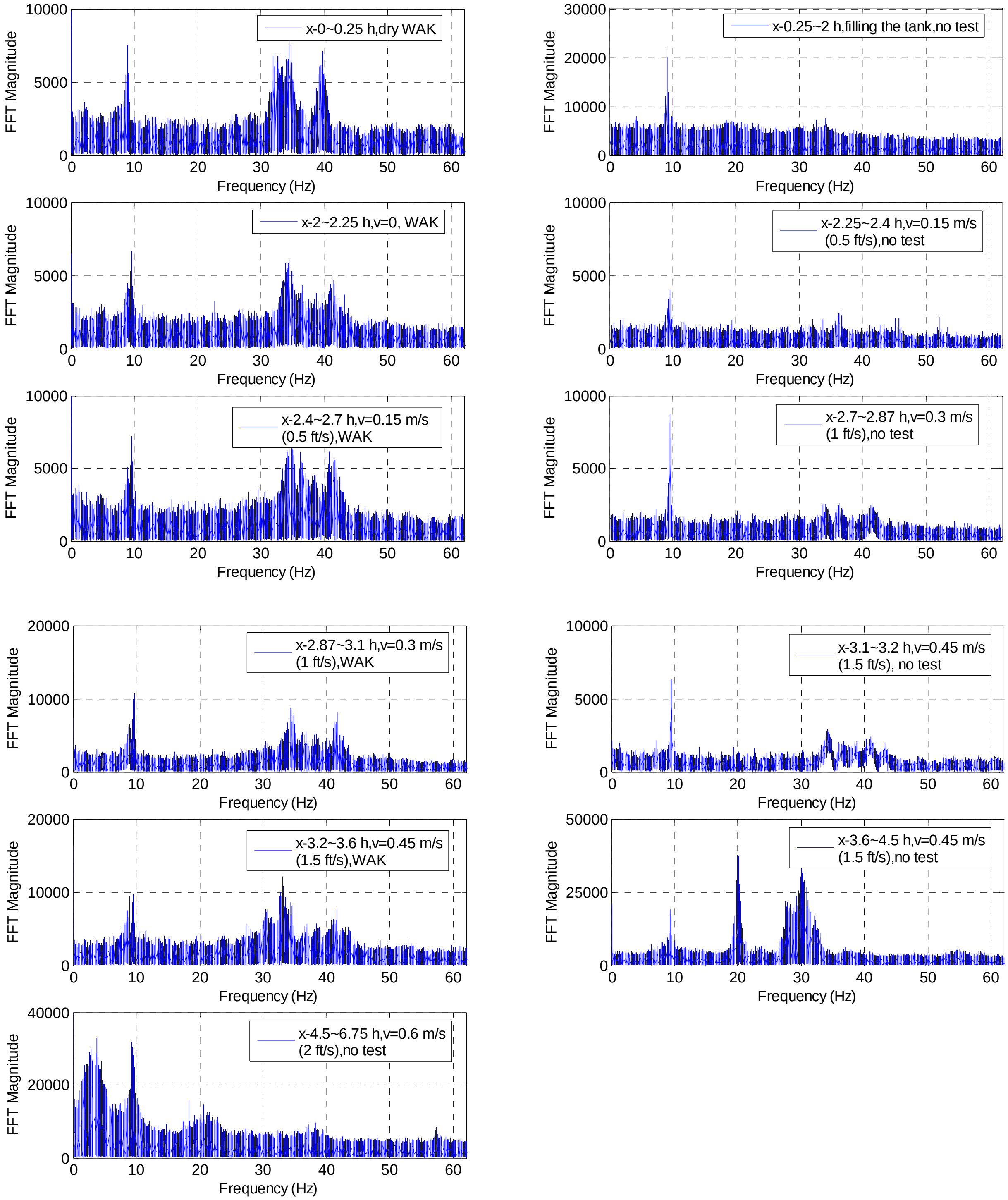


Figure 4-18. FFT in Flow Direction (*x*) in Shallow Foundation Experiment.

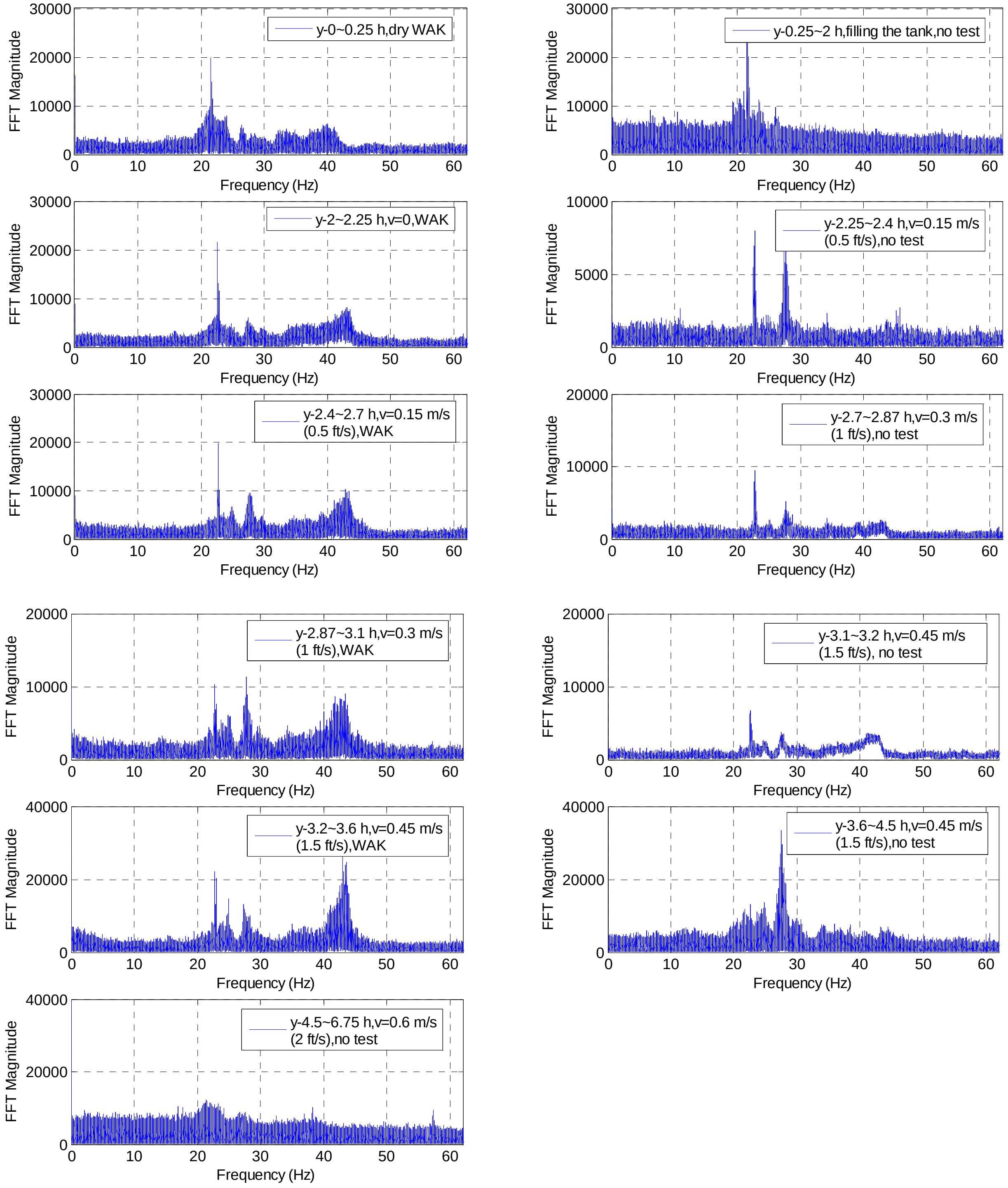


Figure 4-19. FFT in Traffic Direction (*y*) in Shallow Foundation Experiment.

From the FFT plots, it is observed that the natural frequencies of the model bridge with the shallow foundation during the dry condition (no water in the flume) are approximately 10 Hz, 35 Hz, and 40 Hz in the flow direction. These frequencies vary significantly with the progress of the scour and settlement of the column (*t* = 3.6–4.5 h, no test, and *t* = 4.5–6.75 h, no test). The corresponding frequencies in the traffic direction are approximately 20 Hz, 30 Hz, and 40 Hz. These frequencies do not vary significantly as compared to the frequencies in the flow direction. The FFT in the vertical direction does not show any clear frequency as the excitation is insufficient to excite the model bridge in the vertical mode.

The natural frequencies obtained by FFT analysis are plotted as a function of time for the entire duration of the experiment. Figure 4-20 shows the time history plot of the natural frequencies in two directions (flow and traffic). For each direction, the first three natural frequencies are plotted. The natural frequencies in the flow direction are sensitive to the progress of scour. It is observed that the natural frequencies in the flow direction (*x*) started to decrease after 3.6 h. At this time the water velocity was 0.45 m/s (1.5 ft/s). This corresponds to the instance when the scour hole started to develop. The natural frequencies continued to decrease after that. After 4.5 h the scour hole reached the bottom of the foundation, and the column started to settle and rock. At that time the water velocity was 0.6 m/s (2 ft/s). The natural frequencies dropped significantly at this instant. Therefore, by the frequency domain analysis, the starting of the scour hole as well as its development can be monitored. The change in the natural frequencies due to the progress of scour hole is due to the decrease in the stiffness of the foundation caused by the removal of soil around the foundation. The frequencies in the traffic direction do not show any significant change with the progress of the scour. This is due to the fact that in the traffic direction the foundation is restrained by the boundary condition of the slab, which is not significantly affected by the progress of scour hole.

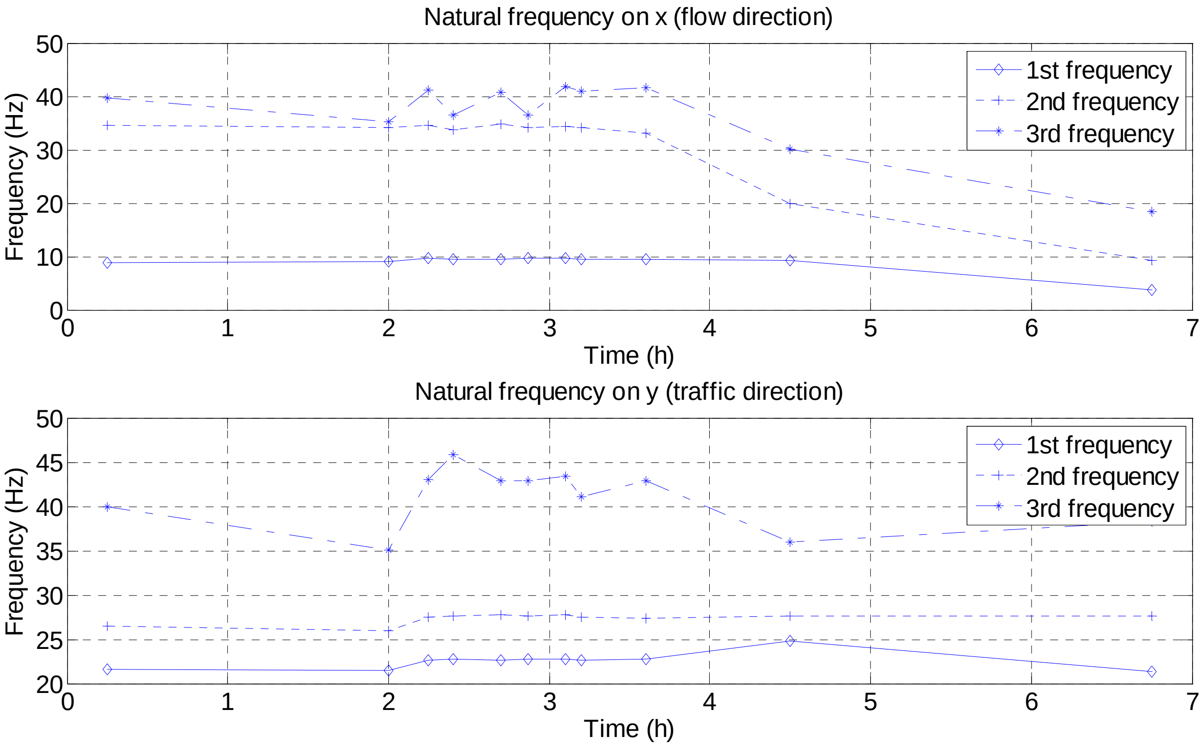


Figure 4-20. Time History of Frequency in Two Directions.

The second approach adopted to analyze the data from the accelerometer is to use the ratio of Root Mean Square (RMS) values of acceleration in two different directions as a parameter to monitor the progress of scour around the model bridge with the shallow foundation. The ratio of RMS is expressed as:

$$\frac{a_x}{a_y} = \frac{\sqrt{\dfrac{a_{x1}^2 + a_{x2}^2 + \ldots + a_{xn}^2}{n}}}{\sqrt{\dfrac{a_{y1}^2 + a_{y2}^2 + \ldots + a_{yn}^2}{n}}} \tag{4-1}$$

$$\frac{a_y}{a_z} = \frac{\sqrt{\dfrac{a_{y1}^2 + a_{y2}^2 + \ldots + a_{yn}^2}{n}}}{\sqrt{\dfrac{a_{z1}^2 + a_{z2}^2 + \ldots + a_{zn}^2}{n}}} \tag{4-2}$$

$$\frac{a_x}{a_z} = \frac{\sqrt{\dfrac{a_{x1}^2 + a_{x2}^2 + \ldots + a_{xn}^2}{n}}}{\sqrt{\dfrac{a_{z1}^2 + a_{z2}^2 + \ldots + a_{zn}^2}{n}}} \tag{4-3}$$

Where, a_x represents the RMS value of measured acceleration in flow direction, a_y represents the RMS value of measured acceleration in traffic direction, and a_z represents the RMS value of measured acceleration in vertical direction. The total number of the acceleration values during the calculating time period is expressed as n. Symbol a_{x1}, a_{x2}, a_{xn}, a_{y1}, a_{y2}, a_{yn}, a_{z1}, a_{z2}, a_{zn} represents the individual measured accelerations during the calculating time period in three directions.

In order to compare the RMS result with the FFT result, the time history of accelerations obtained during the experiment is divided into 11 time intervals as before. For each time interval, the RMS value of the signal in flow direction (*x*), traffic direction (*y*) and vertical direction (z) is calculated. After that the ratios of the RMS are obtained for all the three combinations. Figure 4-21 plots the time history of the ratio of RMS in two directions for the entire duration of the experiment. The ratio of RMS for flow direction over traffic direction and flow direction over vertical direction show significant change with the progress of the scour hole. The change became large when the scour hole reached the bottom of the column and the column started to settle and rock after 4.5 h. This trend is similar to that obtained by the FFT analysis.

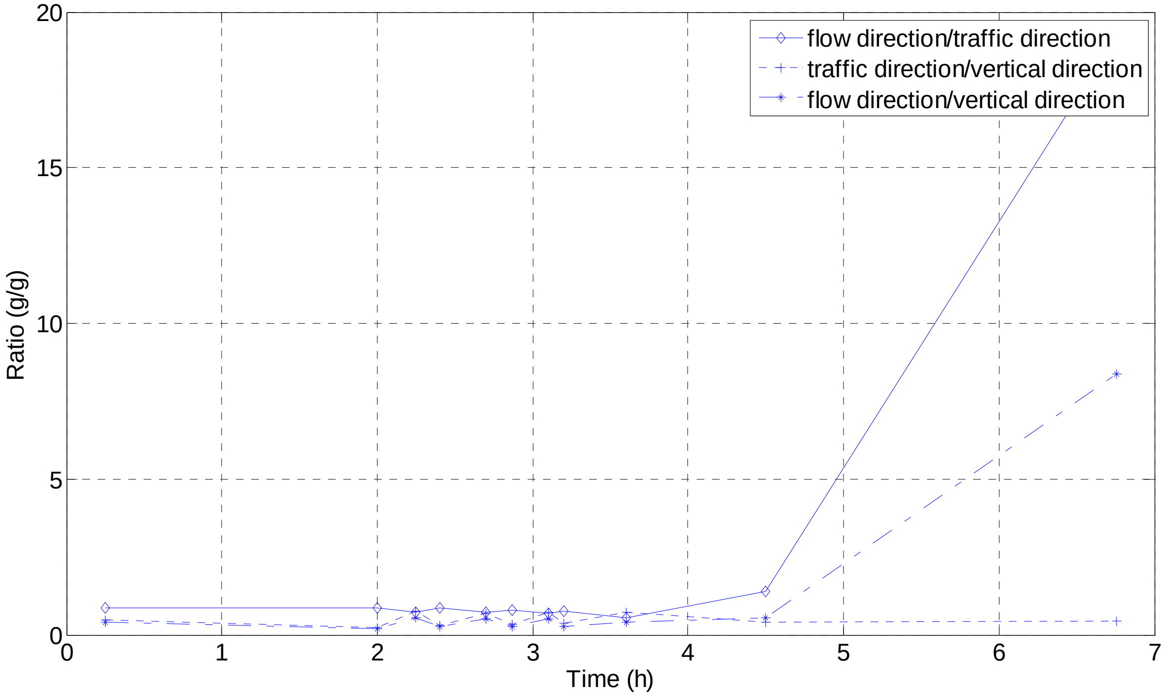


Figure 4-21. Time History of Ratio of RMS.

Tiltmeter

Figure 4-22 shows the time history of the tiltmeter reading for the entire duration of the experiment. The upper graph in Figure 4-22 shows the tilt angle of the slab around the flow direction axis, and the lower graph shows the tilt angle of the slab around the traffic direction axis. Both of the tilt angles varied significantly after 4.5 h, at the instant when the scour hole reached the bottom of the column, and the column started to settle and rock. The tilt readings do not show indication of the starting of the scour hole. The qualitative results of tilt angle readings are in agreement with the FFT and ratio of RMS analysis.

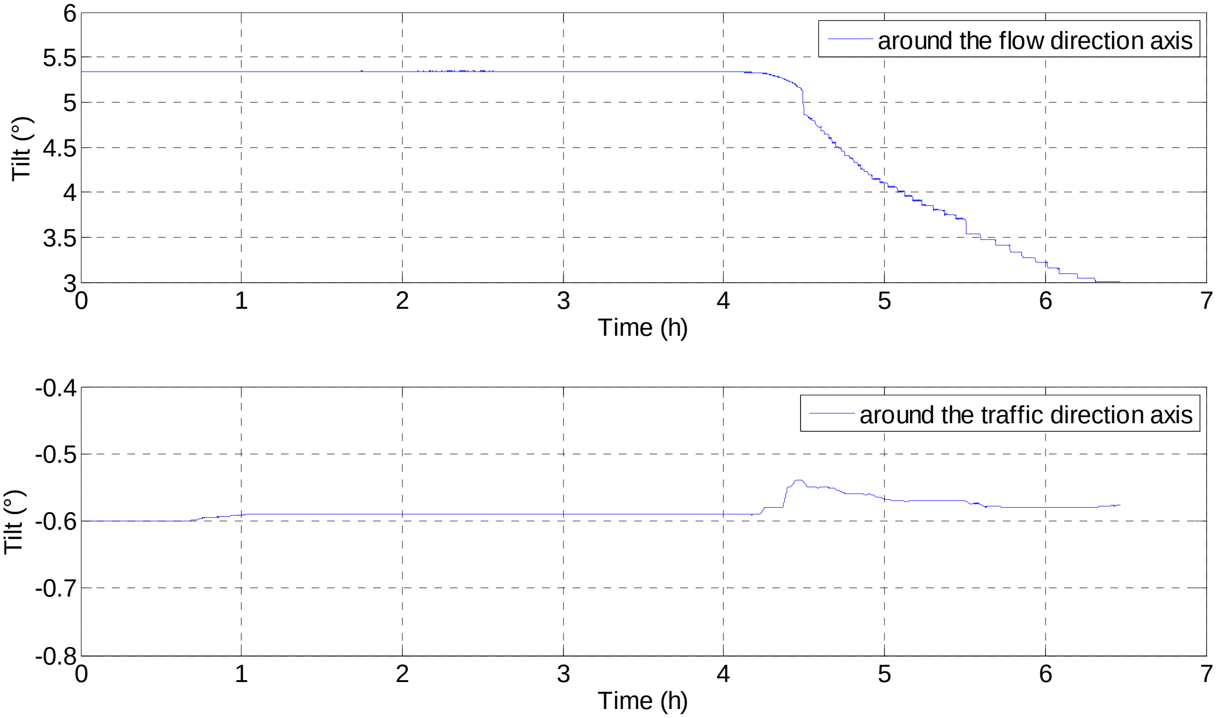


Figure 4-22. Time History of Tilt.

Float-Out Device

The internal radio transmitter of the float-out device transmits a value of 0 to the data acquisition system if the float-out device is in a vertical position and has not floated out. The internal radio transmitter transmits a value of 1 to the data acquisition system if the float-out device floats out, and becomes horizontal. Figure 4-23 shows the time history of the response of the float-out device during the experiment. It is observed that the device floated out after 3.5 h, which indicates that the scour hole reached the bottom of the device after 3.5 h.

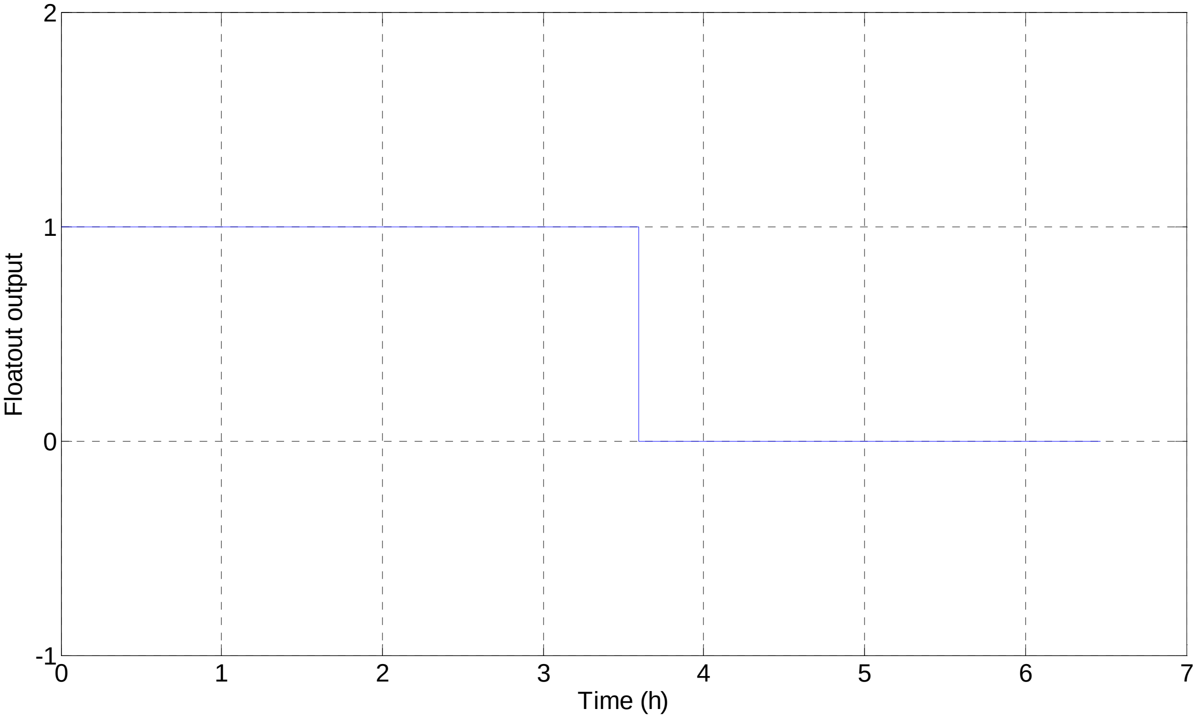


Figure 4-23. Response Time History of Float-Out Device.

Water Stage Sensor

The water stage sensor was mounted on the steel beam at a height of 3.3 m (11 ft) above the sand surface. Figure 4-24 shows the time history of the response of water stage sensor. The water stage sensor measures the distance between the sensor head and the water surface. Before the tank was filled with water, the water stage sensor recorded a reading of 3.3 m (11 ft), which is the distance between the sensor and the soil surface. Then the tank was filled with water until the water level reached a height of 0.9 m (3 ft) in the flume. The water stage sensor recorded a reading of 2.4 m (8 ft), which is the distance between the sensor head and upper surface of the water. The readings of water stage sensor became erratic after 3.7 h.

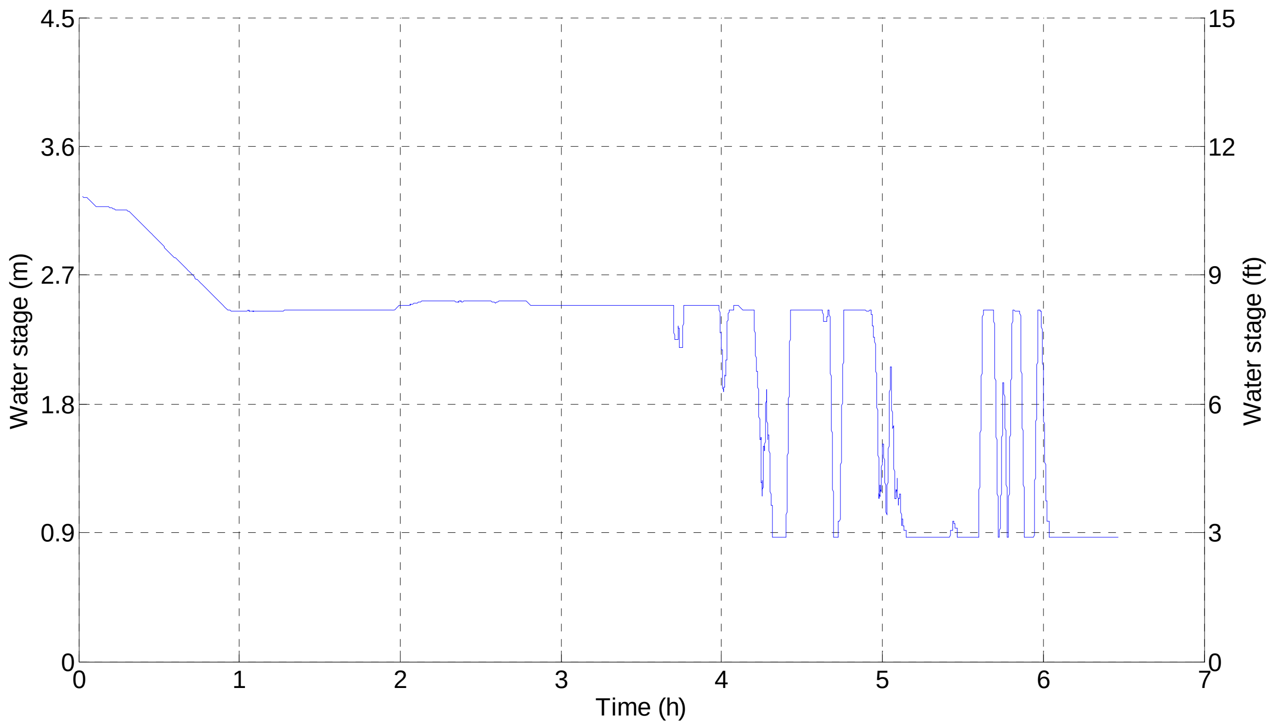


Figure 4-24. Response Time History of Water Stage Sensor.

Sonar Sensor

Figure 4-25 shows the time history of the sonar sensor reading during the experiment. The sonar sensor reading began to increase after 3 h, indicating the start of the formation of the scour hole. After 4.5 h the sonar sensor reading began to decrease, which was caused by the settlement of the column on which the sonar was mounted. The observed trends are in agreement with the readings from the other instruments.

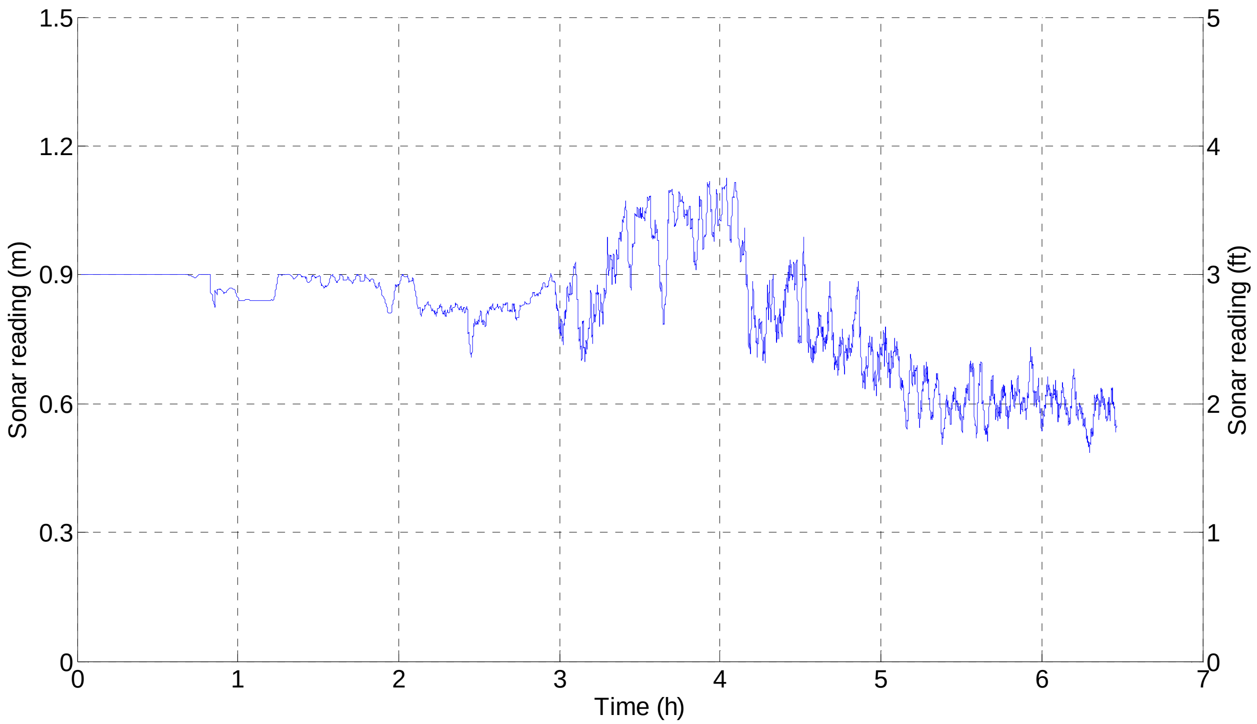


Figure 4-25. Response Time History of Sonar Sensor.

Acoustic Doppler Velocimeter

The ADV was installed in the upstream side of the flume to measure the water velocity during the experiment. Figure 4-26 shows the time history of the water velocity. The gap in data from 0 hour to 2.2 h is due to the fact that the water was given a velocity after 2.2 h when a hydrostatic condition was reached in the flume. Based on the analysis of the data obtained from the instruments it is inferred that the scour hole started to develop when the water velocity was 0.45 m/s (1.5 ft/s) in the experiment, and it reached the bottom of column when the water velocity was 0.60 m/s (2 ft/s). The water velocity data are used for the prediction of the scour hole by performing SRICOS-EFA simulation.

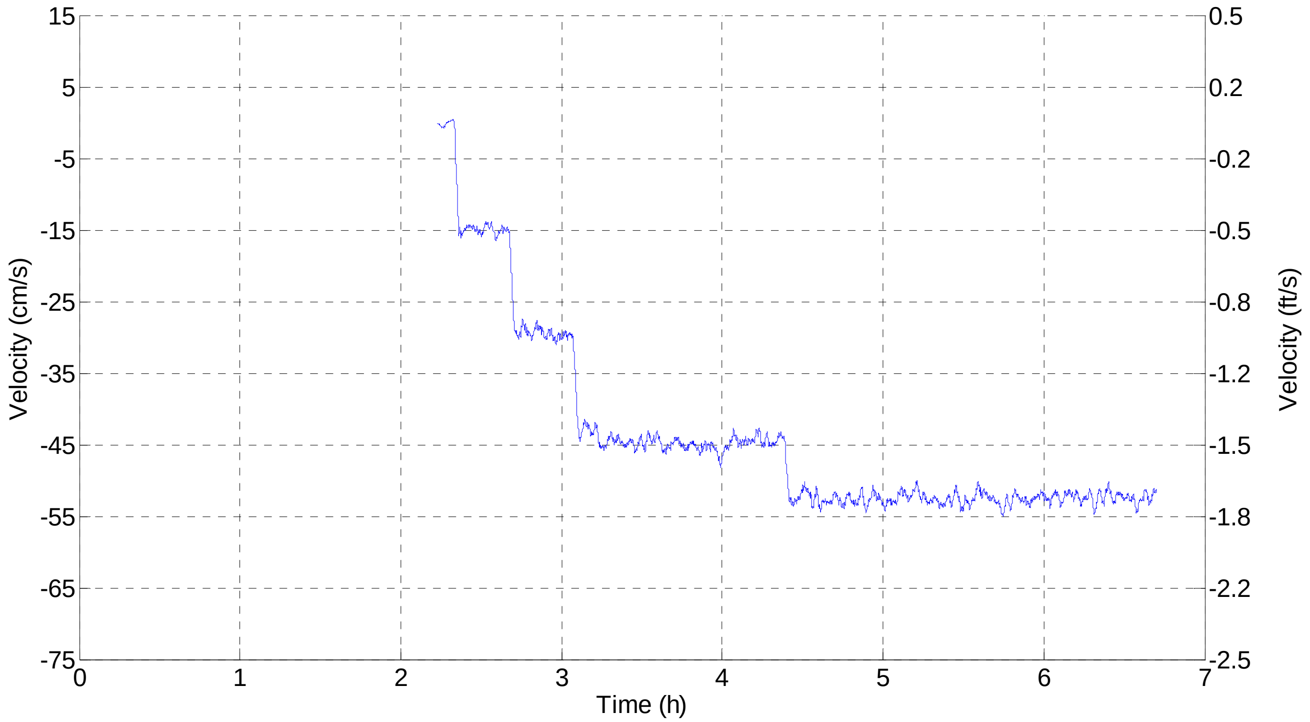


Figure 4-26. Response Time History of ADV.

Discussion

The trends observed in results of the data analysis using FFT, ratio of RMS, tiltmeter readings, and sonar readings are similar. Figure 4-27 shows a combined plot of all the above analysis. The top graph shows the time history plot of the first natural frequency of the model bridge in the flow direction; the graph below shows the time history plot of the ratio of RMS of the acceleration in the flow direction over traffic direction; the third plot shows the time history plot of the tilt of the deck along the flow axis; and the bottom graph shows the time history plot of the sonar reading for the entire duration of the experiment.

The tilt sensor recorded tilt of the deck at 4.5 h when the scour hole became deep enough that the column started to settle and rock. Figure 4-27 also indicates that natural frequency of the system in flow direction dropped at 4.5 h when the scour hole reached the bottom of column and the stiffness of the system decreased. The ratio of RMS values of acceleration in flow direction over traffic direction also changed significantly at 4.5 h due to the stiffness change in the system. The start of the scour hole was confirmed by the sonar measurements, which show a scour starting to develop shortly after 3 h. The sonar data then indicated that the scour hole increased (0.42 m by sounding at the end of the test) until the column started to settle. Because the sonar was mounted on the column, the sonar did not show an increase in scour hole after the column started to settle as the rate of settlement was approximately equal to rate of scour. Therefore, frequency change, ratio of RMS values of acceleration, and tilt are sensitive parameters for scour prediction. Both accelerometer and tiltmeter can be used to monitor bridge scour in laboratory.

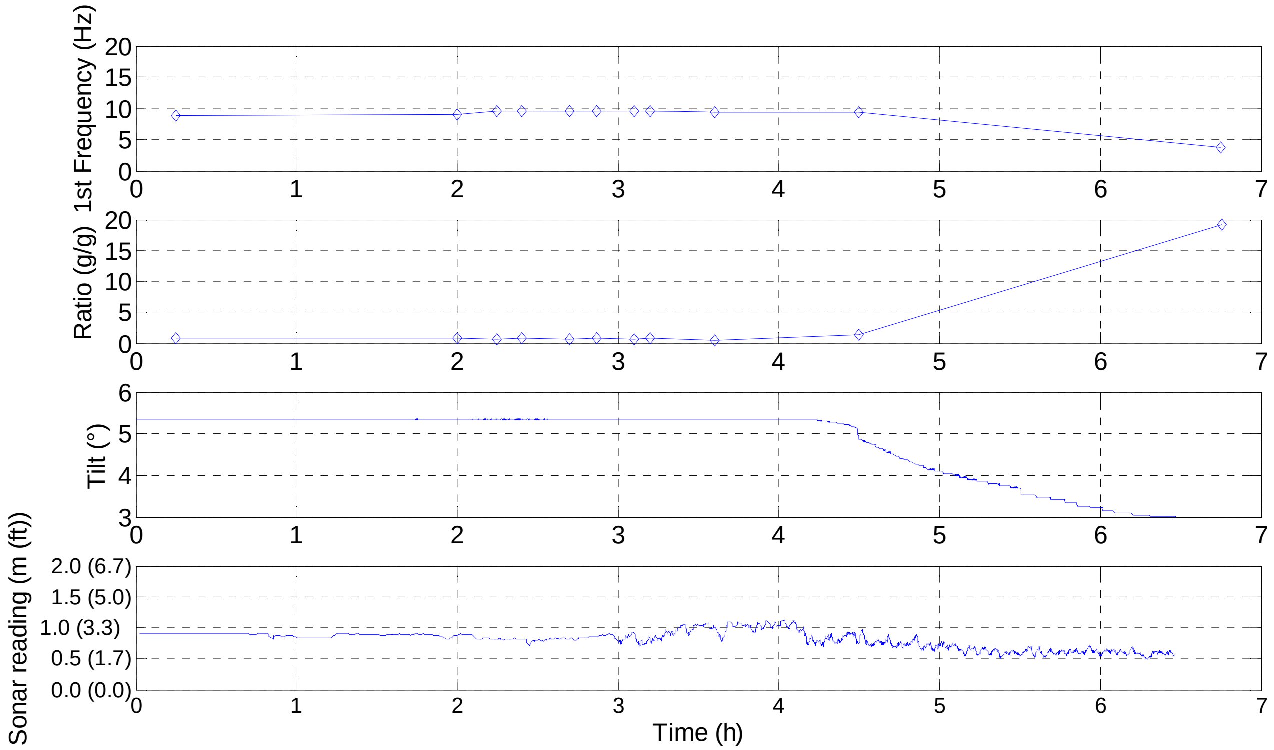


Figure 4-27. Response Time History of the Installed Instruments.

DEEP FOUNDATION EXPERIMENT

A scaled bridge with a deep foundation is used for the second laboratory experiment. The experiment with the deep foundation was performed on March 3, 2009. The column is reconstructed to form a deep (pile) foundation. The model bridge is subjected to growth of progressive scour by increasing the water velocity in the flume. The installed instruments measure the response of the model bridge. The data are analyzed to study the change in response of the model bridge with the deep foundation to indicate the growth of scour. The following sections describe the prefabrication of the model bridge, the experimental setup, installation of the instruments, and experimental procedure. After that the data analysis of the obtained result and discussion of the results are presented.

Prefabrication of the Model Bridge with Deep Foundation

In the second experiment, the column was reconstructed to form a pile foundation. The concrete column was cut from the bottom to a length of 0.3 m (1 ft) thereby exposing the steel bars inside. The exposed steel bars were 0.19 m (7.5 inches) long. There were eight steel bars with a diameter of 1.6 cm (5/8 inch). Four of the bars were single and the other four bars were in groups of two. To model a pile foundation effectively, 0.3 m (1 ft) long PVC pipes and steel pipes were wrapped around the existing bars. For each single bar, a 1.9 cm (0.75 inch) diameter PVC pipe and a 2.54 cm (1 inch) diameter PVC pipe was used to wrap the bar layer by layer. After that, a 3.81 cm (1.5 inches) diameter steel pipe was used to wrap the 2.54 cm (1 inch) diameter PVC pipe. For each bar in the group, a 3.81 cm (1.5 inches) diameter steel pipe was used to wrap the steel bars. After that, glue was injected into the steel pipes to stabilize the foundation. Finally the column had a length of 3.68 m (12.1 ft) for the concrete part and 0.3 m (1 ft) long for the pile part. Figure 4-28 shows the schematic of the pile foundation, and Figure 4-29 shows the remolded pile foundation.

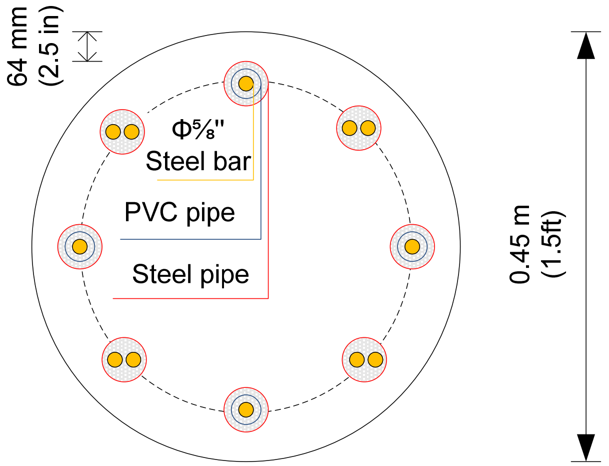


Figure 4-28. Schematic of the Pile Foundation (Bottom View).

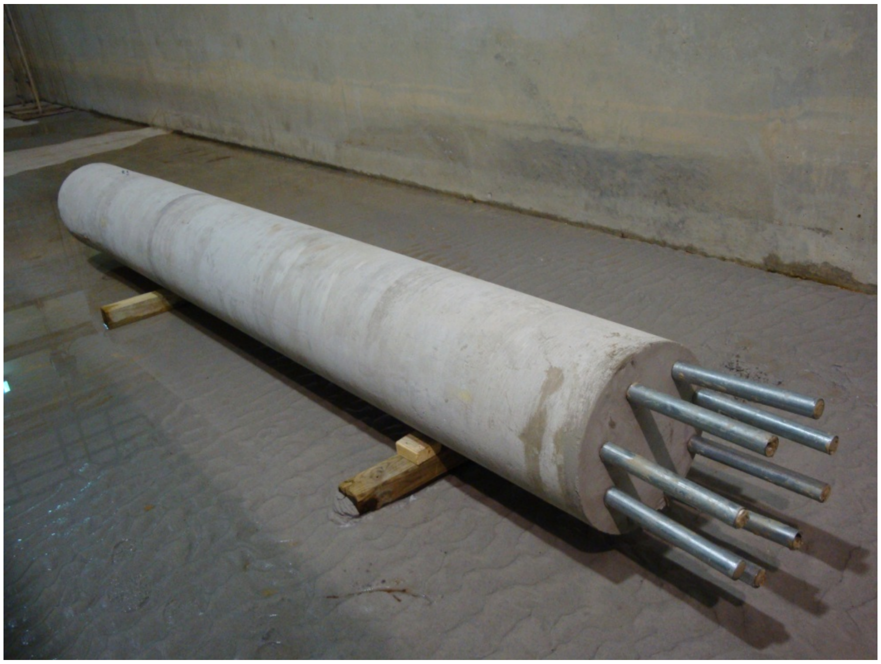
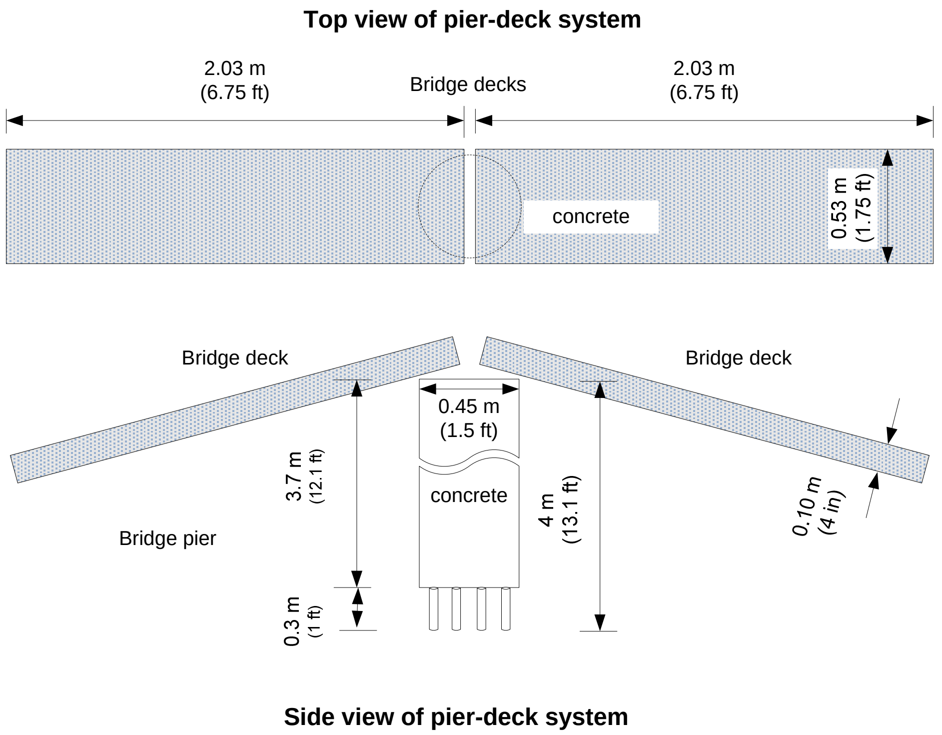


Figure 4-29. Column with Pile Foundation.

Experimental Setup

The experiment was performed in the flume of the laboratory. The soil consisting of fine, clean, and uniform silica was placed and compacted in the pit of the flume in the laboratory. The 0.45 m (1.5 ft) diameter and 4 m (13.1 ft) long reconstructed column was embedded to 0.45 m (1.5 ft) in the sand with 0.15 m (0.5 ft) of column and 0.3 m (1 ft) of pile foundation. After that, the two prefabricated concrete slabs were placed end to end on top of the column. This placement was followed to model a bridge with deep (pile) foundation. Figure 4-30 shows the model bridge with the deep foundation.


Top view of pier-deck system

Side view of pier-deck system

Figure 4-30. Model Bridge with Deep Foundation.

Installation of the Instruments

The scour monitoring system installed on the model bridge consisted of instruments to collect the response of the model bridge with the deep foundation. The instruments installed in the laboratory experiment were: (1) accelerometer, (2) dual-axis tiltmeter, (3) TBS, (4) sonar sensor, (5) water stage, and (6) ADV. A datalogger (CR1000) was used to collect the data and transfer it through a RS232 interface to a server located at Texas A&M University.

The installation of the instruments on the model bridge and data collection was similar to the model bridge with the shallow foundation. The TBS was installed just beneath the sand and hardwired to the data acquisition system. The sonar sensor was mounted on the column at a distance of 0.85 m (2.8 ft) from the bottom of the sensor to the top of the sand. The accelerometer, water stage sensor, tiltmeter, and ADV were installed in the same location as in the shallow foundation experiment. Figure 4-31 shows the schematic of the installed instruments in the laboratory experiment.

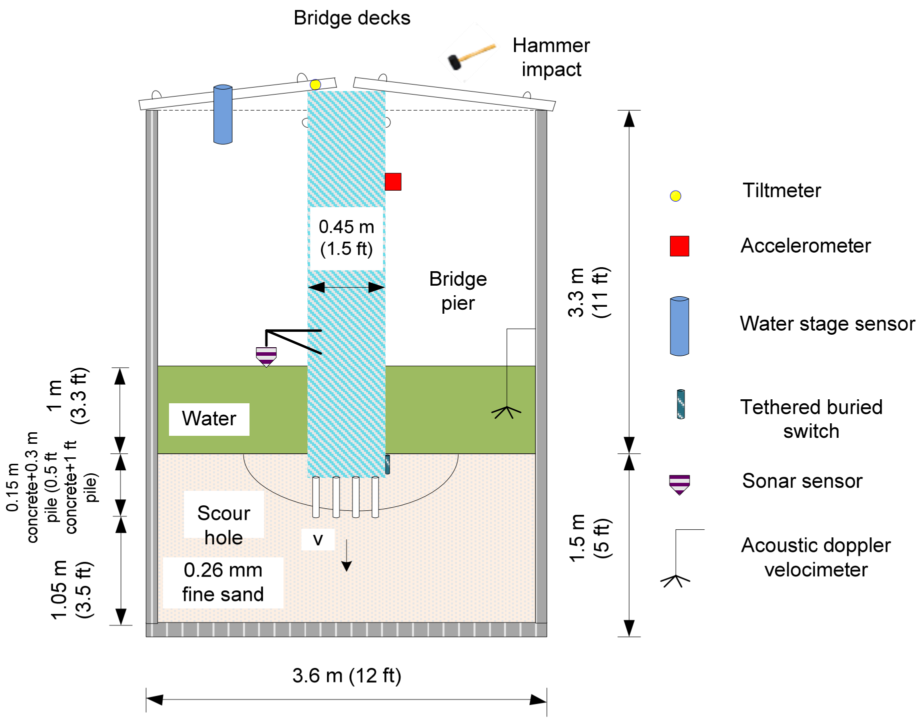


Figure 4-31. Sensors Setup Illustration for the Deep Foundation Experiment.

Experimental Procedure

In the laboratory experiment, the water velocity was increased in controlled steps to induce progressive scour around the deep foundation. The model bridge was excited by striking with the impact hammer (0.45 kg [1 lb]), and the response was recorded by the instruments. The data were transmitted to the datalogger, which was then stored on a computer. The total duration of the experiment was 4 hours and 20 minutes. The experiment was performed in several steps as follows:

1. At the beginning, the flume contained no water. The slab was hit with a 0.45 kg (1 lb) rubber hammer at point 2 (vertical direction), point 5 (flow direction), and point 6 (traffic direction) individually every 5 minutes. Here, point 6 was marked at the center of the shorter side of slab (Figure 4-11). The advantage of this impact test is that it excited the system in one particular direction each time rather than providing a combined impact.
2. The flume was filled until the water reached a level of 1.0 m (3.3 ft). The slab was again impacted as in the previous step with standing water (hydrostatic condition).

3. The impact test was repeated under increasing water velocities. The set of water velocities at which the impact tests were done were 0.2 m/s (0.67 ft/s), 0.36 m/s (1.2 ft/s), 0.45 m/s (1.5 ft/s), and 0.6 m/s (2 ft/s).

The data were continuously collected for the entire duration of the experiment. As the water velocity reached 0.6 m/s (2 ft/s), the depth of the scour hole reached the bottom of the column, and the column began to settle as the scour hole continued to deepen. When the velocity of water reached 0.8 m/s (2.6 ft/s), the tilt sensor indicated a change in the slab inclination, and the column leaned at an angle of 30° with the vertical direction, which was defined as the failure of the model bridge with the deep foundation. The final depth of the scour hole was about 0.32 m (1.08 ft). It had a conical shape with a top diameter of 1.47 m (4.9 ft). The depth of the hole was measured at two points and the width of the hole in two directions. Figure 4-32 shows the schematic of the measured scour hole after the completion of the experiment.

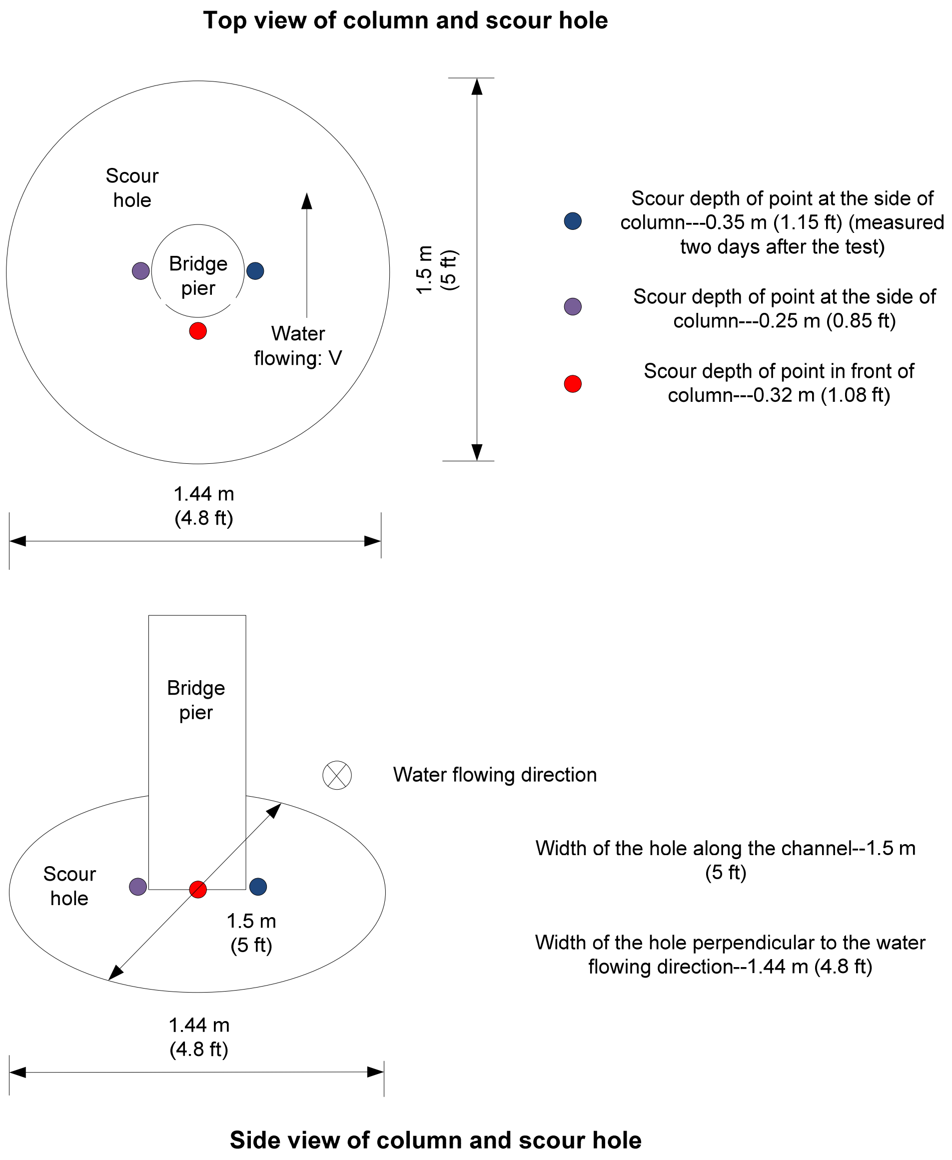


Figure 4-32. Schematic of the Scour Hole.

Data Analysis

The data were collected from the instruments for the entire duration of the experiment. The sampling rate of the accelerometer was 140 Hz. The sampling rate of the other sensors was 1 Hz.

Accelerometer

Figure 4-33 shows the time history of the acceleration of the column in three directions at the location of the instrument for the entire duration of the experiment. The acceleration is converted to the units of *g* (acceleration due to gravity). In the analysis, *x* represents flow direction, *y* represents traffic direction, and *z* represents vertical direction. The impact tests on the slab can be seen clearly as groups of peaks. Approximately after 3.75 h the scour hole reached the bottom of the embedded portion of the column. After that, the column started to settle and rock with the farther deepening of the scour hole. Therefore, the acceleration in flow direction clearly indicates the change in the response of the column with the progress of the scour. After 4 h, the column showed great movement.

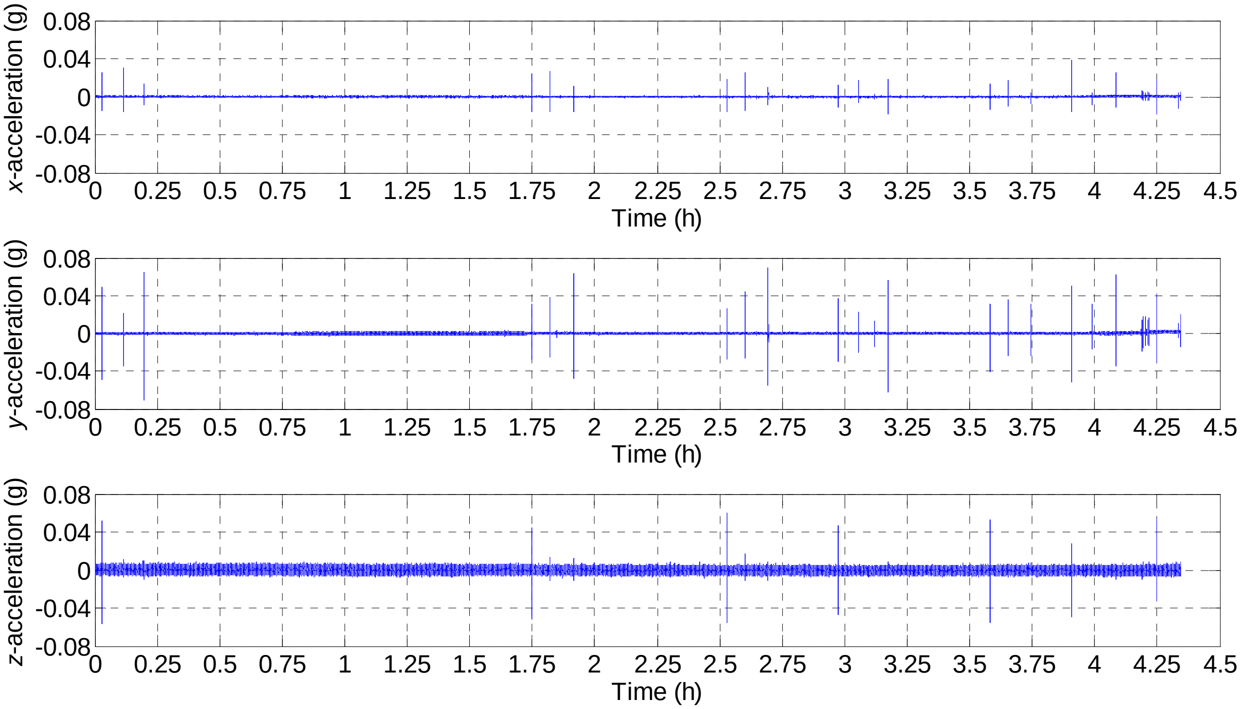


Figure 4-33. Time History of Acceleration in Three Directions.

The acceleration time history is studied in the frequency domain to get further insight of the response of the column. A FFT is performed on the signal to study the variation in response with the changing water velocity and growth of the scour hole. In order to study the signal in the frequency domain, the acceleration time history is divided into time intervals. Twelve time intervals are chosen based on the impact tests in flow direction as follows:

- 0.08–0.14 h (dry WAK test in flow direction).
- 0.25–1.6 h (fill the tank, no test).
- 1.8–1.85 h (no flow, wet WAK test in flow direction).
- 2–2.5 h (v = 0, no test).
- 2.55–2.65 h (v = 0.2 m/s [0.67 ft/s], WAK test in flow direction).

- 2.8–2.9 h (v = 0.36 m/s [1.2 ft/s], no test).
- 3–3.1 h (v = 0.36 m/s [1.2 ft/s], WAK test in flow direction).
- 3.3–3.5 h (v = 0.45 m/s [1.5 ft/s], no test).
- 3.6–3.7 h (v = 0.45 m/s [1.5 ft/s], WAK test in flow direction).
- 3.75–3.9 h (v = 0.6 m/s [2 ft/s], no test).
- 3.95–4.05 h (v = 0.6 m/s [2 ft/s], WAK test in flow direction).
- 4.15–4.3 h (v = 0.8 m/s [2.6 ft/s], no test).

Similarly, 12 time intervals are chosen based on the impact tests in traffic direction as follows:

- 0.18–0.22 h (dry WAK test in traffic direction).
- 0.25–1.6 h (fill the tank, no test).
- 1.85–2 h (no flow, wet WAK test in traffic direction).
- 2–2.5 h (v = 0, no test).
- 2.65–2.8 h (v = 0.2 m/s [0.67 ft/s], WAK test in traffic direction).
- 2.8–2.9 h (v = 0.36 m/s [1.2 ft/s], no test).
- 3.1–3.3 h (v = 0.36 m/s [1.2 ft/s], WAK test in traffic direction).
- 3.3–3.5 h (v = 0.45 m/s [1.5 ft/s], no test).
- 3.7–3.8 h (v = 0.45 m/s [1.5 ft/s], WAK test in traffic direction).
- 3.75–3.9 h (v = 0.6 m/s [2 ft/s], no test).
- 4.05–4.15 h (v = 0.6 m/s [2 ft/s], WAK test in traffic direction).
- 4.15–4.3 h (v = 0.8 m/s [2.6 ft/s], no test).

The FFT of the accelerations versus time plot for each time interval is plotted. The FFT is done for all the three directions: flow, traffic, and vertical. Figures 4-34 to 4-35 shows the FFT plots for the flow and traffic directions because they give a clear indication of the change in frequency with the varying conditions and progress of scour. The natural frequencies obtained in the graph on the left hand side of Figures 4-34 to 4-35 are sharp and clear while the natural frequencies in the right hand side graph are not clear. This difference is due to the fact that the graph on the left hand side corresponds to the impact test and on the right hand side corresponds to no impact.

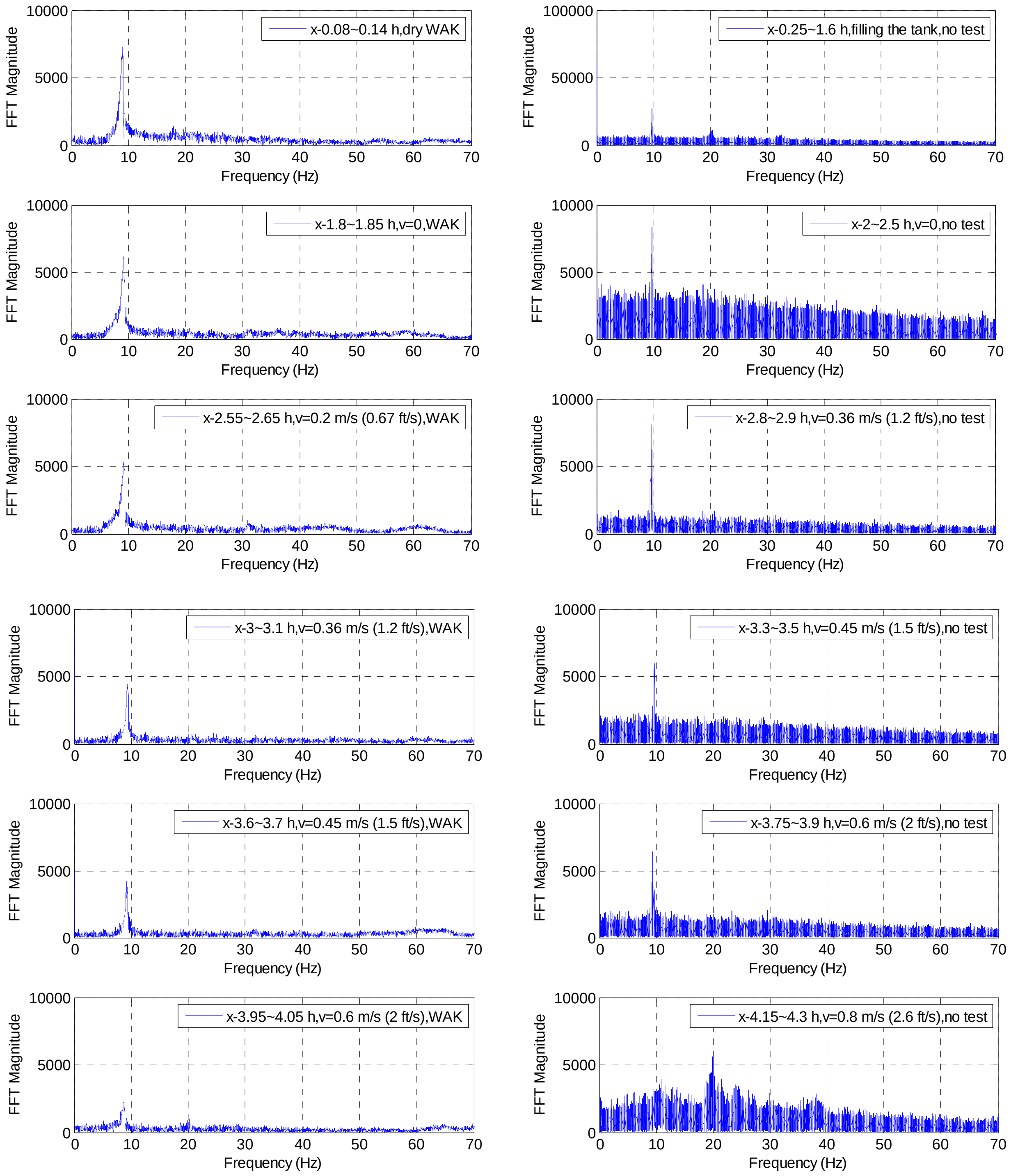


Figure 4-34. FFT in Flow Direction (*x*) for Deep Foundation Experiment.

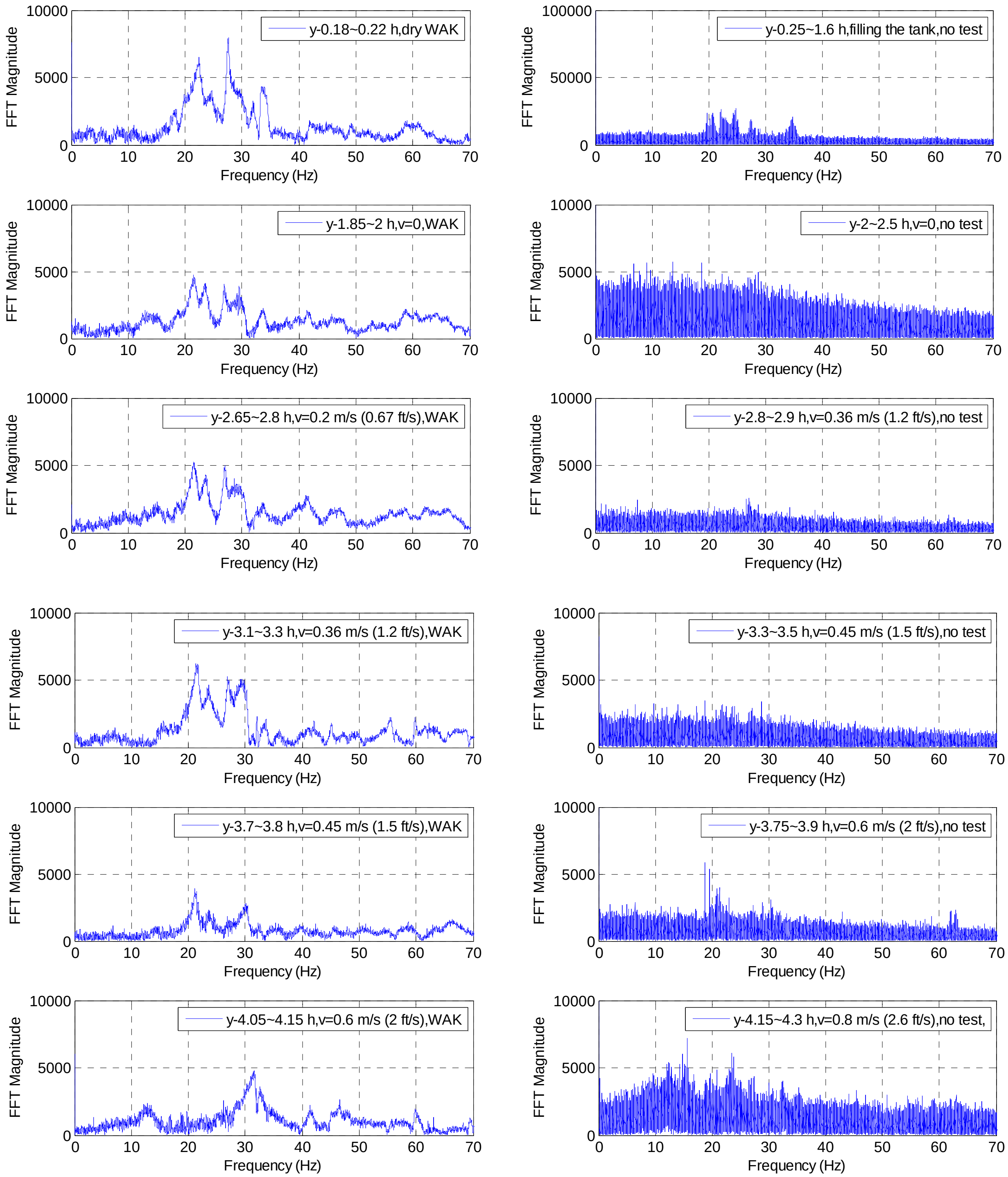


Figure 4-35. FFT in Traffic Direction (*y*) for Deep Foundation Experiment.

From the FFT plots, it is observed that three natural frequencies of the model bridge with deep foundation are identified in the traffic direction and one in flow direction. The natural frequencies obtained by FFT analysis are plotted as a function of time for the entire duration of the experiment. Figure 4-36 shows the time history plot of the natural frequencies in two directions (flow and traffic). Figure 4-36 indicates that the natural frequencies remained steady until the column settled and rotated after 3.75 h. Unfortunately, due to sudden failure of the model bridge with the deep foundation, no data can be collected during the later part of the experiment.

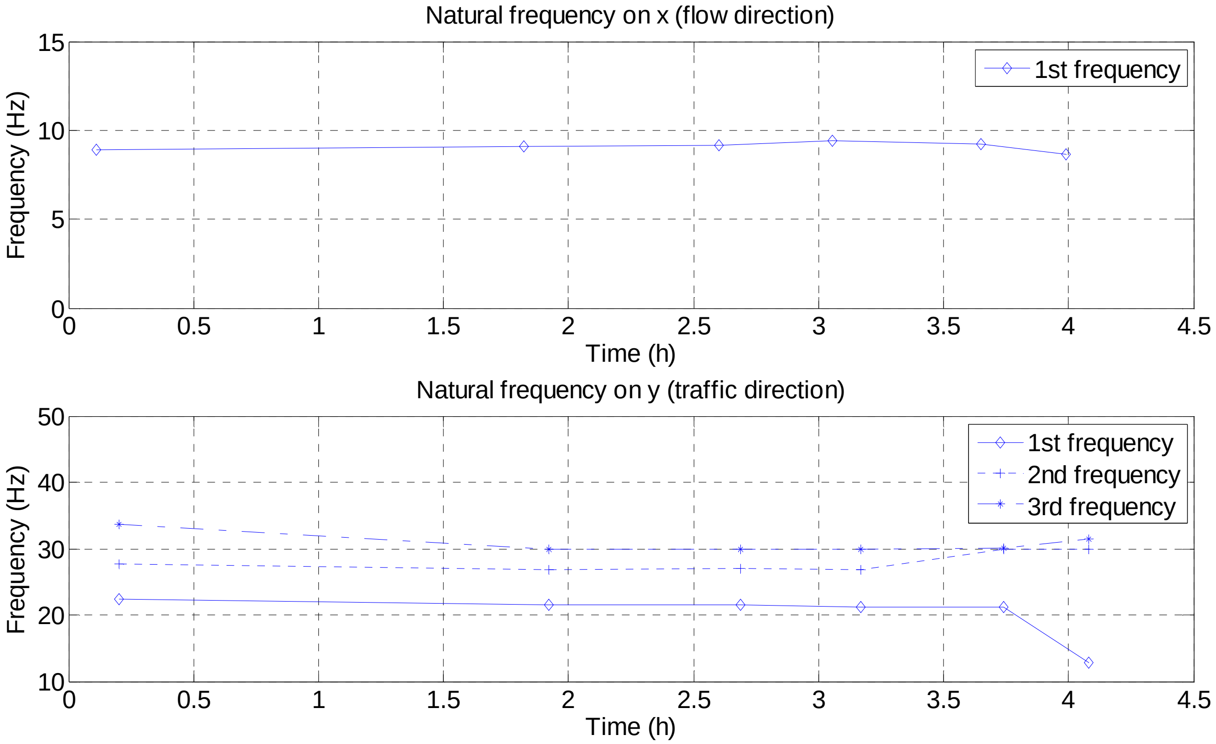


Figure 4-36. Time History of Frequency in Two Directions.

Similar to the analysis performed in the shallow foundation experiment, the ratio of RMS of acceleration analysis approach is followed for the deep foundation experiment. The time history of accelerations obtained during the experiment is divided into 12 time intervals as before. Here, the combined impact test in each time interval is taken into account as a whole. The RMS value is sensitive to the duration of impact test taken to perform the analysis, so only six periods of impact tests are chosen to do the RMS analysis. The time history of the ratio of RMS in two directions for the entire duration of the experiment is plotted in Figure 4-37, which shows a clear change in the ratio of RMS after 3.75 h, when the scour hole reached the bottom of the column and the column started to settle and rock. This trend is similar to that obtained by the FFT analysis.

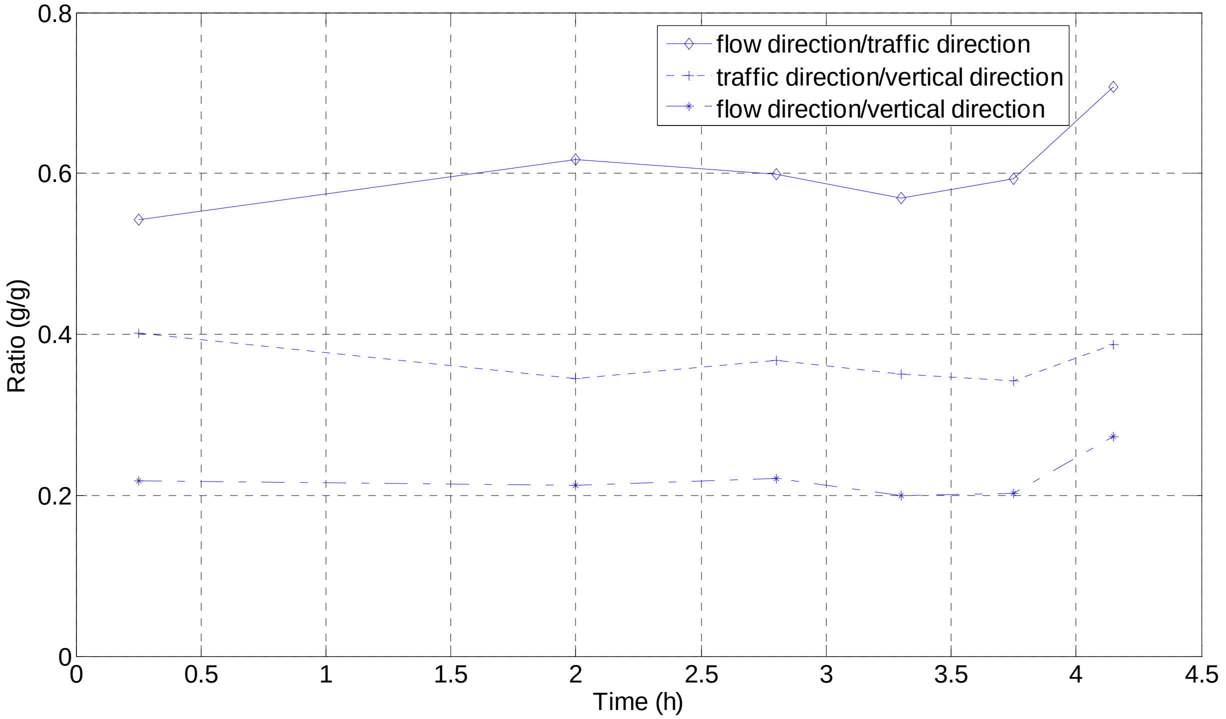


Figure 4-37. Time History of Ratio of RMS.

Tiltmeter

Figure 4-38 shows the time history of the tiltmeter reading for the entire duration of the experiment. The upper graph in Figure 4-38 shows the tilt angle of the slab around the flow direction axis, and the lower graph shows the tilt angle of the slab around the traffic direction axis. The tilt angle of the slab around the flow direction axis varied significantly after 3.75 h, at the instant when the scour hole reached the bottom of the column and the column started to settle and rock. The tilt readings do not show indication of the starting of the scour hole. The qualitative results of tilt angle readings are in agreement with the FFT and ratio of RMS analysis.

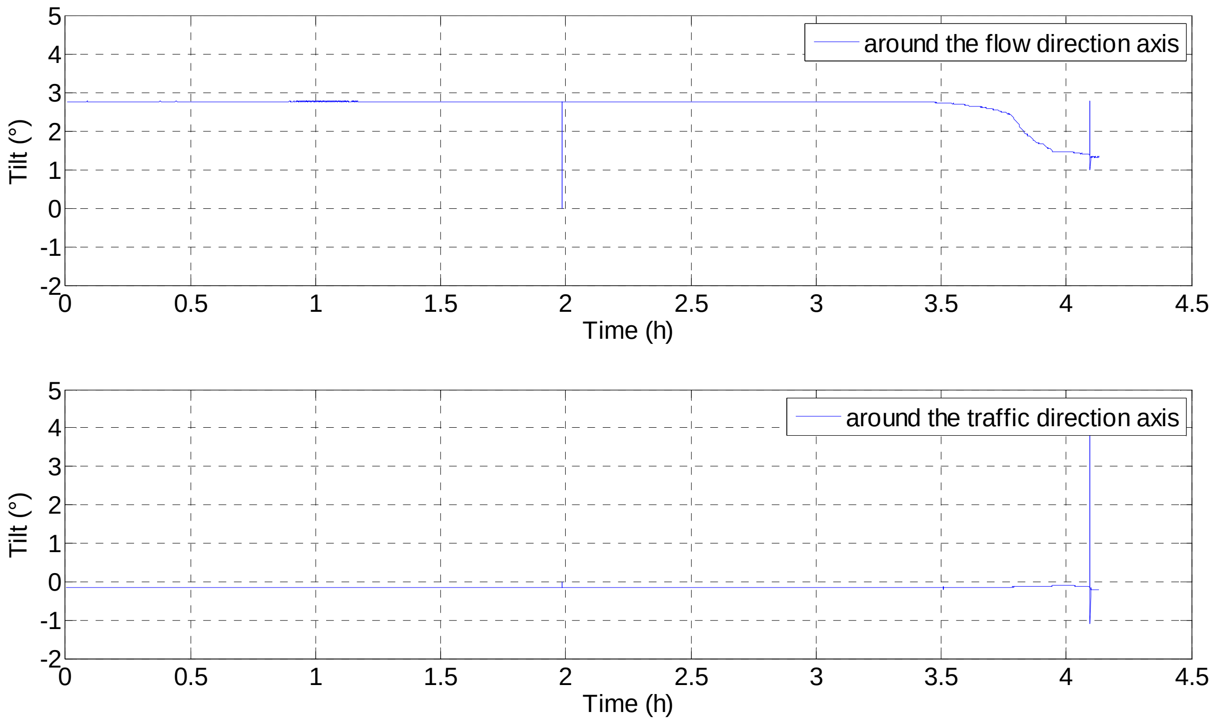


Figure 4-38. Time History of Angle Recorded by Tiltmeter.

Tethered Buried Switch

If the TBS is in a vertical position and the trigger has not been launched, the sensor transmits a value of 1 to the data acquisition system. If the switch is triggered and the scour reaches the buried level, the sensor transmits a value of 2 to the data acquisition system. If the wire of the switch is broken, the sensor transmits a value of 3 to the data acquisition system.

Figure 4-39 shows the time history of the response of TBS. It is observed that the TBS did not float out since it kept transmitting a value of 1 to the datalogger. It means the scour depth did not reach 0.3 m (1 ft) at the location of TBS by the end of the experiment. TBS was buried on the left side of the column, where the scour depth was measured to be 0.28 m (0.85 ft) at the end of experiment, which is less than the buried depth of the TBS. It is concluded from the readings of the instruments that after 3.75 h, the scour depth reached 0.15 m (0.5 ft) depth, which is the bottom of the column, but did not reach 0.3 m (1 ft) by the end of the experiment.

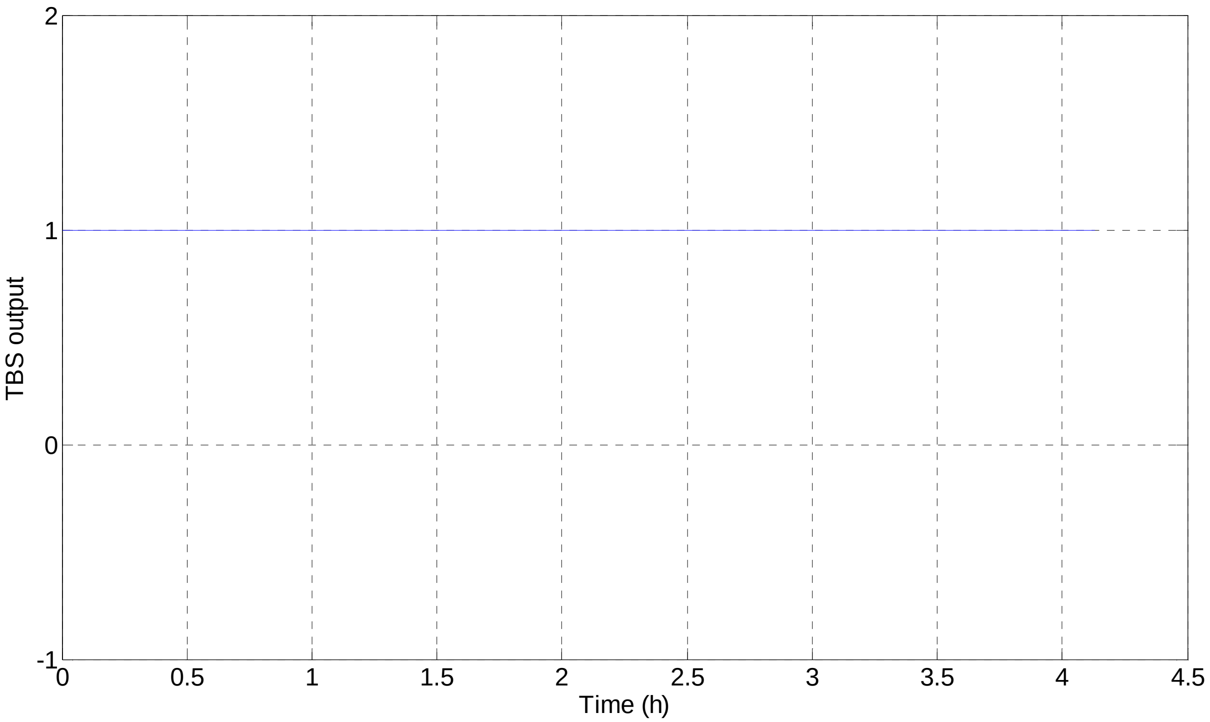


Figure 4-39. Response Time History of TBS.

Water Stage Sensor

The water stage sensor was mounted on the steel beam at a height of 3.3 m (11 ft) above the sand surface. Figure 4-40 shows the time history of the response of the water stage sensor. The water stage sensor measures the distance between the sensor and the water surface. Before the tank was filled with water, the water stage sensor recorded a reading of 3.3 m (11 ft), which is the distance between the sensor head and the soil surface. Then the tank was filled with water until the water level reached a height of 1.0 m (3.3 ft) in the flume. The water stage sensor should record a reading of 2.31 m (7.7 ft), which is the distance between the sensor and upper surface of the water. The water stage sensor gave correct data at the beginning of the experiment and around 1.2 h from the start of the experiment.

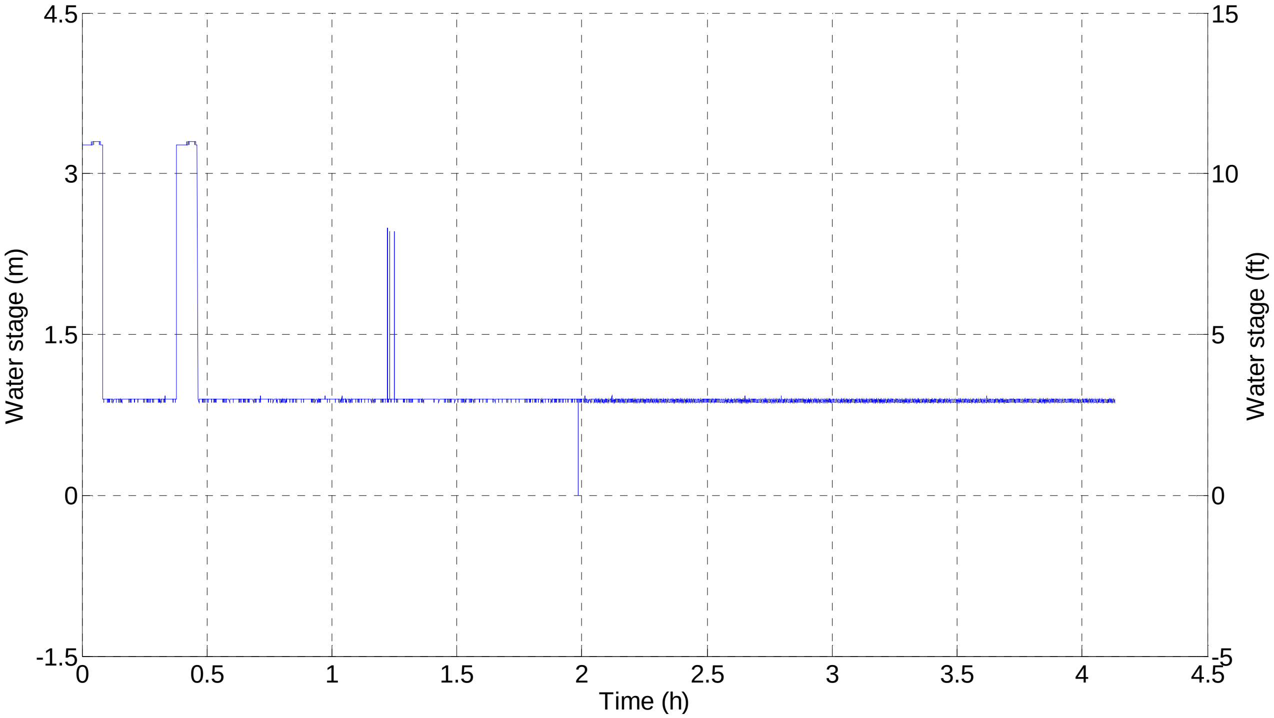


Figure 4-40. Response Time History of Water Stage Sensor.

Sonar Sensor

Figure 4-41 shows the time history of the sonar sensor reading. The sonar sensor reading began to increase after 3 h from the start of the experiment, indicating the start of the formation of the scour hole. After 3.75 h the sonar sensor reading began to decrease, which was caused by the settlement of the column on which the sonar was mounted. The observed trends are in agreement with the readings from the other instruments.

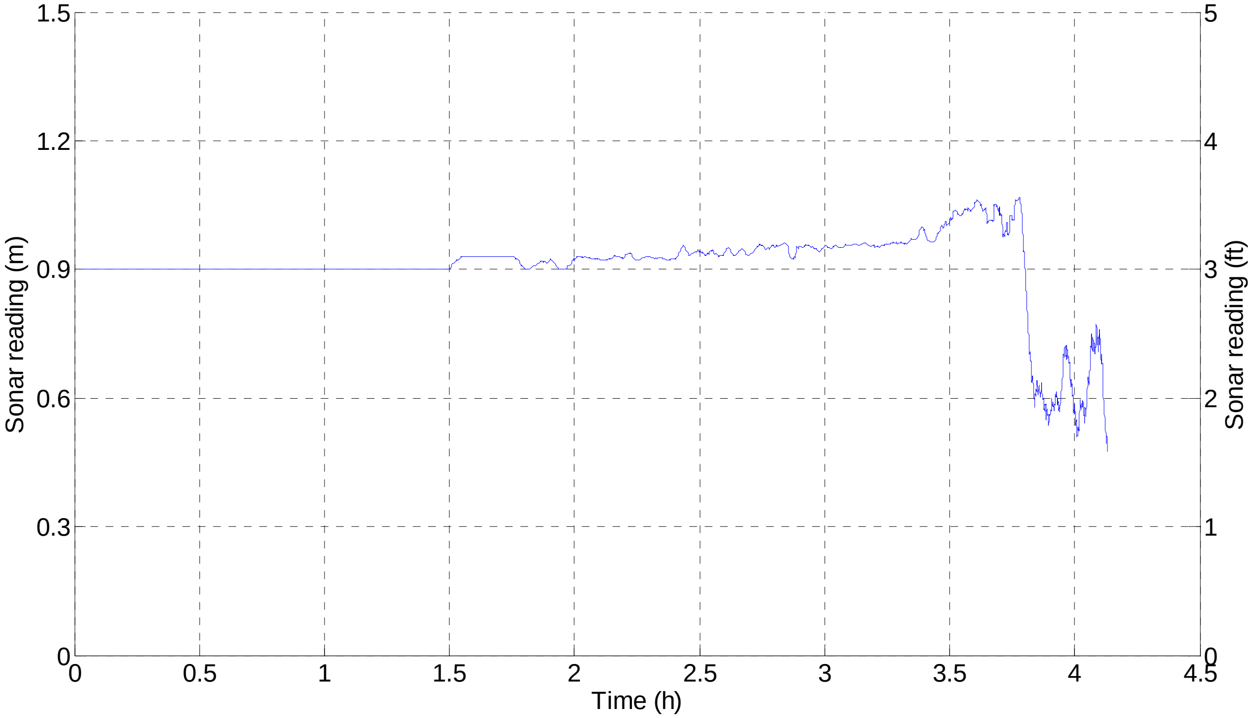


Figure 4-41. Response Time History Sonar Sensor.

Acoustic Doppler Velocimeter

The ADV was installed in the upstream side of the flume to measure the water velocity during the experiment. Figure 4-42 shows the time history of the water velocity. The gap in data from 0 hour to 2.5 h is due to the fact that the water was given a velocity after 2.5 h when a hydrostatic condition was reached in the flume. Based on the analysis of the data obtained from the instruments it is inferred that the scour hole started to develop when the water velocity was 0.36 m/s (1.2 ft/s) in the experiment, and it reached the bottom of column when the water velocity was 0.60 m/s (2 ft/s). The bridge suddenly failed when the water velocity was 80 cm/s (2.6 ft/s). The water velocity data are used for the prediction of the scour hole by performing SRICOS-EFA simulation.

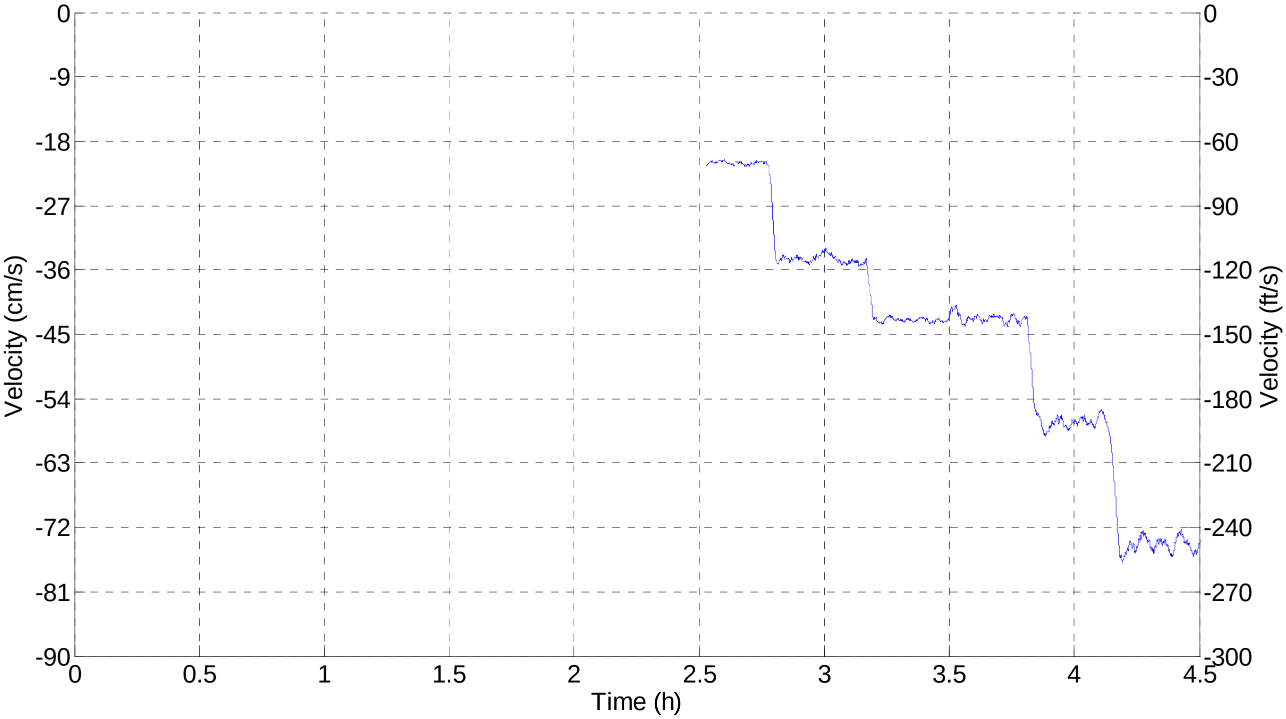


Figure 4-42. Response Time History of ADV.

Discussion

The trends observed in results of the data analysis using FFT, ratio of RMS, tiltmeter readings, and sonar readings are similar. Figure 4-43 shows a combined plot of all the above analysis. The top graph shows the time history plot of the first natural frequency of the model bridge in both flow direction (*x*) and traffic direction (*y*); the graph below shows the time history plot of the ratio of RMS values of the acceleration in the flow direction over traffic direction (*x*/*y*), the ratio of RMS values of the acceleration in the traffic direction over vertical direction (*y*/*z*), the ratio of RMS values of the acceleration in the flow direction over vertical direction (*x*/*z*). The third plot shows the time history plot of the tilt of the deck around the flow direction axis; and the bottom graph shows the time history plot of the sonar reading for the entire duration of the experiment.

The tilt sensor recorded tilt of the deck at 3.75 h when the scour hole became deep enough that the column started to settle and rock. Figure 4-43 also indicates that natural frequency of the system in both flow and traffic direction dropped at 3.75 h when the scour hole reached the bottom of column and the stiffness of the system decreased. The ratio of RMS value of acceleration in flow direction over traffic direction also changed significantly at 3.75 h due to the stiffness change in the system. The ratio of RMS value of acceleration in traffic direction over vertical direction and the ratio of RMS value of acceleration in flow direction over vertical direction also changed slightly at 3.75 h after start. The start of the scour hole was confirmed by the sonar measurements, which showed a scour starting to develop shortly after 3 h. The sonar data then indicated that the scour hole increased 0.15 m (0.5 ft), which is the depth of the embedded column, until the column started to settle. Because the sonar was mounted on the column, the sonar did not show an increase in scour hole after the column started to settle. The decrease in sonar sensor reading after 3.75 h indicated that the settlement of the column was faster than the generation of scour hole, which is typical for pile foundation. Therefore, frequency change, ratio of RMS values of acceleration, and tilt are sensitive parameters for scour prediction. Both accelerometer and tiltmeter can be used to monitor bridge scour in the laboratory.

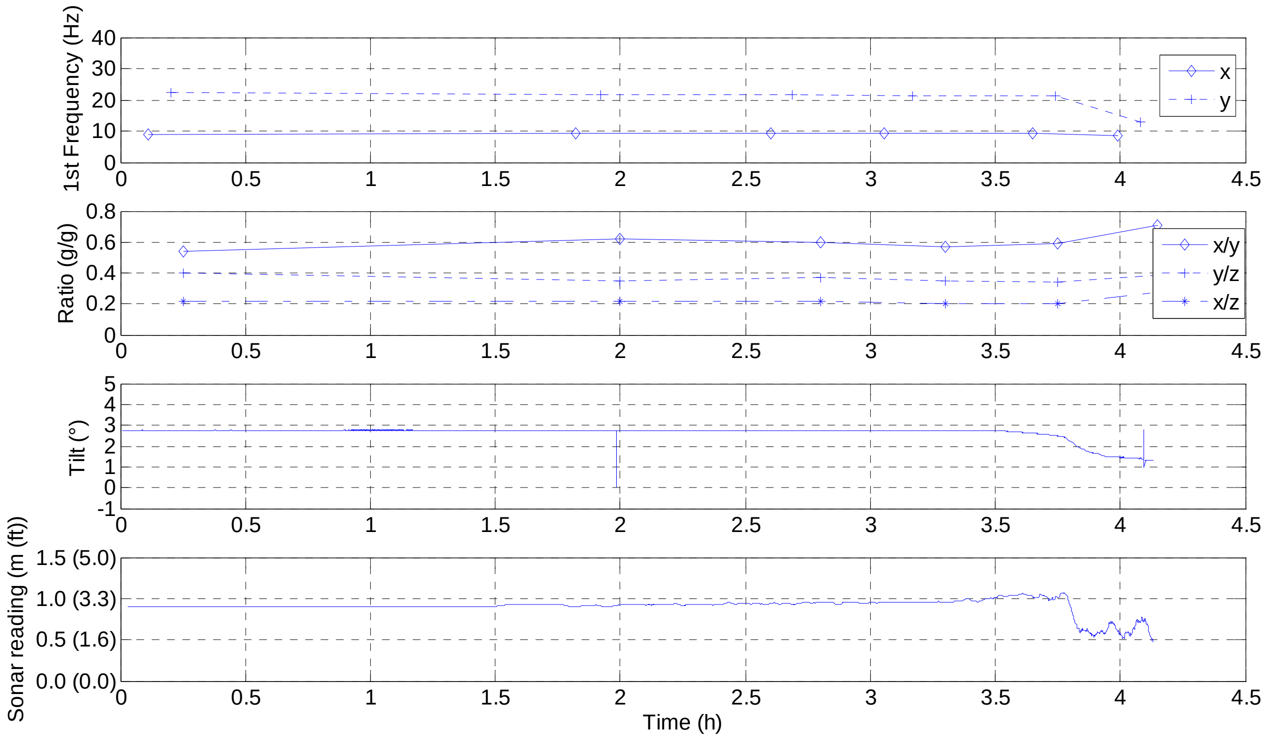


Figure 4-43. Response Time History of the Installed Instruments.

NUMERICAL SIMULATION

Introduction

The response quantities of bridges affected by development of scour need to be identified and defined before actual scour depth becomes critical. Numerical simulations can model the scenarios when the scour depth becomes critical. The simulation helps in monitoring and identifying various quantities of interest. Numerical simulation for the laboratory experiment is performed. Using numerical simulation, different scenarios of scour are generated. Using these different cases, the effect of the scour on quantities of interest is studied. The sensitivity of the quantities of interest with scour can be identified and a recommendation is made for the most critical quantity. These parametric studies can be used to establish relation between the scour and monitored quantities. The critical condition for bridge failure will be identified from the simulations, and suitable warning criteria can be laid. The ratio of RMS of accelerations and change in natural frequency are investigated.

In this study, the commercial finite element program LS-DYNA is used for the analysis. The finite element (FE) models considered in this study are generated by HyperMesh. The report is organized into three sections. Following the introduction section, the numerical simulations of the laboratory experiments are described. The part is divided into explanation of the shallow foundation experiment and the deep foundation experiment. In the shallow foundation section, the natural frequency analysis and the dynamic excitation is described. In the deep foundation, the natural frequency analysis is described.

Finite Element Model

Two scour experiments are simulated using the FE method and a parametric study is undertaken. An eigenvalue analysis is carried out to identify the predominant mode shapes and frequencies and their variation as the scour hole deepens. The results are compared to the experimental data.

The mesh matches the dimensions of the experiment performed in the laboratory. The material properties are obtained by a combination of field testing and manufacturer specifications. The material properties used are as follows (Table 4-2).

Table 4-2. Material Property of Concrete and Soil.

Material	Density	Modulus of elasticity	Poisson's ratio	Unconfined compressive strength	Unconfined tensile strength	Yield stress
	(kg/m^3) (lb/ft^3)	(GPa) (psi)		(MPa) (psi)	(MPa) (psi)	(MPa) (psi)
Concrete	2500 (156.2)	27.0 (3916017)	0.2	30.0 (4351)	0.0 (0.0)	-
Soil	1982 (123.8)	0.012 (1740)	0.35	-	-	

The soil and the concrete are considered elastic. A strain rate dependent elasto-plastic model is used as the material model for the rebars, which are represented explicitly using a one-dimensional element. The contact between the concrete and reinforcements make use of the Lagrangian coupling method. The column, slab, supports, and soil are modeled by a fully integrated quadratic eight node element with nodal rotations. Mesh refinement is done to achieve convergence. The eigenvalue analysis is performed using the lanczos solver.

The penalty method is used to model the contacts between the different elements. In this method normal interface springs are placed between all penetrating nodes and the contact surfaces. The method is stable, and it does not excite mesh hourglassing. It is capable of handling contacts between dissimilar materials, which is well suited for this study.

Shallow Foundation

In the shallow foundation model, the column was embedded in the soil for 0.3 m (1 ft). The reinforced concrete slab rested on the column and on the rail supports. The slab supports were modeled as rigid elements with fixed end conditions at the base. No constraint was applied to the slab, which was free to displace. The boundary condition for the soil block was fixed on the four faces and at the base. This is done to simulate the conditions in the laboratory where the soil is surrounded by concrete walls. In this study, the water is not included except that the soil unit weight is the saturated unit weight. The presence of the scour hole is simulated by changing the contour of the mesh along the soil surface. The scour depth varies in increments of one third of the total embedment of the column, which is 0.3 m (1 ft). Four conditions are simulated:

- No scour, column embedded 0.3 m (1 ft) in the soil (Figure 4-44).

- Scour, column embedded 0.2 m (0.66 ft).
- Scour, column embedded 0.1 m (0.33 ft).
- Scour, column embedded 0 m (0 ft) (Figure 4-45) (the system started to settle at that point).

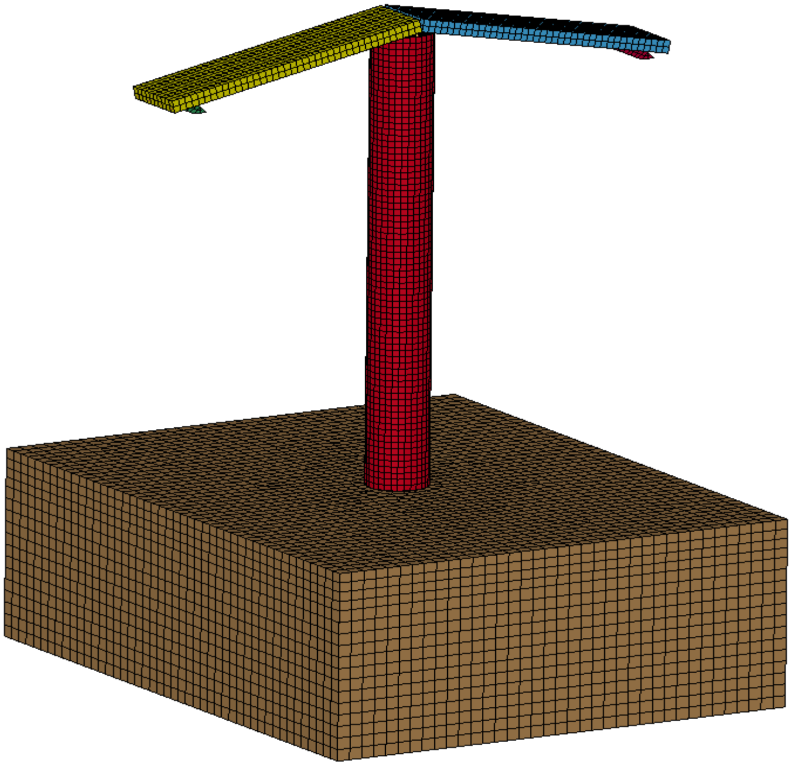


Figure 4-44. FE Model for Shallow Foundation without Scour.

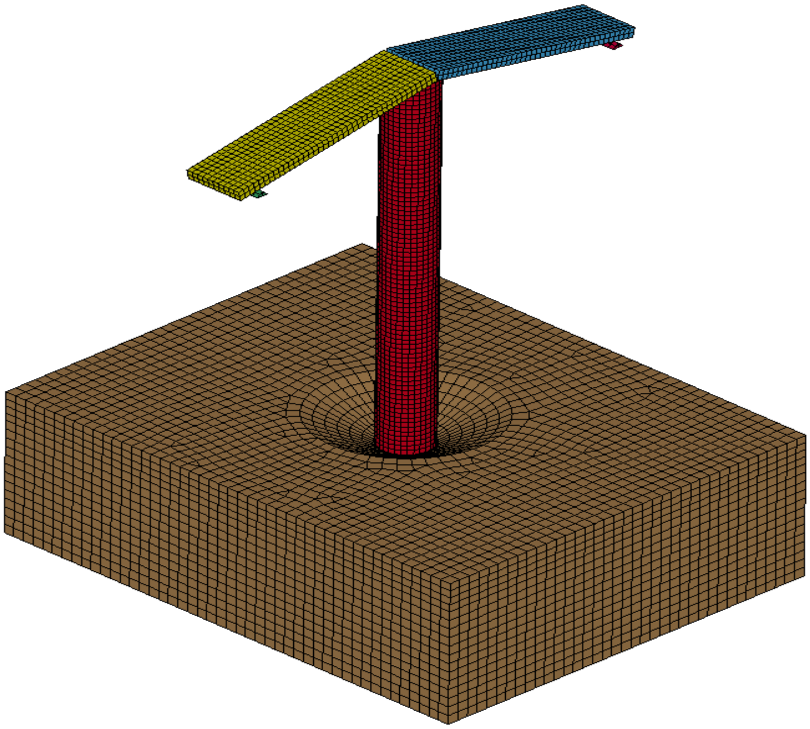


Figure 4-45. FE Model for Shallow Foundation with Full Developed Scour of 0.3 m (1 ft).

Natural Frequency Analysis. The natural frequency analysis gives the frequencies and mode shapes of the entire system. The total response of the system is the combination of these modes. A parametric study is performed by varying the depth of the scour as mentioned above. Figure 4-46 shows the mode shape of the shallow foundation with no scour hole. The mode is in the flow direction.

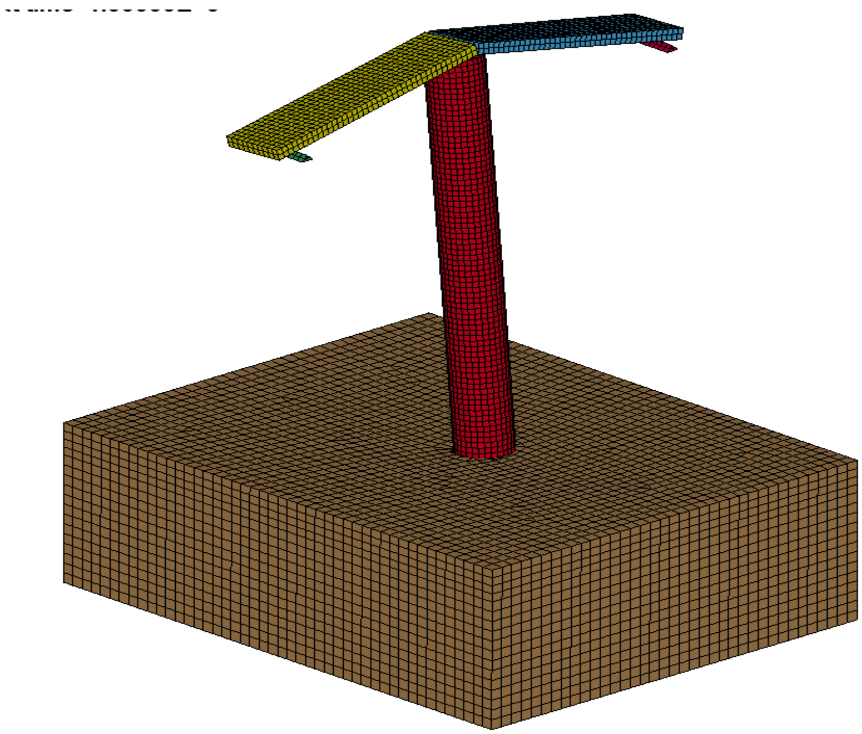


Figure 4-46. Mode Shape of Shallow Foundation Experiment in Flow Direction with No Scour (Natural Frequency = 10.236 Hz).

Figure 4-47 shows the mode shape of the shallow foundation with a fully developed scour hole of 0.3 m (1 ft). The mode is in the flow direction. There is a significant drop in the frequency from 10.236 Hz to 4.223 Hz. Figure 4-48 shows the mode shape of the shallow foundation with no scour. The mode is in the traffic direction.

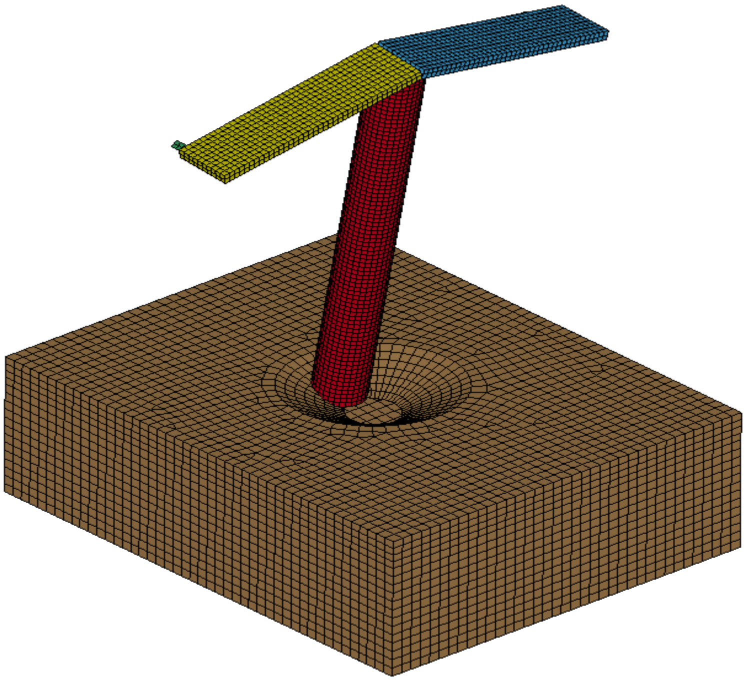


Figure 4-47. Mode Shape of Shallow Foundation Experiment in Flow Direction with Full Scour (Natural Frequency = 4.223 Hz).

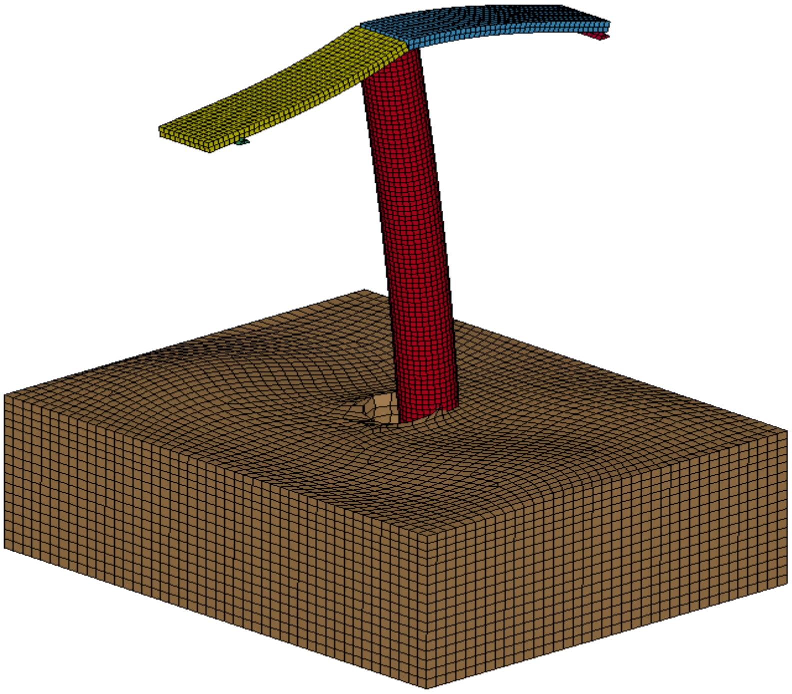


Figure 4-48. Mode Shape of Shallow Foundation Experiment in Traffic Direction with No Scour (Natural Frequency = 20.217 Hz).

Figure 4-49 shows the mode shape of the shallow foundation with a fully developed scour hole of 0.3 m (1 ft). The mode is in the traffic direction. There is nominal drop in the frequency from 20.217 Hz to 18.662 Hz.

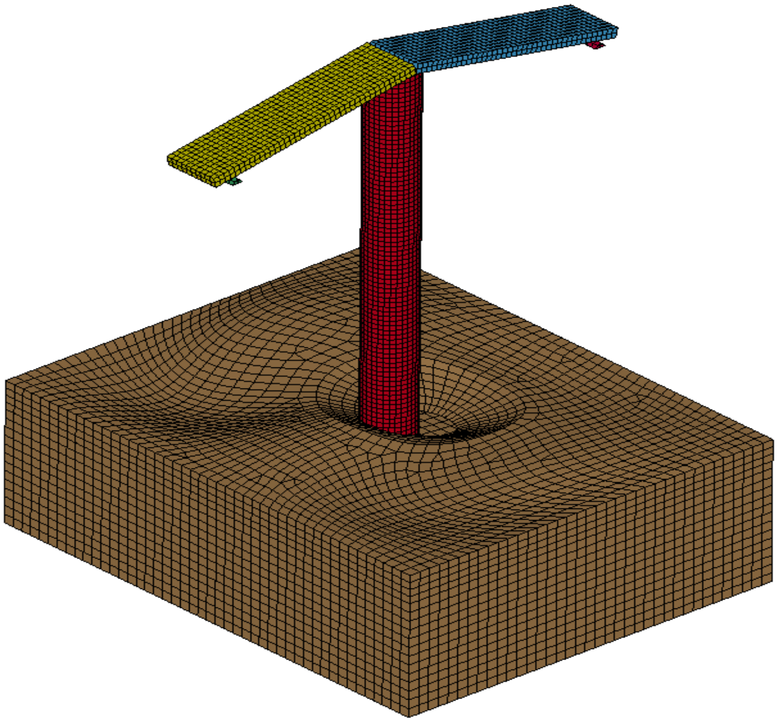


Figure 4-49. Mode Shape of Shallow Foundation Experiment in Traffic Direction with Full Scour (Natural Frequency = 18.662 Hz).

Figure 4-50 shows the variation of the natural frequency with the progress of the scour hole for the shallow foundation. The frequency of the system depends on the boundary conditions, the material properties, and the geometric properties. The material and geometric properties remains the same during the formation of the scour hole. The boundary conditions change due to the formation of the scour hole. Initially, the column has the largest embedment in the soil, which provides restraint to the system. This condition is between a free and a fixed condition. As the scour progresses, the soil is eroded, the effective embedment decreases and so does the restraint. These results in a shift in the boundary condition closer to a free condition (lower frequency) due to a decrease in the effective horizontal stiffness provided to the column by the soil. The natural frequency in flow direction is sensitive with the progress of scour depth.

The numerical simulation results compares well with the results obtained from the laboratory experiment.

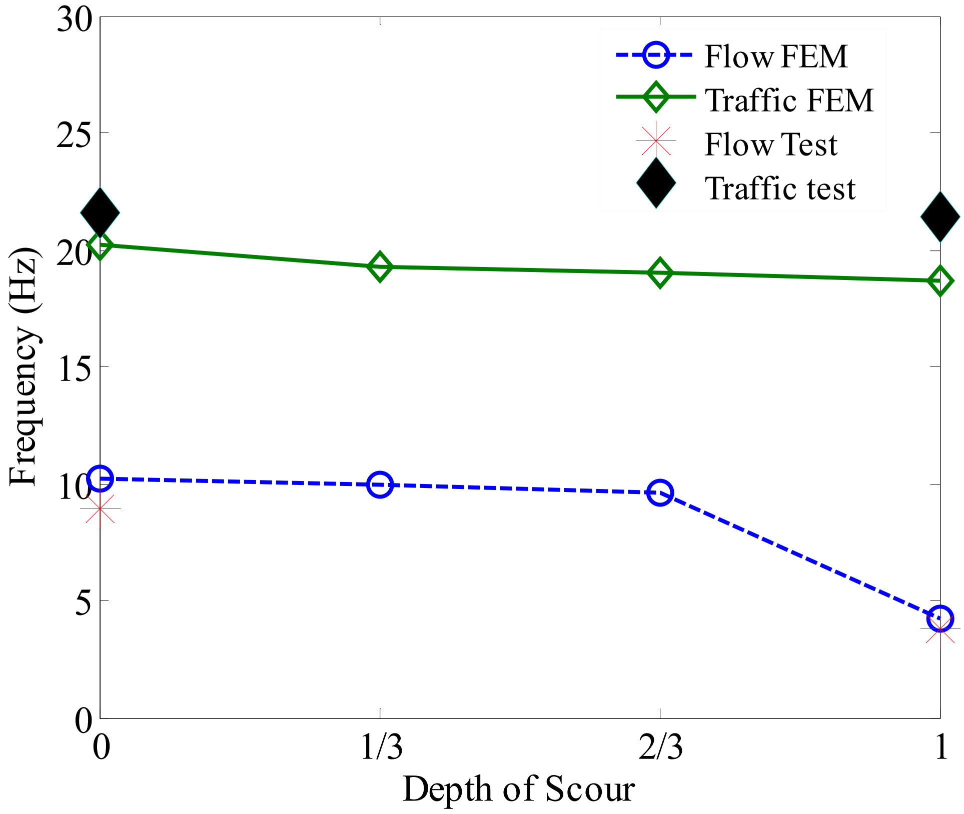


Figure 4-50. Variation of Frequencies with Depth of Scour for Shallow Foundation Experiment.

Dynamic Excitation. A dynamic analysis is performed to study the effect of change in scour depth to the acceleration in the system. The acceleration at the top of the piers is monitored. The ratio of the RMS of the acceleration is the quantity used for the parametric study.

Figure 4-51 shows the variation of the ratio of RMS for the different scour depths. The ratio of RMS is normalized with the ratio of RMS when there is no scour. The result is presented as percentage change in the ratio of RMS for different directions. The ratio of RMS values of flow direction over traffic direction increases. The increase in RMS ratio is approximately 1.8 times. The ratio of RMS values of flow direction over vertical direction also increases. The increase in RMS ratio is approximately 1.4 times. The change ratio of RMS with scour depth follows a non linear increase with a steep increase as the scour progresses. The ratio of RMS values of traffic direction over vertical direction does not show any consistent trend.

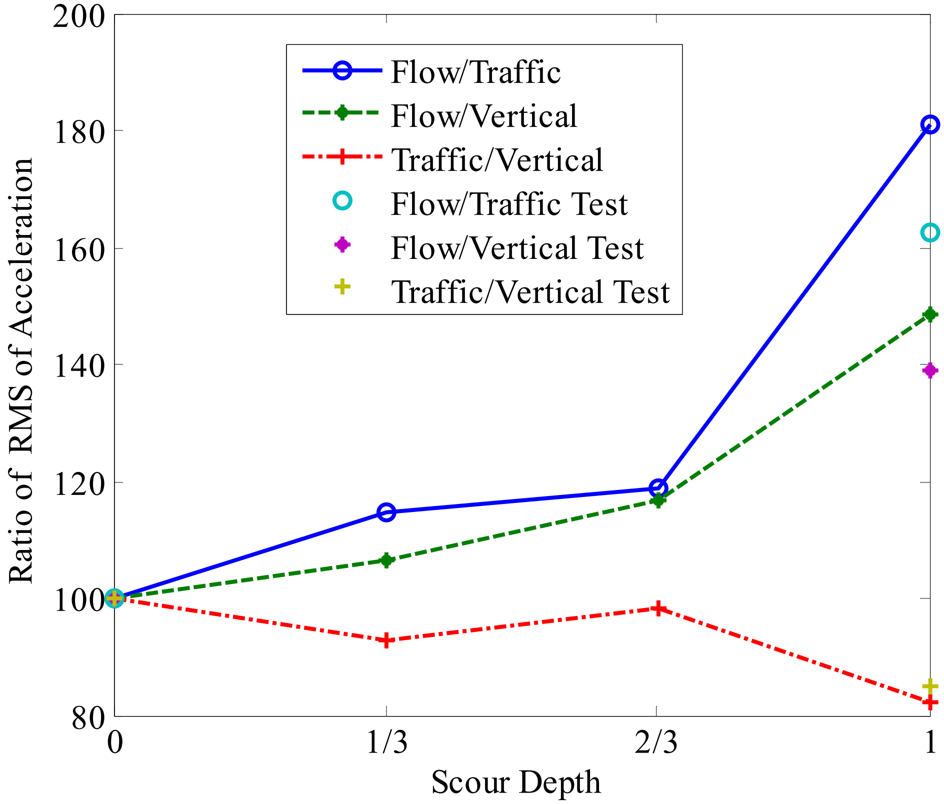


Figure 4-51. Variation of Ratio of RMS with Depth of Scour for Shallow Foundation.

The change in ratio of RMS is direction dependent. The magnitude of change is also direction dependent. The ratio of RMS values of flow direction over vertical direction and ratio of RMS values of flow direction over traffic direction are sensitive with the progress of scour. The numerical simulation results compares well with the results obtained from laboratory experiment.

Deep Foundation

In the deep foundation model, the column was embedded 0.15 m (0.5 ft) in the soil. The pile dimensions in the model match the dimensions in the experiment (0.3 m or 1 ft length). The other details of the modeling process are the same as for the shallow foundation case. The scour depth varies in increments of one third of the total embedment of the column and the pile, which was 0.45 m (1.5 ft). Therefore, four conditions are simulated:

- No scour, column embedded 0.15 m (0.5 ft) in soil, pile embedded length 0.3 m (1 ft).
- Bottom of scour hole at the bottom of the column, pile embedded length 0.3 m (1 ft).

- Bottom of scour hole halfway through the pile embedment length, (failure of the system is observed near this point 0.32 m (1.08 ft) in the experiment).
- Bottom of scour hole at the bottom of the piles.

Natural Frequency Analysis. The natural frequency analysis gives the frequencies and mode shapes of the entire system. The total response of the system was the combination of these modes. A parametric study was performed by varying the depth of the scour as mentioned above.

Figure 4-52 shows the mode shape of the deep foundation with no scour. The mode is in the flow direction. Figure 4-53 shows the mode shape of the deep foundation with a fully developed scour hole of 0.45 m (1.5 ft). The mode is in the flow direction. There is a significant drop in the frequency from 9.394 Hz to 1.594 Hz.

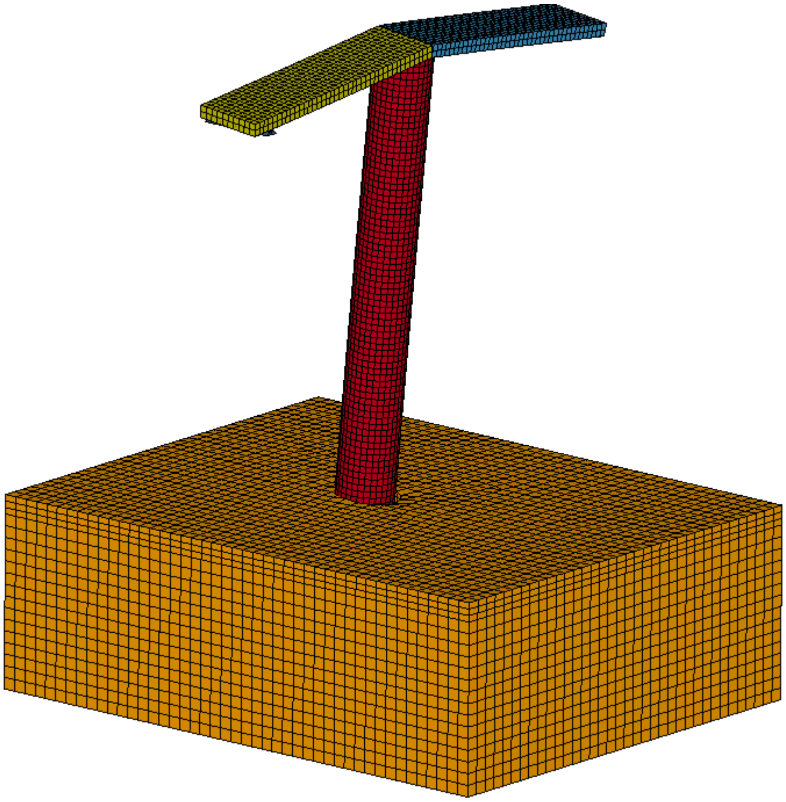


Figure 4-52. Mode Shape of Deep Foundation Experiment in Flow Direction with No Scour (Natural Frequency = 9.394 Hz).

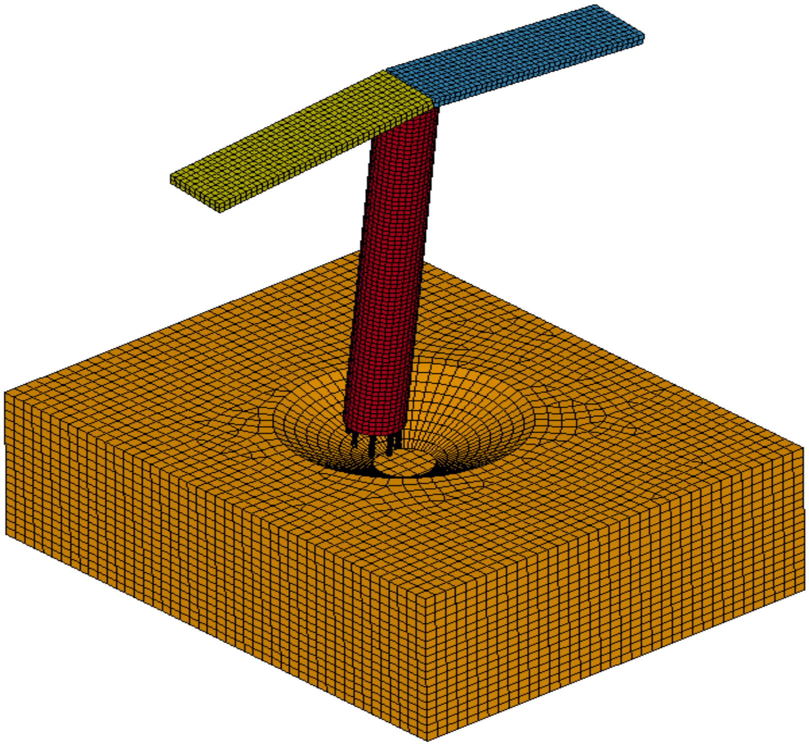


Figure 4-53. Mode Shape of Deep Foundation Experiment in Flow Direction with Full Scour (Natural Frequency = 1.594 Hz).

Figure 4-54 shows the mode shape of the deep foundation with no scour. The mode is in the traffic direction. Figure 4-55 shows the mode shape of the deep foundation with a fully developed scour hole of 0.45 m (1.5 ft). The mode is in the traffic direction. There is nominal drop in the frequency from 20.149 Hz to 14.067 Hz. This trend is consistent with the trend observed in the shallow foundation.

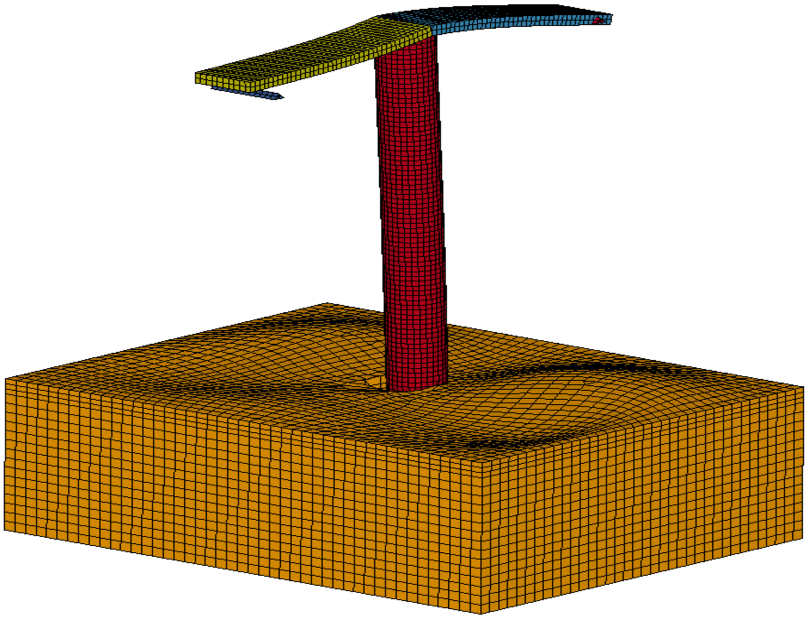


Figure 4-54. Mode Shape of Deep Foundation Experiment in Traffic Direction with No Scour (Natural Frequency = 20.149 Hz).

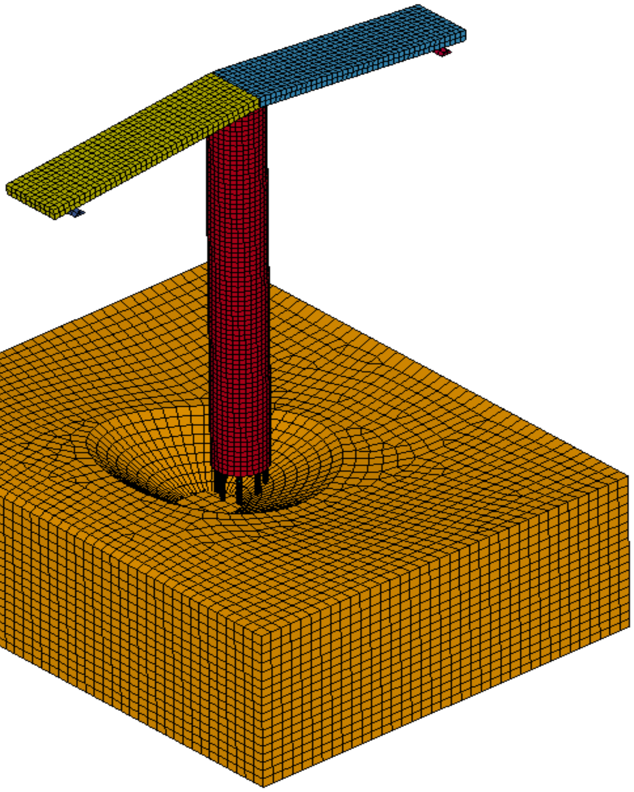


Figure 4-55. Mode Shape of Deep Foundation Experiment in Traffic Direction with Full Scour (Natural Frequency = 14.067 Hz).

Figure 4-56 shows the variation of the natural frequency with the progress of the scour hole for the deep foundation. The trend compares well with the trend observed for the shallow foundation. The natural frequency in the flow direction is significantly affected with the progress of the scour. This is due to the decrease in retrain provided by the soil in the flow direction. With the decrease in the restraint, the stiffness also decreases. In the traffic direction, the slab restraint prevents the stiffness to be dramatically affected by the change in scour depth. Hence the decrease is less dominant. But as the scour progresses, frequency in flow direction decreases significantly while the frequency in the traffic direction remains constant.

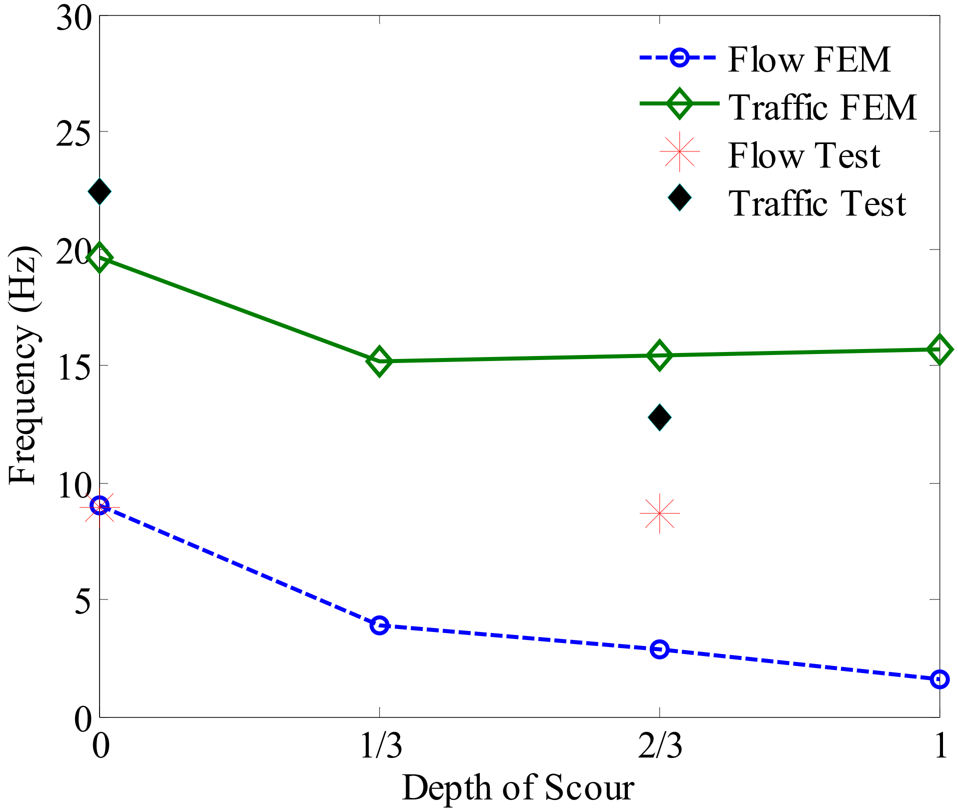


Figure 4-56. Variation of Frequencies with Depth of Scour for Deep Foundation Experiment.

ONLINE DATA MONITORING USING WEBSITE

The Scour Monitoring Center website address is: http://scour.civil.tamu.edu. Once you log into the website, you will see three projects in the project list: Laboratory Experiments, US59 over Guadalupe River, and SH80 at San Antonio River. Click on each of them, and you will be directed to the webpage of the particular project. One photo and one schematic of instrumentation are shown for each project. Click on the photo of the project, and you will see the plots of sensors' readings during that project. Since the dataloggers on the two bridges are transmitting data every 10 minutes, the idea for the monitoring website is to show the real-time plots every 10 minutes. Therefore, the webpage should be refreshed every 10 minutes, but currently this is not the case for the laboratory experiments webpage.

For the laboratory test webpage, since we already finished the experiments in 2009, there will be no new data coming into the server. We simply put one group of data in the server to generate plots. The webpage for the laboratory test will not be refreshed every 10 minutes.

During the experiments, we used one accelerometer (three plots for acceleration in three directions), one dual-axis tiltmeter (two plots for tilt angle around the flow directions axis and traffic direction axis), one water stage sensor (water level), one sonar sensor (scour depth), and one float-out device (scour level reached). Therefore, eight figures are shown on this webpage.

1. "Acceleration in the flow direction," "Acceleration in the traffic direction," and "Acceleration in the vertical direction" plots show the acceleration detected by the accelerometer over 90 seconds period. The unit for the accelerometer is the number of g's (acceleration due to gravity).
2. "Sonar Reading" plot shows the distance between the sensor and the soil surface during the experiment. The unit for the sonar reading is feet.
3. "Tilt angle around the flow direction axis" and "Tilt angle around the traffic direction axis" plots show the tilt angle of the slab around the flow direction axis and the traffic direction axis respectively. The unit is degree.
4. "Water Stage" plot shows the distance between the sensor and the water surface during the experiment. The unit for the sonar depth is feet.
5. "Float-out" plot shows the information of the float-out device.
   - If the float-out device is working properly, and has not floated out, the plot will show a smiling face.
   - If the scour hole becomes deep enough that the float-out device floats out, the plot will show a danger sign.
   - Since the sensor was removed in 2009, there is a danger sign, which means the float-out sensor has floated out.

CONCLUSION

This chapter describes two large scale laboratory experiments performed in Haynes Coastal Engineering Laboratory at Texas A&M University. Both the shallow foundation experiment and the deep foundation experiment give promising results that the accelerometer can be used to predict bridge failure as well as tiltmeter and sonar sensor. The FFT approach as well as RMS approach is proved to be effective to analyze the accelerometer data as they showed significant change when the scour depth reached the bottom of the column, and the column started to settle and rock. The numerical simulation identifies the quantities of natural frequency in flow direction and ratio of RMS of acceleration in flow direction over traffic direction and in flow direction over vertical direction to be indicators of the progress of scour. The experimental and numerical simulation results agree well. The tiltmeter was reliable, stable, and robust. Both the float-out device and the TBS worked very well during the experiment; both of them showed great potential to be applied in the field to monitor scour events. The sonar sensor worked well as long as the minimum water depth of 0.6 m (2 ft) was met. Note that the sonar sensor cannot predict scour depth if the sonar sensor is attached to the column and the column starts to settle. Indeed, then the sonar sensor also settles. If this is not a problem, the sonar sensor can be used to monitor scour depth at that location. The water stage sensor did not work very well in these two experiments. The two laboratory experiments show great potential of monitors to be used in scour monitoring events.

CHAPTER 5:
SCOUR MONITORING OF US59 OVER GUADALUPE RIVER BRIDGE

INTRODUCTION

The failure of bridges due to scour problem has become a predominant cause. A scour monitoring system is developed in the present research to monitor the response of bridges that are affected by the scour. The responses are correlated with the development of scour to develop an early warning system. Numerical simulation is performed to study the worst case scenario of the scour development and the response of the bridge.

This chapter is organized into seven sections. Following the introduction, the bridge case history is described in the second section. In the third section, the installation of the scour monitoring system is discussed. The fourth section presents the data collection and analysis. The fifth section describes the numerical simulation. The monitoring process is described in the sixth section. Finally, the chapter concludes by presenting conclusions, recommendations, and budget.

THE BRIDGE CASE HISTORY

General Location of the Bridge

The southbound bridge on US59 crosses the Guadalupe River southwest of Victoria, Texas. Figure 5-1 and Figure 5-2 show the location of the bridge in Google Maps. In Figure 5-1, SB0 represents the northeast abutment, SB1 and SB2 represents the bents, and SB3 represents the southwest abutment of the bridge.

Figure 5-1. Layout of the Bridge with Convention (from Google Maps).

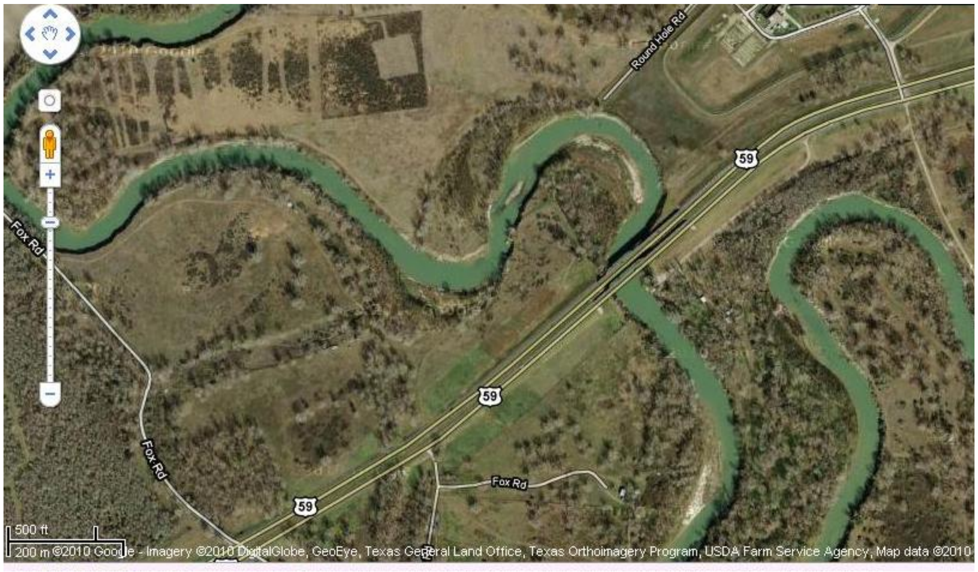


Figure 5-2. Current River Path in Bridge Area (from Google Maps).

Guadalupe River

The Guadalupe River flows from Kerr County, Texas, to San Antonio Bay in the Gulf of Mexico. The Guadalupe River has several dams along its length, the most notable of which forms Canyon Lake located northwest of New Braunfels.

The US59 over Guadalupe River Bridge is experiencing erosion problems in the form of stream migration and bridge scour. This has resulted in a threat to the integrity of the bridge structure. During the period between 1987 and 2002, the river bend upstream of the bridge on US59 has migrated approximately 81 m (270 ft) toward the northeast bridge abutment. The stream continues to migrate in that direction and has become a threat to the bridge and adjoining highway.

The Bridge Structure

The northbound and southbound of US59 over Guadalupe River Bridge are 111 m (333 ft) long with three spans. The bridge is supported by two web-wall piers. The foundation is made of H-piles extending to a depth of approximately 9 m (27 ft) below the pile cap. The pile cap is about 1 m (3 ft) below the river bed. Figure 5-3 shows the layout of the bridge.

The existing bridge is originally a three span pre-cast multiple beam structure built in 1967. In October 1998, the northbound bridge was lengthened by one span to the west as a protective measure after the record flood that year. In 2001, both northbound and southbound bridges were lengthened to the east by two spans as the river channel continued eroding in that direction. Currently, TxDOT is constructing the extension for both eastern and western sides on the southbound bridge (Figure 5-4).

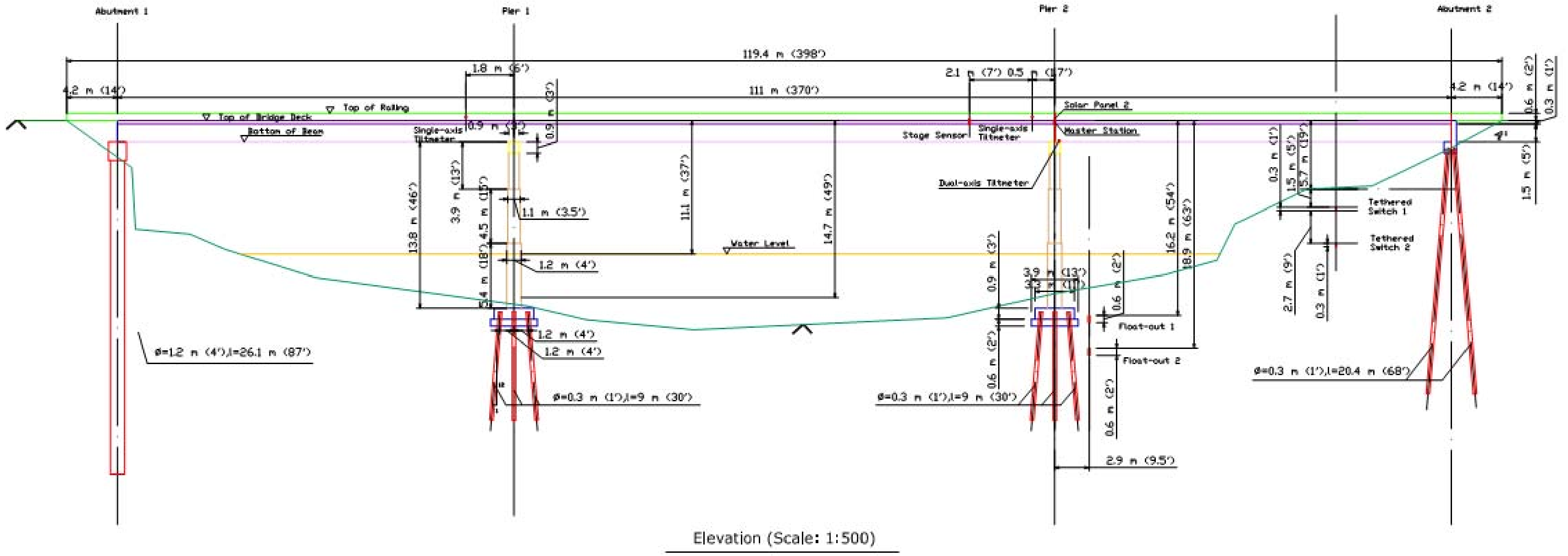


Figure 5-3. Layout of US59 over Guadalupe River Bridge.

Figure 5-4. Construction on the Extension of the Southbound Lane of US59 over Guadalupe River Bridge.

Soil

According to the 1982 soil survey for Victoria County by the Natural Recourses Conservation Service (NRCS), the bridge site lies within alluvial material known as the Meguin soil series. The soil is characterized by deep, moderately permeable, well drained clayey soils on flood plans. The overbank soil consists of surface layers of about 0.3 m (1 ft) of dark grayish-brown silty clay over 0.6 m to 1 m (2 to 3 ft) of grayish-brown silty clay loam. The soil survey describes these soils as having only a slight water erosion hazard, except in areas subject to stream bank caving. These soils are used for rangeland and are well suited to improved pastures of bermudagrass and kleingrass. During the site investigation and soil sample analysis, we concluded that the soil beneath the bridge varies significantly, with layers of all gradations from gravel to clay, tending toward silt and sand.

Scour Problem

A USGS recording stream gauge (No. 08176500) is located on the Guadalupe River in Victoria approximately 10.2 km (6.4 miles) upstream of the bridge. This is the closest gauge to the project site, with a contributing watershed area of 13306 km^2 (5198 square miles). Historical flow is available for this gauge dating from 1936 to the present. Annual peak storm flow records show that three of the top eight flood events have occurred since 1998. The Guadalupe River experienced its most severe flood on October 20, 1998, with a peak discharge of 13092 m^3/s (466000 ft^3/s). The fifth ranked peak flood was 2014 m^3/s (71700 ft^3/s) recorded on July 10, 2002. In contrast, the mean average daily flow for the stream based on gage records ranges from about 28 m^3/s (1000 ft^3/s) to near 196 m^3/s (7000 ft^3/s).

Due to the flood issue in Texas, the bridge is experiencing severe scour problem on both northeast side (SB0) and southwest side (SB3) of the river bank. This is seen in Figures 5-5 and Figure 5-6. On the northeast side of the bridge, the drill shaft was exposed in the 1998 flood. Figure 5-5 shows the status of the drill shaft in 2009. Figure 5-6 shows the drill shaft in 2010. From Figure 5-6, we concluded that the soil around the top of drill shaft has been flushed away during floods.

Figure 5-5. Drill Shaft on Northeast Side (SB0) of US59 over Guadalupe River Bridge in 2009.

Figure 5-6. Drill Shaft on Northeast Side (SB0) of US59 over Guadalupe River Bridge in 2010.

INSTALLATION OF THE MONITORING SYSTEM

The monitoring system was installed and started to transmit data to the server on May 28, 2009. The instruments during the initial installation included a hardwired accelerometer glued on the top of Pier SB2, a wireless accelerometer glued on the top of Pier SB1, one dual-axis tiltmeter bolted on the bridge deck to measure the tilt angle of the deck around two axes, one water stage sensor fixed to the bridge deck near the dual-axis tiltmeter to measure the water elevation, two float-out devices buried in a boring near the pile cap (SB2) at the depths of 0.6 m (2 ft) and 3.3 m (11 ft) below the pile cap (SB2), respectively, and two TBS, tethered sensors, which behave similarly to float-out devices buried near the southwest abutment SB3. The datalogger CR1000 collected data every 10 minutes and transmitted data by cellular modem to a remote server. A monitoring website shows real time plots of the data. Figure 5-7 shows the layout of the initial instrumentation on the US59 over Guadalupe River Bridge.

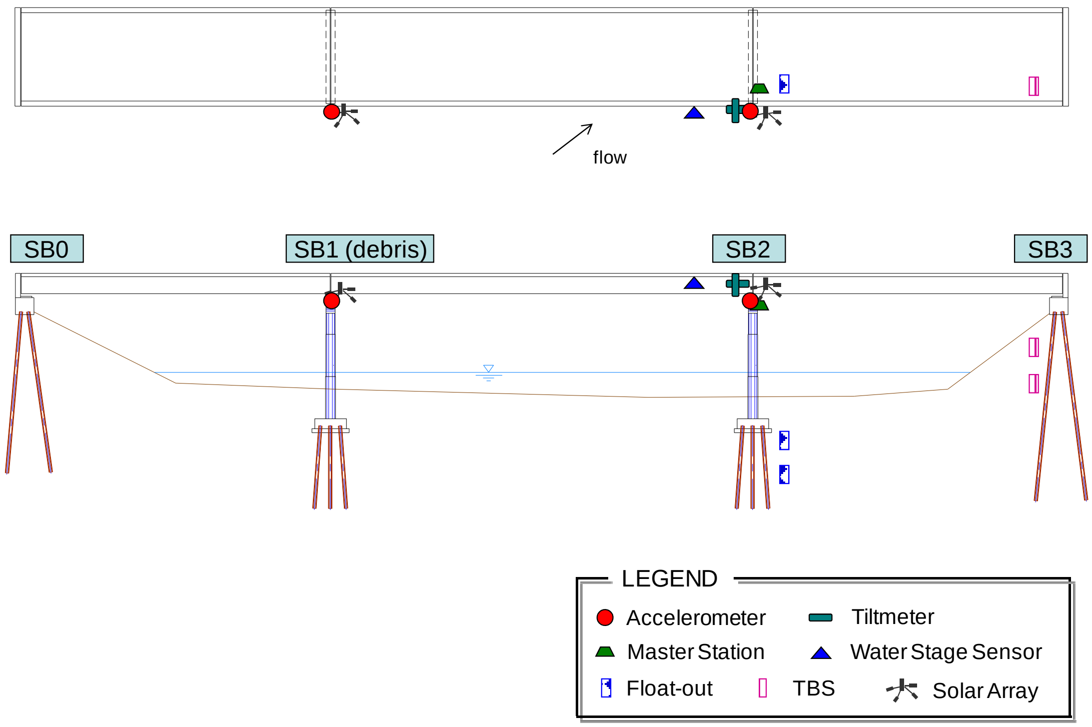


Figure 5-7. Schematics of Initial Instrumentation on US59 over Guadalupe River Bridge.

Due to the large amount of data transmitted by the accelerometer, more power was required than the initial estimate of the power consumption, thus the monitoring system was running out of power. Therefore, a modified monitoring system was installed on US59 over Guadalupe River Bridge on June 5, 2010. The two accelerometers were replaced by one dual-axis tiltmeter (Tiltmeter3 and Tiltmeter4) and two single-axis tiltmeters (Tiltmeter1 and Tiltmeter2) on the bridge. The water stage sensor, float-out devices, and TBS equipments remained at the same location. The datalogger was reprogrammed to transmit data every 20 minutes. Figure 5-8 shows the sketch of modified instrumentations on US 59 over Guadalupe River Bridge.

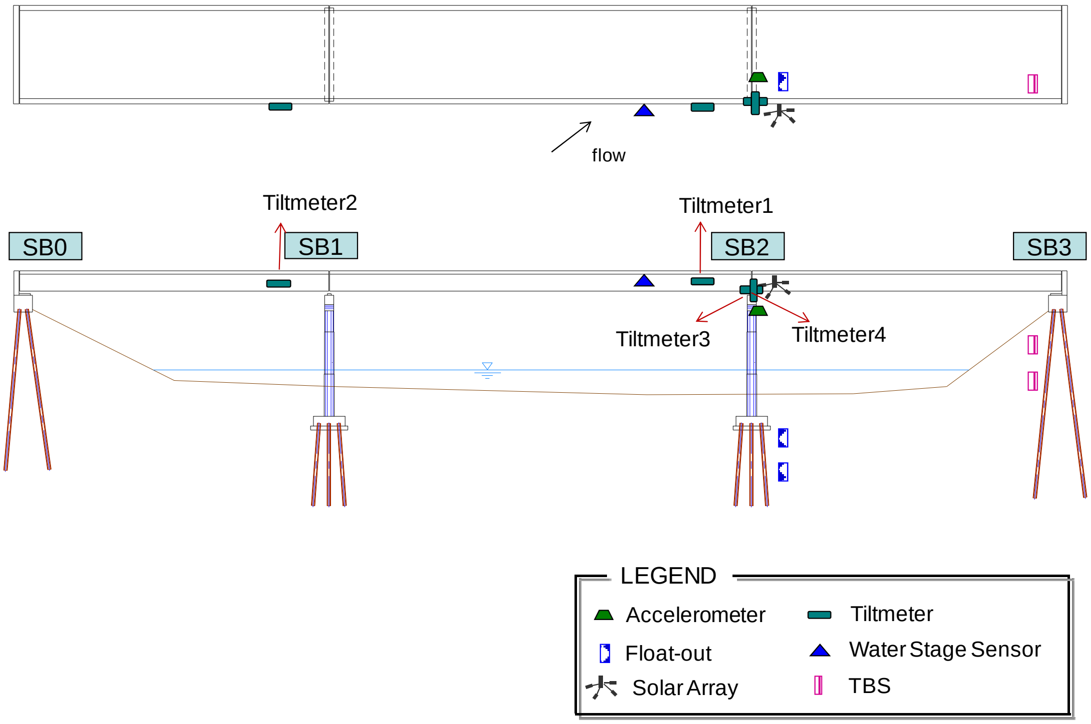


Figure 5-8. Schematics of Modified Instrumentation on US59 over Guadalupe River Bridge.

Schedule of Installation and Maintenance

The schedule of installation and maintenance of the instrumentation on US59 over Guadalupe River Bridge from May 28, 2009, to August 23, 2010, is listed below.

05/28/2009	Installation of monitoring system and data collection. The sensors included two accelerometers, one dual-axis tiltmeter, two flout-out devices, two TBS equipments, and one water stage sensor.
06/08/2009	Loss of connection due to the loss of IP address.
10/14/2009	Connection restored. Hit bridge in three directions with impact hammer.
12/01/2009	Battery voltage dropped.
12/09/2009	Changed battery and added a trigger to monitor battery voltage.
03/11/2010	Removed accelerometer on top of Pier SB2 and changed battery. Reprogrammed the datalogger so that the data was recorded every twenty minutes. Noticed extensive bridge scour near the southwest abutment.

05/22/2010	Wire of TBS was broken due to the bridge extension construction. The monitoring system successfully indicated the loss of connection to TBS.
06/05/2010	Removed accelerometer on top of Pier SB1. Installed one dual-axis tiltmeter (Tiltmeter3 and Tiltmeter4) on Pier SB2, and two single-axis tiltmeters (Tiltmeter1 and Tiltmeter2) on bridge deck.
06/07/2010	Water stage sensor not working properly.
08/07/2010	Reprogrammed the water stage sensor.
08/07/2010	Water stage sensor not working properly.
08/14/2010	Water stage sensor taken out.
08/21/2010	New water stage sensor installed.

Initial Installation of the Monitoring System

A detailed and careful study of the bridge plan and site investigation was made on US59 over Guadalupe River Bridge. The bridge scour monitoring system was established and installed on US59 over Guadalupe River Bridge on May 28, 2009. During the installation, several parties were involved. TxDOT was responsible for the traffic control. The TxDOT traffic inspection team provided deck coring and the snooper truck for below-deck access. The drilling contractor installed the two float-out devices and two TBS equipments in the soil with the help from TTI. TTI researchers and consultants from ETI Instrument Systems, Inc. (ETI) and STV Incorporated were responsible for installing the instruments on the bridge.

Installation of Tiltmeters

A dual-axis tiltmeter was bolted and glued to the bridge deck level at a distance of 0.5 m (1.7 ft) horizontally away from master station to measure the tilt angle of the deck around both the flow direction axis and the traffic direction axis. One single-axis tiltmeter, which measures the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), was mounted in the back of the enclosure. The output is positive when the sensor is rotated clockwise (when facing the sensor). The other single-axis tiltmeter, which measures the tilt angle of the deck around the traffic direction axis, was mounted on the right side perpendicular to previously mentioned one (when facing the enclosure). The output is positive when the sensor is rotated clockwise. The wires of the tiltmeter were connected to the master station. Figure 5-9 shows the installed dual-axis tiltmeter.

Figure 5-9. Installed Dual-Axis Tiltmeter.

Installation of Water Stage Sensor

The water stage sensor was mounted in a bracket to the parapet of the bridge at the height of deck bottom. It measures the water surface elevation at the US59 over Guadalupe River Bridge. It is about 2.1 m (7 ft) horizontally away from the dual-axis tiltmeter. The bracket was fixed on the bridge deck by four bolts. The wires of the stage sensor were connected to the master station after installation. Figure 5-10 shows the installed water stage sensor.

Figure 5-10. Installed Water Stage Sensor.

Installation of Master Station

The master station was mounted on the same fixture as the solar panel. Two solar panels were installed near the master station to provide the power. One more solar panel was installed near the accelerometer on top of Pier SB1 to provide power. Figure 5-11 to Figure 5-12 shows the master station and solar panel installation.

Figure 5-11. Mount the Master Station.

Figure 5-12. Solar Panel on the Pier SB1.

Installation of Accelerometers

Two accelerometers were installed on the top of two in-river-piers in the initial monitoring system. The hardwired accelerometer was fixed on top of Pier SB2. The wireless accelerometer was fixed on top of Pier SB1 (Figure 5-13).

Figure 5-13. Wireless Accelerometer on Top of Pier SB1.

Installation of Float-Out Devices

The float-out devices used in field are 0.6 m (2 ft) in length and 8.9 cm (3.5 inches) in diameter. To install the two float-out devices, one hole was cored through the bridge deck. The hole was about at a distance of 2.4 m (8 ft) away from the edge of the deck parapet and 2.85 m (9.5 ft) away from the center of Pier SB2. The TxDOT inspection team cored the hole through the deck. Figure 5-14 shows the installation process.

Figure 5-14. Drill the Hole through the Deck.

In order to ensure that the float-out devices are installed at the right position, a rebuilt PVC pipe was used as an extension of the device. Figure 5-15 to Figure 5-18 show the process of installation of float-out device.

Figure 5-15. PVC Pipe as an Extension of Float-Out Device.

Figure 5-16. Float-Out Device.

Figure 5-17. Lower the Float-Out Device.

Figure 5-18. Refilling the Drilled Hole.

After the final installation, one of the float-out devices (Float-out1) was buried 1.5 m (5 ft) below the surface of the soil at a distance of 16.2 m (54 ft) from the top of the deck. The other float-out device (Float-out2) was buried at a distance of 2.7 m (9 ft) below Float-out1 and at a distance of 18.9 m (63 ft) from the top of the deck.

Installation of TBS Equipments

Two TBS equipments were buried in the soil near Pier SB3. TBS1 was buried 1.5 m (5 ft) below the ground surface near the southwest abutment at a distance of 7.2 m (24 ft) from the top of the deck. TBS2 was buried 3 m (10 ft) below TBS1 at a distance of 10.2 m (34 ft) from the top of the deck. Similar to the installation of the float-out devices, one hole was cored through the deck first. Since the TBS is wired and thinner than the float-out device, it was easier to install than the float-out device. Three soil samples were obtained during this process. After the two TBS equipments were buried at the right position, the wire was connected to the master station. In order to protect the wire from vandalism and flood dragging force, a PVC pipe was used in this process. Figure 5-19 to Figure 5-23 shows the installation process of the TBS equipments.

Figure 5-19. Installation of TBS.

Figure 5-20. Remove Soil from the Drill Bit.

Figure 5-21. Fill the Hole.

Figure 5-22. Installed TBS.

Figure 5-23. Wire the TBS to Master Station.

Figure 5-24 shows the initial installation of the bridge scour monitoring system.

Figure 5-24. Initial Bridge Scour Monitoring System.

Modification of the Bridge Scour Monitoring System

The initial monitoring system worked well for 10 days. After that the connection with the bridge was lost due to the loss of IP address. The problem was fixed in October 2009. The data analysis of accelerometers did not give satisfactory results as was obtained in the laboratory tests. The signal to noise ratio was too low to accurately differentiate the mode shapes of the bridge. In order to obtain a better signal, a series of impact tests were performed on the bridge in October 2009. The excitation influenced the quality of data obtained. The traffic excitation was not significant enough to produce clear data. Also due to the large amount of data transmitted by the accelerometer, more electrical power of the master station was needed than the initial estimate.

It is concluded that the idea to use accelerometers for monitoring of bridge scour has potential, but it requires further research, time, and resources to conclusively achieve results. Due to the limited period of this project, a modified monitoring system was installed on US59 over Guadalupe River Bridge on June 5, 2010. The aim of the modification was to focus on the scour monitoring using tiltmeters and TBS equipments.

The two accelerometers were removed. One dual-axis tiltmeter was installed on top of Pier SB2 to measure simultaneously the tilt angle of the bridge pier around the flow direction axis and the traffic direction axis (perpendicular to the flow direction). The single-axis tiltmeter, which was located at the back of the enclosure on the deck remained at the same place, measured the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction). The other single-axis tiltmeter in the same enclosure was removed and installed at the back of another enclosure approximately at a distance of 47 m (154.3 ft) from the previous location. It is measuring of the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction). All tiltmeters were wired to the datalogger CR1000. The water stage sensor, float-out devices, and TBS equipments remained at the previous location. Figure 5-25 to Figure 5-27 show the new installed tiltmeters on the bridge.

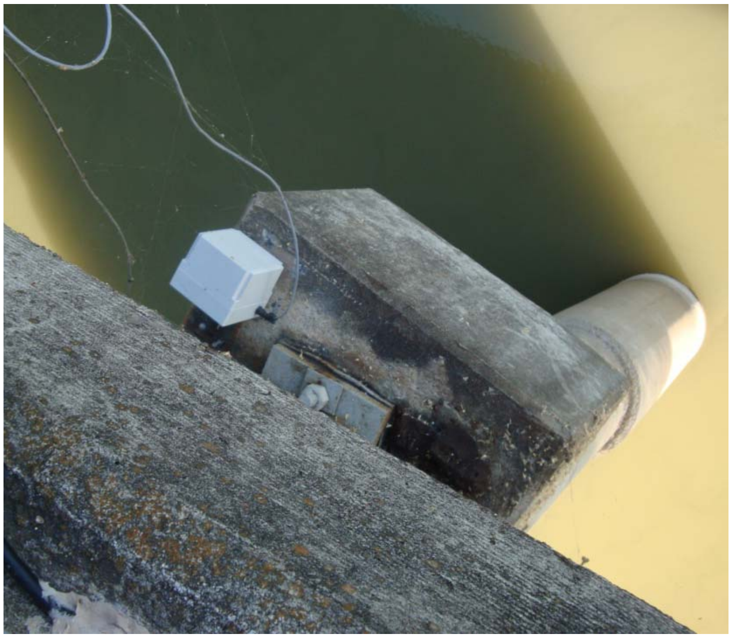


Figure 5-25. Dual-Axis Tiltmeter (Tiltmeter3 and Tiltmeter4) on Top of Pier SB2.

Figure 5-26. Single-Axis Tiltmeter (Tiltmeter1) on the Deck (Near Pier SB2).

Figure 5-27. Single-Axis Tiltmeter (Tiltmeter2) on the Deck (Near Pier SB1).

Figure 5-28 and Figure 5-29 show the modified bridge scour monitoring system installed on US59 over Guadalupe River Bridge.

Figure 5-28. Modified Bridge Scour Monitoring System.

Figure 5-29. Modified Bridge Scour Monitoring System.

DATA COLLECTION AND ANALYSIS

In the initial monitoring system, the data were collected in the datalogger every 10 minutes and transmitted to the server every hour. In the modified monitoring system, the data were collected in the datalogger every 20 minutes and transmitted to the server every hour.

Data Collection

Accelerometer

The range of the accelerometers is ±2g (g= 9.81 m/s^2 = 32.2 ft/s^2). The data of both accelerometers were collected at a sampling rate of 80 Hz. The datalogger collected the data every 10 minutes, but due to the large amount of data transmitted from accelerometers, the data logger overwrote the data from accelerometers, keeping one set of data every hour, and sent it to the server.

The data format for the accelerometer on top of Pier SB2 is shown as follows:

```
"2009-06-02 10:00:00",3312000,254,-910,16633
"2009-06-02 10:00:00",3312001,255,-901,16610
"2009-06-02 10:00:00",3312002,244,-927,16669
"2009-06-02 10:00:00",3312003,249,-921,16650
```

The first column is the date and time of the corresponding collected data, the second column is a counter, the third column is the relative acceleration value in flow direction, the fourth column is the relative acceleration value in traffic direction, and the last column is the relative acceleration value in vertical direction. The relative acceleration value obtained directly from the datalogger has to be converted in the physical units (g) by multiplying with the corresponding calibration factor. The calibration factor is 2/32768.

Other Master Station Sensors

The data format for the modified monitoring system for the bridge scour is shown below:

```
"2010-06-16 02:40:00",747,0,11.2,2.84,2.42,-2.27,-2.39,27.47,3,3,0,0,12.9
"2010-06-16 03:00:00",748,0,11.2,2.84,2.42,-2.27,-2.39,27.37,3,3,0,0,12.89
"2010-06-16 03:20:00",749,0,11.2,2.84,2.41,-2.27,-2.39,27.31,3,3,0,0,12.88
"2010-06-16 03:40:00",750,0,11.21,2.84,2.41,-2.27,-2.39,27.18,3,3,0,0,12.88
```

1. The first column is the timestamp, including the date and time of the corresponding data collected.
2. The second column is the counter.
3. The third column is the alarm.
4. The fourth column is the reading from stage sensor (in ft).
5. The fifth column is the reading from Tiltmeter1 on the deck (in degree).
6. The sixth column is the reading from Tiltmeter2 on the deck (in degree).
7. The seventh column is the reading from Tiltmeter3 on top of Pier SB2 (in degree).
8. The eighth column is the reading from Tiltmeter4 on top of Pier SB2 (in degree).
9. The ninth column shows the temperature of master station (in units of °C).
10. The tenth column is the reading from TBS1 located at 7.2 m (24 ft) from the bridge deck.
11. The eleventh column is the reading from TBS2 located at 10.2 m (34 ft) from the bridge deck.
12. The twelfth column is the reading from Float-out1 located at 16.2 m (54 ft) from the bridge deck.
13. The thirteenth column is the reading from Float-out2 located at 18.9 m (63 ft) from the bridge deck.
14. The last column is the master station battery reading (in volts).

Data Analysis

Accelerometers

(1). Hardwired Accelerometer. The data were collected from May 31, 2009, till March 11, 2010. Figure 5-30 to Figure 5-32 show the overall information about the continuity of the data collected by the accelerometer on top of Pier SB2 over the period of time in flow direction, traffic direction, and vertical direction, respectively. Only one line of data per hour was chosen to plot Figure 5-30 to Figure 5-32. The bands in these figures shows that continuous data were collected in early June in 2009 and from mid-October to late November in 2009.

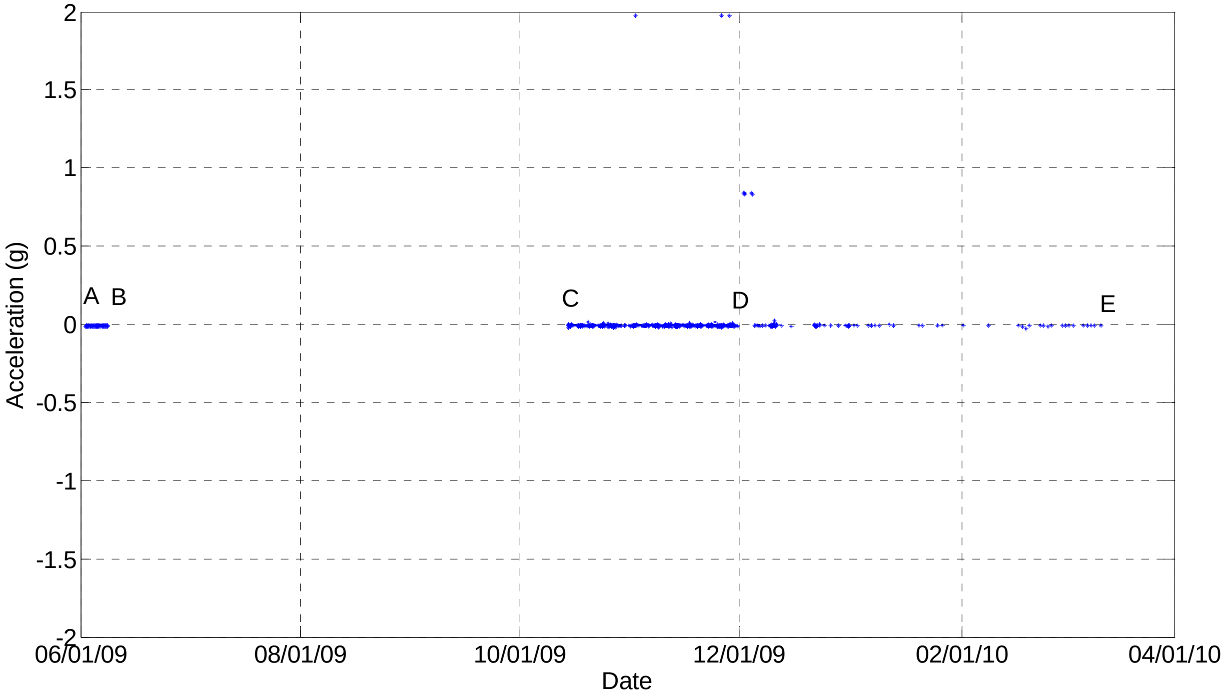


Figure 5-30. Acceleration Data from Accelerometer on Top of Pier SB2 (Flow Direction).

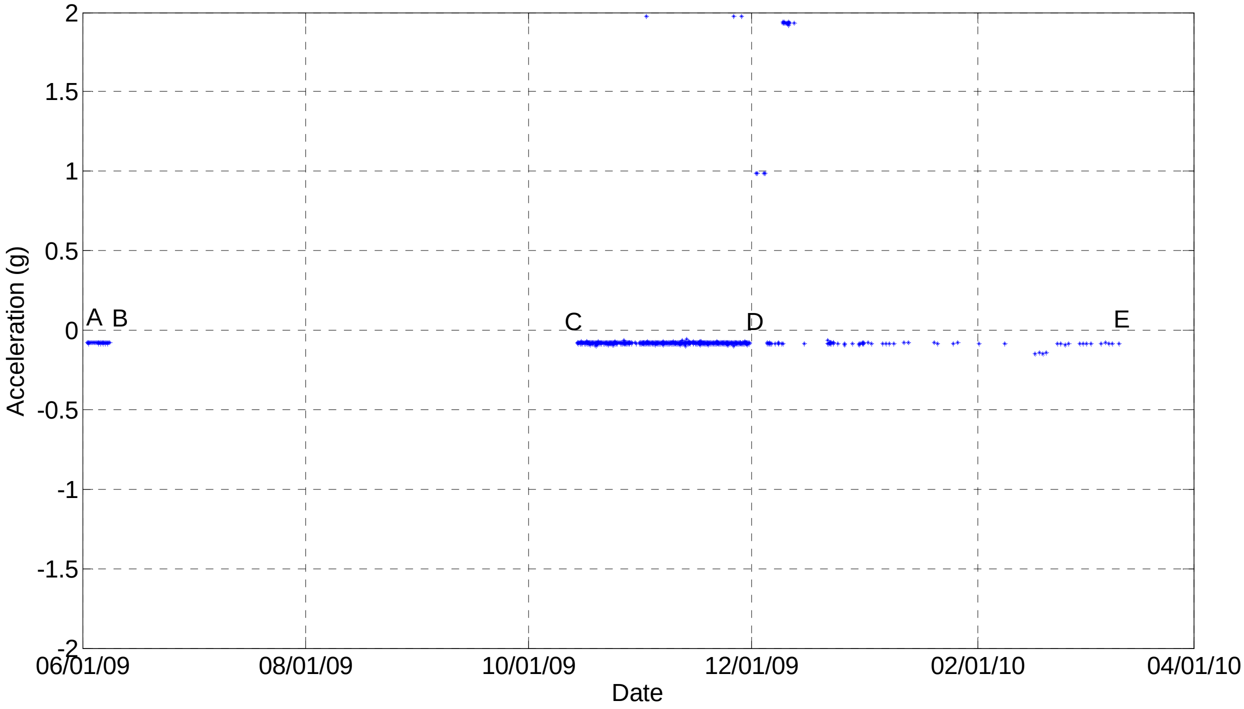


Figure 5-31. Acceleration Data from Accelerometer on Top of Pier SB2 (Traffic Direction).

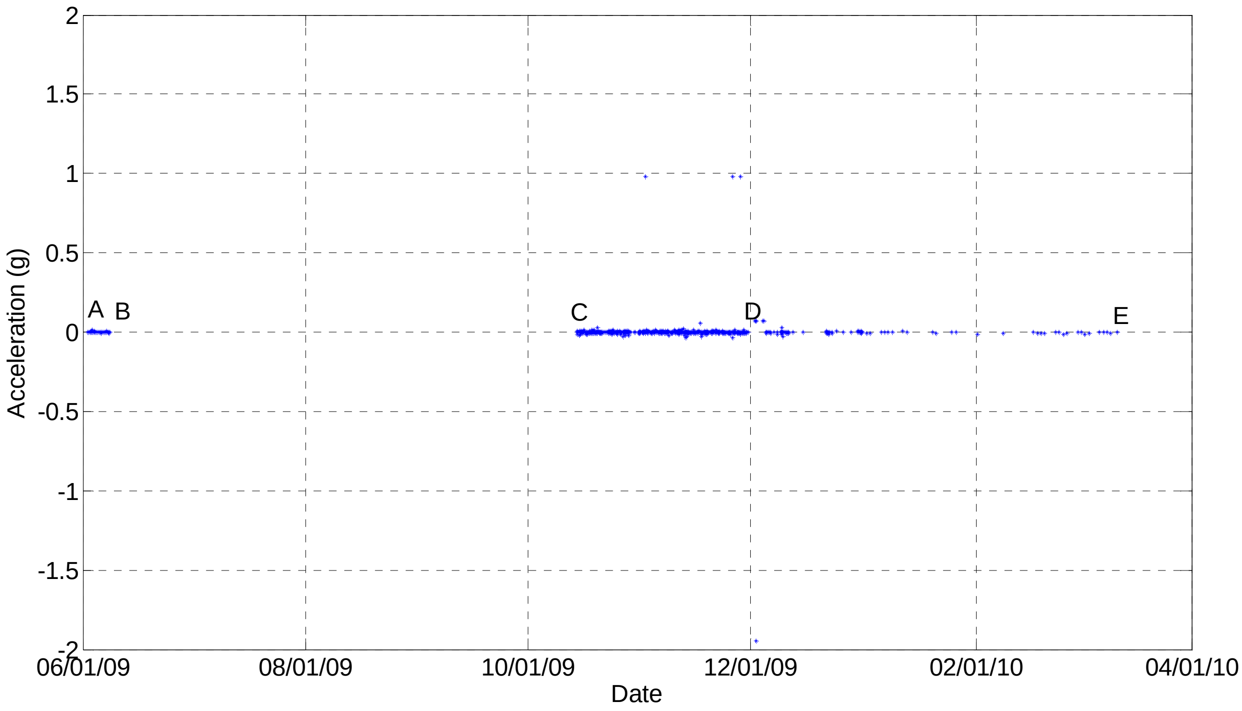


Figure 5-32. Acceleration Data from Accelerometer on Top of Pier SB2 (Vertical Direction).

In Figure 5-30, Figure 5-31, and Figure 5-32, the whole period is separated into several phases.

- Phase A-B (May 28, 2009–June 8, 2009): Good data were collected.
- Phase B-C (June 8, 2009–October 14, 2009): Gap in data due to the loss of connection with the bridge.
- Phase C-D (October 14, 2009–December 2, 2009): Continuous data were collected.
- Phase D-E (December 2, 2009–March 11, 2010): Discontinuous, unsteady data stream were obtained.

ETI made a trigger for the system on December 9, 2009, so that when the battery dropped below 12 volts, the whole system would shut down. This is the reason for the missing data for the period from December 2009 to March 2010. The accelerometer on top of Pier SB2 was removed from the bridge on March 11, 2010. Figure 5-33 to Figure 5-35 shows plots on a group of good data (one minute) collected from accelerometer on top of Pier SB2 on US59 over Guadalupe River Bridge. The data were collected on June 2, 2009, at 2:00 p.m. Clear vehicle excitation can be recognized from the plots.

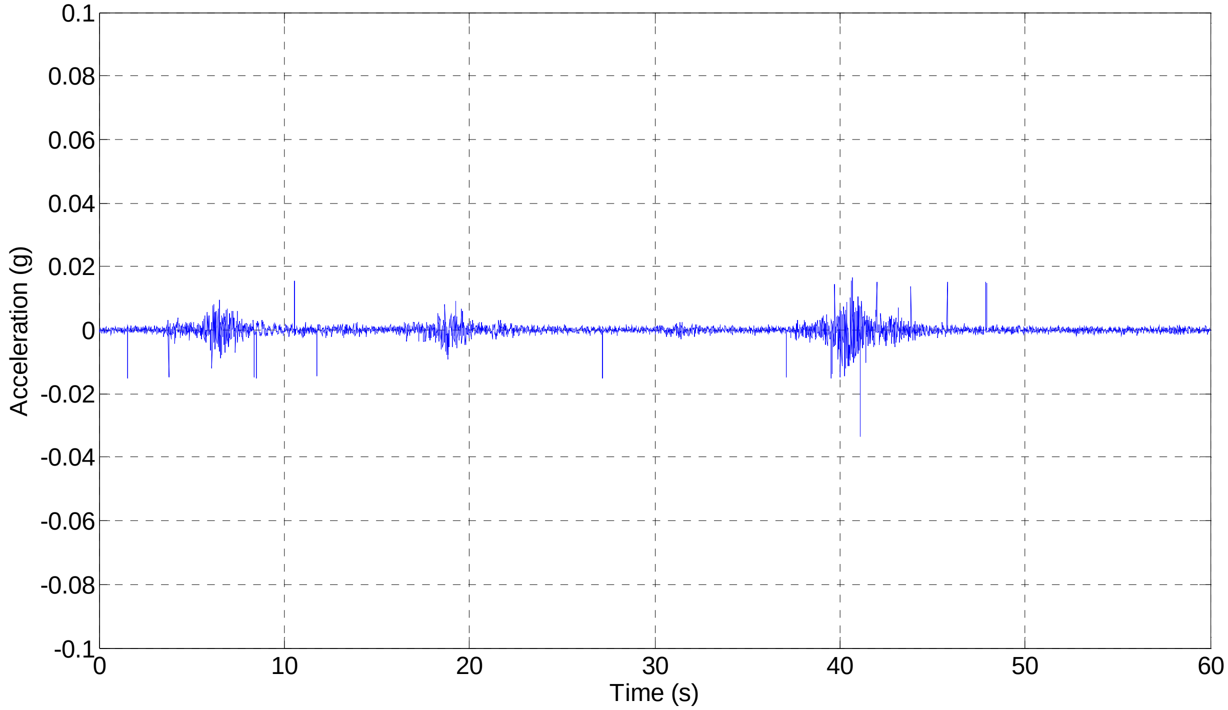


Figure 5-33. Data Collected from Accelerometer on Top of Pier SB2 on June 2, 2009 (Flow Direction).

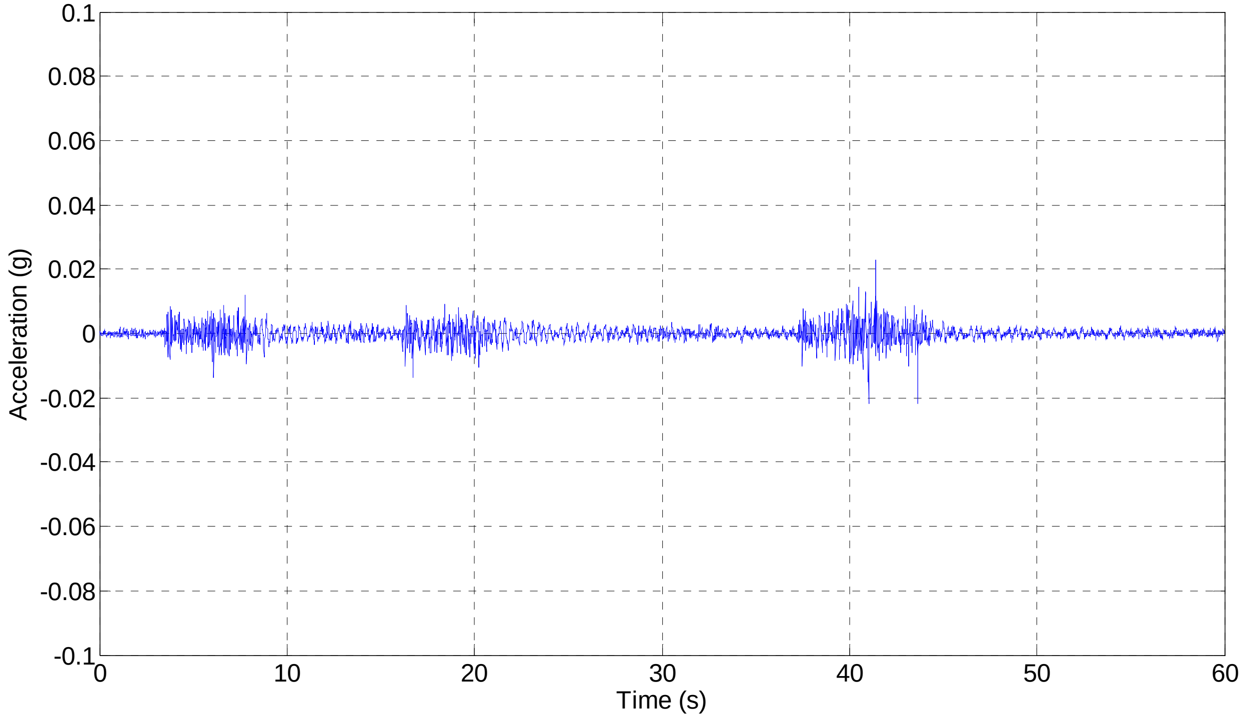


Figure 5-34. Data Collected from Accelerometer on Top of Pier SB2 on June 2, 2009 (Traffic Direction).

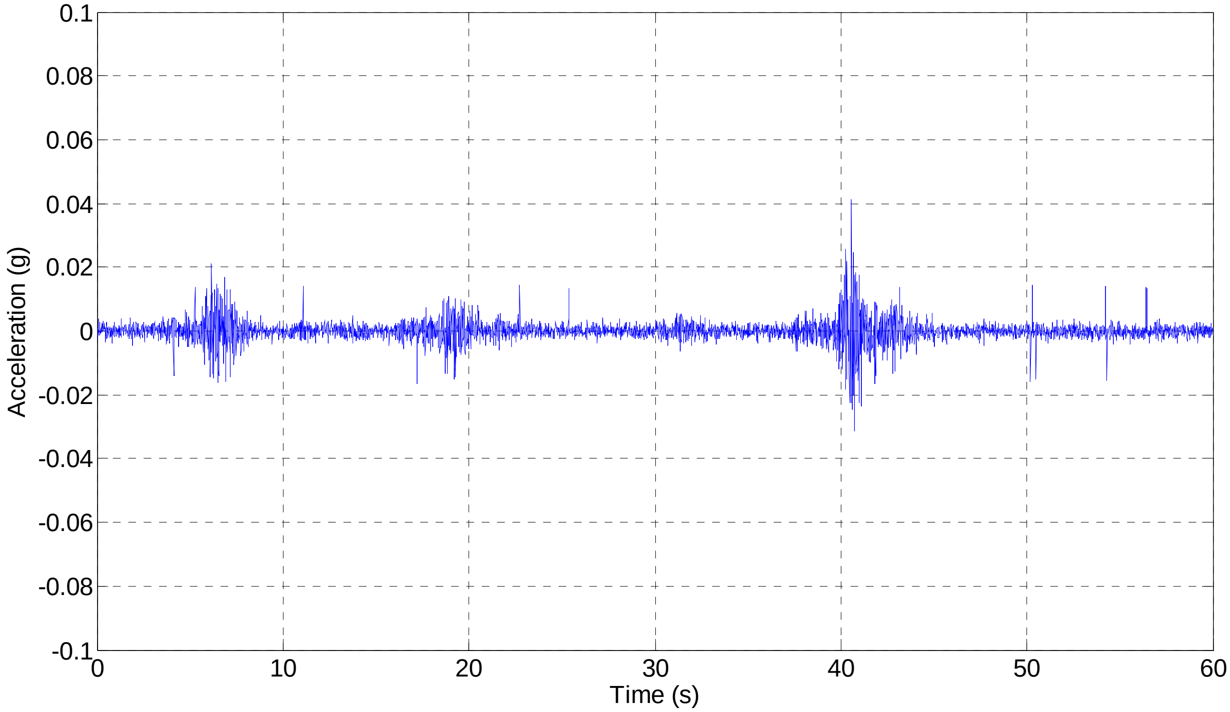


Figure 5-35. Data Collected from Accelerometer on Top of Pier SB2 on June 2, 2009 (Vertical Direction).

The data collected from the accelerometers is analyzed by an FFT to obtain the natural frequency of the system. The Japan Railway Technical Research Institute (RTRI) published a study in 2008 (Shinoda et al., 2008) that presents a method correlating the status of the foundation with the natural frequency of the railway bridge column. This method is called the Impact Vibration Method. The authors showed that the natural frequency of the column decreases as a result of the decrease in the stiffness of the bridge column and its foundation due to the occurrence of bridge scour. Thus the integrity of the column can be judged by comparing the natural frequency during normal operational condition to the natural frequency during big floods that may cause bridge scour. In the present research, the natural frequency of the bridge obtained by analyzing accelerometer data is studied to evaluate its effectiveness as a parameter for scour monitoring system.

FFT analyzed for each group 148 groups of acceleration data (148 h) obtained from the accelerometer on top of Pier SB2 on US59 over Guadalupe River Bridge from June 2, 2009, at 10:00 a.m. to June 8, 2009, at 1:00 p.m. The first, second, and third natural frequencies of the signal in flow direction are plotted in the time domain (Figure 5-36). The first, second, and third natural frequencies of the signal in traffic direction are plotted in the time domain (Figure 5-37). The frequency analysis of the signal in vertical direction does not showed any clear frequency. Only the first natural frequency of the signal in vertical direction is plotted in the time domain (Figure 5-38).

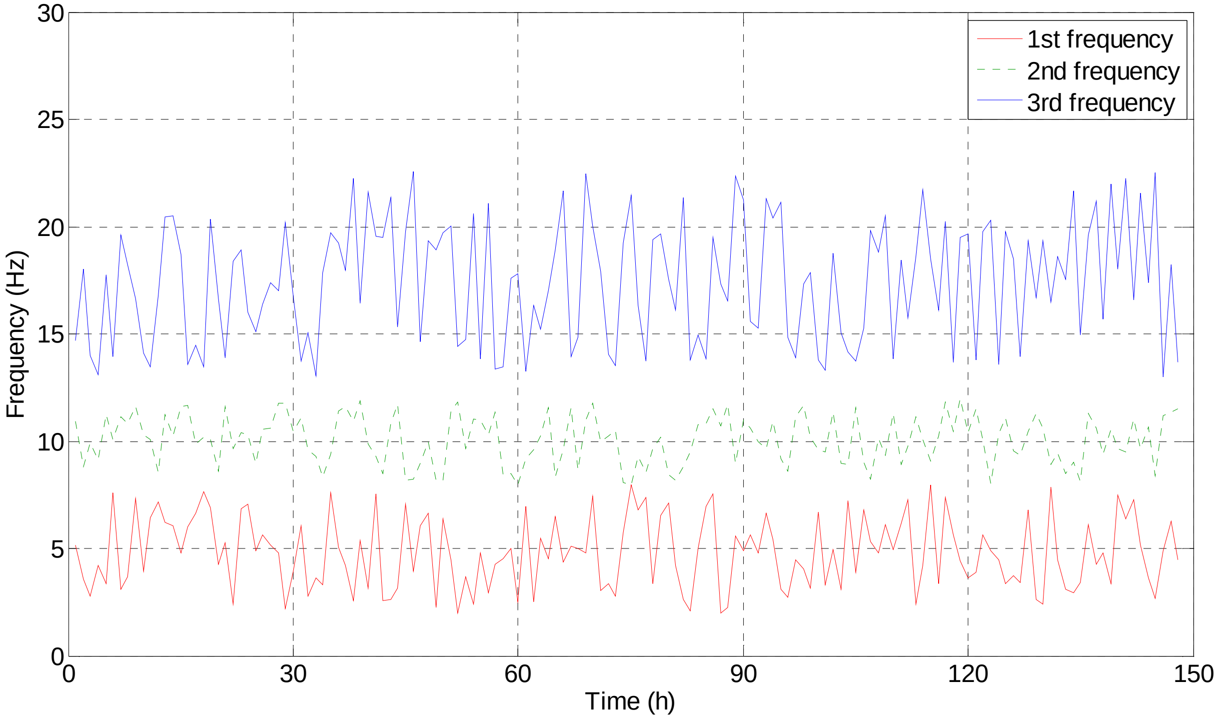


Figure 5-36. Frequency Response Curve (Flow Direction).

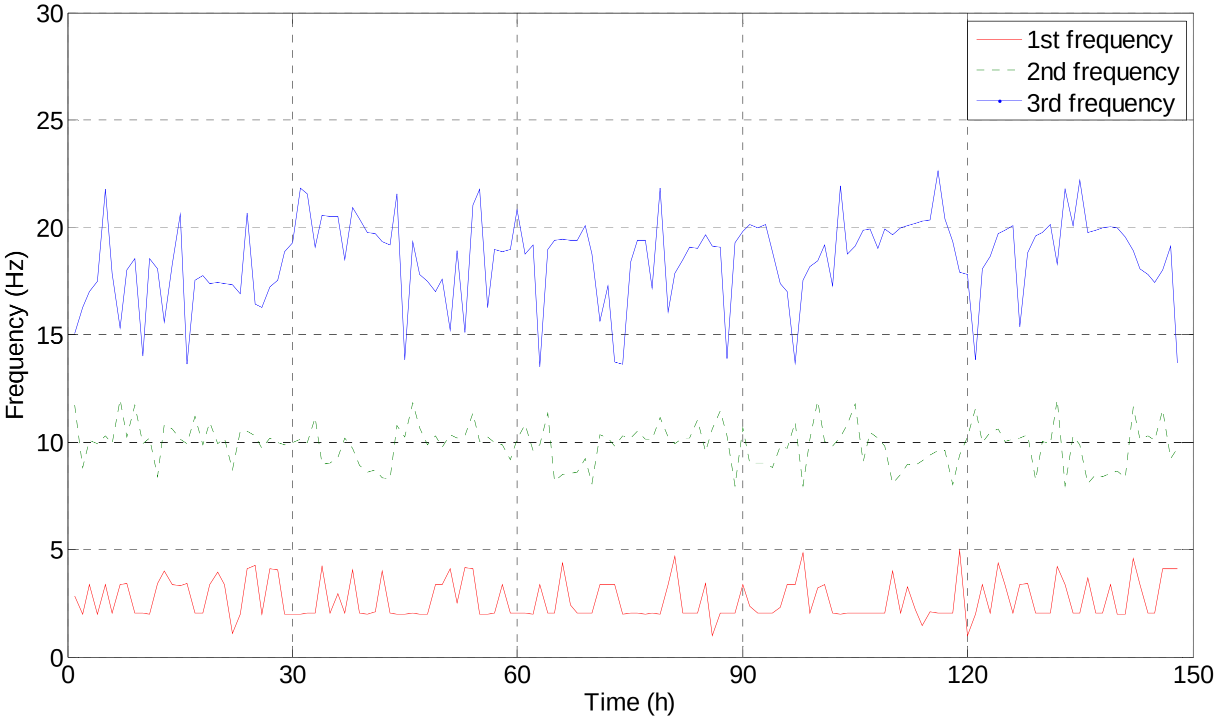


Figure 5-37. Frequency Response Curve (Traffic Direction).

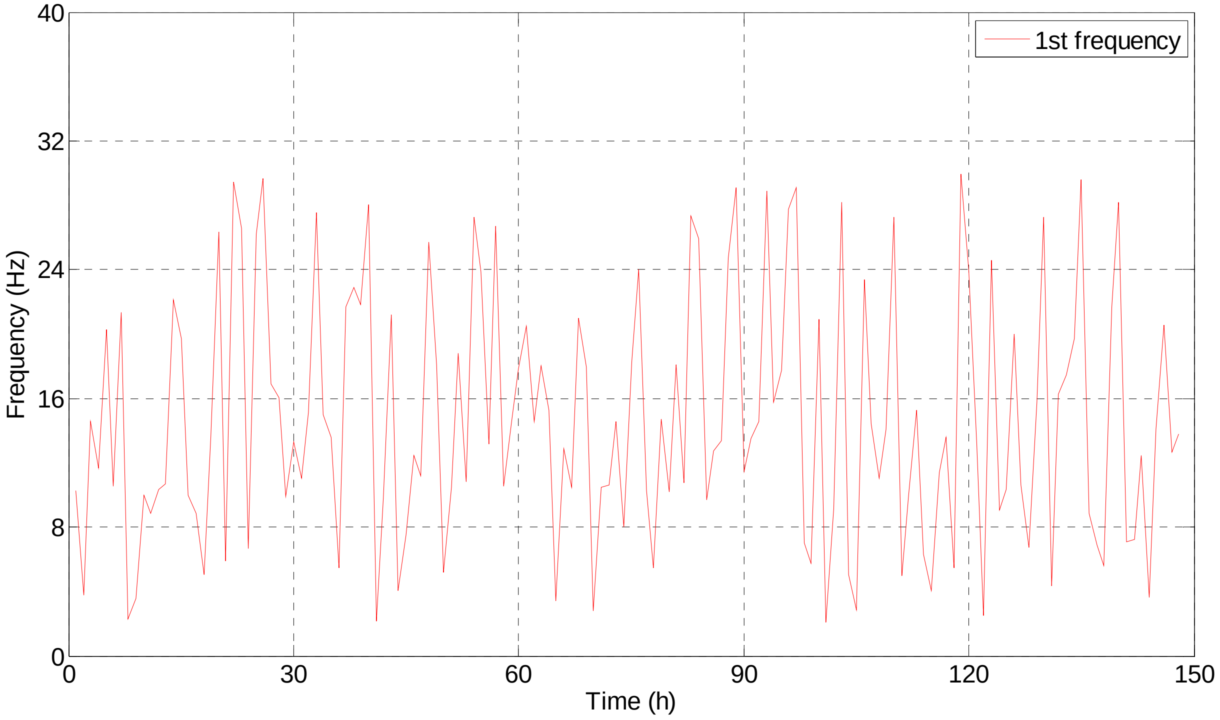


Figure 5-38. Frequency Response Curve (Vertical Direction).

The following conclusions are drawn from the natural frequency analysis. The natural frequencies obtained are very closely spaced. A careful selection of the first three natural frequencies is made and plotted in Figure 5-36 to Figure 5-38. The frequency response curve obtained over a period of time does not show any stable trend. The selected frequencies vary well over 100 percent for all the cases. It may be due to the fact that the system is not excited in the desired mode from the traffic only and requires a stronger excitation. The low signal to noise ratio also contributes to the observed unstable frequency trend from the analysis. It is concluded that this method requires further research and resources.

The second approach adopted to analyze the data from the accelerometer is to use the ratio of Root Mean Square (RMS) values of acceleration in two different directions as a parameter to monitor the bridge scour. This method is based on the work by Suzuki et al., 2007. They conducted research on the health monitoring of railway bridge piers and found that the gradient of linear regression line between vertical and transverse acceleration response changed due to the loss of sediment support around the bridge foundation. The same set of 148 groups of acceleration data obtained from the accelerometer on top of Pier SB2 is analyzed using the ratio of RMS method (Figure 5-39).

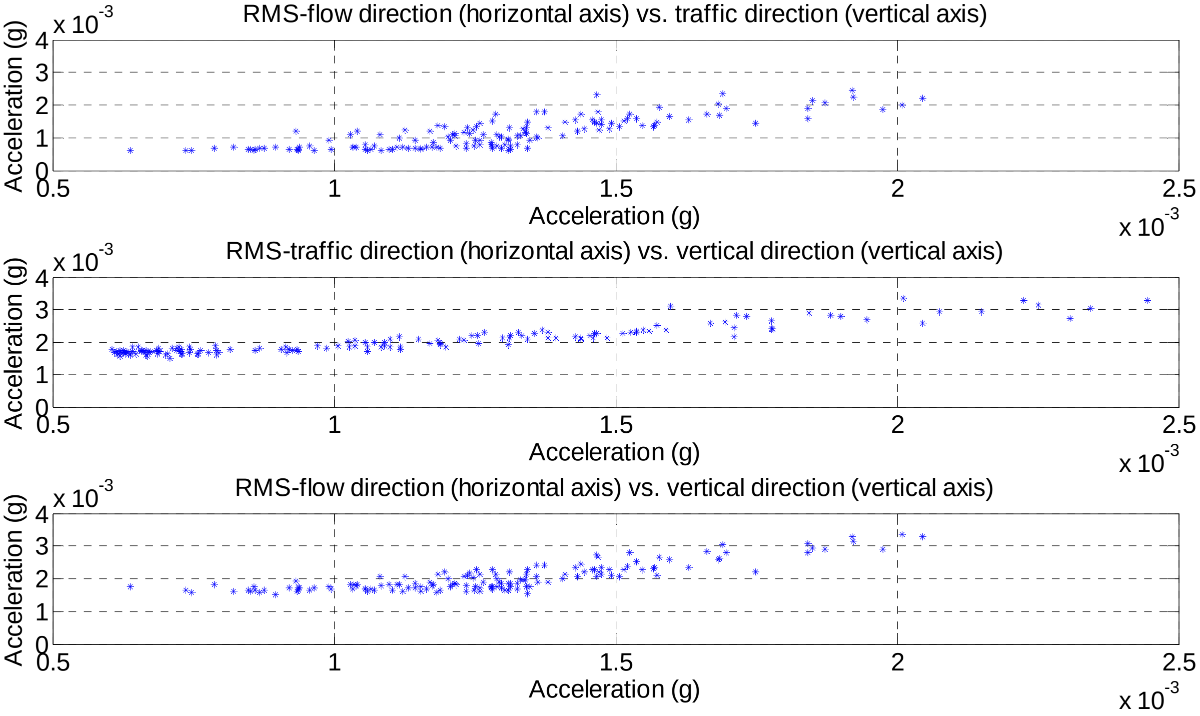


Figure 5-39. Ratio of Root Mean Square Response Curve.

The response curve for the ratio of RMS of the acceleration in two directions is not very stable for the analyzed time. This makes the response very sensitive to the nature of excitation. It is concluded the response quantity of ratio of RMS of acceleration in two different directions cannot be used as an effective monitoring parameter for the current research. It requires further analysis to be used as an appropriate parameter.

(2). Wireless Accelerometer. The data were collected from May 31, 2009, till March 11, 2010. Figure 5-40 to Figure 5-42 show the overall information about the continuity of the data collected by the accelerometer on top of Pier SB1 over the period of time in flow direction, traffic direction, and vertical direction, respectively. Only one line of data per hour is chosen for plotting in Figure 5-40 to Figure 5-42. The bands in these figures show that continuous data were collected in early June in 2009 and from mid-October to late November in 2009.

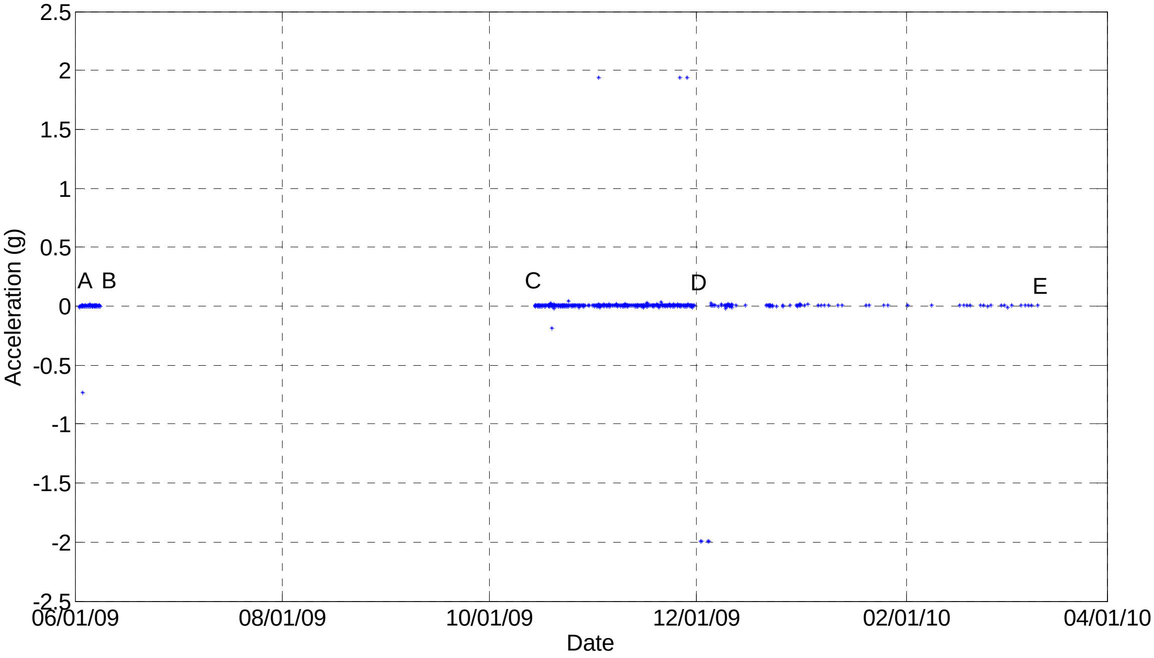


Figure 5-40. Acceleration Data from Accelerometer on Top of Pier SB1 (Flow Direction).

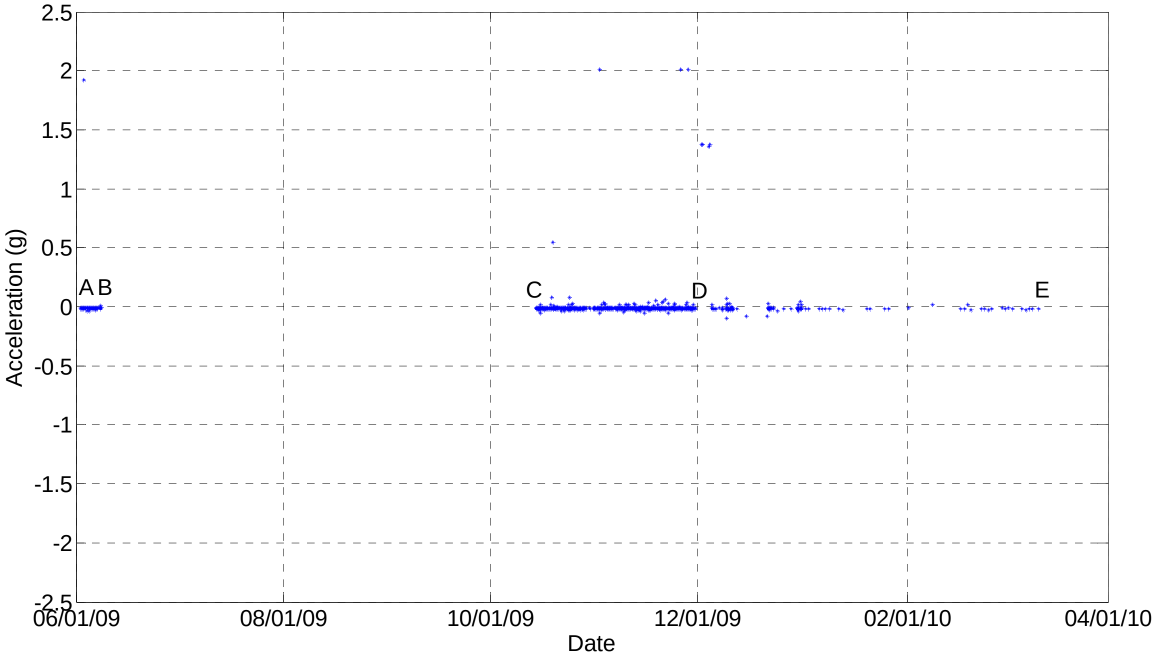


Figure 5-41. Acceleration Data from Accelerometer on Top of Pier SB1 (Traffic Direction).

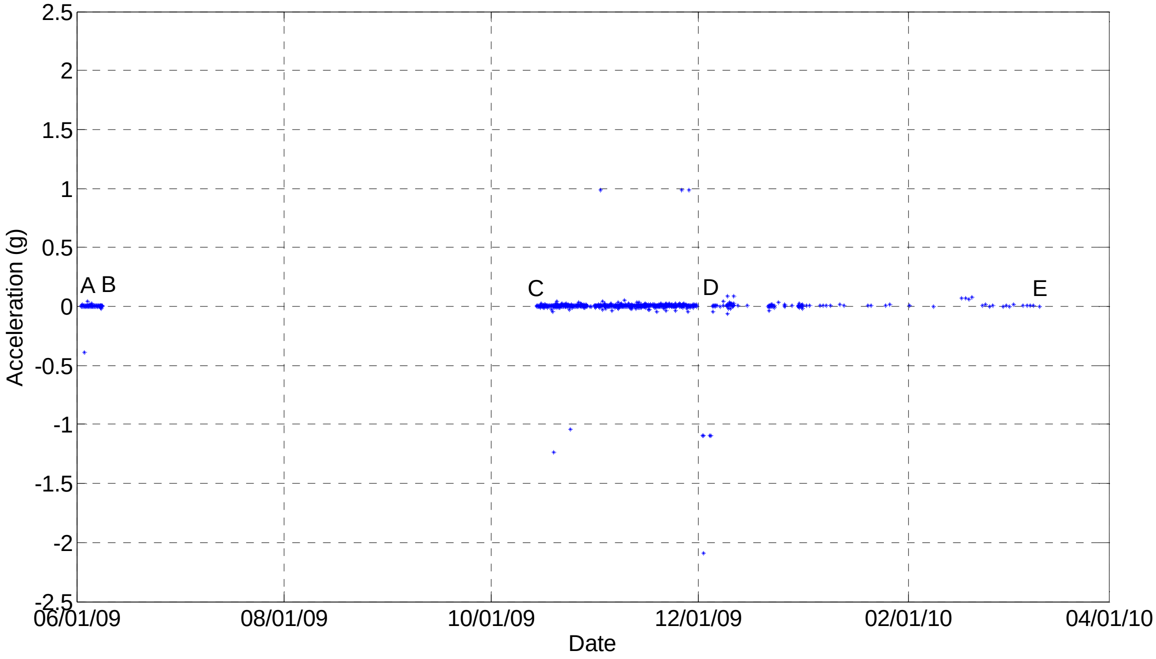


Figure 5-42. Acceleration Data from Accelerometer on Top of Pier SB1 (Vertical Direction).

In Figure 5-40, Figure 5-41, and Figure 5-42, the whole period is separated into several phases.

- Phase A-B (May 28, 2009–June 8, 2009): Good data were collected.
- Phase B-C (June 8, 2009–October 14, 2009): Gap in data due to the loss of connection with the bridge.
- Phase C-D (October 14, 2009–December 2, 2009): Continuous data were collected.
- Phase D-E (December 2, 2009–March 11, 2010): Discontinuous, unsteady data stream were obtained.

ETI made a trigger for the system on December 9, 2009, so that when the battery dropped below 12 volts, the whole system would shut down. This is the reason for the missing data for the period from December 2009 to March 2010. The accelerometer on top of Pier SB1 was removed from the bridge on March 11, 2010.

Figures 5-43 to Figure 5-45 show plots on a group of good data (one minute) collected from the accelerometer on top of Pier SB1 on US59 over Guadalupe River Bridge. The data were collected on June 2, 2009, at 2:00 p.m. Clear vehicle excitation can be recognized from the plots.

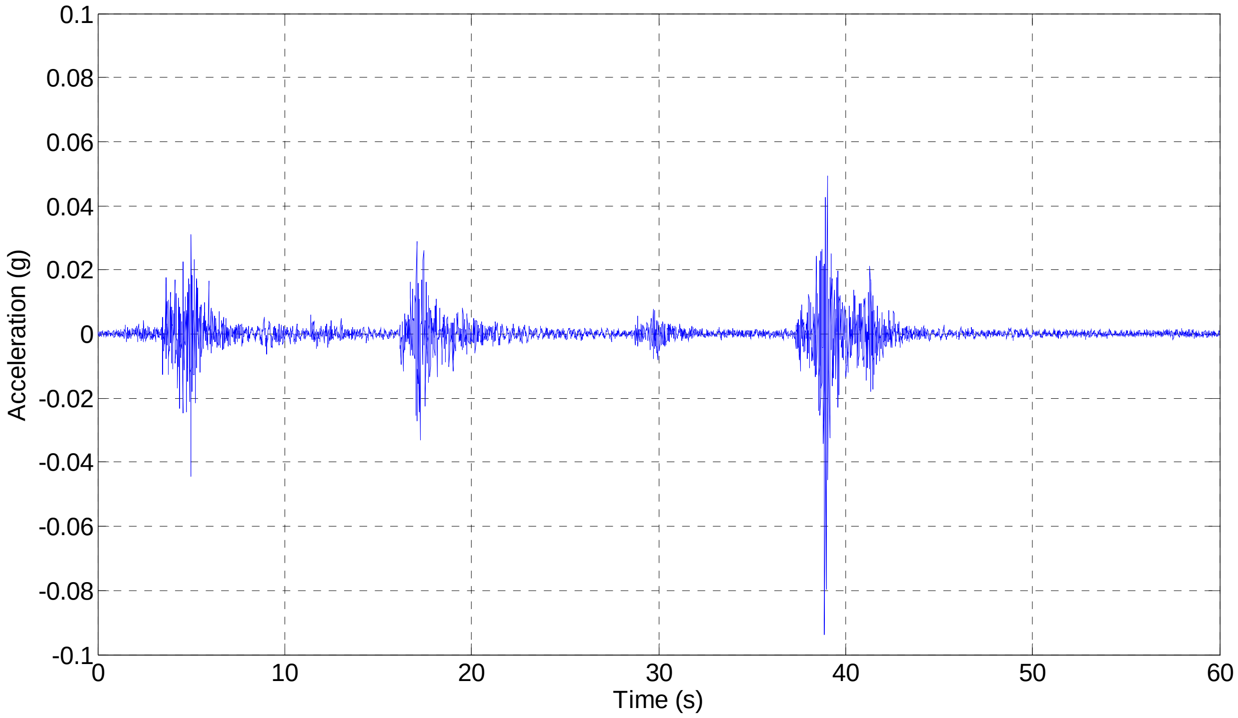


Figure 5-43. Data Collected from Accelerometer on Top of Pier SB1 on June 2, 2009 (Flow Direction).

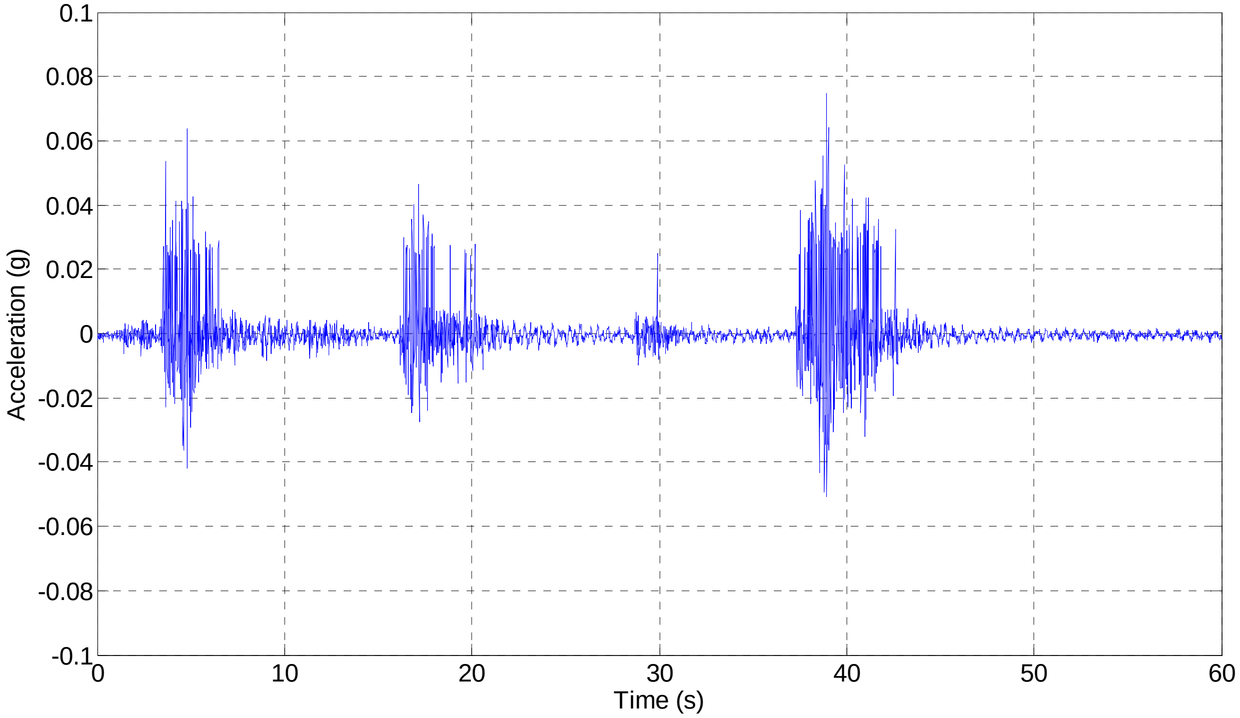


Figure 5-44. Data Collected from Accelerometer on Top of Pier SB1 on June 2, 2009 (Traffic Direction).

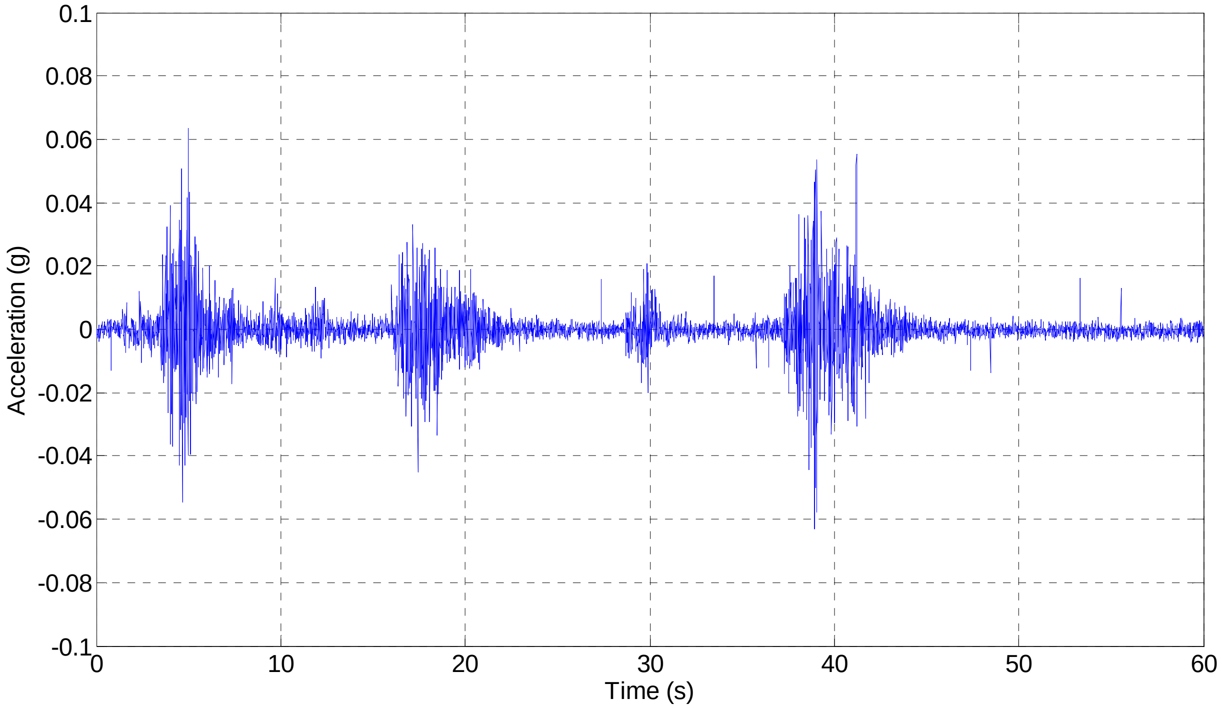


Figure 5-45. Data Collected from Accelerometer on Top of Pier SB1 on June 2, 2009 (Vertical Direction).

The data obtained from the accelerometer on top of Pier SB1 are analyzed in a similar way by an FFT to obtain the natural frequency of the system. A set of 148 groups of acceleration data obtained from the accelerometer on top of Pier SB1 on US59 over Guadalupe River Bridge from June 2, 2009, at 10:00 a.m. to June 8, 2009, at 1:00 p.m. is analyzed by FFT for each group. The frequency response curve in three directions is shown in Figure 5-46 to Figure 5-48. The first, second, and third natural frequencies of the signal in flow direction are plotted in the time domain (Figure 5-46). The first, second, and third natural frequencies of the signal in traffic direction are plotted in the time domain (Figure 5-47). The first, second, and third natural frequency of the signal in vertical direction is plotted in the time domain (Figure 5-48).

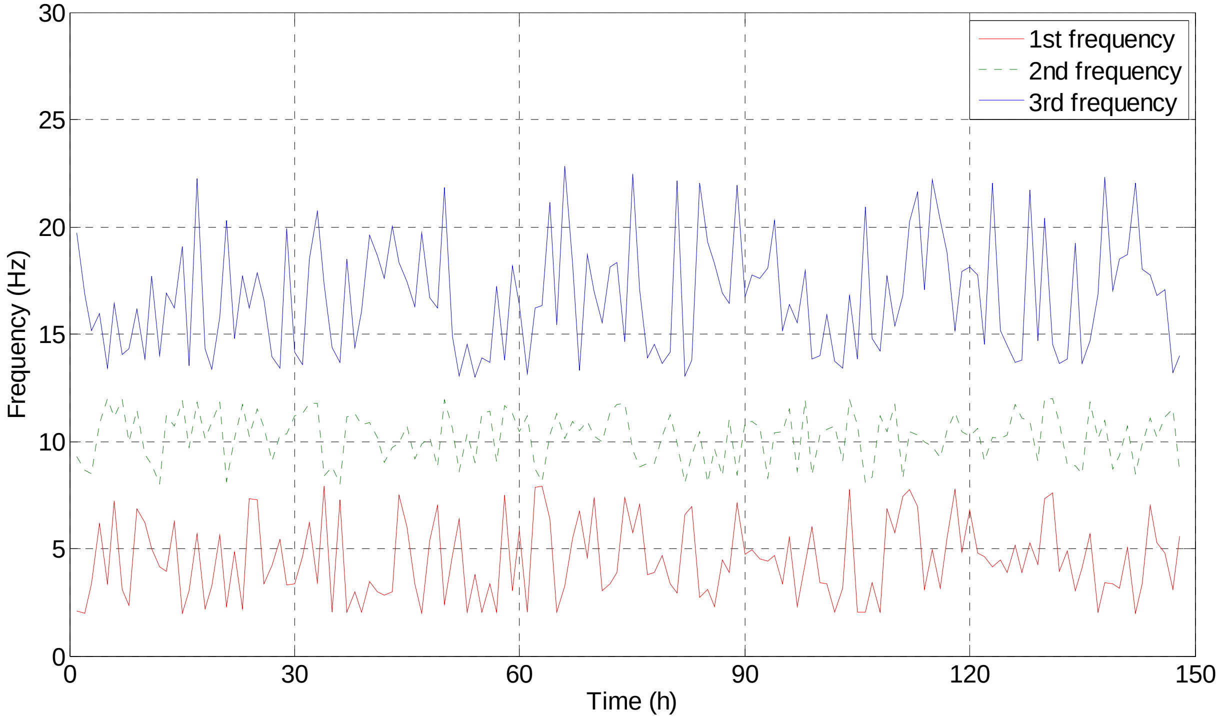


Figure 5-46. Frequency Response Curve (Flow Direction).

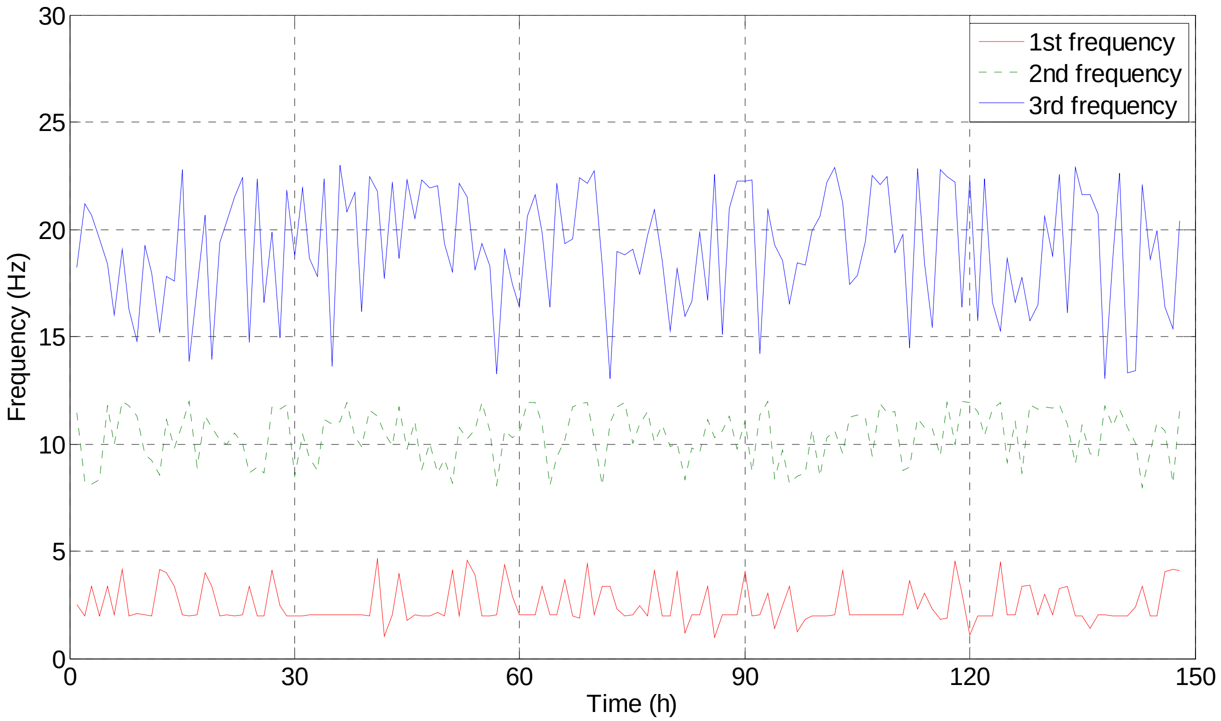


Figure 5-47. Frequency Response Curve (Traffic Direction).

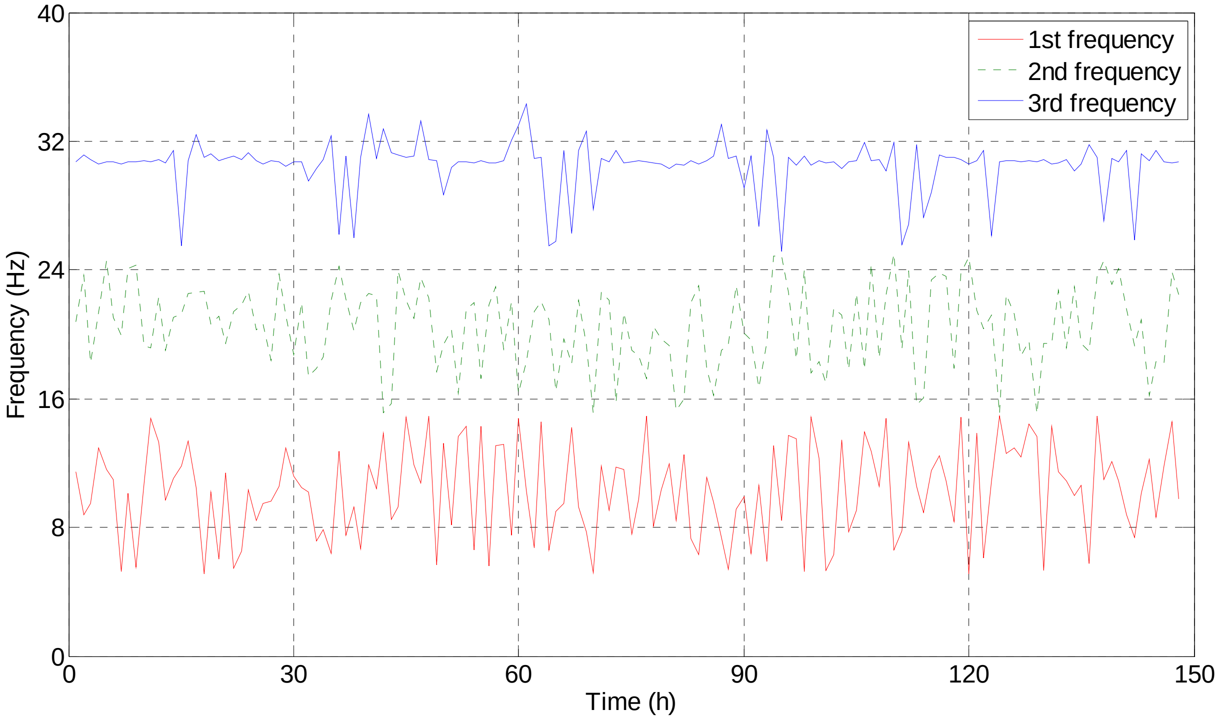


Figure 5-48. Frequency Response Curve (Vertical Direction).

Similar conclusions are drawn from the natural frequency analysis of the data from the accelerometer on top of Pier SB1. A careful selection of the first three natural frequencies is made and plotted in Figure 5-46 to Figure 5-48. The frequency response curve obtained over a period of time does not show any stable trend. The selected frequencies vary well over 100 percent for all the cases. It may be due to the fact that the system is not excited in the desired mode from the traffic only and requires a stronger excitation. The low signal to noise ratio also contributes to the observed unstable frequency trend from the analysis. Researchers concluded that this method requires further research and resources.

The second approach adopted to analyze the data from the accelerometer is to use the ratio of RMS values of acceleration in two different directions as a parameter to monitor the bridge scour. This is similar to the analysis performed on the acceleration data obtained from the accelerometer on top of Pier SB2. The same set of 148 groups of acceleration data obtained from the accelerometer on top of Pier SB1 on US59 over Guadalupe River Bridge is analyzed using the ratio of RMS method (Figure 5-49).

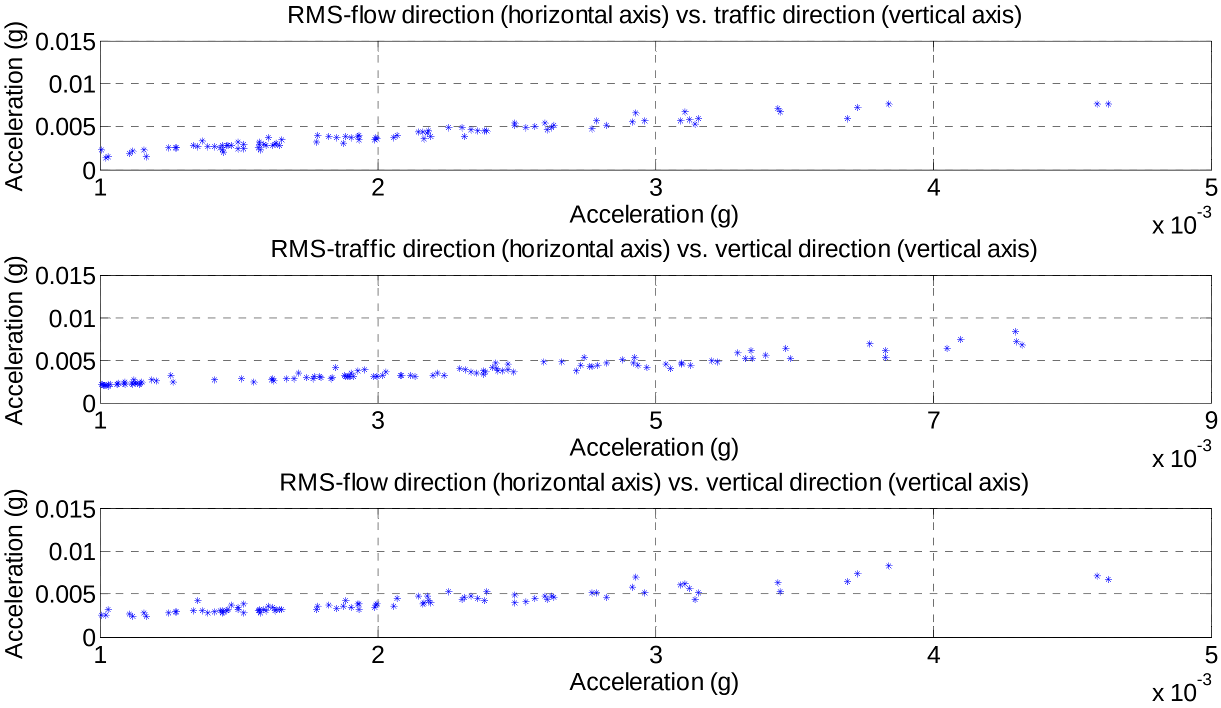


Figure 5-49. Ratio of Root Mean Square Response Curve.

The trend in results is similar to the response of the ratio of RMS of the acceleration obtained from the other accelerometer. The response curve for the ratio of RMS of the acceleration in two directions is also not stable for the analyzed time. This makes the response very sensitive to nature of excitation. Researchers concluded the response quantity of ratio of RMS of acceleration in two directions cannot be used as an effective monitoring parameter for the current research. It requires further analysis to be used as an appropriate parameter.

The large amount of data transmitted by accelerometers resulted in an increase in the power demand. Analysis is performed on the data sets to reduce the sampling rate and data collection period to reduce the power requirement. It is concluded that the data recording time can be reduced to 15 seconds without causing significant loss in the quality of data collected. No conclusive estimate on the efficient sampling rate could be obtained from the analysis. The idea of using accelerometers is abandoned due to the inconclusive results obtained. The accelerometers were removed from the US59 over Guadalupe River Bridge on March 11, 2010.

Tiltmeters

The data from the tiltmeters were collected from 9:50 a.m. on May 28, 2009, to 7:00 a.m. on August 9, 2010. The four tiltmeters give readings every 20 minutes. The collected data are labeled as follows: X1Tilt, Y1Tilt, X2Tilt and Y2Tilt. X1Tilt records the data obtained from Tiltmeter1 near Pier SB2, measuring the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction). Y1Tilt records the data obtained from Tiltmeter2 near Pier SB1, measuring the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction) at the other location. X2Tilt records the data obtained from Tiltmeter3 on top of Pier SB2, measuring the tilt angle of the pier around the flow direction axis. Y2Tilt records the data obtained from Tiltmeter4 on top of Pier SB2, measuring the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction). Figure 5-50 shows the location of tiltmeters on US59 over Guadalupe River Bridge. Here, Tiltmeter2a represents the tiltmeter that was measuring the tilt angle of the deck around the traffic direction axis and was removed on June 5, 2010. Tiltmeter2b represents the reinstalled tiltmeter that is measuring the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction) after June 5, 2010.

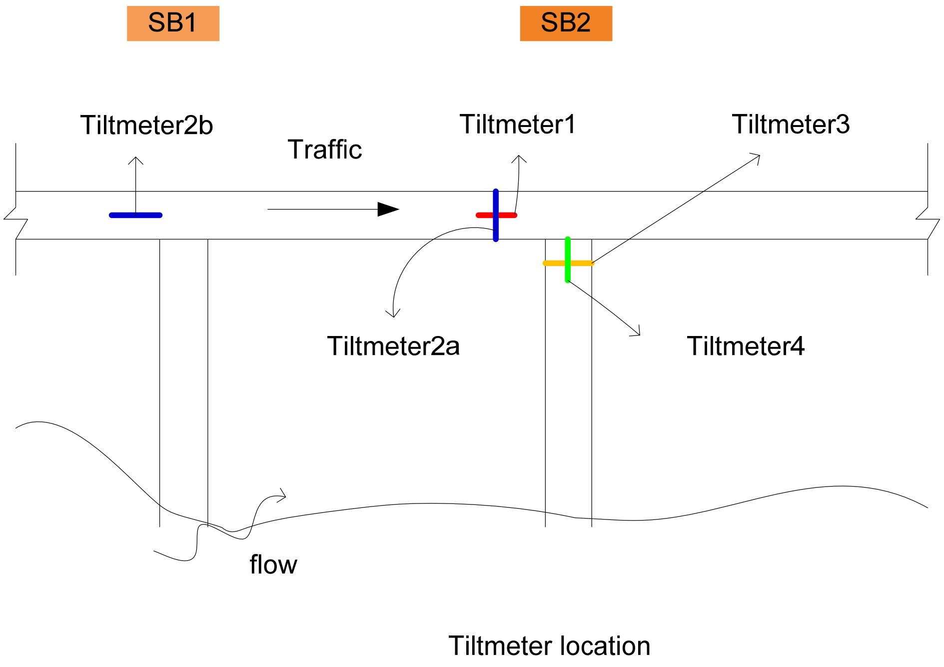


Figure 5-50. Layout of the Tiltmeter Location on US59 over Guadalupe River Bridge.

(1). Data Analysis on Tiltmeter1 (May 28, 2009—August 9, 2010). Figure 5-51 shows the time history plot of the data obtained from Tiltmeter1 located on the deck near Pier SB2, which is measuring the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction).

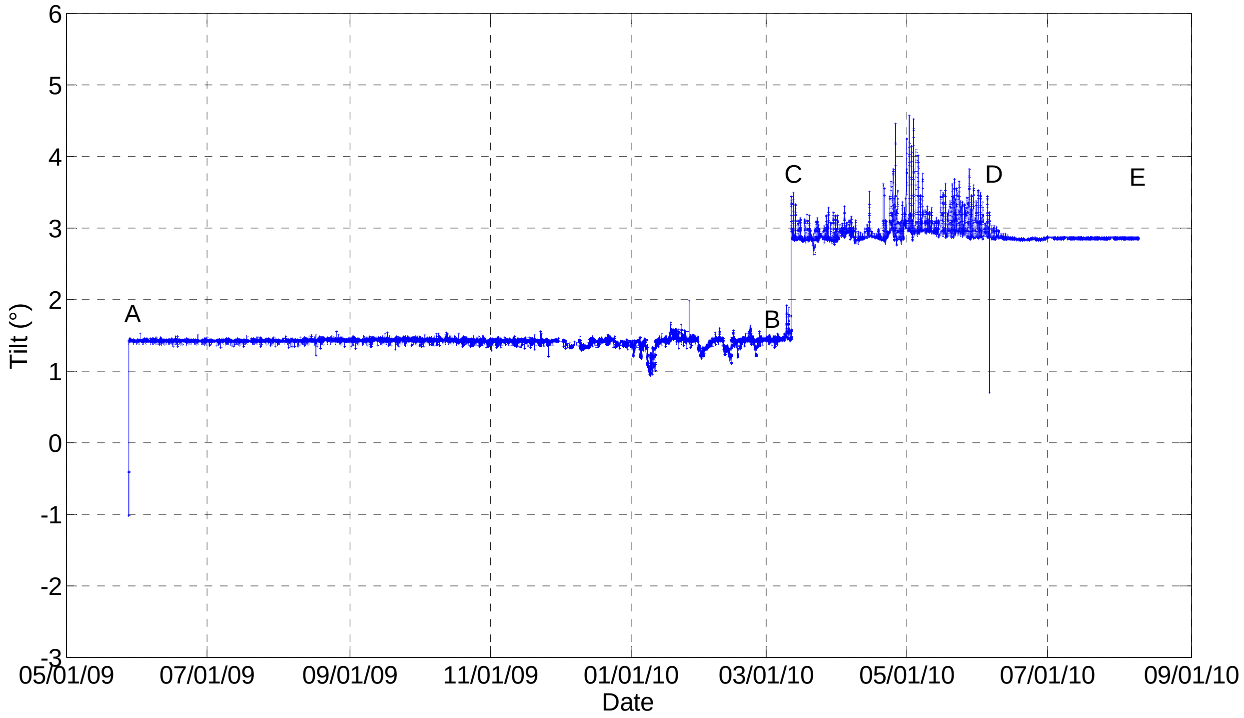


Figure 5-51. Tiltmeter1 Time History Plot on US59 over Guadalupe River Bridge.

The data collected from Tiltmeter1 is categorized into different phases according to the maintenance and modifications done on the scour monitoring system.

Phase A-B (May 28, 2009–March 11, 2010). Figure 5-52 shows the time history plot of all the data collected from Tiltmeter1 and the temperature recorded before the system was modified on March 11, 2010. The blue line shows the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the two curves of deck's rotation and temperature are correlated. This is due to the response of the bridge deck, on which Tiltmeter1 is mounted, with the change in temperature. This is the reason of the positive correlation of the two quantities.

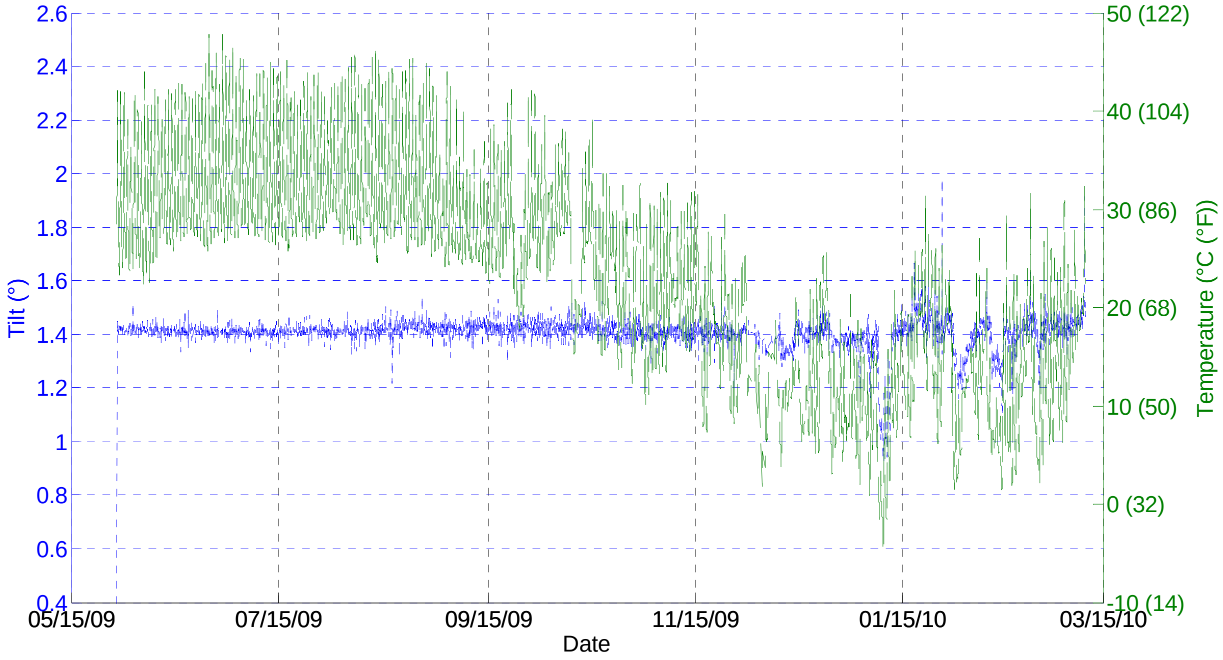


Figure 5-52. Tiltmeter1 and Temperature Response Plot for Phase A-B.

Phase C-D (March 11, 2010–June 5, 2010). Figure 5-53 shows the time history plot of all the data collected from Tiltmeter1, and the temperature recorded after the system was modified in March 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

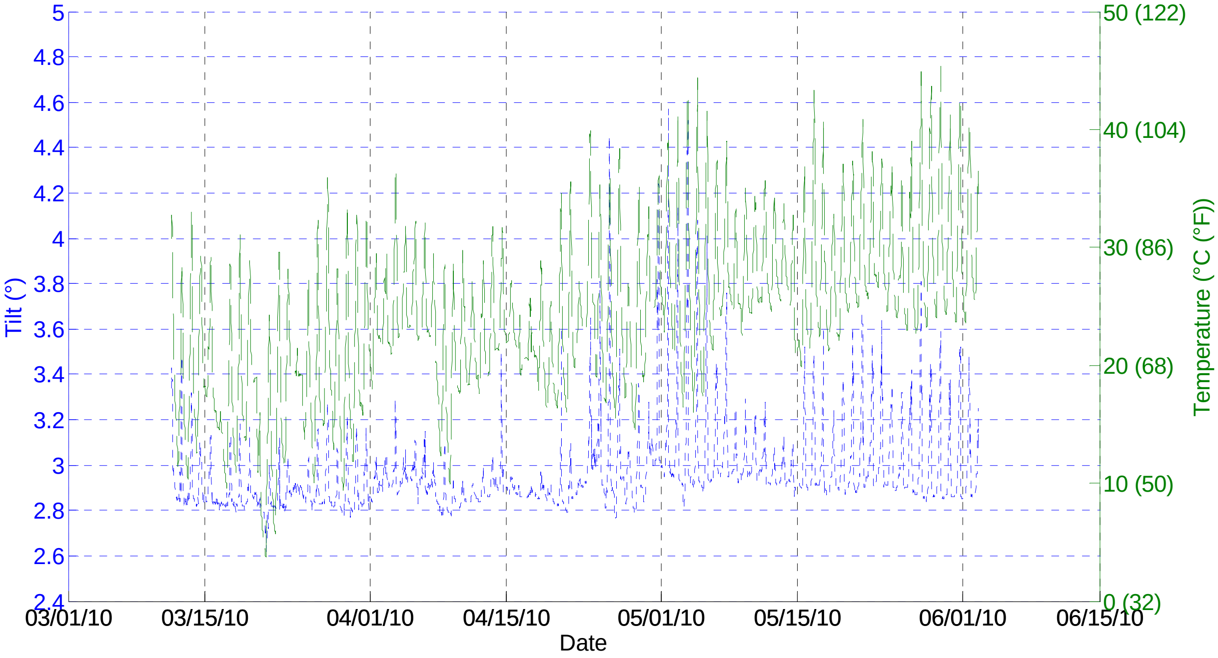


Figure 5-53. Tiltmeter1 and Temperature Response Plot for Phase C-D.

Phase D-E (June 5, 2010–August 9, 2010). Figure 5-54 shows the time history plot of all the data of Tiltmeter1 and the temperature recorded after maintenance was performed on the system in June 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

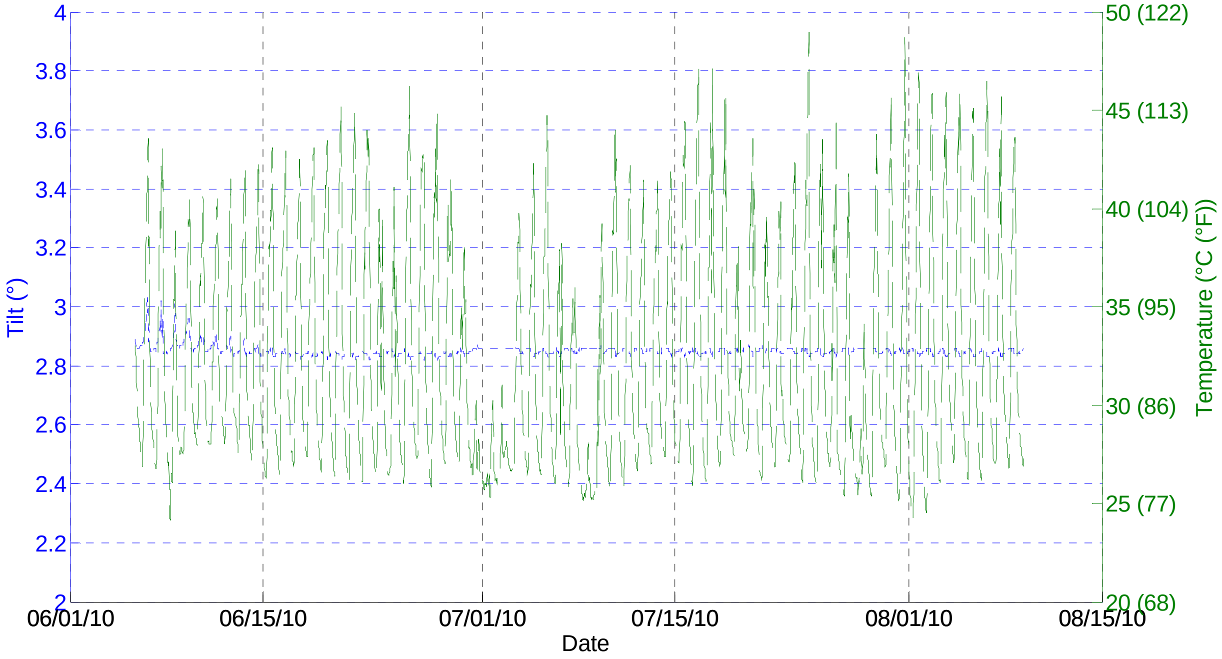


Figure 5-54. Tiltmeter1 and Temperature Response Plot for Phase D-E.

(2). Data Analysis on Tiltmeter2 (May 28, 2009–August 9, 2010). Figure 5-55 shows the time history plot of the data obtained from Tiltmeter2 (including both Tiltmeter2a and Tiltmeter2b).

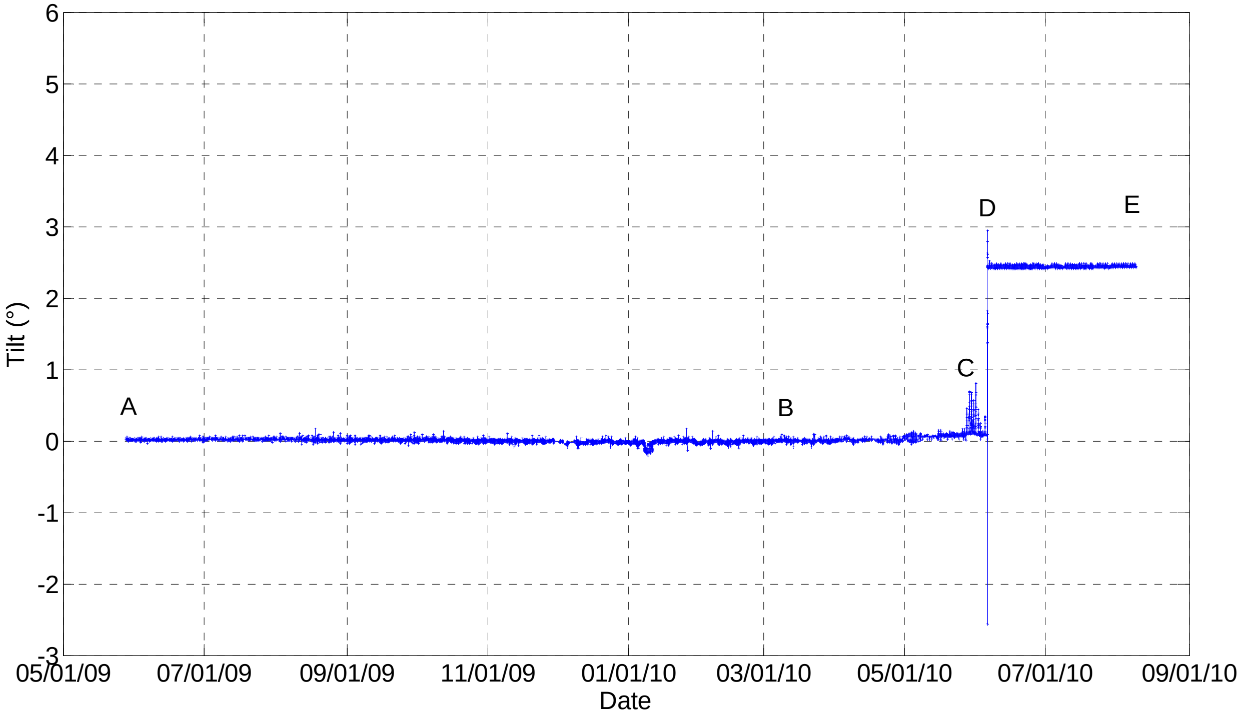


Figure 5-55. Tiltmeter2 Time History Plot on US59 over Guadalupe River Bridge.

In Figure 5-55, the point B represents the day when the system was reprogrammed. Point C represents the day when Tiltmeter2 was removed from the dual-axis tiltmeter enclosure to another location on the bridge deck as shown in Figure 5-50.

Phase A-B (May 28, 2009–March 11, 2010). Figure 5-56 shows the time history plot of all the data collected from Tiltmeter2, and the temperature recorded before the system was reprogrammed in March 2010. The blue line shows the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the data collected from Tiltmeter2.

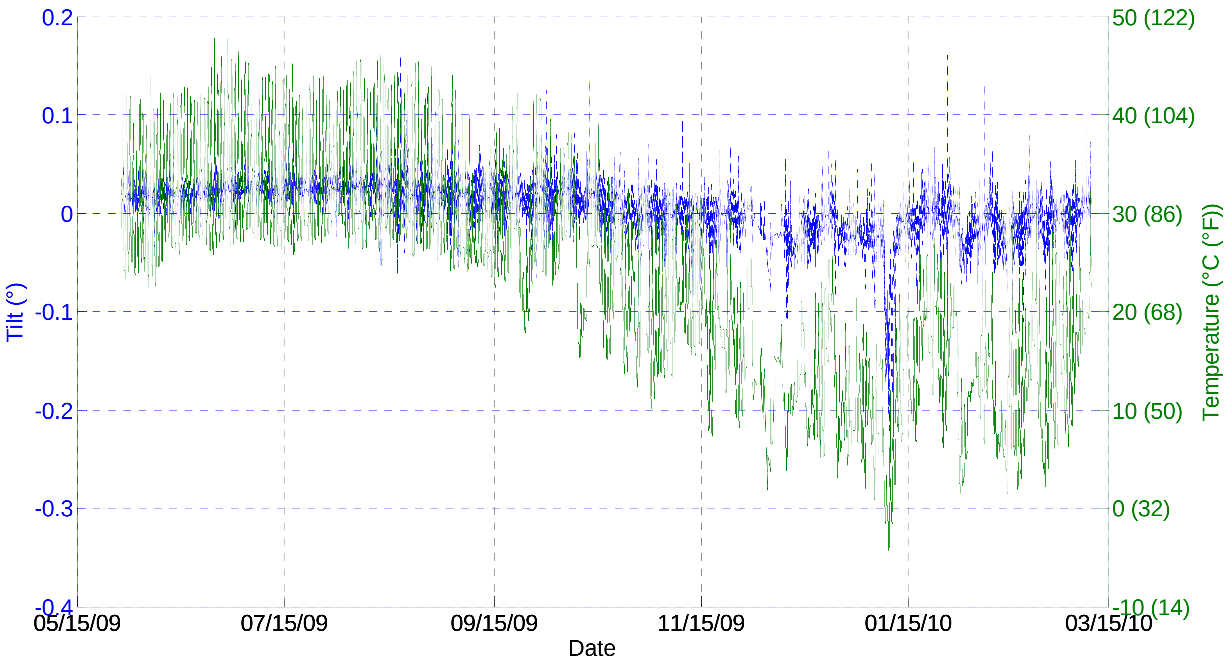


Figure 5-56. Tiltmeter2 and Temperature Response Plot for Phase A-B.

Phase B-C (March 11, 2010–June 5, 2010). Figure 5-57 shows the time history plot of data collected from Tiltmeter2, and the temperature recorded after the system was reprogrammed in March 2010. The blue line shows the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), and the green line in the figure shows the temperature in the master station box. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

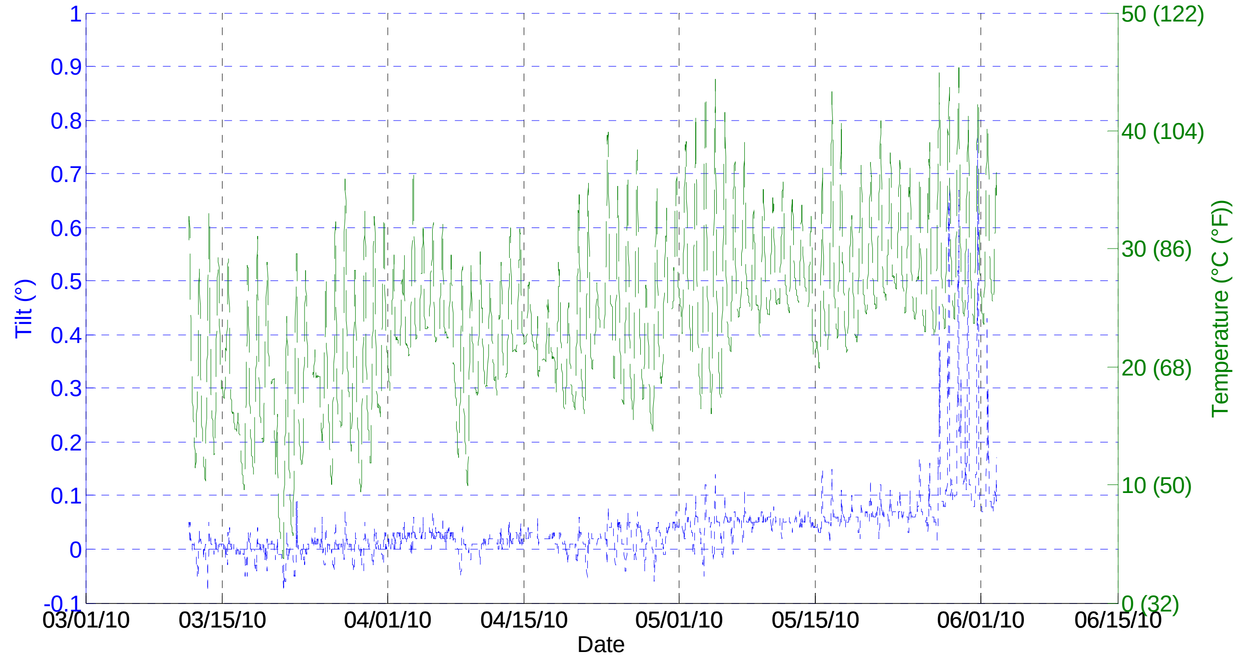


Figure 5-57. Tiltmeter2 and Temperature Response Plot for Phase B-C.

Phase D-E (June 5, 2010–August 9, 2010). Figure 5-58 shows the time history plot of data collected from Tiltmeter2 and the temperature recorded in the modified monitoring system in June 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

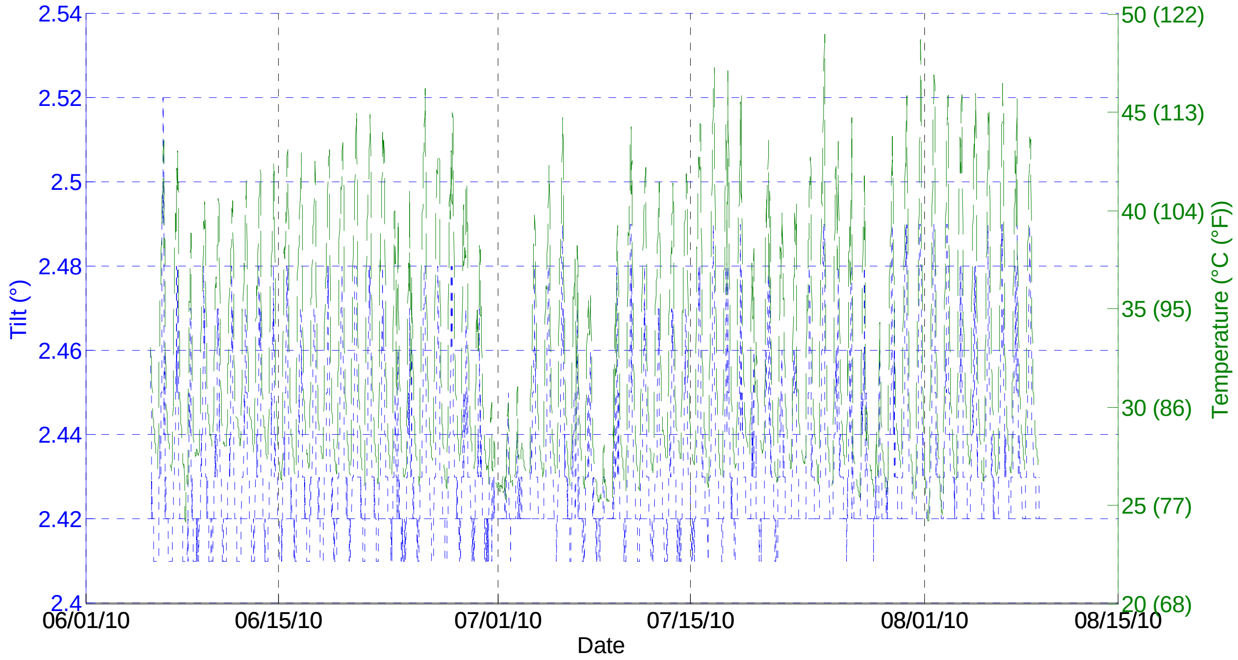


Figure 5-58. Tiltmeter2 and Temperature Response Plot for Phase D-E.

(3). Data Analysis on Tiltmeter3 (May 28, 2009–August 9, 2010). Tiltmeter3 was installed on top of Pier SB2 on US59 over Guadalupe River Bridge on June 5, 2010, measuring the tilt angle of the pier around the flow direction axis. Figure 5-59 shows the time history plot of all the data collected from Tiltmeter3, and the temperature recorded after the system was modified on June 5, 2010. The blue line shows the tilt angle of the pier around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the previous data collected from Tiltmeter3.

Figure 5-59. Tiltmeter3 and Temperature Response Plot.

(4). Data Analysis on Tiltmeter4 (May 28, 2009–August 9, 2010). Tiltmeter4 was installed on top of Pier SB2 on US59 over Guadalupe River Bridge on June 5, 2010, measuring the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction). Figure 5-60 shows the time history plot of the data collected from Tiltmeter4 and the temperature recorded after the system was modified on June 5, 2010. The blue line shows the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the previous data collected from Tiltmeter4.

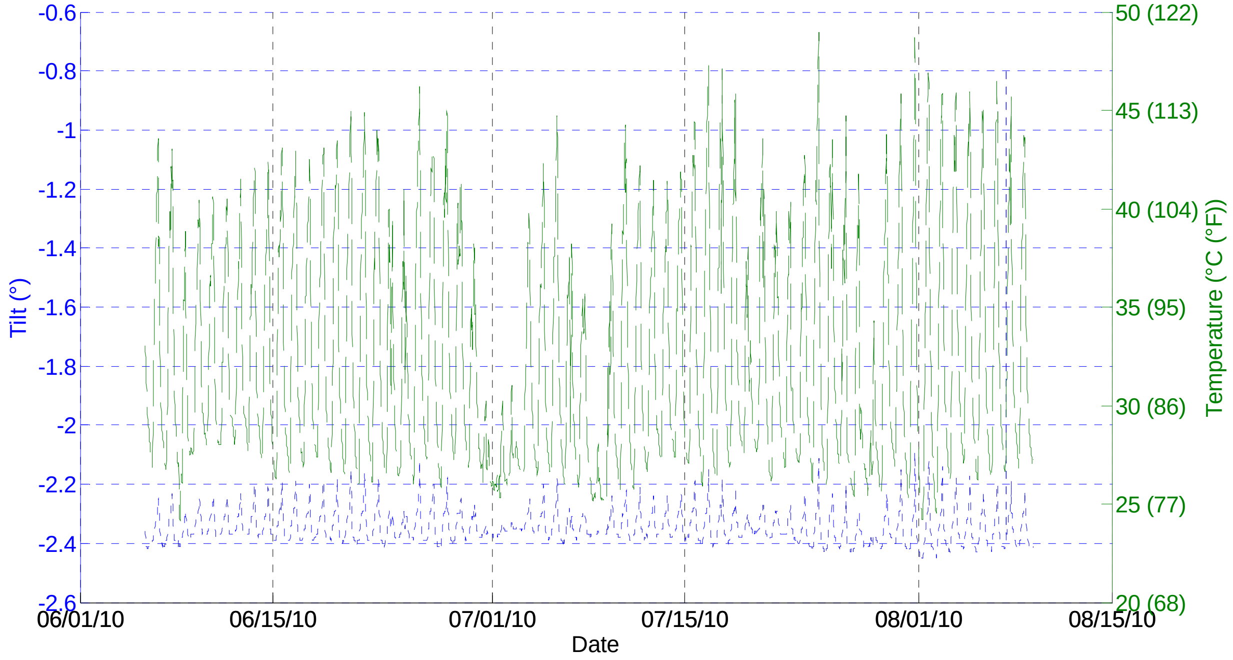


Figure 5-60. Tiltmeter4 and Temperature Response Plot.

TBS Equipments

The data for TBS equipments were collected from 9:50 a.m. on May 28, 2009, to 7:00 a.m. on August 9, 2010. If the TBS is in a vertical position and the trigger has not been launched, the sensor will transmit a value of 1 to the data acquisition system. If the switch is triggered and the scour reaches the buried level, the sensor will transmit a value of 2 to the data acquisition system. If the wire of the switch is broken, the sensor will transmit a value of 3 to the data acquisition system. Figure 5-61 shows the data collected from the two TBS equipments installed on US59 over Guadalupe River Bridge. TBS1 was buried 1.5 m (5 ft) below the ground surface near the southwest abutment at a distance of 7.2 m (24 ft) below the top of the deck. TBS2 was buried 3 m (10 ft) below TBS1 at a distance of 10 m (34 ft) below the top of the deck.

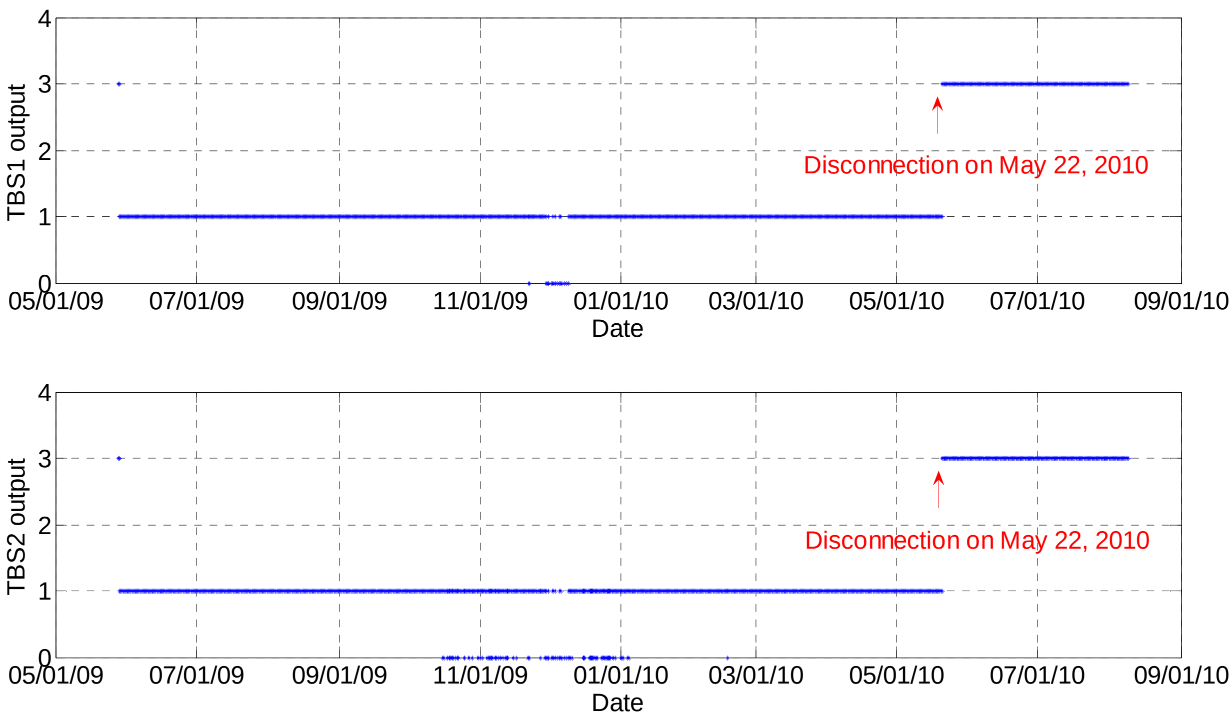


Figure 5-61. TBS Response on US59 over Guadalupe River Bridge.

Figure 5-61 shows that the two TBS equipments transmitted a value of 1 before May 22, 2010, indicating that the trigger was not launched. From May 22, 2010, a value of 3 was received indicating that the TBS connection was broken. This occurred due to the construction of the extension on southwest side of the US59 over Guadalupe River Bridge.

The site visits in March 2010 revealed the increased scour on the southwest side of the US59 over Guadalupe River Bridge at the location where TBS equipments were buried. In 2009, the TBS equipments were installed 2.4 m (8 ft) away from the edge of soil. In 2010 the TBS equipments were only 0.9 m (3 ft) away from the edge of soil (Figure 5-62).

(a) (b)

Figure 5-62. Scour Level at the Location of the TBS: (a) Tape Measure in Detail and (b) Tape Measure.

Float-Out Devices

The float-out device gives output in the form of two discrete values of 0 and 1. The internal radio transmitter will transmit a value of 0 to the data acquisition system if the float-out device is vertical and has not floated out. The radio transmitter will transmit a value of 1 to the data acquisition system if the float-out device floats out, and becomes horizontal. Figure 5-63 shows the data collected from the two float-out devices installed on US59 over Guadalupe River Bridge. Float-out1 was buried 1.5 m (5 ft) below the soil surface at a distance of 16 m (54 ft) below the top of the deck. Float-out2 was buried 2.7 m (9 ft) below Float-out1 at a distance of 19 m (63 ft) below the top of the deck.

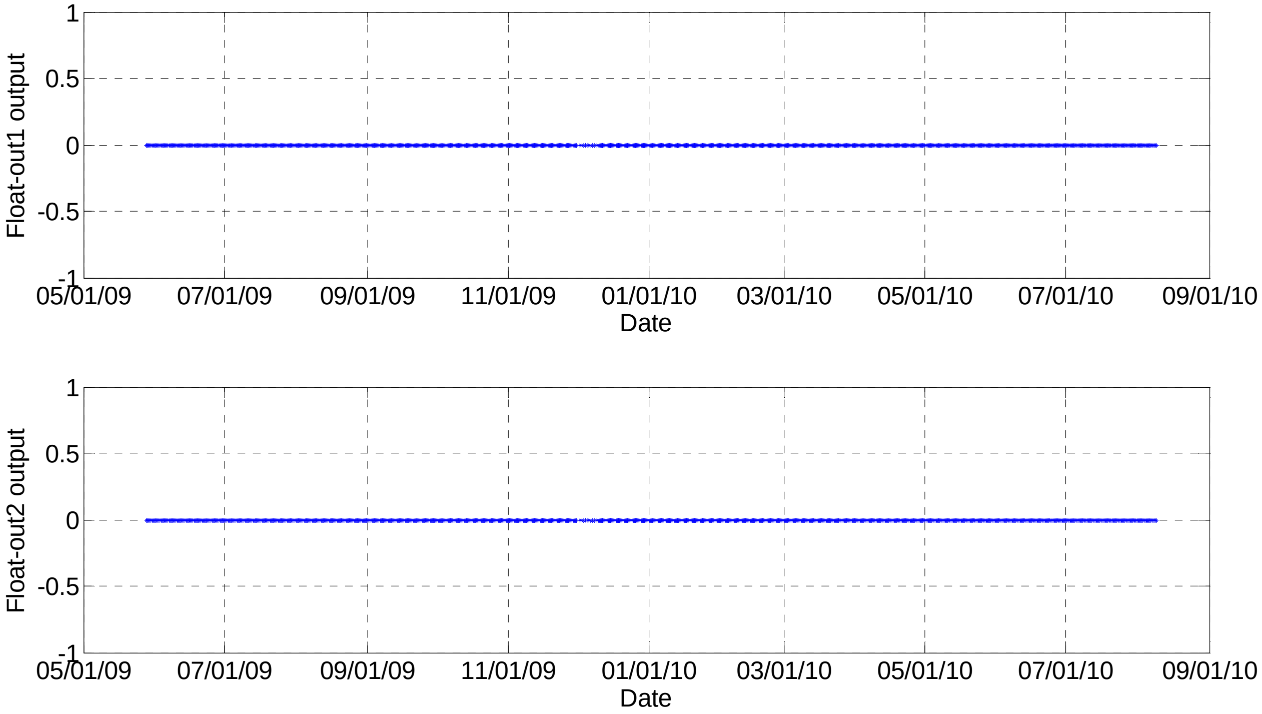


Figure 5-63. Float-Out Device Response at US59 over Guadalupe River Bridge.

Figure 5-63 shows that the two float-out devices transmitted a value of 0 since their installation on May 28, 2010, indicating that the devices are vertical and have not floated out.

Water Stage Sensor

The water stage sensor gives the elevation of the water level at the US59 over Guadalupe River Bridge as the output. The Mean Sea Level is taken as datum. The elevation of the top surface of the bridge deck is 18.3 m (61 ft) above the datum. The elevation of the bottom deck is 18 m (60 ft) above the datum. The water stage sensor was installed at the level of bridge deck so the water stage sensor is at a height 18 m (60 ft) above the datum. The elevation of the water level is obtained by subtracting the distance between the sensor and the water surface from the elevation of deck 18.3 m (61 ft).

The water gage reading from USGS is used to validate the data collected from the water stage sensor. The USGS station number USGS 08176500 is located 10.2 km (6.4 miles) upstream of the US59 over Guadalupe River Bridge. So the reading collected at this site is used for the comparison of water stage sensor reading. The gage height historic data are obtained from the USGS website. The gage height measures the water elevation above the gage datum, which is 8.74 m (29.15 ft) above the sea level NGVD 29. After doing the offset of the USGS gage reading, the water stage reading is compared with the gage reading. Figure 5-64 shows the description of measurement from water stage sensor. Figure 5-65 shows the location of project and USGS gages.

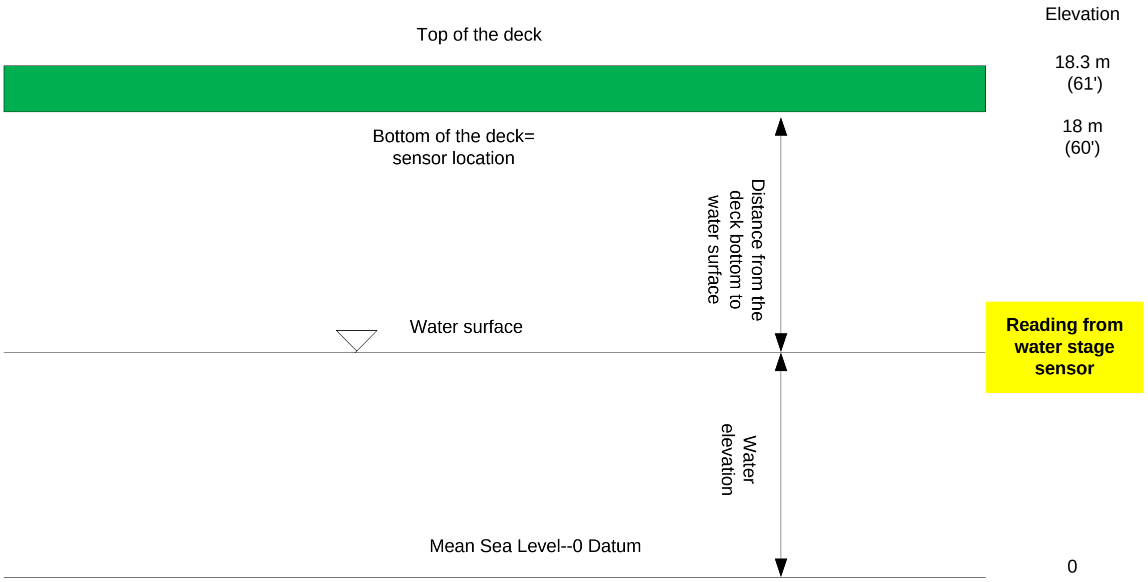


Figure 5-64. Description of the Measurement from the Water Stage Sensor.

Figure 5-65. Location of USGS Gage Sensors.

Figure 5-66 shows the comparison of the readings obtained from the water stage sensor with the readings obtained from USGS gage sensor. The two readings compare well for some parts. There is a discrepancy in other parts of the comparison. The reason of the discrepancy is that the monitoring system lost power. So it recorded default values that are not the indicator of the actual water elevation. Hence these values do not compare with the USGS gage readings.

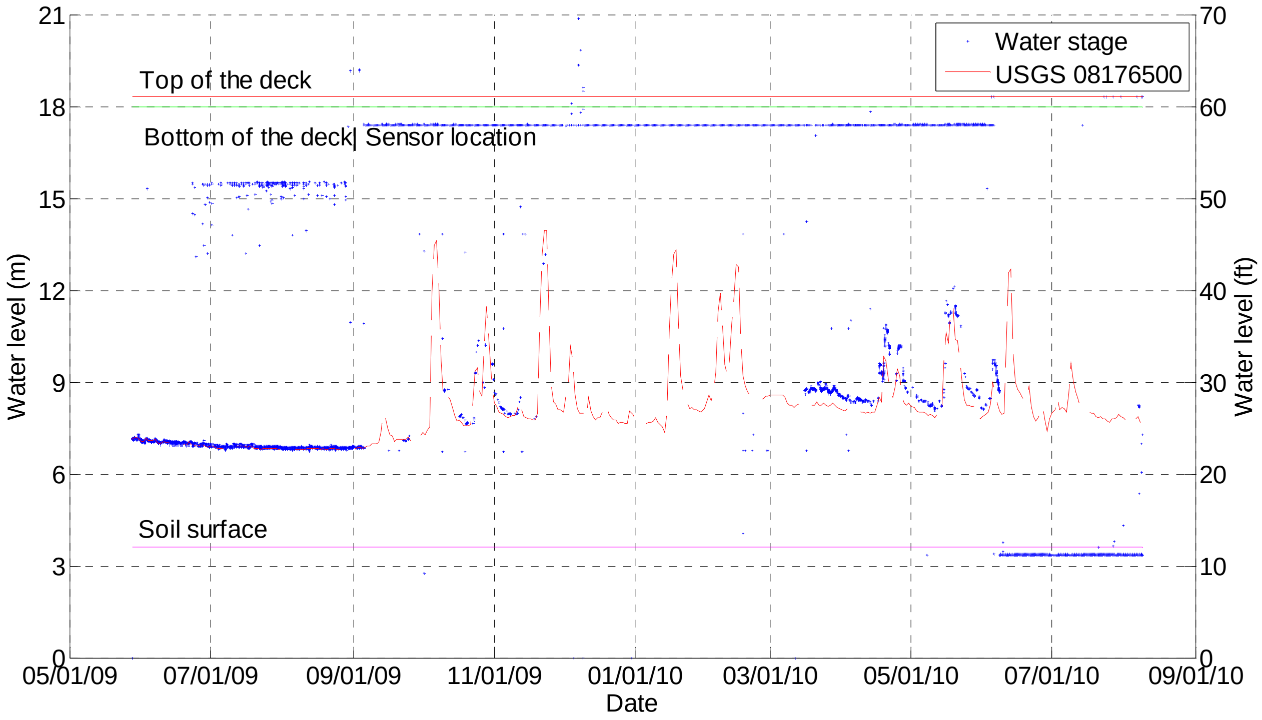
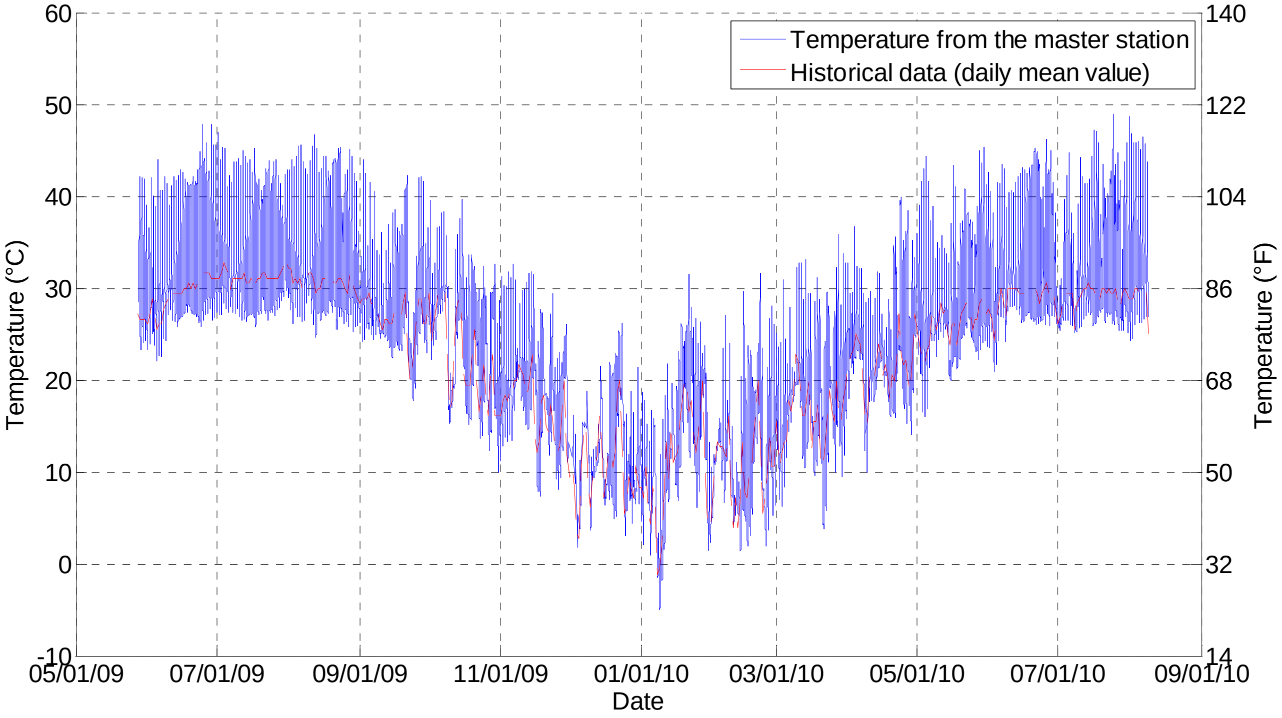


Figure 5-66. Comparison of Water Stage Sensor and USGS08176500 Gage Readings.

Other Readings

In addition to the data from the installed instruments at the US59 over Guadalupe River Bridge, the scour monitoring system also records the reading from the temperature sensor located in the master sensor enclosure and voltage.

Figure 5-67 shows the temperature reading for the system. The daily mean temperature in Victoria is also plotted in the figure for comparison. The temperature data from the monitoring system compares well with the daily mean temperature in Victoria. Figure 5-68 shows the battery reading for the system. The battery voltage is also correlated with the temperature data. This is due to the fact that the battery is charged using solar panels, which is dependent on the temperature.



*Historical data source:

http://www.wunderground.com/history/airport/KVCT/2009/5/28/CustomHistory.html?dayend=19&monthend=2&yearend=2010&req_city=NA&req_state=NA&req_statename=NA

Figure 5-67. Temperature Reading for US59 over Guadalupe River Bridge.

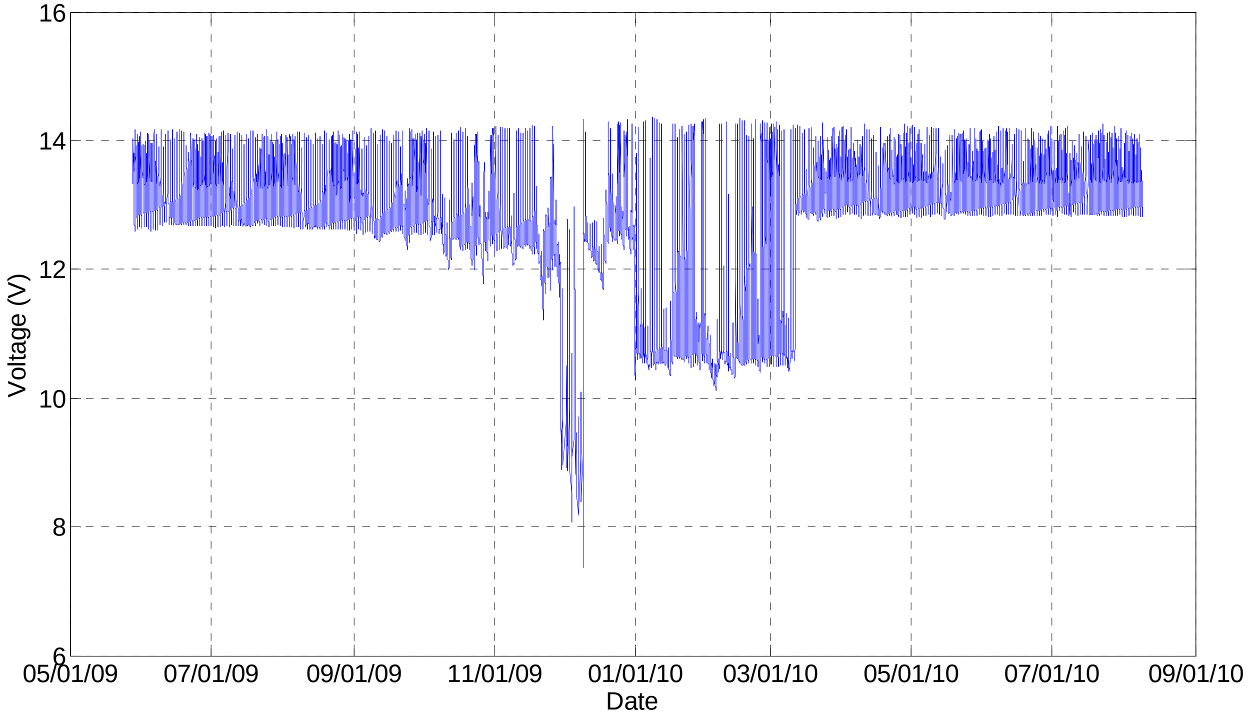


Figure 5-68. Battery Reading for US59 over Guadalupe River Bridge.

Interpretation of the Collected Data

For the modified monitoring system, the results can be interpreted in the following way.

Tiltmeters

The four installed tiltmeters give the tilt angle at different locations on the bridge around the axis of flow and traffic direction. A consistent reading is interpreted as the bridge is stable and is not affected by the scour threat. If the reading exceeds a preset threshold value, then a warning has to be issued and decision regarding the closure of the bridge has to be taken. The threshold value of the tilt angle for the US59 over Guadalupe River Bridge is studied and established in Chapter 7 in this report.

Float-Out Devices

The reading of 0 obtained from the flout-out device means that it is still in the vertical position, and reading 1 means it has floated out. Flout-out1 was buried 1.5 m (5 ft) below the soil surface, and Float-out2 was buried 2.7 m (9 ft) below Float-out1 when they were installed on US59 over Guadalupe River Bridge in 2009. The floating out of the device means that the scour depth has reached the instrument buried depth, which has not happened yet.

TBS Equipments

The reading 1 means the TBS is in the vertical position; reading 2 means the switch has floated out; and reading 3 means the wire of the switch is broken. On August 7, 2010, TTI researchers went to the bridge to repair the water stage sensor and found that the TBS cable was lost, which might be due to the excavation during the construction of the bridge extension. Currently, the TBS is showing a value of 3, which means that the connection is broken.

Water Stage Sensor

The water stage sensor gives the water surface elevation on the location of sensor, which is located at a distance of 2.25 m (7.5 ft) from the pier SB2 (Figure 5-7).

NUMERICAL SIMULATION

Introduction

A Finite Element (FE) model of the bridge is made from the drawings and details obtained from the TxDOT. The material properties are obtained from the drawings and are also evaluated at the site. The FE model has the advantage that the critical scour cases can be simulated to study their effect on the response parameters. This section describes the FE model of the bridge and presents the parametric study of the responses with the progress of the scour.

Finite Element Model

Two kinds of FE models for the bridge are made. The first one is made using equivalent area and moment of inertia for the bridge. The bridge is modeled using one-dimensional beam elements. The soil is modeled using fully integrated quadratic eight node elements with nodal rotations. This is called simplified model. The second model is made using fully integrated quadratic eight node elements with nodal rotations for the bridge as well as the soil. This is called full scale model.

Simplified Model

In the simplified model, the soil and the concrete are considered elastic. The penalty method is used to model the contacts between the different elements. In this method normal interface springs are placed between all penetrating nodes and the contact surfaces. The method is stable and it does not excite mesh hour glassing. It is capable of handling contacts between dissimilar materials, which is well suited for this study.

A parametric study is performed to study the response of the bridge with the progress of scour. Three different cases of scour are simulated as follows:

- No scour (0 relative depth of scour).
- Scour depth of 3.6 m (12 ft) (2/3 relative depth of scour).
- Scour depth of 5.4 m (18 ft) (1 relative depth of scour).

Figure 5-69 shows the simplified model of the bridge without scour. Figure 5-70 shows the simplified model with 5.4 m (18 ft) of scour.

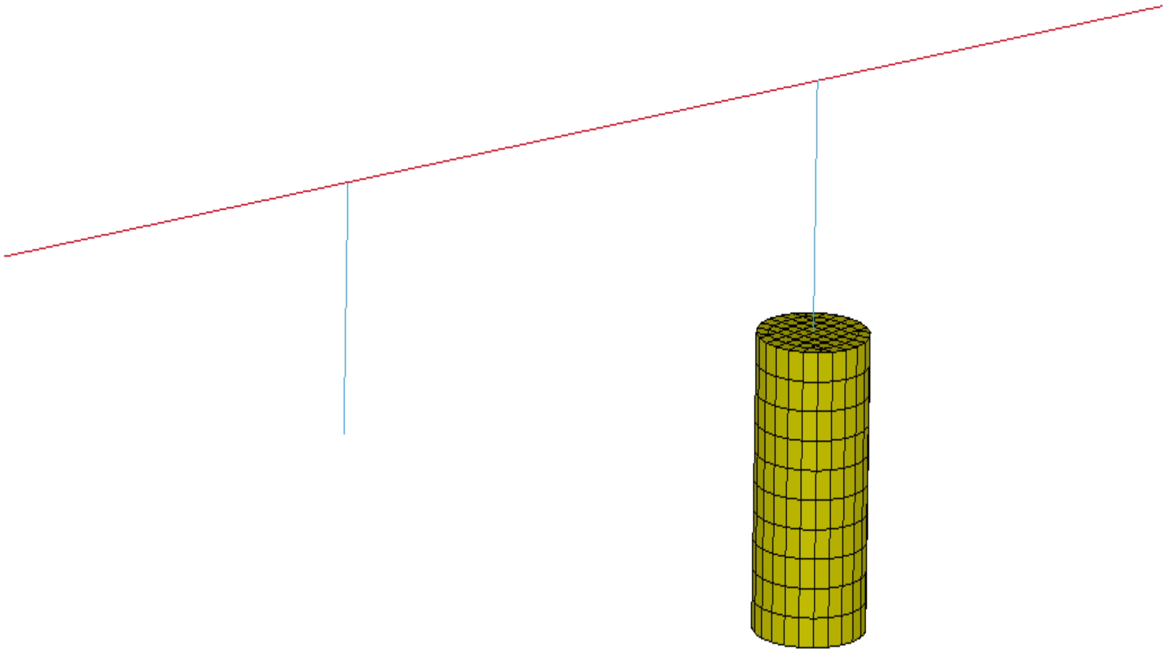


Figure 5-69. Simplified FE Model for US59 over Guadalupe River Bridge without Scour.

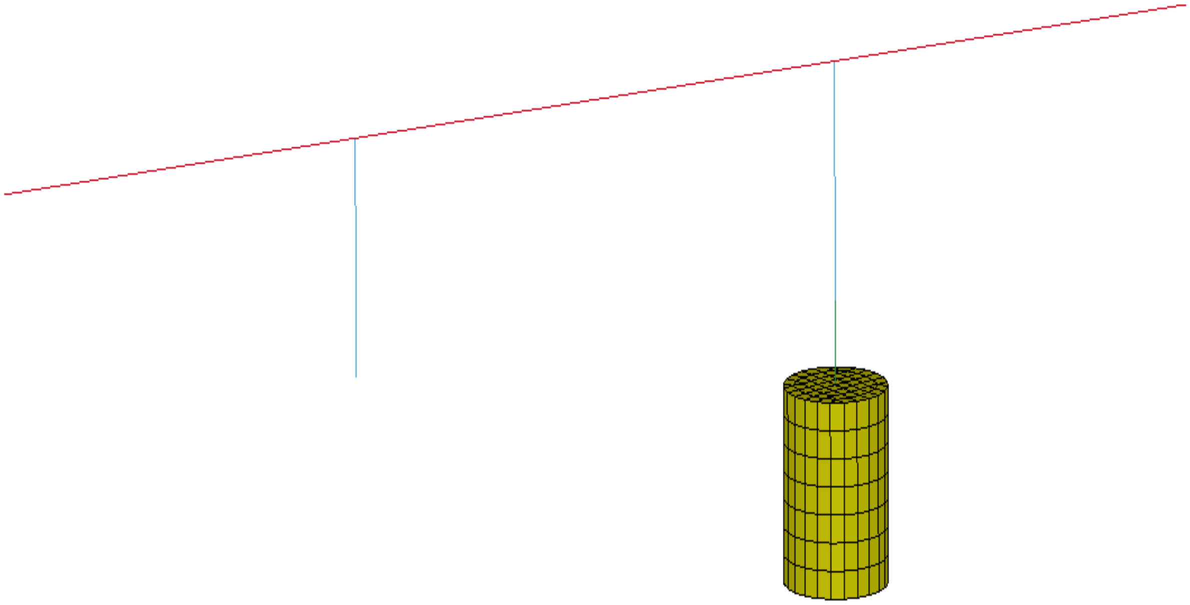


Figure 5-70. Simplified FE Model for US59 over Guadalupe River Bridge with Scour of 5.4 m (18 ft).

Table 5-1 shows the comparison of the natural frequencies of the simplified bridge model. The two compared cases are one with no scour and the other with 5.4 m (18 ft) of scour. The relevant modes are compared to study the variation of frequency with the progress of the scour. The first mode in bending in the flow direction does not show significant change. The modes in bending of the pier for flow and traffic direction are sensitive to the progress of scour. The vertical mode of the pier is also sensitive to the scour but does not have the similar sensitivity as the bending mode of the pier. The bending mode of pier in flow and traffic direction can be used as parameters for the scour monitoring.

Table 5-1. Comparison of Natural Frequencies of Simplified Bridge.

No scour			Scour depth 5.4 m (18 ft)		
Mode no.	Type	Frequency (Hz)	Mode no.	Type	Frequency (Hz)
1	Bending in flow direction	3.7	1	Bending in flow direction	3.56
23	Bending of pier in flow direction	20.1	5	Bending of pier in flow direction	5.57
20	Bending of pier in traffic direction	16.4	11	Bending of pier in traffic direction	8.3
14	Vertical pier	12.1	13	Vertical pier	10.5

A dynamic analysis is performed to study the effect of pulse on the model. The quantity of interest monitored is the acceleration at the top of the bridge pier. The explicit integration scheme based on the central difference method is used for the analysis.

Figure 5-71 shows the variation of the ratio of RMS values in each two directions for the different scour depths for pulse excitation in flow direction. The ratio of RMS values of acceleration in each two directions is normalized with the ratio of RMS values when there is no scour. The result is presented as percentage change in the ratio of RMS values. The ratio of RMS values of acceleration in flow direction over traffic direction increases. The increase in RMS ratio is approximately 10 times. The change in ratio of RMS values of acceleration in flow direction over traffic direction with scour depth follows a non linear trend with a steep increase as the scour progresses. The ratio of RMS values of acceleration in flow direction over vertical direction decreases by 0.04 times. The ratio of RMS values of acceleration in traffic direction over vertical direction also decreases with the development of scour.

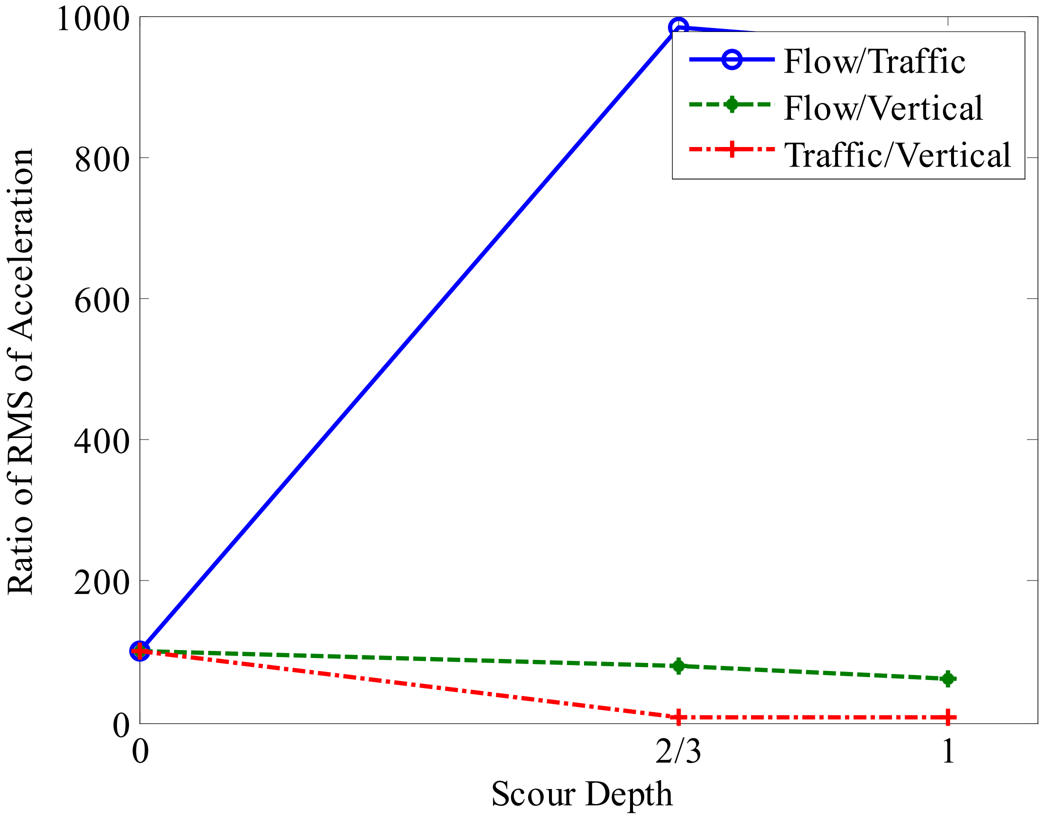


Figure 5-71. Variation of Ratio of RMS Values of Acceleration with Scour for Simplified Bridge Model for Pulse Excitation in Flow Direction.

Figure 5-72 shows the variation of the ratio of RMS values of acceleration in each two directions for the different scour depths for pulse excitation in traffic direction. The ratio of RMS values of acceleration in flow direction over traffic direction and in flow direction over vertical direction decreases by 0.7 times. The change in ratio of RMS values of acceleration in flow direction over traffic direction with scour depth follows a non linear trend with a steep decrease as the scour progresses. So does the ratio of RMS values of acceleration in flow direction over vertical direction. The ratio of RMS values of acceleration in traffic direction over vertical direction increases slightly with the development of scour.

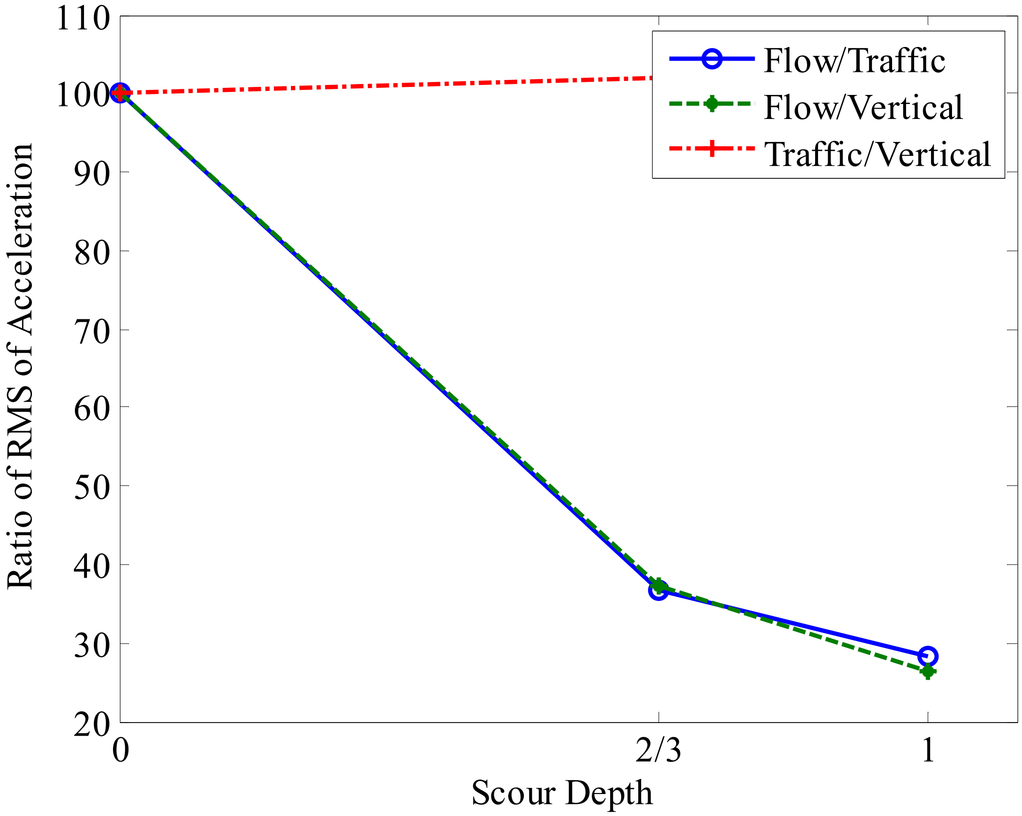


Figure 5-72. Variation of Ratio of RMS Values of Acceleration with Scour for Simplified Bridge Model for Pulse Excitation in Traffic Direction.

Figure 5-73 shows the variation of the ratio of RMS values of acceleration in each two directions for the different scour depths for pulse excitation in vertical direction. All the ratios of RMS values of acceleration do not show any consistent trend.

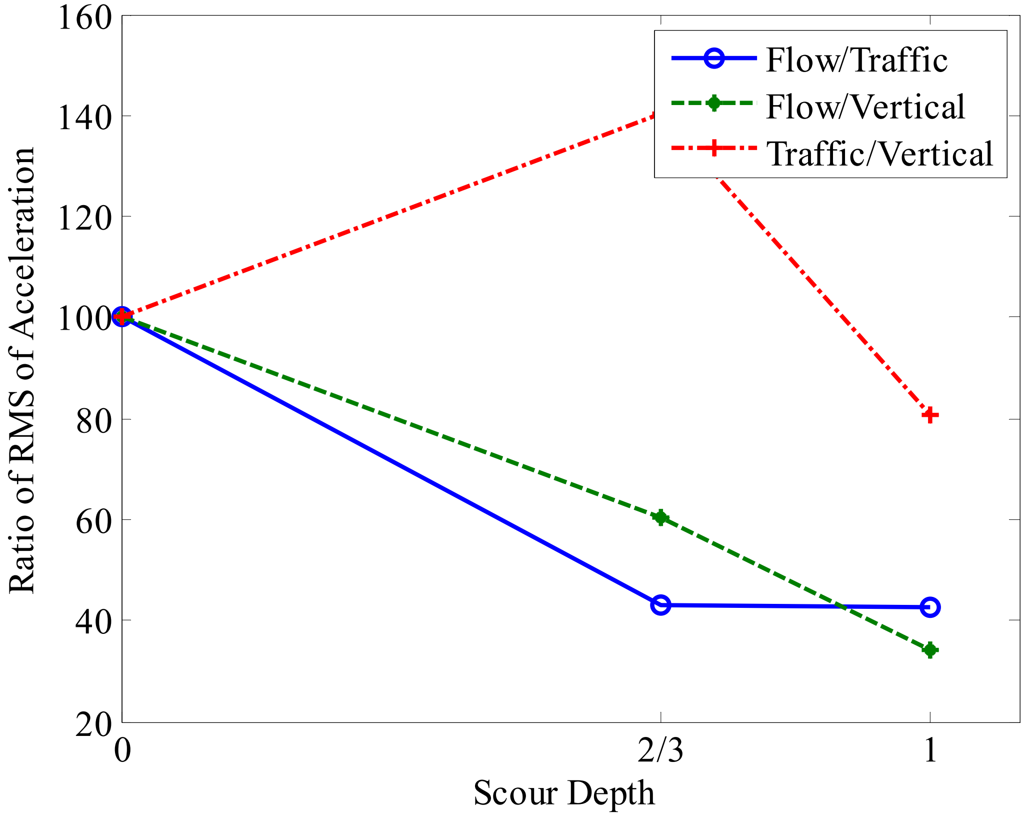


Figure 5-73. Variation of Ratio of RMS Values of Acceleration with Scour for Simplified Bridge Model for Pulse Excitation in Vertical Direction.

Based on the above analysis, the change in ratio of RMS values of acceleration in each two directions is direction dependent. The magnitude of change is also direction dependent. The ratio of RMS values of acceleration in flow direction over vertical direction and in flow direction over traffic direction are sensitive with the progress of scour.

Full Scale Model

A three-dimensional solid model is used for modeling the elements. The bridge is modeled by fully integrated quadratic eight node elements with nodal rotations. The gravitational load is transferred using dynamic relaxation. The foundation is modeled by fully integrated quadratic eight node elements with nodal rotations. Mesh refinement achieves convergence, and hourglass energy is minimized.

Material Models. A rate dependent material model is applied for all the materials due to the sensitivity of material properties with loading rate. In this research, a continuous surface cap model available in the software is used to model the concrete. This model also takes into account the strain rate dependency of the concrete strength.

Contact Algorithm. The contact between the different parts is modeled using the "Contact_Automatic_Surface_To_Surface" algorithm. In tied contact types, the slave nodes are constrained to move with the master surface. At the beginning of the simulation, the nearest master segment for each slave node is located based on an orthogonal projection of the slave node to the master segment. If the slave node is deemed close to the master segment based on established criteria, the slave node is moved to the master surface. In this way, the initial geometry may be slightly altered without invoking any stresses. As the simulation progresses, the isoperimetric position of the slave node with respect to its master segment is held fixed using kinematic constraint equations. Figure 5-74 shows the model of the full scale bridge. Mesh refinement is done to achieve convergence. Figure 5-75 shows the model of the full scale bridge without soil.

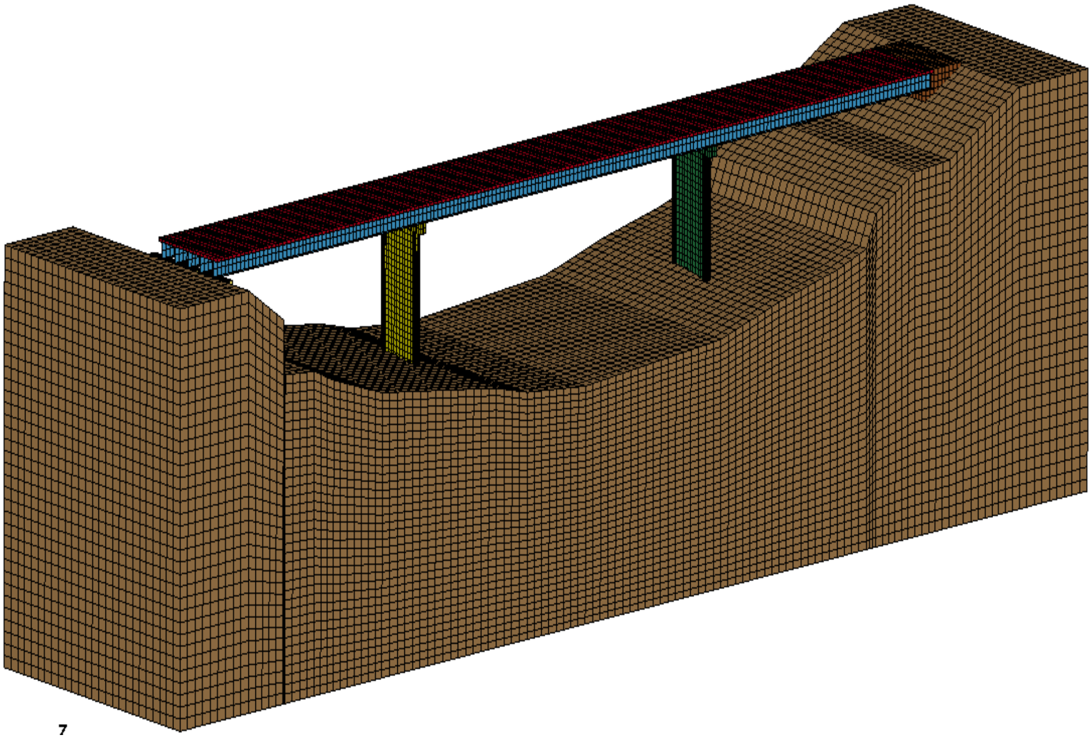


Figure 5-74. Full Scale Model of US59 over Guadalupe River Bridge with Soil.

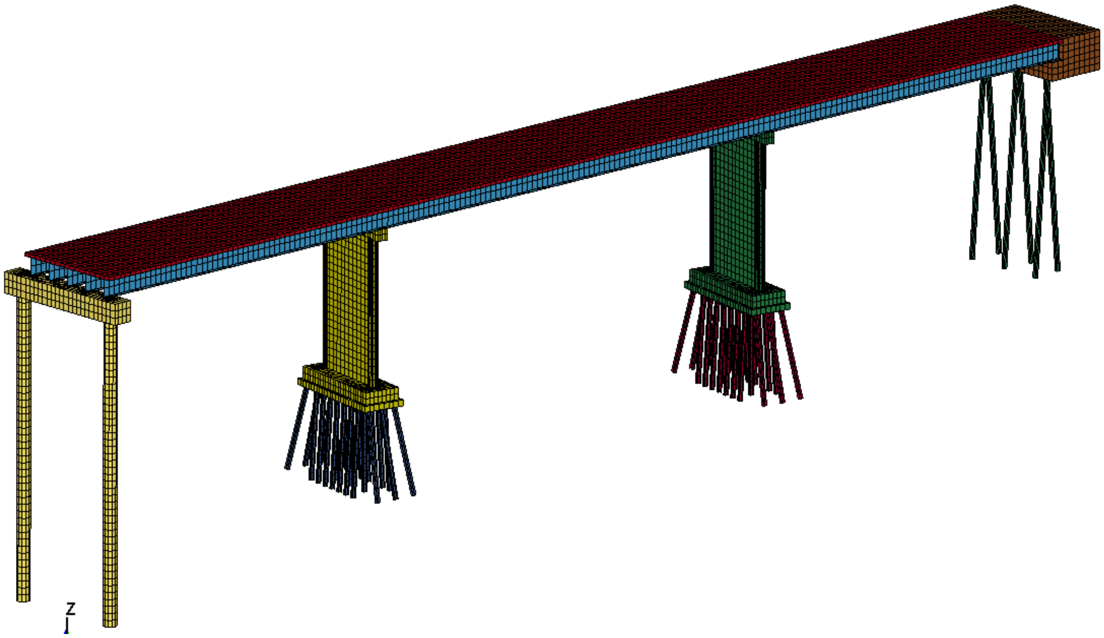


Figure 5-75. Full Scale Model of US59 over Guadalupe River Bridge without Soil.

A parametric study is done to study the effect of progress of the scour on the natural frequency of the full scale bridge similar to the simplified model. For the parametric study of the variation of the response quantity with the scour, two different models are created. The first model is the bridge with no scour; and the second one is the bridge with scour of 6 m (20 ft). Figure 5-76 shows the model with 6 m (20 ft) scour.

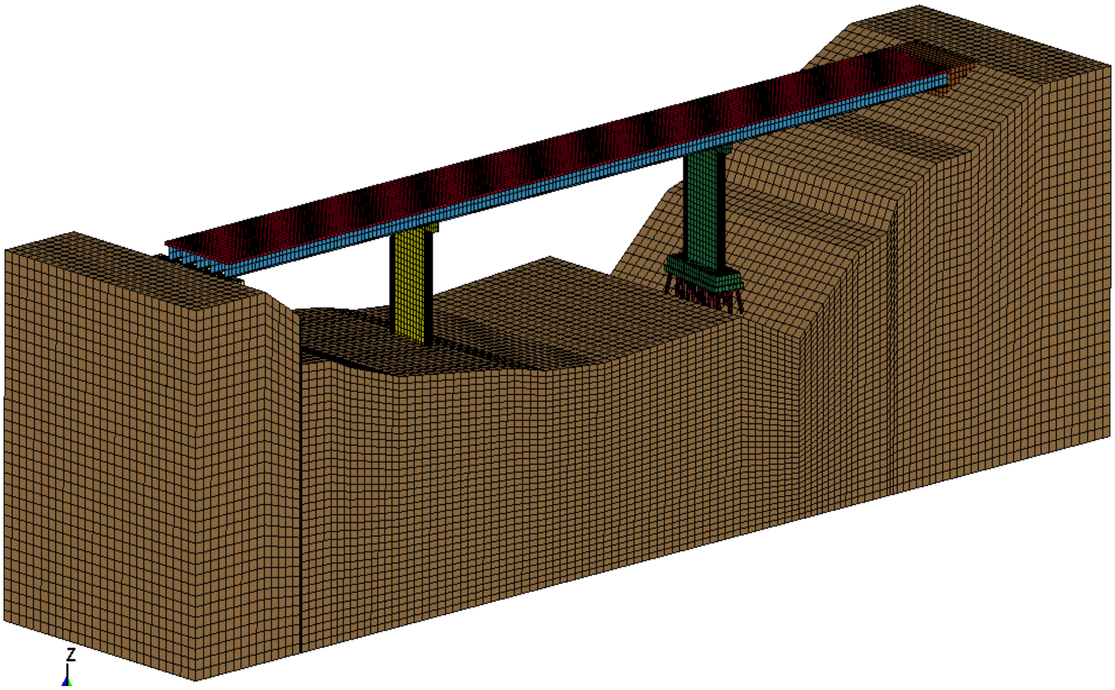


Figure 5-76. Full Scale Model of US59 over Guadalupe River Bridge with Scour of 6 m (20 ft).

Figure 5-77 shows the mode shape of the full scale bridge with no scour. The mode is in the flow direction. Figure 5-78 shows the mode shape of the bridge with scour of 6 m (20 ft) at the pier. The mode is in the traffic direction. There is decrease in the frequency from 2.054 Hz to 1.868 Hz.

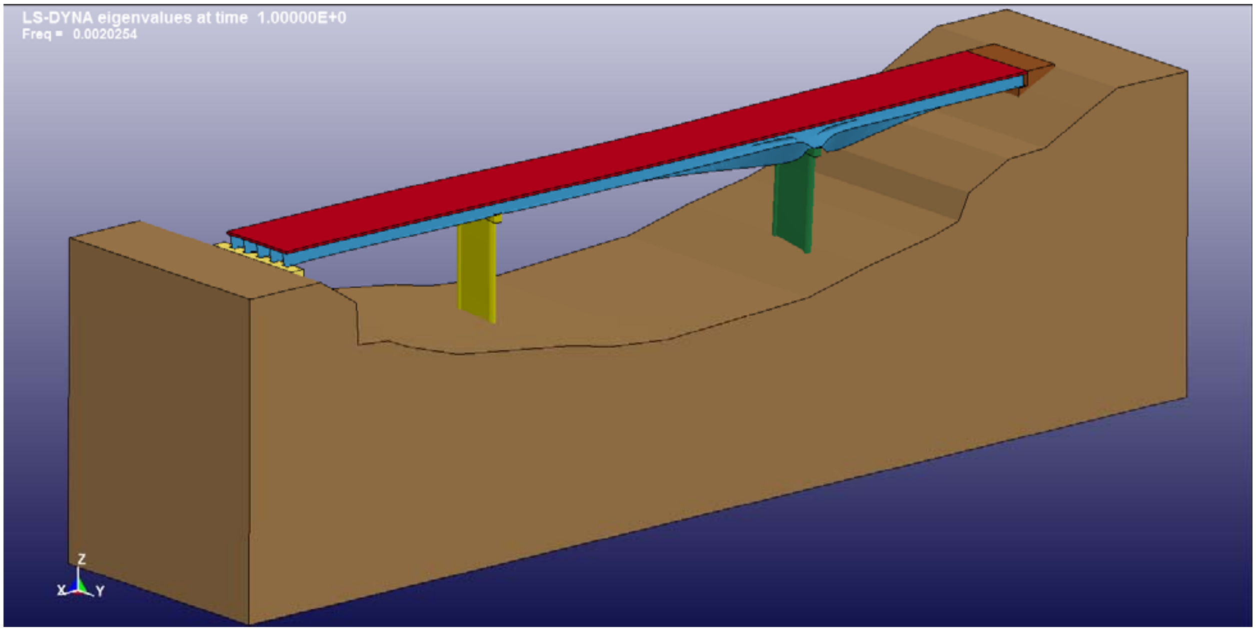


Figure 5-77. Mode Shape of the Full Scale Bridge with No Scour.

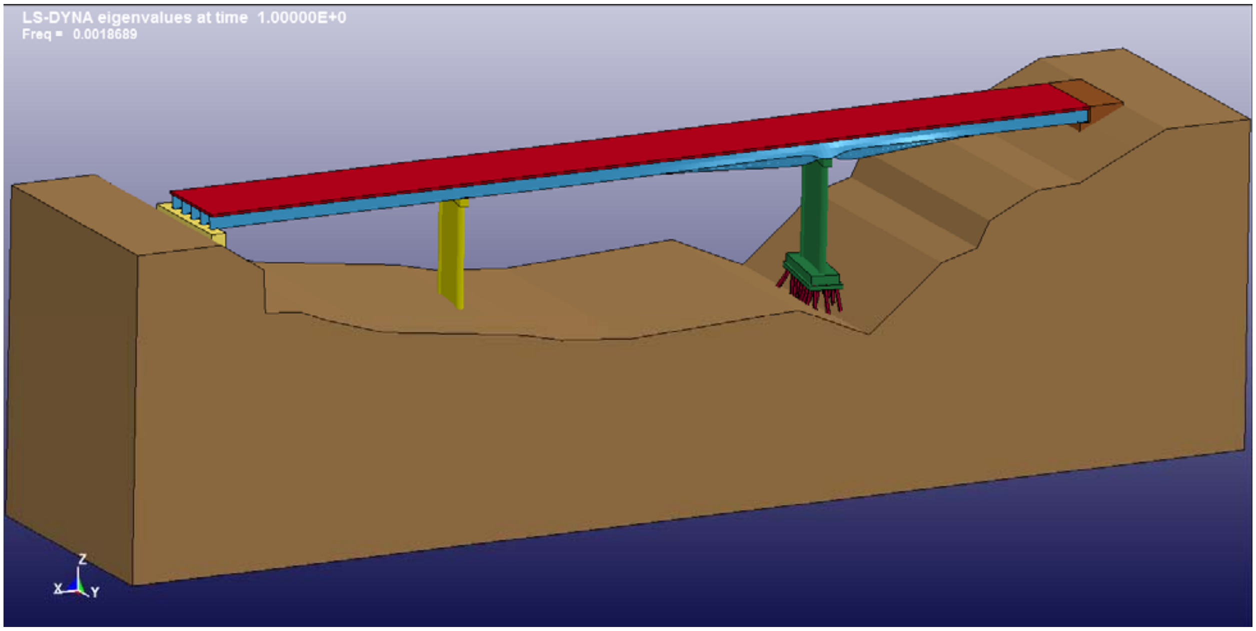


Figure 5-78. Mode Shape of the Full Scale Bridge with Scour of 6 m (20 ft) beneath the Pier.

Table 5-2 presents the comparison of the natural frequencies of the full scale bridge in different modes. The first natural frequency in traffic direction decreases by 7.75 percent. The other modes change by less than 5 percent. The change is small with respect to the progress of scour. The frequency response is not used as an indicator for the scour due to its less sensitivity for the full scale model.

Table 5-2. Comparison of Natural Frequencies of Full Scale Bridge.

No scour		Scour depth 6 m (20 ft)		Percentage Change (%)
Mode no.	Frequency (Hz)	Mode no.	Frequency (Hz)	
1	2.025	1	1.868	7.75
2	2.368	2	2.342	1.11
3	2.992	3	2.871	4.04
4	5.092	4	5.028	1.25

A dynamic analysis is performed to study the effect of change in scour depth to the acceleration in the system. The acceleration at the top of the pier is monitored. The ratio of the RMS values of acceleration in each two directions and natural frequency is the quantity used for the parametric study similar to the laboratory experiments. Figure 5-79 shows an FFT analysis of the acceleration in the flow direction. The analysis shows a dominant mode around 2 Hz, which is consistent with the natural frequency analysis done above. There are a number of closely spaced modes present and it is difficult to determine the modes with inspection only. So due to these reasons, the natural frequency analysis is not pursued further as a parameter for scour monitoring.

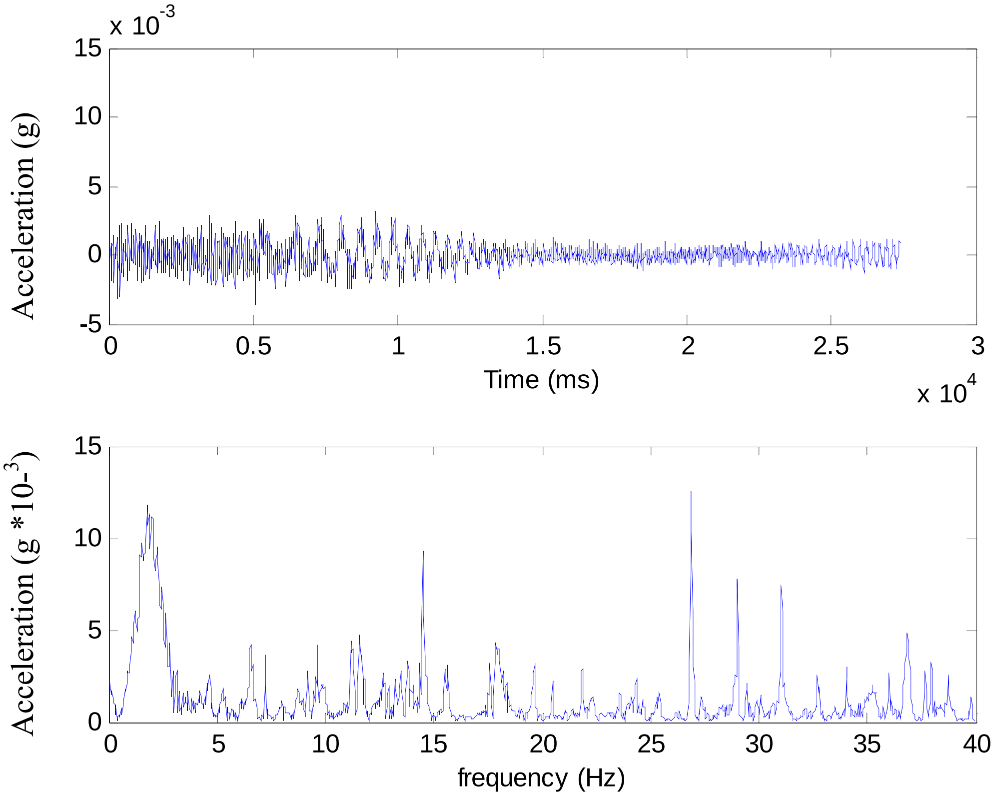


Figure 5-79. FFT Analysis of the Acceleration in Flow Direction.

The ratio of RMS values of acceleration in each two directions is further investigated to study the response with the progress of scour. An acceleration excitation is applied to the pier of the full scale model in the flow direction. The acceleration applied is similar to a traffic excitation experienced by the bridge in the field (Figure 5-80). The variation of ratio of RMS values of acceleration in each two directions is studied.

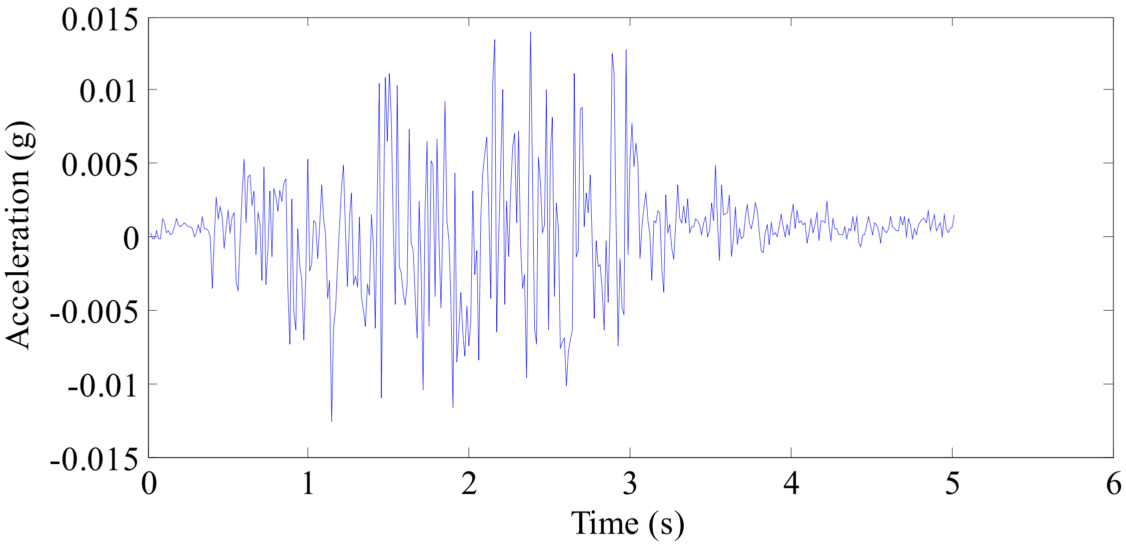


Figure 5-80. Acceleration Excitation Similar to Traffic Loading.

Figure 5-81 shows the variation of the ratio of RMS values of acceleration in each two directions with different scour depths. The ratio of RMS values of acceleration in flow direction over traffic direction decreases. The decrease in RMS ratio is approximately 0.4 times. The ratio of RMS values of acceleration in flow direction over vertical direction increases slightly. The ratio of RMS values of acceleration in traffic direction over vertical direction increases by 2 times at the maximum scour depth. The change of ratio of RMS values of acceleration with scour depth follows a non linear trend.

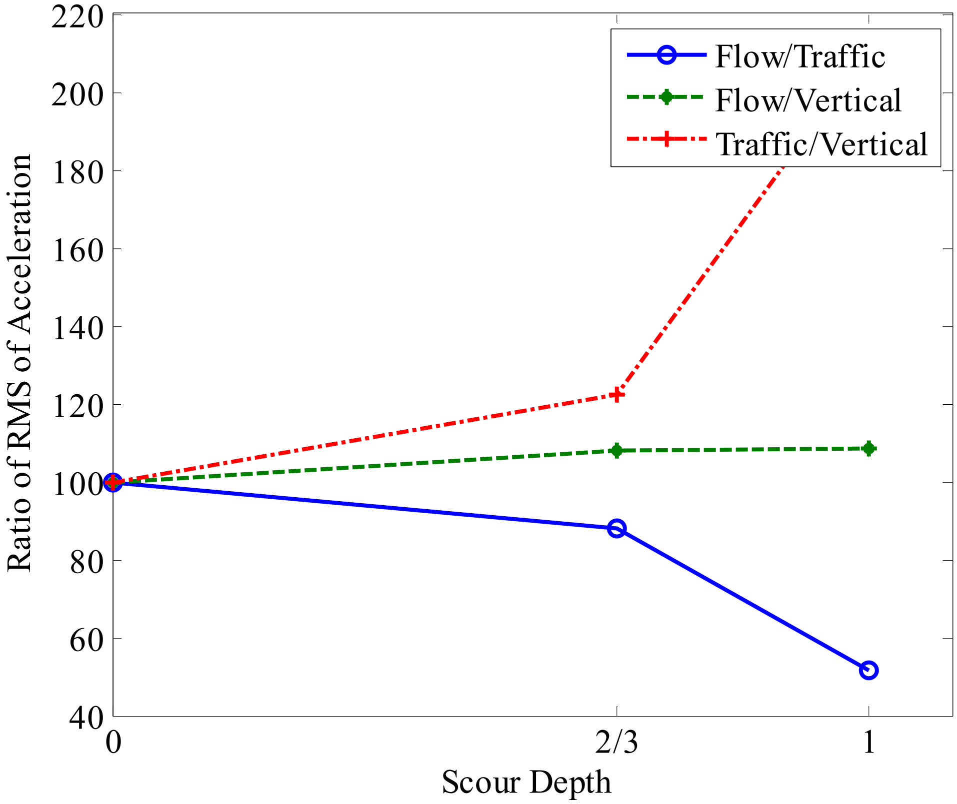


Figure 5-81. Variation of Ratio of RMS Values of Acceleration with Scour for Full Scale Bridge Model for Truck Excitation in Flow Direction.

Overall, the trends observed by ratio of RMS values of acceleration are not consistent. They are direction dependent. The magnitude of change is also direction dependent. The sensitivity of the ratio of RMS values of acceleration also varies. So due to unavailability of a consistent trend, the ratio of RMS values of acceleration is also not pursued further. An attempt was made to simulate the progress of the scour in real time, but due to the limitations of the software and resources, the study could not be completed at this time.

MONITORING PROCESS, COMMUNICATION WITH THE SYSTEM, WEBPAGE

How to Connect and Download Data

The link to download the raw data collected from sensors on US59 over Guadalupe River Bridge is: http://scour.civil.tamu.edu/us59_sensors.dat.

Website

The Scour Monitoring Center website address is: http://scour.civil.tamu.edu. Once you log into the website, you will see three projects in the project list: Laboratory Experiments, US59 over Guadalupe River, and SH80 over San Antonio River. Clicking on each of them will direct to the webpage of the corresponding project. One photo and one schematic of the instrumentation are shown for each project. Clicking on the photo of the project will lead to the webpage containing the plots of data collected from the sensors for the corresponding project. The dataloggers on two bridges transmit data every 20 minutes. So the monitoring website shows the real-time plots every 20 minutes. The webpage is refreshed every 20 minutes. The webpage shows the data for a period of 20 hours for each project.

Interpretation of US59 over Guadalupe River Bridge Plots (Updated System)

The instrumentation includes one dual-axis tiltmeter (two plots showing the tilt angle of the pier around both flow and traffic direction axes) on the bridge pier, two single-axis tiltmeters on the deck (two plots showing the tilt angle of the deck around the flow direction axis), one water stage (water level), two float-out devices (scour level reached) and two TBS equipments (scour level reached) at the US59 over Guadalupe River Bridge. In addition to the above data, the master station records the temperature and the battery condition for the monitoring system. A total of 11 figures are shown on the webpage.

1. “Tiltmeter3 on the pier – around the flow direction axis,” “Tiltmeter4 on the pier – around the traffic direction axis” plots show the tilt angle of the pier around the flow direction axis and around the traffic direction (perpendicular to the flow direction) respectively. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is degrees.
2. “Tiltmeter1 on the deck – around the flow direction axis,” “Tiltmeter2 on the deck – around the flow direction axis” plots show the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction) for two single-axis tiltmeters. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is degrees.
3. “Water Stage” plot shows the water stage sensor reading at the bridge. It gives the water elevation above the mean sea level. The unit is ft.

4. “Float-out1” plot shows the status of Float-out1 located at the bridge. The Float-out1 was buried 1.5 m (5 ft) below the soil surface at a distance of 16 m (54 ft) below the top of the deck. “Float-out2” plot shows the status of Float-out2 located at the bridge. The Float-out2 was buried 2.7 m (9 ft) below Float-out1 at a distance of 19 m (63 ft) below the top of the deck.
   - If the float-out device is in the vertical position, and has not floated out, the plot will show a smiling face (Figure 5-82a).
   - If the float-out device has floated out, the plot will show a danger sign (Figure 5-82b).
5. “Tethered Buried Switch 1” plot shows the status of TBS1 located at the bridge. The TBS1 was buried 1.5 m (5 ft) below the ground surface near the southwest abutment at a distance of 7.2 m (24 ft) below the top of the deck. “Tethered Buried Switch 2” plot shows the status of TBS2 located at the bridge. The TBS2 was buried 3 m (10 ft) below TBS1 at a distance of 10 m (34 ft) below the top of the deck.
   - If the TBS is in the vertical position, and has not floated out, the plot will show a smiling face (Figure 5-82a).
   - If the TBS has floated out, the plot will show a danger sign (Figure 5-82b).
   - If the wire of the switch is broken, the plot will show a disconnection logo (Figure 5-82c).
6. “Temperature” plot shows the temperature in the master station. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is °C.
7. “Battery” plot shows the battery condition in the master station. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is volts.

(a) (b) (c)

Figure 5-82. Logos for Website: (a) Smiling Face, (b) Danger Sign, and (c) Disconnection.

Communication with the System and Recommendations

The website shows the real-time plot of all the sensor readings for a 20-hour window. Routine data monitoring consists of daily checking of the website and weekly analysis of the data collected by the monitoring system, which is currently stored on the server located at Texas A&M University. Also the on-site bridge inspection every year is recommended. In the hurricane season, every hour check of data is recommended. On-site bridge inspection includes visual inspection of the bridge and the installed instruments.

Another option for data monitoring is using the "emailsend" program in LoggerNet, which can help to monitor the installed system easily. When the reading exceeds the set threshold or reading changes for TBS equipments or float-out devices, the software will send an email to the person in charge of the monitoring system. The frequency of the email may be increased in a storm season to actively monitor the system.

Comments on the nature of data observed till now are as follows:

1. If the tilt angle goes beyond the threshold, and immediately drops back, the data should be closely monitored. It does not necessarily require any action. If the tilt angle goes beyond the threshold, and lasts for 40 minutes (2 data points), an on-site inspection of the bridge is recommended and may also lead to the decision about the closure of the bridge.
2. If the Float-out1 reading is showing 1, it means that the scour depth under Pier SB2 is at most 2.1 m (7 ft). If the Float-out2 reading is showing 1, it means that the scour depth under Pier SB2 is at most 4.8 m (16 ft). When the float-out device floats out, maintenance of the bridge to mitigate scour is recommended.

3. The water stage sensor shows the water elevation of the river at the location of the water stage sensor on the US59 over Guadalupe River Bridge. During the flood season, the water level will be very high. Every hour checking of the data is recommended. If the water level reaches up to the level of the bridge deck, i.e., 18 m (60 ft), the closure of the bridge is recommended.

In the long term, the above water instruments need to be checked during yearly bridge inspections. Because all of the instruments are sealed, the inspection will simply require checking of the instrument for visible damages. Routine monitoring provides the best chance of catching any irregularities, but because daily monitoring is not likely to continue infinitely, a backup by visual inspection is a reasonable precaution.

One set of instruments, the float-out devices at Pier SB2, will need to be retrieved periodically in order to replace batteries and ensure that the instrument is functioning properly. The maintenance period can be either after a flood washes the float-out device loose or at two-year interval after installation. While batteries nominally last 10 years, field results are typically well shy of that time.

CONCLUSIONS, RECOMMENDATIONS, AND BUDGET

Conclusions

The monitoring system was installed at the southbound of US59 over Guadalupe River Bridge on May 28, 2009. Two accelerometers installed on the bridge recorded good data for one week after installation. Then the connection with the bridge was lost after June 8, 2009, and was fixed on October 15, 2009. The two accelerometers recorded good data again until late November 2009. Due to the power demand on the system and unfavorable weather condition for the solar power system, the bridge scour monitoring system was programmed to shut down automatically when the battery voltage dropped below 12 volts. Therefore, data from late December 2009 to early March 2010 was sparse.

With respect to the accelerometers, the frequency domain analysis and the ratio of RMS approach require a lot of data to be collected and stored. Therefore accelerometers require a lot of power to acquire and transmit the data. The two approaches (frequency domain analysis and ratio of RMS) worked well for the model bridge because the structure and its vibration were simple. The response to vibrations of full scale bridges is much more complex and requires controlled and large excitation for useful data to be collected. The frequency content of the response is complex, and the accelerations ratios are not consistent. The noise level can impact the true content of the transmitted signal. Using accelerometers to predict bridge scour is a good idea but requires much more work, which is beyond the time and budget of this project. Therefore they have been abandoned as a viable solution in this project.

All the sensors of master station give us consistent data, including water stage sensor, tiltmeters, float-out devices, and TBS equipments. The water stage sensor is fixed to the bridge parapet at the height of deck bottom and is measuring the water surface elevation of the US59 over Guadalupe River Bridge. The water stage sensor readings are compatible with USGS database. The tiltmeters give us very good information about the tilt angle of the bridge. The tilt of the bridge is related to the temperature. Two float-out devices are buried in the soil near Pier SB2. The Float-out1 is buried 16.2 m (54 ft) away from the top of the deck, and the Float-out2 is buried 18.9 m (63 ft) away from the top of the deck. Two TBS equipments are buried in the soil near Pier SB3. The TBS1 is buried 7.2 m (24 ft) away from the top of the deck. The TBS2 is buried 10 m (34 ft) away from the top of the deck. The two float-out devices are in the vertical position. The two TBS equipments have lost connection due to the construction on the bridge. The temperature of the system matches with the weather history in Victoria very well. Basically the master station works very well on US59 over Guadalupe River Bridge.

Recommendations

Tiltmeter is a reliable, simple, and relatively low cost instrument. It is recommended as an integrating behavior sensor that works when failure approaches. It can be helpful for other than scour.

TBS is new and likely helpful, but relatively costly to install and covers only one location chosen by the engineer. It is recommended for early warning but in combination with tiltmeters. In comparison, a float-out device is likely helpful but not addressable and has limited battery life. A float-out device is recommended for short term warning systems.

A camera is a very good idea, indicates water stage, presence of debris, large movements, and its use should be pursued. At night, infrared still photos can be used. The power required for movies to be transmitted is likely too large for solar panels or turbines. Still photos are sufficient and require much less power including transmission. A smart way to install the camera and secure it needs to be developed.

Budget

The total budget for instrumentation on US59 over Guadalupe River Bridge is $95,710. The detailed budget has been attached as Appendix A in this report.

CHAPTER 6:
SCOUR MONITORING OF SH80 OVER SAN ANTONIO RIVER BRIDGE

INTRODUCTION

A scour monitoring system is developed on SH80 over San Antonio River Bridge to monitor the response of bridge, which is affected by the scour. This chapter introduces the scour monitoring system installed on the bridge. Following the introduction, this chapter has five more sections. The first section describes the bridge case history. Second, the installation of the scour monitoring system is discussed. The third section presents the data collection and analysis. The monitoring process is described in the fourth section. Finally, the chapter concludes by presenting conclusions, recommendations, and budget.

THE BRIDGE CASE HISTORY

General Location of the Bridge

The bridge on SH80 crosses the San Antonio River northeast of the Karnes City, Texas. Figure 6-1 and Figure 6-2 show the general location of the bridge in Google Earth and Google Maps, respectively. In Figure 6-1, P1 represents the compound web-wall in the northeast of the bridge. P2 represents the in-river-pier. P3 and P4 represent two compound web-walls in the southwest of the bridge. SW abutment is the southwest abutment of SH80 over San Antonio River Bridge.

Figure 6-1. Layout of the Bridge Displaying Naming Convention Used (from Google Earth).

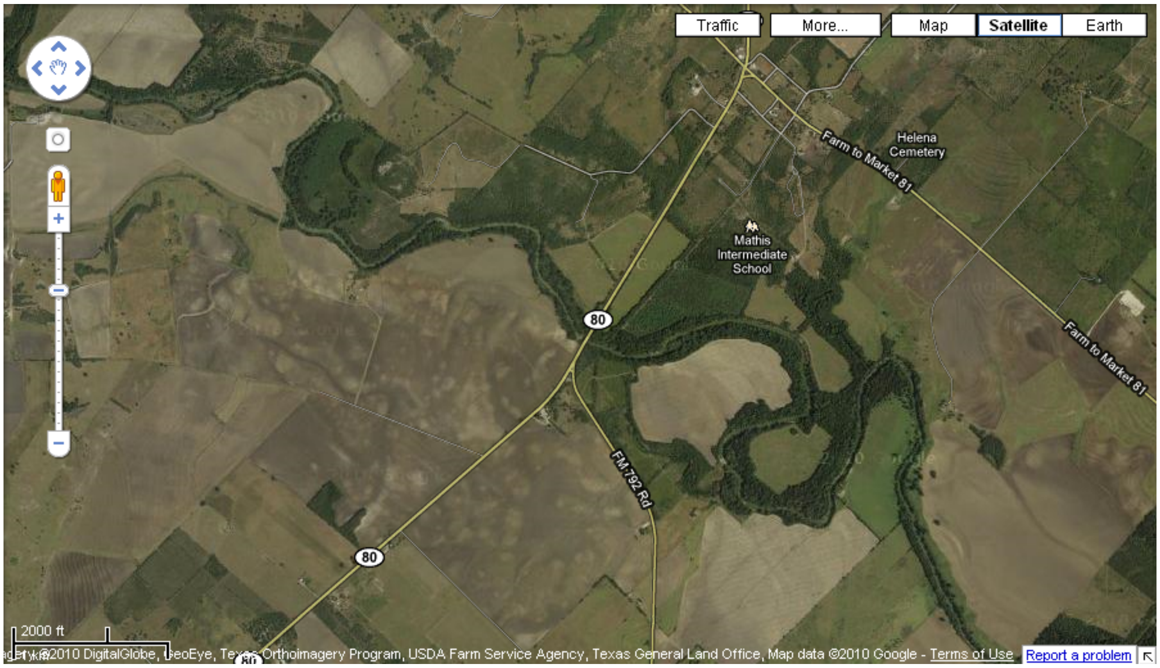


Figure 6-2. Current River Path in Bridge Area (from Google Maps).

San Antonio River

The San Antonio River is a major waterway that originates in central Texas in a cluster of springs in north central San Antonio, approximately 6.4 km (4 miles) north of downtown, and follows a roughly southeastern path through the state. It eventually feeds into the Guadalupe River about 16 km (10 miles) from San Antonio Bay on the Gulf of Mexico. The river is 384 km (240 miles) long and crosses five counties: Bexar, Goliad, Karnes, Refugio, and Wilson.

The Bridge Structure

The bridge is a multi-span, 148 m (493 ft) long, two-lane bridge (Figure 6-3). The main bridge consists of three spans and is 63 m (207 ft 7 inches) long. It contains one in-river-pier (P2), which is a web-wall (Figure 6-4). The supporting structure of the main bridge is a compound web-wall of cylindrical and trapezoidal bridge bents (P1) (Figure 6-5). The supporting structure of the eastern line of the bridge consists of combination of cylindrical piers and square piers (Figure 6-6).

Figure 6-3. State Highway 80 over San Antonio River Bridge, Texas.

Figure 6-4. In-River Pier in the Form of Web-Wall (P2).

Figure 6-5. Compound Web-Wall on the Main Bridge Span (P1).

Figure 6-6. Eastern Line of the SH80 over San Antonio River Bridge.

The Soil

The soil beneath the bridge foundation has a large variation. Under the piers, there are two types of soil: clay and sand. Figure 6-7 shows the riprap failure around Pier P1. This is the location where the TBS are buried. The soil sample was taken during the drilling process of the installation of TBS. Soil beneath the pier is silty clay (see Figure 6-8).

(a) (b)

Figure 6-7. Rip Rap Failure near the Pier P1: (a) Zoom out View and (b) Zoom in View.

Figure 6-8. Silty Clay beneath Pier P3.

The Scour Problem

The northern and southern bank of the San Antonio River at the downstream are experiencing a meandering problem. Layered soil with vegetation can be seen clearly in Figure 6-9 and Figure 6-10.

Figure 6-9. Northern Riverbank of San Antonio River (Downstream).

Figure 6-10. Southern Riverbank of San Antonio River (Downstream).

INSTALLATION OF THE MONITORING SYSTEM

The monitoring system was installed and started to transmit data to the server on October 16, 2009. The instruments during the initial installation included two accelerometers installed on individual piers (P1 and P2) at the bridge and two TBS equipments buried at 12.3 m (41ft) and 11.4 m (38 ft) respectively below the top of the deck. A datalogger collected data every 10 minutes and transmitted the data by a cellular modem to a remote server. A monitoring website shows real time plots of the data. Figure 6-11 shows the layout of the initial instrumentation on SH80 over San Antonio River Bridge.

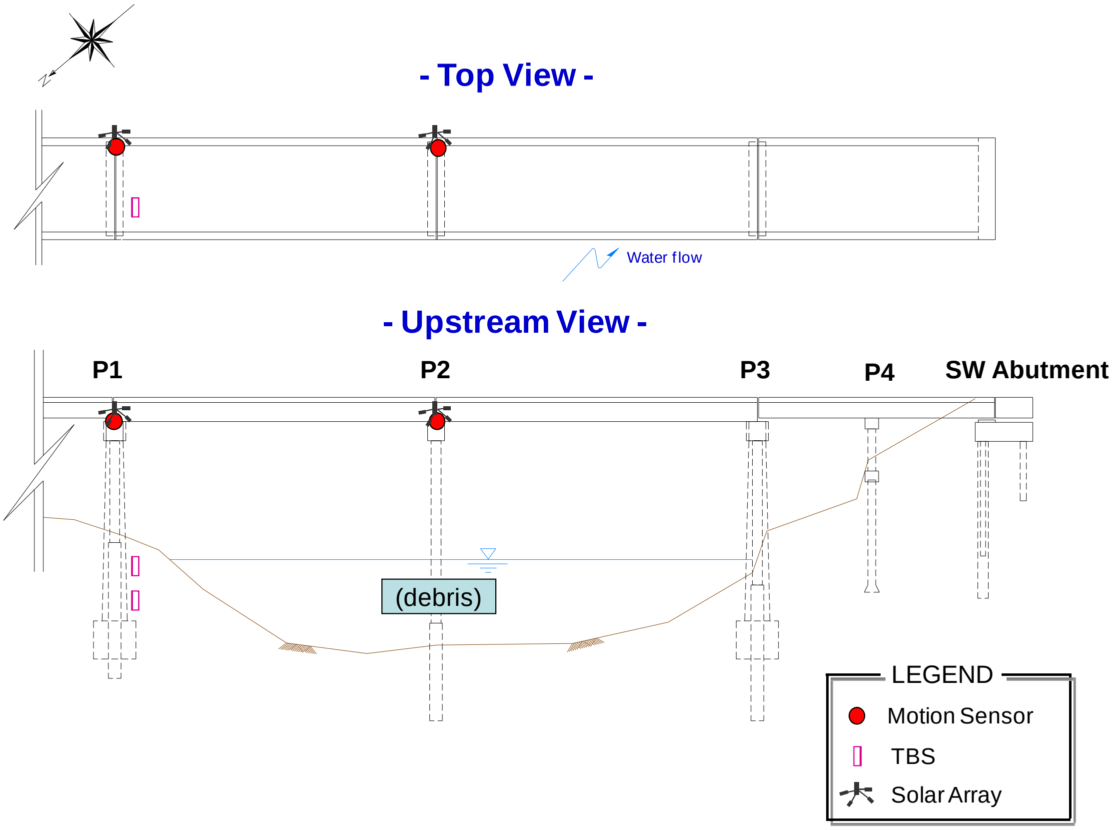


Figure 6-11. Schematics of Initial Instrumentation on SH80 over San Antonio River Bridge.

Due to the large amount of data transmitted by the accelerometers, more power was required than the initial estimate of the power consumption, thus the monitoring system ran out of power. A modified monitoring system was installed on SH80 over San Antonio River Bridge on March 11, 2010. The two accelerometers were removed. One dual-axis tiltmeter (Tiltmeter1 and Tiltmeter2) was bolted and glued on the pier cap of the in-river-pier (P2). Two single-axis tiltmeters (Tiltmeter3 and Tiltmeter4) were bolted and glued on the bridge deck near the dual-axis tiltmeter. TBS equipments remained at the same location. The datalogger was reprogrammed to transmit data every 20 minutes. Figure 6-12 shows the sketch of modified instrumentations on SH80 over San Antonio River Bridge.

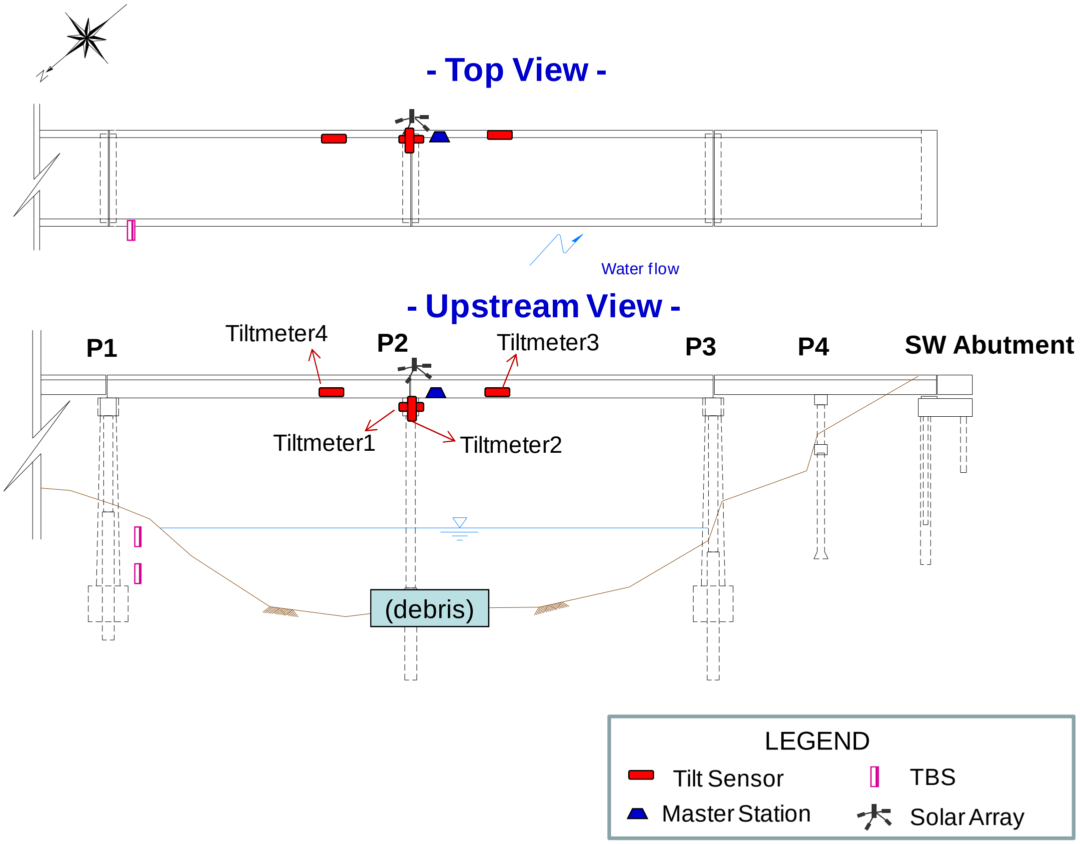


Figure 6-12. Schematics of Modified Instrumentation on SH80 over San Antonio River Bridge.

Schedule of Installation and Maintenance

The schedule of installation and maintenance of the instrumentation on SH80 over San Antonio River Bridge is listed below.

10/16/2009	Installation of monitoring system and data collection per 10 minutes. The sensors included two accelerometers and two TBS equipments.
10/26/2009	Loss of connection with the bridge.
12/09/2009	Changed battery and added a “trigger” to monitor the battery voltage.
12/09/2009	Removed accelerometer on top of Pier P1 and sent it back to ETI.

03/11/2010	Removed accelerometer on top of Pier P2. Installed one dual-axis tiltmeter (Tiltmeter1 and Tiltmeter2) on Pier P2, two single-axis tiltmeters (Tiltmeter3 and Tiltmeter4) on the deck. Reprogrammed the datalogger so that the data were recorded every 20 minutes.
06/05/2010	Adjusted the dual-axis tiltmeter (Tiltmeter1 and Tiltmeter2) on Pier P2.

Initial Installation of the Monitoring System

A detailed and careful study of the bridge plan and site investigation was made on SH80 over San Antonio River Bridge. The bridge scour monitoring system was established and installed on SH80 over San Antonio River Bridge on October 16, 2009.

During the installation, several parties were involved. TxDOT was responsible for the traffic control. The TxDOT traffic inspection team was responsible for the snooper truck for below-deck access. TTI researchers and consultants from ETI and STV were responsible for installing the instruments on the bridge.

Installation of Accelerometers

One hardwired accelerometer and one wireless accelerometer were installed on the top of piers in the initial monitoring system. The hardwired accelerometer was fixed on pier cap of the in-river-pier P2 and was wired to the master station (Figure 6-13). The wireless accelerometer was fixed on the pier cap of Pier P1 (Figure 6-14). The solar panel that was wound on the curb provided the power for the wireless accelerometer (Figure 6-15).

(a) (b)

Figure 6-13. Accelerometer on the Cap Beam of Pier P2: (a) Front View and (b) Side View.

(a) (b)

Figure 6-14. Accelerometer on the Cap Beam of Pier P1: (a) Front View and (b) Side View.

Figure 6-15. Solar Panel for the Accelerometer on the Cap Beam of Pier P1.

Installation of Master Station

The master station was mounted near Pier P2. Two solar panels were installed on the bridge. One solar panel was installed near the master station to provide the power for monitoring system; the other one was installed near accelerometer on the cap beam of Pier P1 to provide power. Figure 6-16 shows installation of the master station at SH80 over San Antonio River Bridge.

(a) **(b)**

Figure 6-16. Master Station on SH80 over San Antonio Bridge: (a) During Installation and (b) After Installation.

Installation of TBS Equipments

Two TBS equipments were installed in the soil near Pier P1. TBS1 was buried 2.4 m (8 ft) below the ground surface at a distance of 12.3 m (41 ft) below the top of the deck. TBS2 was buried 0.9 m (3 ft) above the TBS1 at a distance of 11.4 m (38 ft) from the top of the deck. A hand-auger was used to drill a hole into soil (Figure 6-17). The drilled hole was 2.7 m (9 ft) deep. Figure 6-18 shows the photos after TBS installation.

Figure 6-17. Hand-Auger.

(a) (b)

Figure 6-18. Installed TBS Equipments: (a) Conduit and (b) Zoom in View.

The second step is to wire the TBS to the master station. The conduit, which was connected with the TBS wire directly, was fixed on Pier P1 vertically. The wire coming from the master station in the downstream side of the bridge was mounted in an “L” route along the bridge deck and Pier P1, covered by a cable-protection-pipe.

Modification of the Bridge Scour Monitoring System

The initial monitoring system worked well for 10 days. After that the connection with the bridge was lost due to the loss of IP address. The problem was fixed in December 2009. Data analysis on the accelerometers did not give satisfactory results. Due to the large amount of data transmitted by the accelerometers, more power was needed than the initial estimate. The stream of data produced by the accelerometers was not steady for the most period of data collected.

It was concluded that the idea to use accelerometers for monitoring of bridge scour has potential, but it requires further research, time, and resources to conclusively achieve results. Due to the limited period of this project, a modified monitoring system was installed on SH80 over San Antonio River Bridge on March 11, 2010. Two accelerometers were removed, one dual-axis tiltmeter (Tiltmeter1 and Tiltmeter2) and two single-axis tiltmeters (Tiltmeter3 and Tiltmeter4) were installed. The dual-axis tiltmeter was located on the top of cap beam of the in-river-pier P2. In the enclosure, one single-axis tiltmeter, which measures the tilt angle of the pier around the flow direction axis, was mounted at the back of the enclosure. The output is positive when the sensor is rotated clockwise (when facing the sensor). The other single-axis tiltmeter measuring the tilt angle of the pier around the traffic direction axis was mounted on the left side perpendicular to the other one (when facing the sensor). The output is positive when the sensor is rotated clockwise. Figure 6-19 shows the dual-axis tiltmeter at SH80 over San Antonio River Bridge.

Two single-axis tiltmeters were installed on the bridge deck on the left and right side of in-river-pier (P2), respectively. Both of them are measuring the tilt angle of the deck around the flow direction axis. The horizontal distance between each single-axis tiltmeter and dual-axis tiltmeter is 3.75 m (12.5 ft). All the tiltmeters were wired to the datalogger CR1000. TBS equipments remained at the same location. Figure 6-20 shows the modified monitoring system for the bridge.

(a) (b)

Figure 6-19. Installed Dual-Axis Tiltmeter: (a) Side View and (b) Top View.

Figure 6-20. Modified Bridge Scour Monitoring System.

DATA COLLECTION AND ANALYSIS

In the initial monitoring system, the data were collected in the datalogger every 10 minutes and transmitted to the server every hour. In the modified monitoring system, the data were collected in the datalogger every 20 minutes and transmitted to the server every hour.

Data Collection

Accelerometers

The working scope of the accelerometers is ±2g ($g = 9.81\ \text{m/s}^2 = 32.2\ \text{ft/s}^2$). The data of both accelerometers were collected at a frequency of 80 Hz.

The data format for two accelerometers is shown as follows:

"2009-10-20 08:10:00",2649607,-351,72,16816

"2009-10-20 08:10:00",2649608,-363,59,16806

"2009-10-20 08:10:00",2649609,-360,54,16826

The first column is the date and time of the corresponding collected data; the second column is a counter; the third column is the relative acceleration value in flow direction; the fourth column is the relative acceleration value in traffic direction; and the last column is the relative acceleration value in vertical direction. The relative acceleration value obtained directly from the datalogger has to be converted in the physical units (*g*) by multiplying with the corresponding calibration factor. The calibration factor is 2/32768.

Other Master Station Sensors

The data format for the modified monitoring system for the bridge scour is shown below:

```
"2010-06-25 21:20:00",7658,4,0.03,-0.06,0.1,-0.07,1,1,0,0,29.38,13.04
"2010-06-25 21:40:00",7659,4,0.03,-0.06,0.09,-0.07,1,1,0,0,28.95,13.04
"2010-06-25 22:00:00",7660,4,0.03,-0.06,0.09,-0.07,1,1,0,0,28.46,13.03
"2010-06-25 22:20:00",7661,4,0.03,-0.07,0.09,-0.07,1,1,0,0,28.1,13.03
```

Here, the first column is the timestamp, including the date and time of the corresponding collected data; the second column is the counter; the third column is the alarm; the fourth column is the reading from Tiltmeter1 on the top of Pier P2 (in degree); the fifth column is the reading from Tiltmeter2 on the top of Pier P2 (in degree); the sixth column is the reading from Tiltmeter3 on the deck (in degree); the seventh column is the reading from Tiltmeter4 on the deck (in degree); the eighth column is the reading from TBS1 located at 12.3 m (41 ft) from the bridge deck; the ninth column is the reading from TBS2 located 11.4 m (38 ft) from the bridge deck; the tenth column is the reading of the first pulse; the eleventh column is the reading of the second pulse; the twelfth column is the temperature of master station (in units of °C); and the last column is the master station battery reading (in volts).

Data Analysis

Tiltmeters

The tiltmeters were installed on SH80 over San Antonio River Bridge on March 11, 2010. The four tiltmeters gave readings every 20 minutes. The collected data are labeled as follows: X1Tilt, Y1Tilt, X2Tilt, and Y2Tilt. X1Tilt records the data collected from Tiltmeter1 on the top of Pier P2, measuring the tilt angle of the pier around the flow direction axis. Y1Tilt records the data collected from Tiltmeter2 on the top of Pier P2, measuring the tilt angle of the pier around the traffic direction axis. X2Tilt records the data collected from Tiltmeter3 on the deck, measuring the tilt angle of the deck around the flow direction axis. Y2Tilt records the data collected from Tiltmeter4 on the deck, measuring the tilt angle of the deck around the flow direction axis at another location. Figure 6-21 shows the location of tiltmeters on SH80 over San Antonio River Bridge.

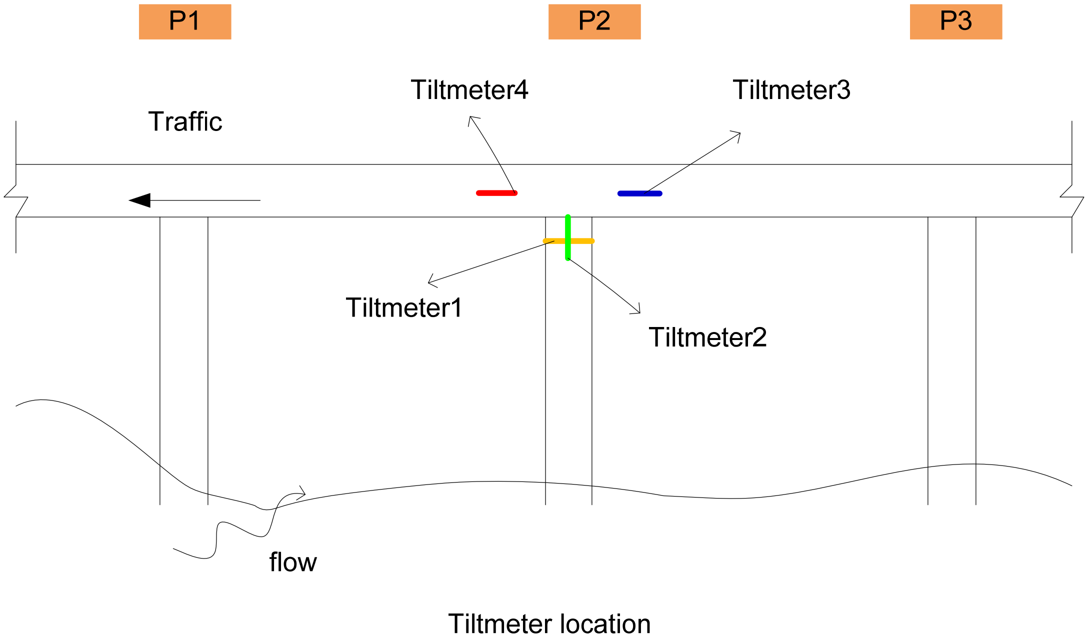


Figure 6-21. Layout of the Tiltmeter Location on SH80 over San Antonio River Bridge.

(1). Data Analysis on Tiltmeter1. Figure 6-22 shows the time history plot of the data collected from Tiltmeter1 located on the top of Pier P2 measuring tilt angle of the pier around the flow direction axis. The data were collected from March 11, 2010, to August 9, 2010.

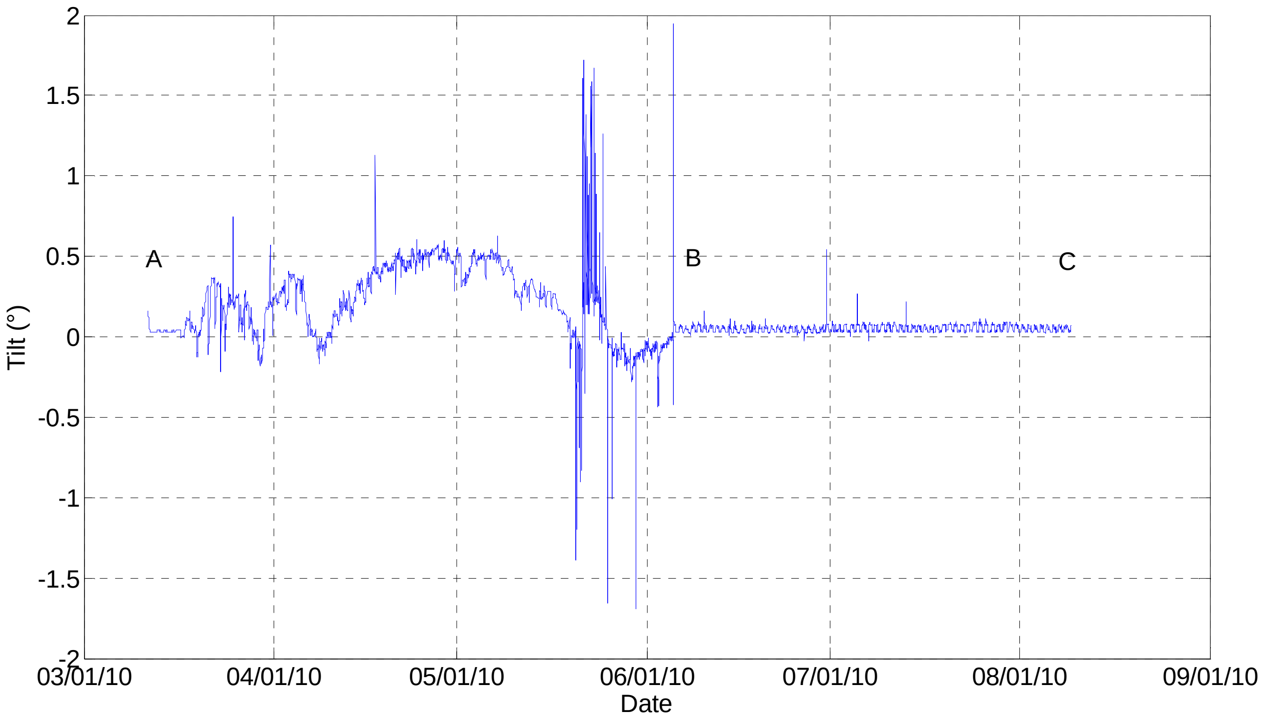


Figure 6-22. Tiltmeter1 Time History Plot on SH80 over San Antonio River Bridge.

The data collected from Tiltmeter1 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter1 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers adjusted the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. From Figure 6-22, it can be seen that Tiltmeter1 did not work properly before June 5, 2010, since the reading fluctuated from −1.5° to 1.5°. But after the replacement of Tiltmeter1, Tiltmeter1 showed reasonable data.

The reading from Tiltmeter1 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure 6-23 to study the correlation between these two quantities. The blue line shows the tilt angle of the pier around the flow direction axis, and the green line shows the temperature reading in the master station box. It can be inferred from the figure that the two curves of rotation of the pier and temperature are correlated. This is due to the response of the bridge pier, on which Tiltmeter1 is mounted, with the change in temperature.

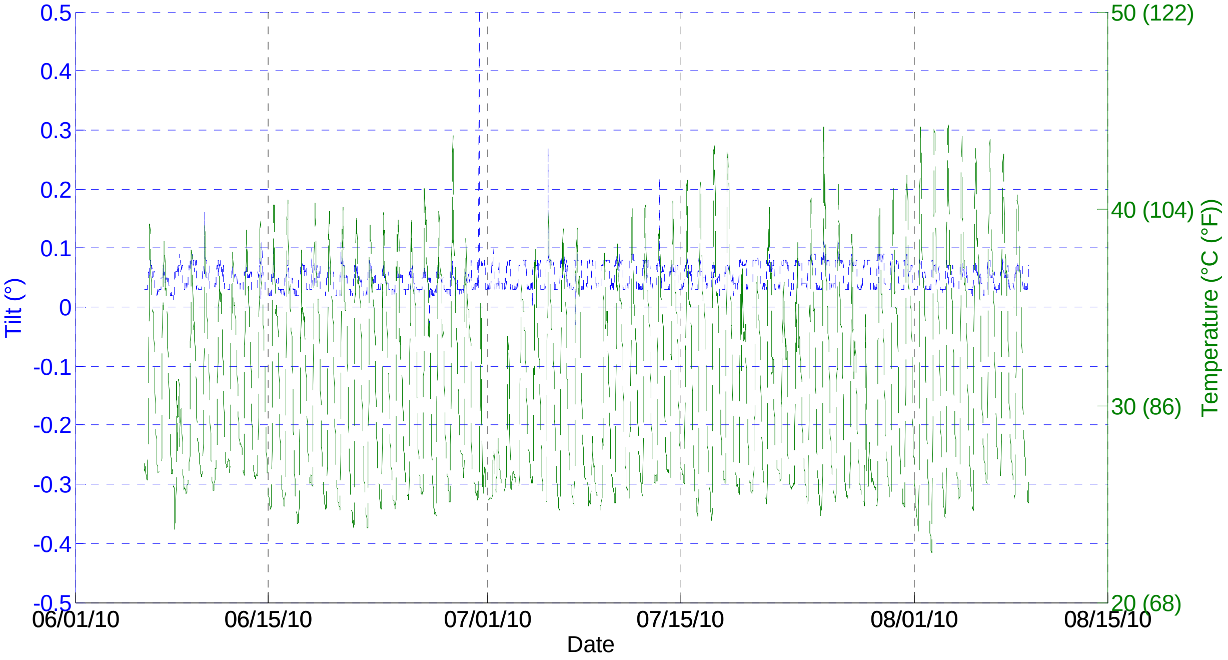


Figure 6-23. Tiltmeter1 and Temperature Response Plot for Phase B-C.

(2). Data Analysis on Tiltmeter2. Figure 6-24 shows the time history plot of the data obtained from Tiltmeter2 on the SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter2 is located on top of Pier P2 and measures tilt angle of the pier around the traffic direction axis.

The data collected from Tiltmeter2 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter2 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers adjusted the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. From Figure 6-24, it can be seen that Tiltmeter2 did not work properly before June 5, 2010, since the reading fluctuated from −1.3° to 0.4°. But after the replacement of Tiltmeter2, Tiltmeter2 showed reasonable data.

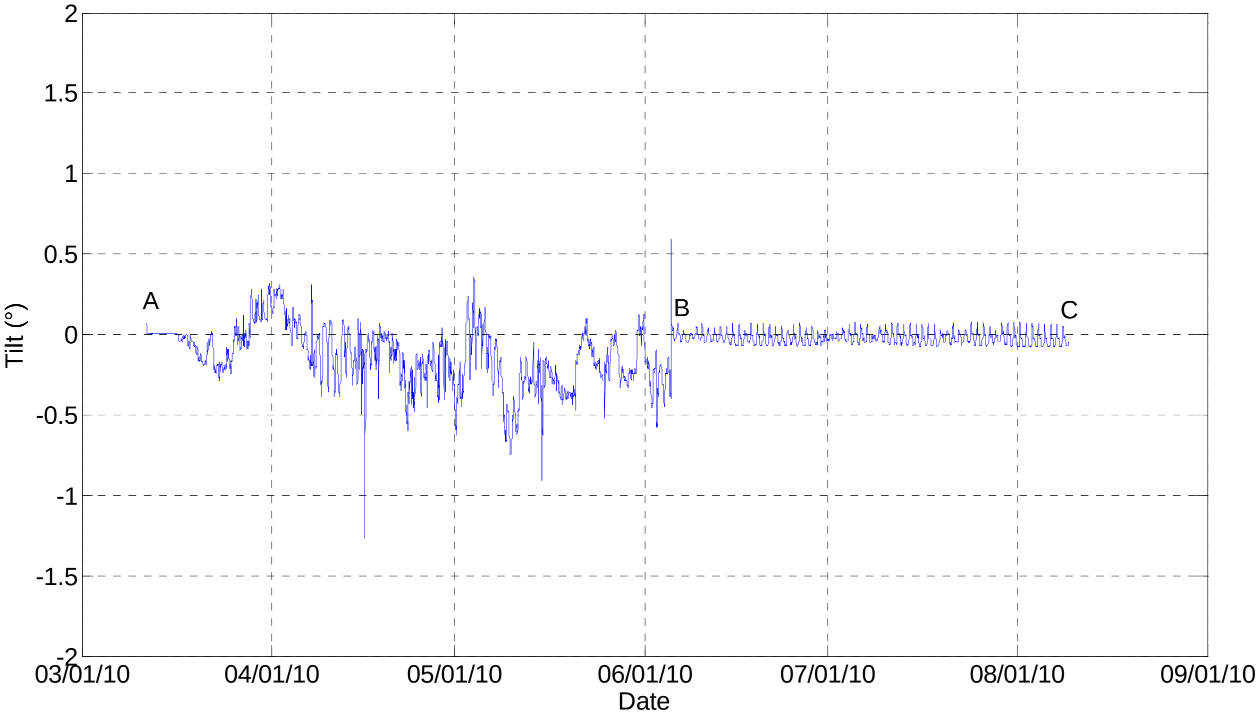


Figure 6-24. Tiltmeter2 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter2 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure 6-25 to study the correlation between these two quantities. The blue line shows the tilt angle of the pier around the traffic direction axis, and the green line in the figure shows the temperature reading in the master station box. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

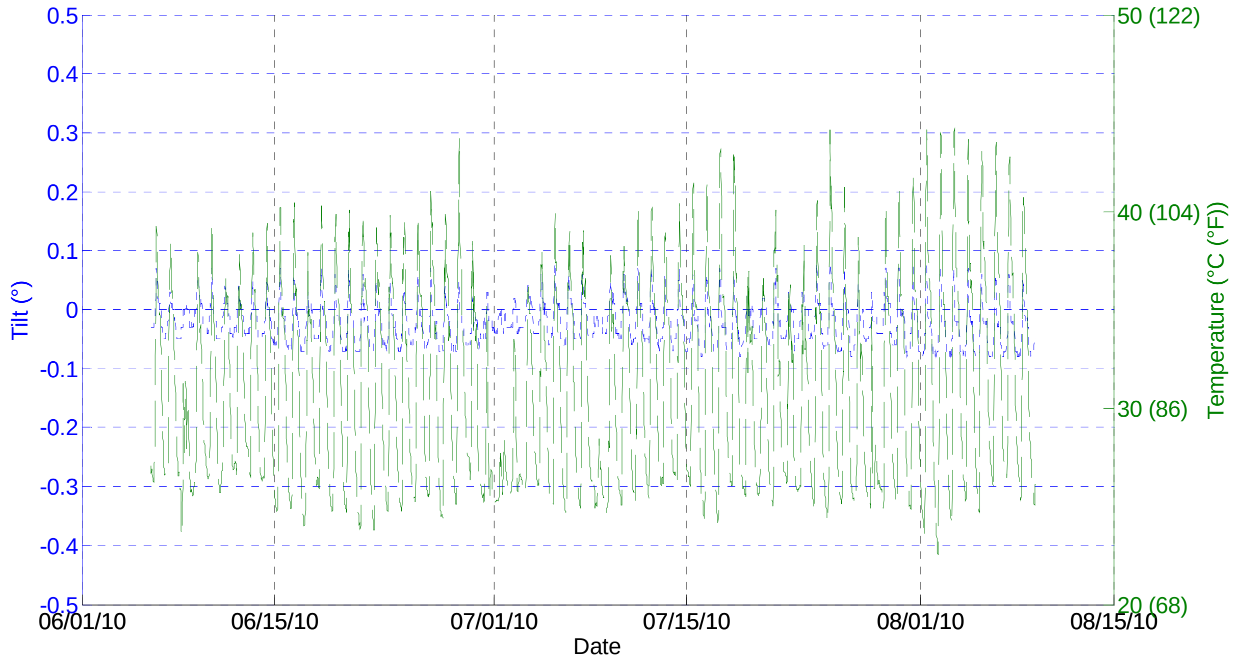


Figure 6-25. Tiltmeter2 and Temperature Response Plot for Phase B-C.

(3). Data Analysis on Tiltmeter3. Figure 6-26 shows the time history plot of the data collected from Tiltmeter3 on SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter3 is located on the deck of the bridge 3.8 m (12.5 ft) away from Tiltmeter2 and measures tilt angle of the deck around the flow direction axis.

The data collected from Tiltmeter3 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter3 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers replaced the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. Tiltmeter3 worked well during the monitoring process.

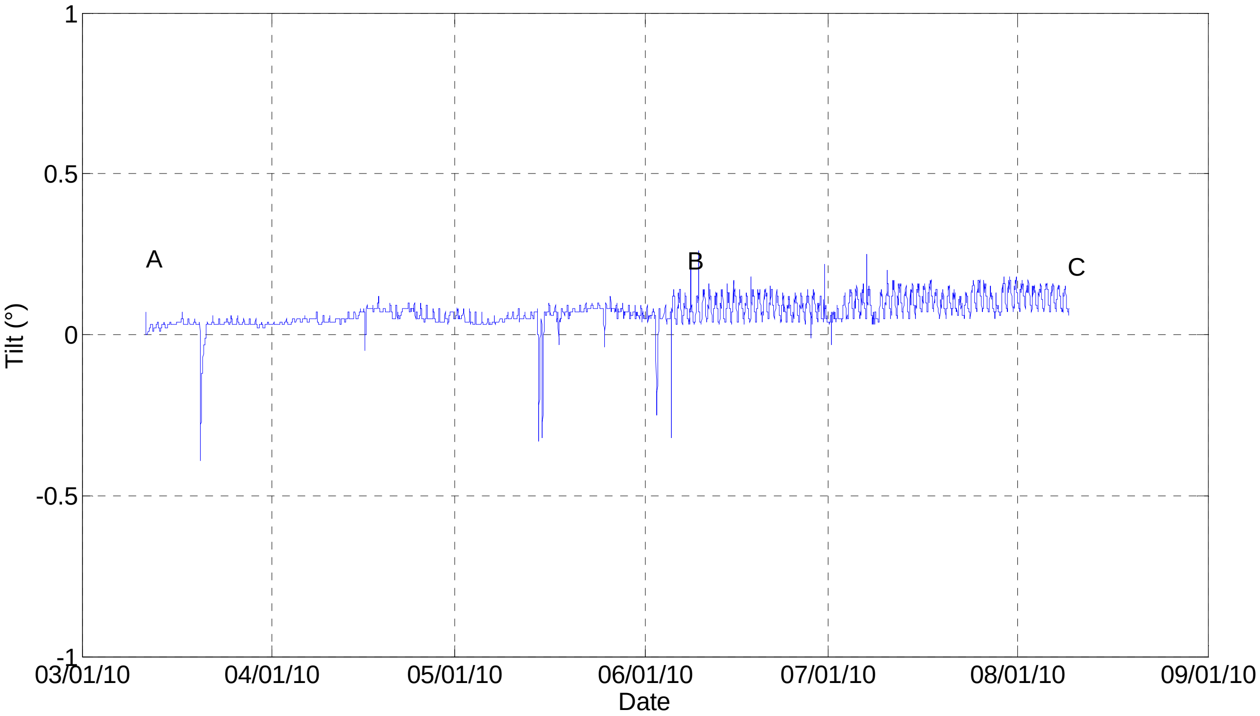


Figure 6-26. Tiltmeter3 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter3 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure 6-27 to study the correlation between these two quantities. The blue line shows the tilt angle of the deck around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

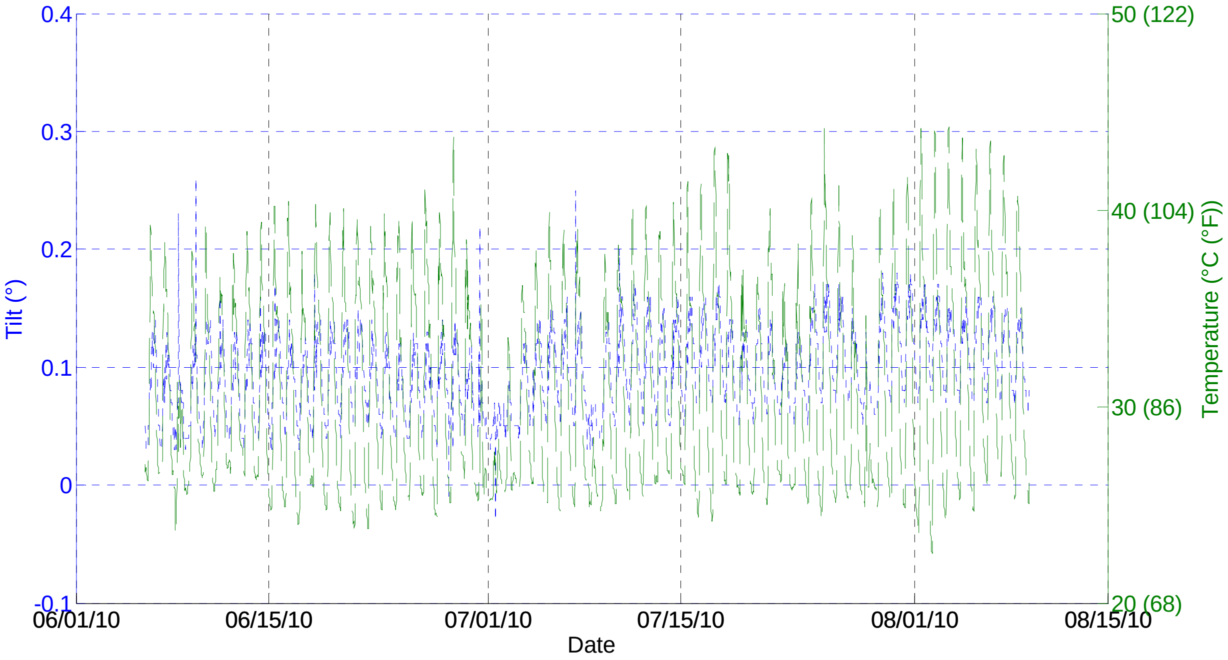


Figure 6-27. Tiltmeter3 and Temperature Response Plot for Phase B-C.

(4). Data Analysis on Tiltmeter4. Figure 6-28 shows the time history plot of the data collected from Tiltmeter4 on SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter4 is located on the deck of the bridge 3.8 m (12.5 ft) away from Tiltmeter2 and measures the tilt angle of the deck around the flow direction axis.

The data collected from Tiltmeter4 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter4 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers replaced the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. Tiltmeter4 works well during the monitoring process.

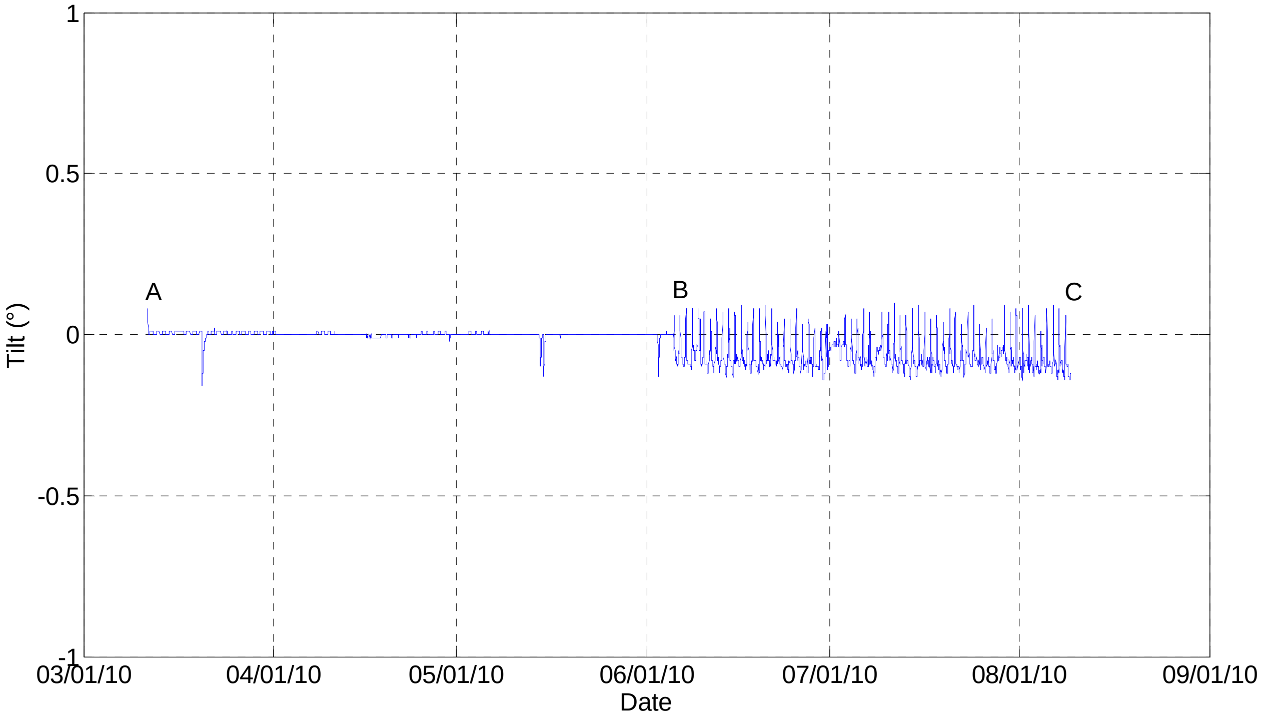


Figure 6-28. Tiltmeter4 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter4 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure 6-29 to study the correlation between these two quantities. The blue line shows the tilt angle of the deck around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

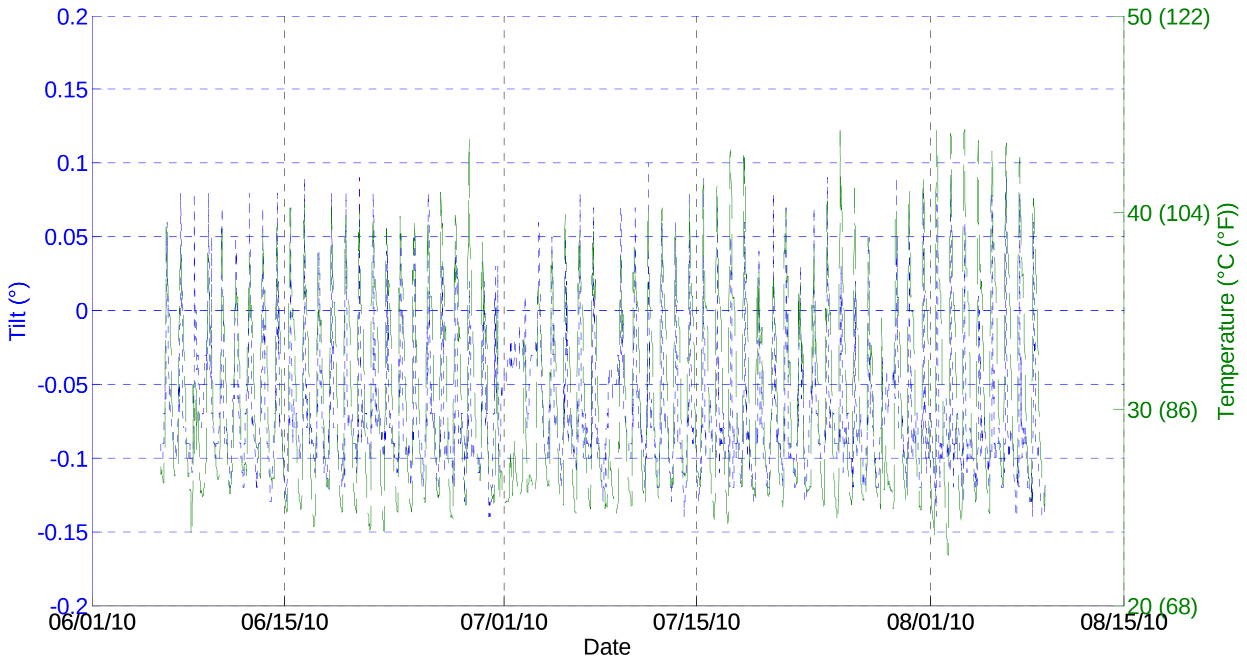


Figure 6-29. Tiltmeter4 and Temperature Response Plot for Phase B-C.

TBS Equipments

The data for two TBS equipments were collected from 12:10 p.m. on October 16, 2009, to August 9, 2010. If the TBS is in the vertical position and the trigger has not been launched, the sensor will transmit a value of 1 to the data acquisition system. If the switch is triggered and the scour reaches the buried level, the sensor will transmit a value of 2 to the data acquisition system. If the wire of the switch is broken, the sensor will transmit a value of 3 to the data acquisition system. Figure 6-30 shows the data collected from the two TBS equipments installed on SH80 over San Antonio River Bridge. TBS1 was buried 2.4 m (8 ft) below the ground surface near the southwest abutment at a distance of 12.3 m (41 ft) below the top of the deck. TBS2 was buried 0.9 m (3 ft) above TBS1 at a distance of 11.4 m (38 ft) below the top of the deck.

The connection was lost with the bridge for approximately one and a half month, from late October to early December 2009. This is the reason for the missing data between late October and early December in Figure 6-30.

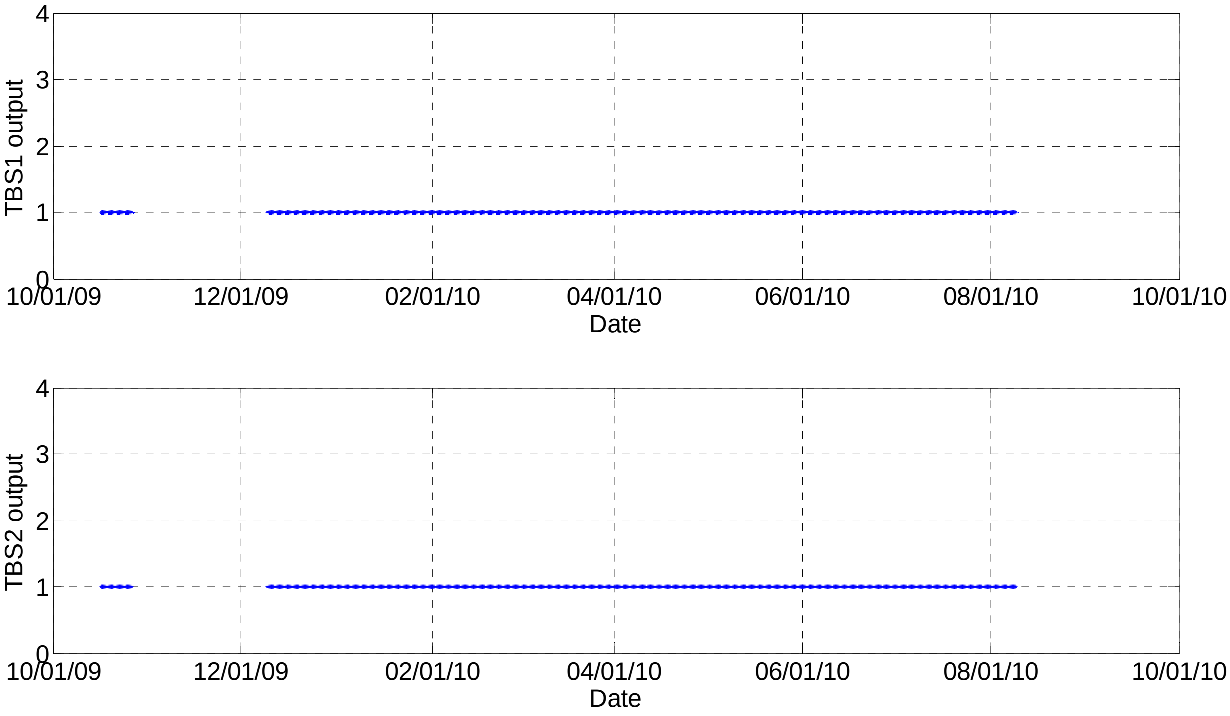


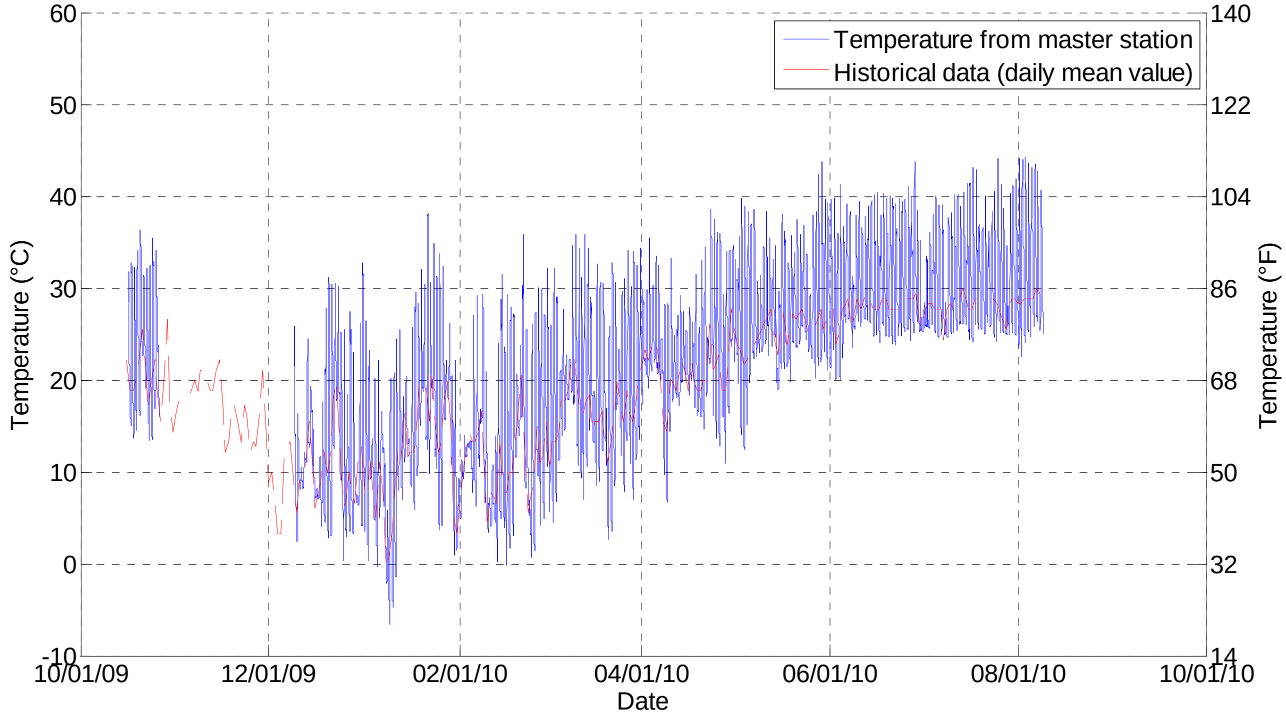
Figure 6-30. TBS Response on SH80 over San Antonio River Bridge.

The TBS equipments give a constant value 1, which means that the scour depth has not reached to the instrument buried depth.

Other Readings

In addition to the data from the installed instruments on SH80 over San Antonio River Bridge, the scour monitoring system also records the reading from the temperature sensor located in the master sensor enclosure and voltage. Figure 6-31 shows the temperature reading for the system. The daily mean temperature in Karnes City, Texas, is also plotted in the figure for comparison. The temperature data from the monitoring system compare well with the daily mean temperature in Karnes City, Texas. Figure 6-32 shows the battery reading for the system. The battery voltage is also correlated with the temperature data.

The connection was lost with the bridge for approximately one and a half month, from late October to early December 2009. This is the reason for the missing data between late October and early December in Figure 6-31 and Figure 6-32.



*Historical data source:

http://www.wunderground.com/history/airport/KBEA/2009/10/16/CustomHistory.html?dayend=21&monthend=2&yearend=2010&req_city=NA&req_state=NA&req_statename=NA

Figure 6-31. Temperature Reading for SH80 over San Antonio River Bridge.

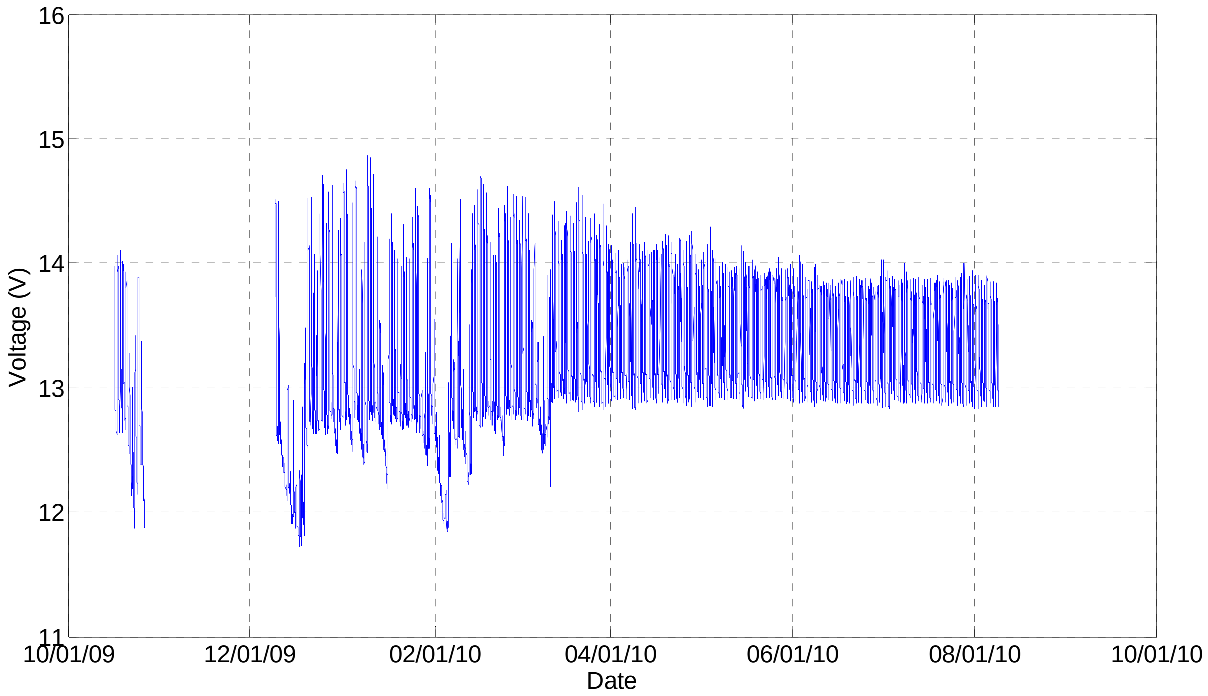


Figure 6-32. Battery Reading for SH80 over San Antonio River Bridge.

Interpretation of the Collected Data

For the modified monitoring system, the results can be interpreted in this way.

Tiltmeters

The four installed tiltmeters give the tilt angle at different locations on the bridge along the axis of flow and traffic direction. A consistent reading is interpreted as the bridge is stable and is not affected by the scour threat. If the reading exceeds a preset threshold value, then a warning has to be issued and decision regarding the closure of the bridge has to be taken. The threshold value of the tilt angle for SH80 over San Antonio River Bridge is studied and established in Chapter 7 in this report.

TBS Equipments

The reading 1 means the TBS is in the vertical position and the trigger has not been launched; reading 2 means the switch is in the horizontal position, indicating the scour hole has reached the instrument level; and reading 3 means the wire of the switch is broken.

MONITORING PROCESS, COMMUNICATION WITH THE SYSTEM, WEBPAGE

How to Connect and Download Data

The link to download the raw data collected from the sensors on SH80 over San Antonio River Bridge is: http://scour.civil.tamu.edu/sh80_sensors.dat.

Website

The Scour Monitoring Center website address is: http://scour.civil.tamu.edu. Once you log into the website, you will see three projects in the project list: Laboratory Experiments, US59 over Guadalupe River, and SH80 over San Antonio River. Clicking on each of them will direct to the webpage of the corresponding project. One photo and one schematic of the instrumentation are shown for each project. Clicking on the photo of the project will lead to the webpage containing the plots of data collected from the sensors for the corresponding project. The dataloggers on two bridges transmit data every 20 minutes. The webpage is refreshed every 20 minutes. The webpage shows the data for a period of 20 hours for each project.

Interpretation of SH80 over San Antonio River Bridge Plots (Updated System)

The instrumentation includes one dual-axis tiltmeter on the pier (two plots showing tilt angle of the pier around both flow and traffic direction axes), two single-axis tiltmeters on the deck (two plots showing tilt angle of the deck around the flow direction axis), and two TBS equipments (scour level reached) on SH80 over San Antonio River Bridge. In addition to the above data, the master station records the temperature and the battery condition for the monitoring system. A total of eight figures are shown on the webpage.

1. "Tiltmeter1 on the pier – around the flow direction axis," "Tiltmeter2 on the pier – around the traffic direction axis" plots show the tilt angle of the pier around the flow direction axis and traffic direction axis respectively. The unit is degrees.
2. "Tiltmeter3 on the deck –around the flow direction axis," "Tiltmeter4 on the deck – around the flow direction axis" plots show the tilt angle of the deck around the flow direction axis for two single-axis tiltmeters. The unit is degrees.
3. "Tethered Buried Switch 1" plot shows the status of TBS1 located at the bridge. The TBS1 was buried 2.4 m (8 ft) below the ground surface near the southwest abutment at a distance of 12.3 m (41 ft) below the top of the deck. "Tethered Buried Switch 2" plot shows the status of TBS2 located at the bridge. The TBS2 was buried 0.9 m (3 ft) above TBS1 at a distance of 11.4 m (38 ft) below the top of the deck.
    - If the TBS is in the vertical position, and has not floated out, the plot will show a smiling face (Figure 6-33a).
    - If the TBS has floated out, the plot will show a danger sign (Figure 6-33b).
    - If the wire of the switch is broken, the plot will show a disconnection logo (Figure 6-33c).
4. "Temperature" plot shows the temperature in the master station. The unit is °C.
5. "Battery" plot shows the battery voltage in the master station. The unit is volts.

(a) (b) (c)

Figure 6-33. Logos for the TBS Condition: (a) Smiling Face, (b) Danger Sign, and (c) Disconnection.

Communication with the System and Recommendations

The website shows the real-time plot of all the sensor readings for a 20-hour window. Routine data monitoring consists of daily checking of the website and weekly analysis of the data collected by the monitoring system. Also the on-site bridge inspection every year is recommended. In the hurricane season, every hour check of data is recommended. On-site bridge inspection includes visual inspection of the bridge and the installed instruments.

Another option for data monitoring is using the “emailsend” program in LoggerNet, which can help to monitor the installed system easily. When the reading exceeds the set threshold or reading changes for TBS equipments, the software will send an email to the person in charge of the monitoring system. The frequency of the email may be increased in a storm season to actively monitor the system.

Comments on the nature of data observed till now are as follows:

- If the tilt angle goes beyond the threshold, and immediately drops back, the data should be closely monitored. It does not necessarily require any action. If the tilt angle goes beyond the threshold, and lasts for 40 minutes (2 data points), an on-site inspection of the bridge is recommended and may also lead to the decision about the closure of the bridge.
- If the TBS1 reading shows 2, it means the scour depth under Pier P1 is reaching 2.7 m (9 ft). If the TBS2 reading shows 2, it means the scour depth under Pier P1 is reaching 1.8 m (6 ft). When the TBS equipments float out, maintenance of the bridge to mitigate scour is recommended.

Although no water stage sensor was installed on SH80 over San Antonio River Bridge, a close eye on USGS gage is recommended especially at flood season. There are two USGS gages near the bridge, one (USGS 08188500) is located in Goliad 56 km (35 miles) downstream from the bridge; the other (USGS 08183500) is located in Falls City 12.8 km (8 miles) upstream from the bridge.

In the long term, the above water instruments need to be checked during yearly bridge inspections. Because all of the instruments are sealed, the inspection will simply require checking of the instrument for visible damages. Routine monitoring provides the best chance of catching any irregularities, but because daily monitoring is not likely to continue infinitely, a backup by visual inspection is a reasonable precaution.

CONCLUSIONS, RECOMMENDATIONS, AND BUDGET

Conclusions

The monitoring system was installed on SH80 over San Antonio River Bridge on October 16, 2009. The connection with the bridge was lost for one and a half month, from late October to early December 2009. The accelerometers on the bridge did not give much information, therefore, the two accelerometers were removed from the bridge on December 9, 2009, and March 11, 2010, respectively. Four tiltmeters were installed on the bridge on March 11, 2010. All tiltmeters are giving stable and reasonable reading so far. Data analysis shows that the tilt reading is correlated to the system temperature.

Two TBS equipments are buried in the soil near Pier P1. The TBS1 is buried 12.3 m (41 ft) away from the top of deck. The TBS2 is buried 11.4 m (38 ft) away from the top of the deck. Both of the two TBS equipments are giving almost a constant value of 1 in this project, which means the sensors are in the vertical position and not floated out. The monitoring system also gives the reading of temperature and battery. The reading of temperature matches very well with weather history in Karnes City, Texas.

Recommendations

With respect to the accelerometers, the frequency domain analysis requires a lot of data to be collected and stored. Therefore accelerometers require a lot of power to acquire and transmit the data.

A tiltmeter is a reliable, simple, and relatively low cost instrument. It is recommended as an integrating behavior sensor that works when failure approaches. It can be helpful for other than scour. TBS is new and likely helpful, but relatively costly to install and covers only one location chosen by the engineer. It is recommended for early warning but in combination with tiltmeters.

Budget

The total budget for instrumentation on SH80 over San Antonio River Bridge is $71,110. The detailed budget has been attached as Appendix B in this report.

CHAPTER 7:
THRESHOLD FOR TILTMETERS IN BRIDGE SCOUR MONITORING

INTRODUCTION

The threshold for tiltmeters in bridge scour monitoring is established in this chapter. The chapter is organized into six sections. Following the introduction, four basic bridge failure modes due to scour are introduced, including big scour hole, settlement and rotation of the pier, loss of the deck, and loss of the pier. After that a general recommendation on the establishment of threshold for tiltmeters is proposed. The following two sections present the specific criteria for tiltmeter threshold on two bridges, US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge in Texas, respectively. Finally, conclusions are presented.

BRIDGE FAILURE MODES DUE TO SCOUR

There are four typical bridge failure modes due to scour: big scour hole; settlement and rotation of the pier; loss of the deck; and loss of the pier. After studying 35 cases of bridge failure due to scour, researchers at Texas A&M University concluded that settlement and rotation of the pier and big scour hole are the top two most common occurrences.

Failure Mode 1: Big Scour Hole

Figure 7-1 shows the first failure mode: big scour hole. In this mode, a bridge does not actually fail, but the foundation of the bridge is greatly weaken due the scour hole generated around it.

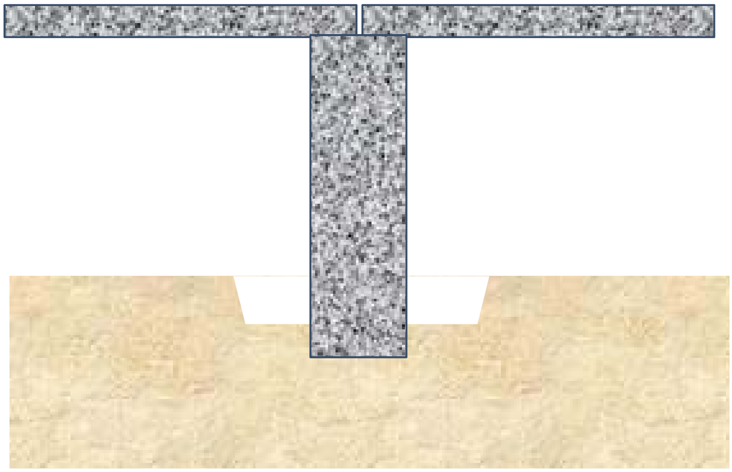
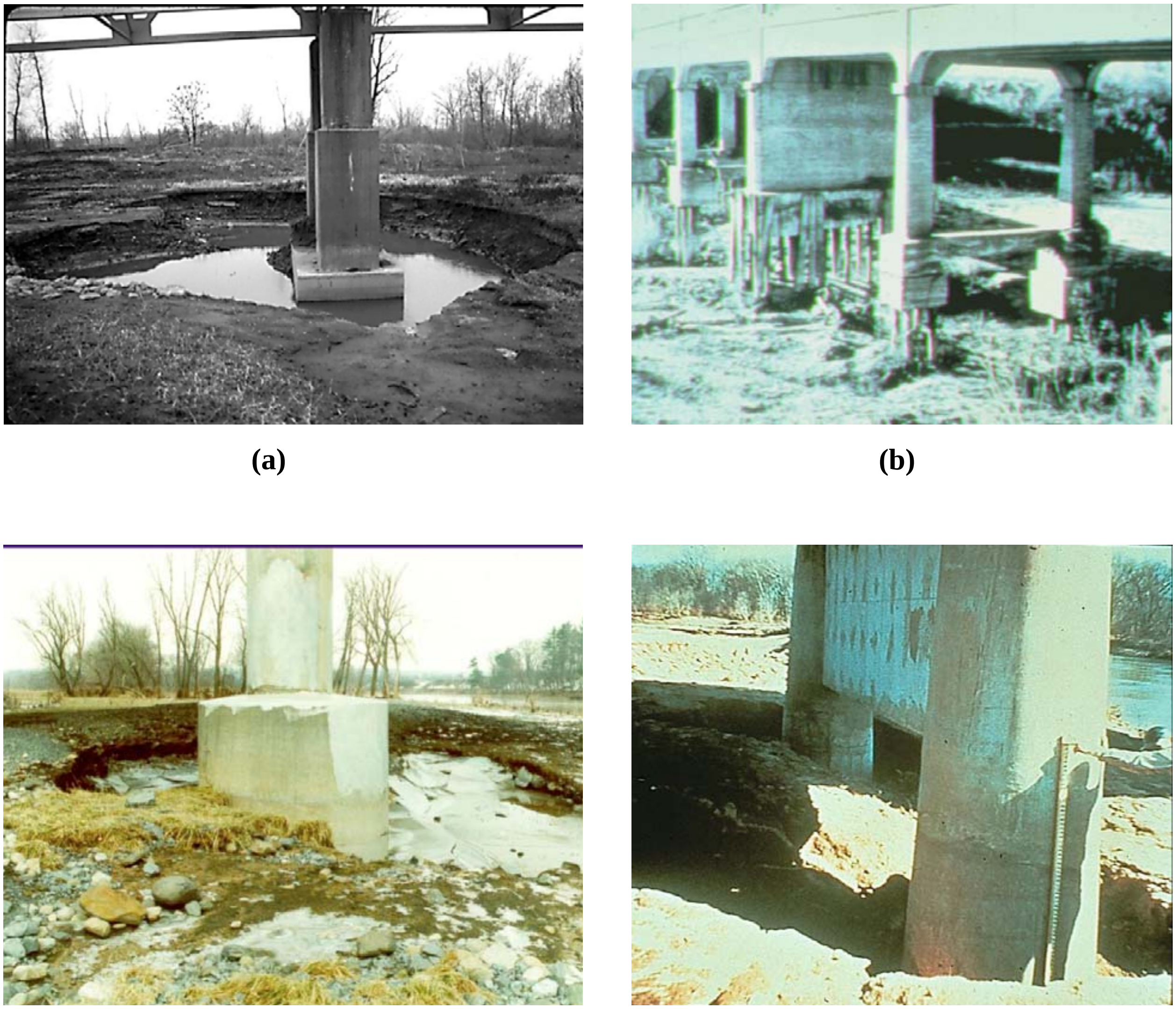


Figure 7-1. Bridge Failure Mode 1: Big Scour Hole, 26 Percent Observed Occurrence.

Among the 35 bridge failure cases, 9 bridges exhausted in the first mode, which means 26 percent observed occurrence. Figure 7-2 shows four examples of bridge failure due to big scour hole.



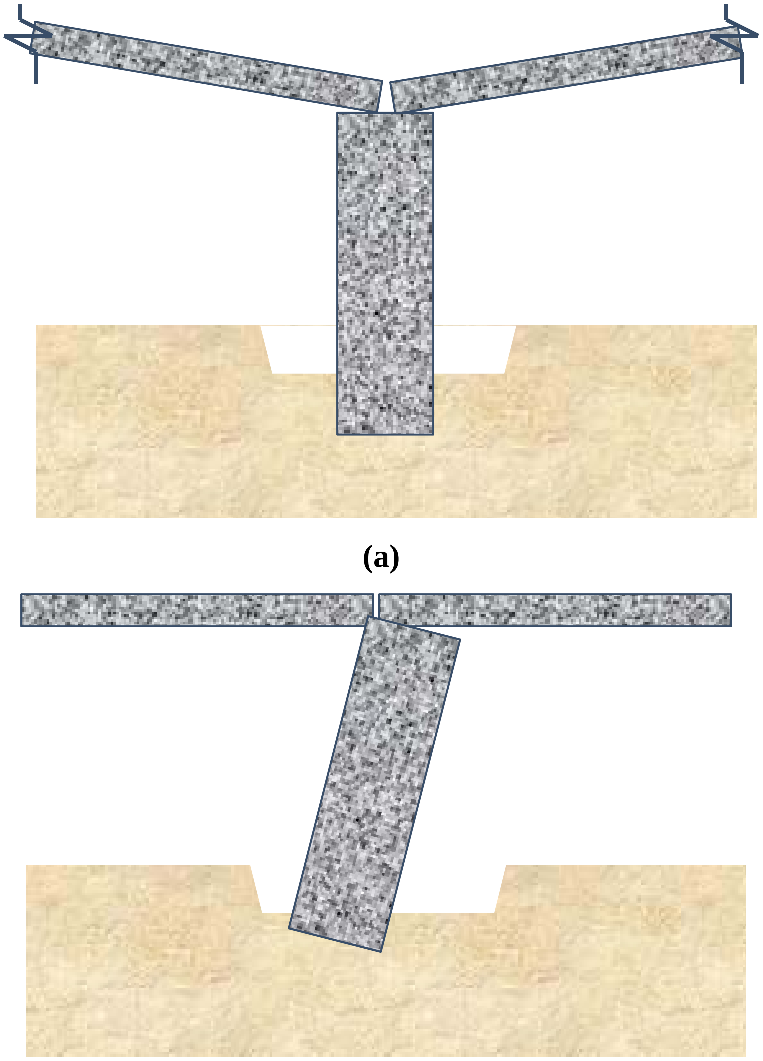
(a) (b)

(c) (d)

Figure 7-2. Generation of Big Scour Hole: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

Failure Mode 2: Settlement and Rotation of the Pier

Figure 7-3 shows the second failure mode: settlement and rotation of the pier. In this mode, a bridge fails due to the excessive settlement or rotation of the pier. Excessive settlement of the pier will generate excessive tilt of the bridge deck, which is very common for bridge failure (Figure 7-3a). The rotation of the pier will also cause the bridge failure (Figure 7-3b).



(a)

(b)

Figure 7-3. Bridge Failure Mode 2: Settlement and Rotation of the Pier, 37 Percent Observed Occurrence: (a) Settlement of the Pier and (b) Rotation of the Pier.

Among the 35 bridge failure cases, 13 bridges failed in the second mode, which means 37 percent observed occurrence. Figure 7-4 shows the examples of the bridge failure due to settlement of the pier. Figure 7-5 shows the examples of the bridge failure due to rotation of the pier.

(a) (b)

Figure 7-4. Settlement of the Pier: (a) Case 1 and (b) Case 2.

(a) (b)

Figure 7-5. Rotation of the Pier: (a) Case 1 and (b) Case 2.

Failure Mode 3: Loss of the Deck

Figure 7-6 shows the third failure mode: loss of the deck. In this mode, a bridge fails due to the loss of the deck. One possible reason for loss of the deck is that the settlement of the pier is so large that the deck moves out of the pier support and it falls down. Another possible reason for loss of the deck is that the rotation of the pier is very large. The possibility of this type of failure can be reduced by increasing the width of the support (Figure 7-7).

Among the 35 bridge failure cases, 5 bridges failed in the third mode, which means 14 percent observed occurrence. Figure 7-8 shows the examples of the bridge failure in the third failure mode.

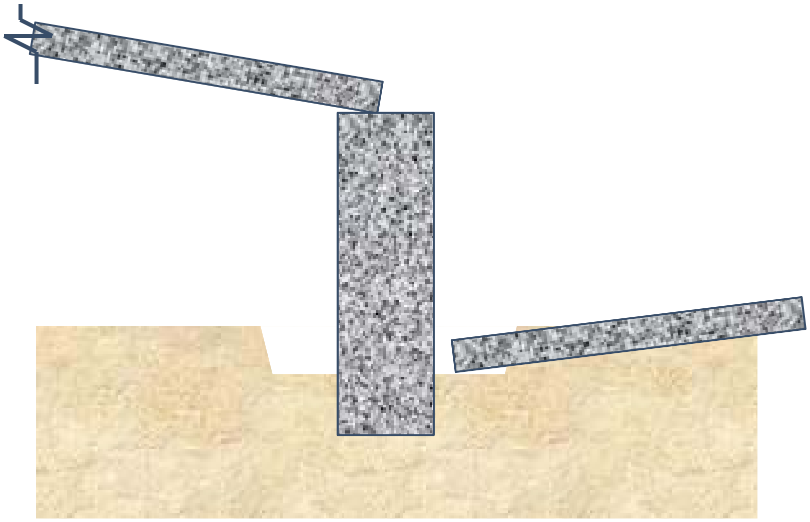


Figure 7-6. Failure Mode 3: Loss of the Deck, 14 Percent Observed Occurrence.

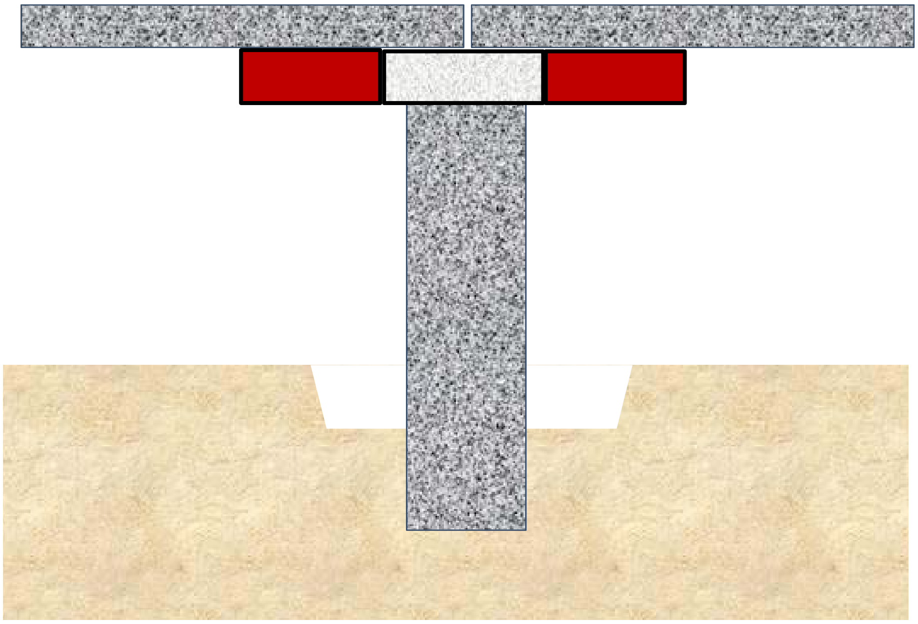
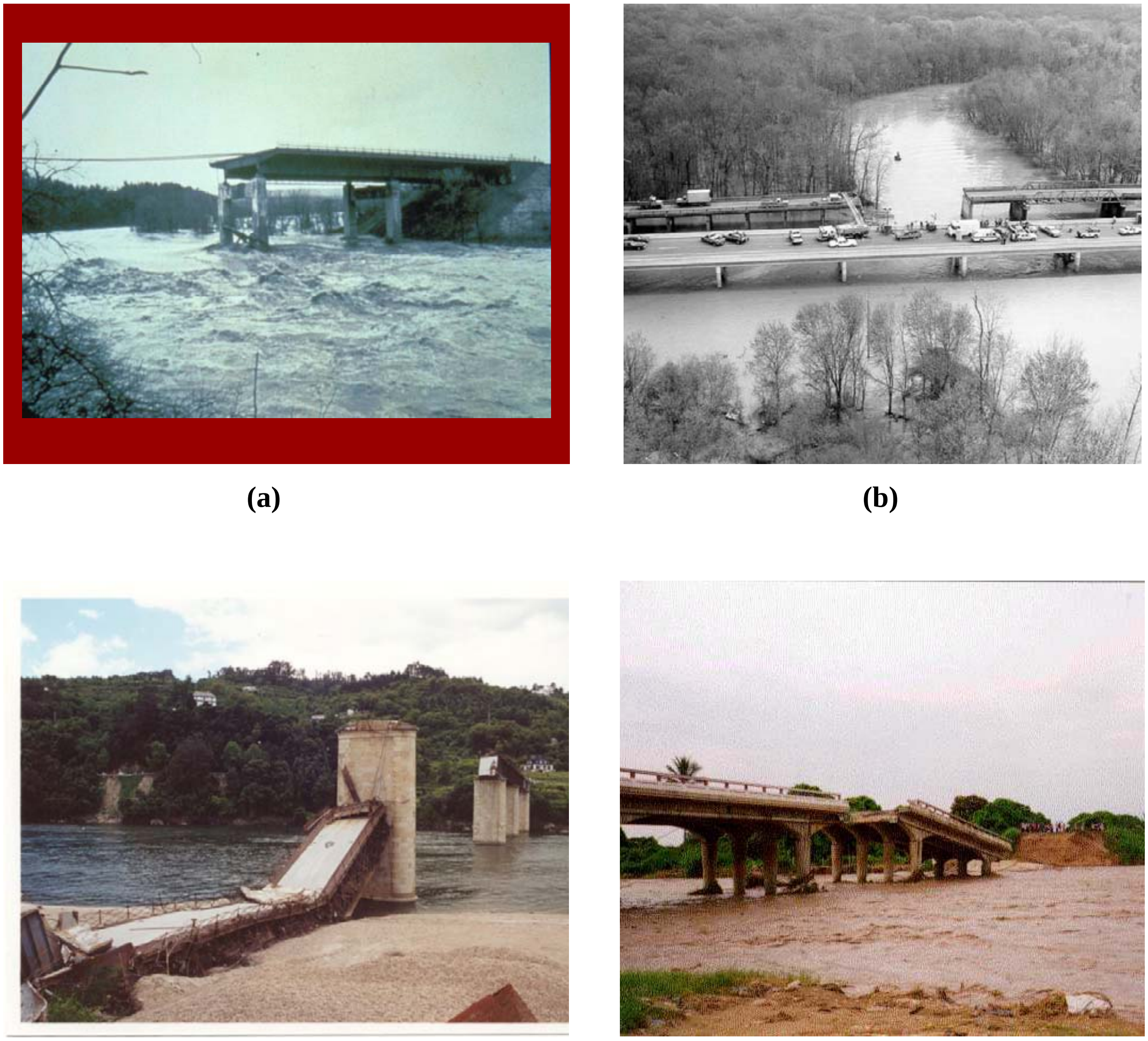


Figure 7-7. One Solution for Decreasing the Risk of Collapse.



(a) **(b)**

(c) **(d)**

Figure 7-8. Loss of the Deck: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

Failure Mode 4: Loss of the Pier

Figure 7-9 shows the fourth failure mode: loss of the pier. In this mode, a bridge fails due to the loss of the pier. Among the 35 bridge failure cases, 8 bridges failed in the third mode, which means 23 percent observed occurrence. Figure 7-10 shows a bridge failure process captured by two photos. Figure7-10a shows the rotation of the pier before it falls down, while Figure 7-10b shows the falling down of the pier. Figure 7-11 shows two more examples of bridge failure due to loss of the pier.

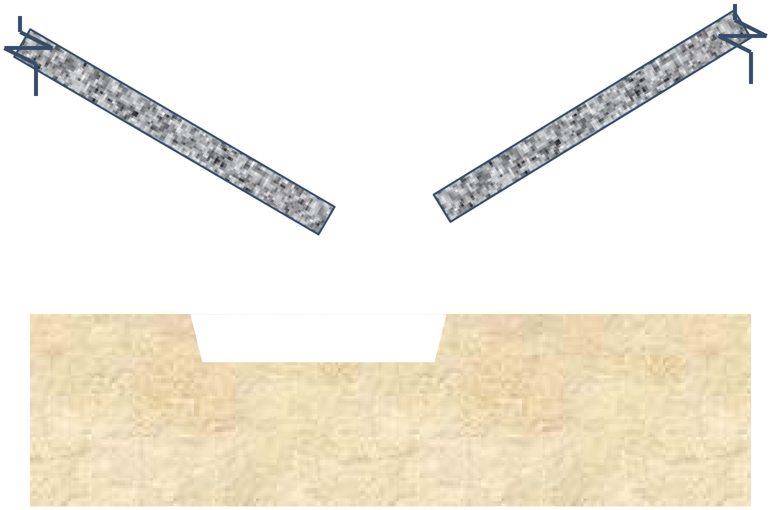


Figure 7-9. Failure Mode 4: Loss of the Pier, 23 Percent Observed Occurrence.

(a) (b)

Figure 7-10. Case of Loss of the Pier: (a) Rotation of the Pier and (b) Loss of the Pier.

(a) (b)

Figure 7-11. Loss of the Pier: (a) Case 1 and (b) Case 2.

GENERAL RECOMMENDATION

The four failure modes are caused by two mechanisms: the settlement of the pier and the rotation of the pier. The settlement of the pier can cause the tilt of the deck, which can be captured by the tiltmeter installed on the deck. If the pier settles too much; the deck loses its support on the pier, and the deck falls down. Depending on how badly the pier is rotated, the rotation of the pier can cause two events: loss of the deck and loss of the pier.

In this project, tiltmeters were installed both on the deck and on the top of pier. Therefore, analysis on the threshold for tiltmeters is performed on two cases below: from the pier point of view and from the deck point of view.

Analysis from the Pier Point of View

The tiltmeter installed on the top of pier can capture the tilt or rotation angle of the pier around two axes: the flow direction axis and the traffic direction axis. Figure 7-12 shows the failure mechanism of the bridge from the pier point of view.

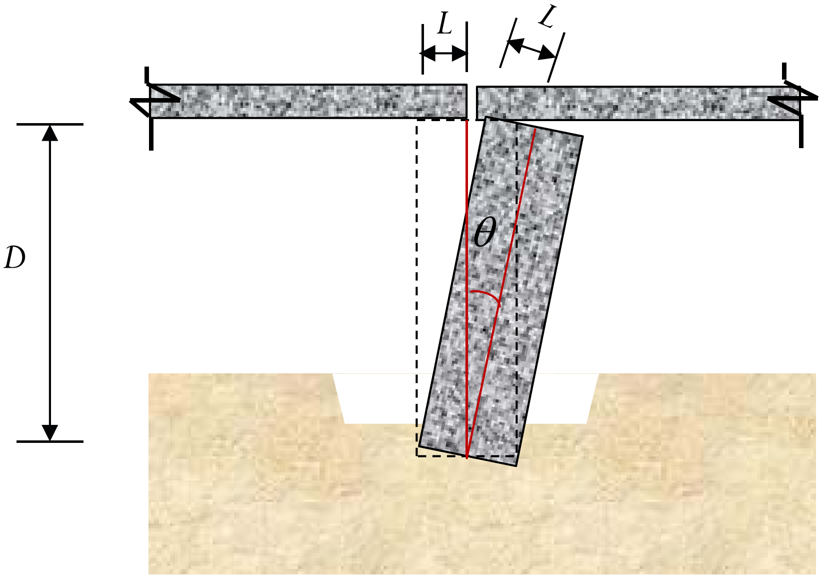


Figure 7-12. Threshold for Tiltmeter Installed on the Top of Pier.

Here, L represents the supporting width between the deck and the pier, which is at most equal to half of the width of the capping beam. D represents the length of the pier above the soil. θ represents the tilt angle of the pier around the flow direction axis (or traffic direction axis). When the tilt of the bridge is small, the tilt angle of the pier in radians can be obtained by Equation 7-1.

$$\theta = \frac{L}{D} \tag{7-1}$$

Considering a safety factor of 4, the threshold for the tiltmeter from the pier point of view is shown in Equation 7-2, and represents a warning point.

$$\theta_{check} = \frac{1}{4} \times \frac{L}{D} \tag{7-2}$$

The criterion for closing the bridge is suggested in Equation 7-3.

$$\theta_{close} = \frac{1}{2} \times \frac{L}{D} \tag{7-3}$$

Analysis from the Deck Point of View

The tiltmeter installed on the deck can capture the tilt angle of the deck around the flow direction axis. Figure 7-13 shows the failure mechanism of the bridge from the deck point of view.

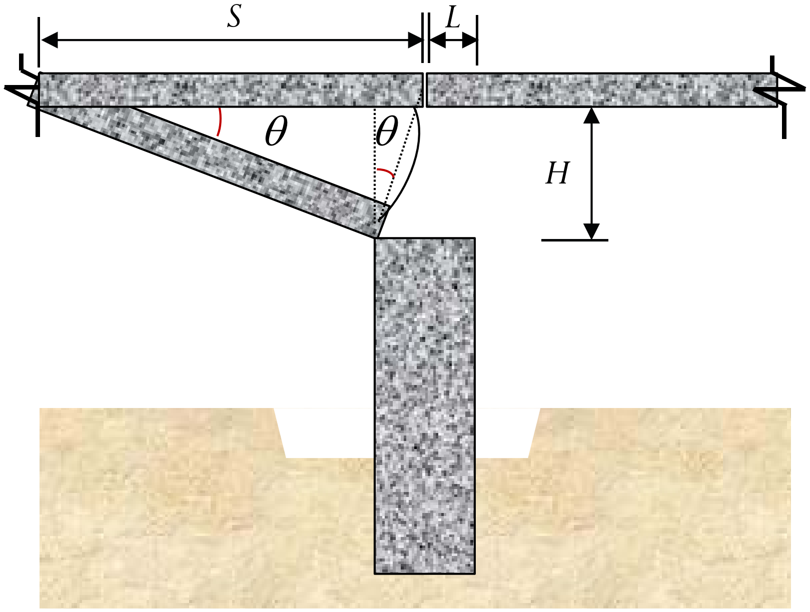


Figure 7-13. Threshold for Tiltmeter Installed on the Deck.

Here, L represents the supporting width between the deck and the pier, which is at most equal to half of the width of the capping beam. S represents the span of the bridge. H represents the settlement of the pier, which will cause the tilt of the deck. θ represents the tilt angle of the deck around the flow direction axis. When the tilt of the bridge deck is small, the tilt angle of the deck can be obtained from Equation 7-4 and Equation 7-5.

$$\sin\theta = \frac{L}{S \times \theta} \tag{7-4}$$

Since θ is small, $\sin\theta \approx \theta$, therefore:

$$\theta = \sqrt{\frac{L}{S}} \tag{7-5}$$

Usually the loss of deck criterion based on Equation 7-5 leads to a very large settlement of the pier. It is better in this case to establish an excessive settlement criterion for the pier that would require closing of the bridge. A value of 0.6 m (2 ft) is suggested. The criterion can be reestablished on that basis using Equation 7-6 and Equation 7-7. Here two is a factor of safety.

$$\theta_{check} = \frac{H_{excessive}}{2 \times S} \tag{7-6}$$

$$\theta_{close} = \frac{H_{excessive}}{S} \tag{7-7}$$

CASE FOR US59 OVER GUADALUPE RIVER BRIDGE

There are four tiltmeters installed on US59 over Guadalupe River Bridge (Figure 7-14).

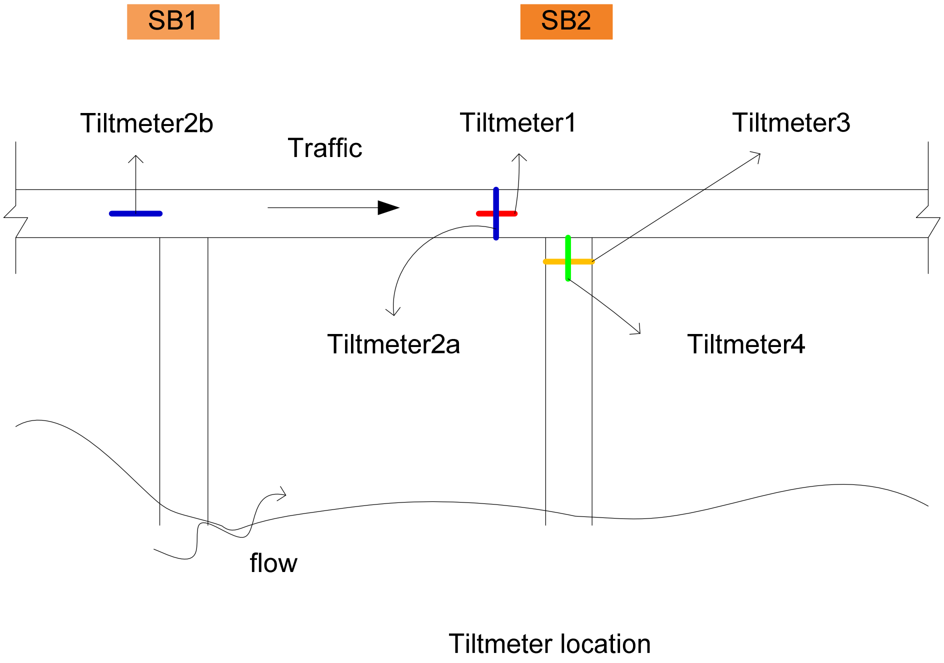


Figure 7-14. Layout of the Tiltmeter Location on US59 over Guadalupe River Bridge.

Tiltmeter1 and Tiltmeter2 are installed on the deck to measure the tilt of the deck around the flow direction axis (perpendicular to the traffic direction). The threshold for Tiltmeter1 and Tiltmeter2 on US59 over Guadalupe River Bridge can be obtained through Equation 7-5, Equation 7-6, and Equation 7-7.

- Loss of the deck criterion:

$$\theta = \sqrt{\frac{L}{S}} = \sqrt{\frac{0.45\text{ m}}{45\text{ m}}} = \sqrt{\frac{1.5\text{ ft}}{150\text{ ft}}} = 0.1\,\text{radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta = 5.71^{\circ}$$

The value 5.71° is very large and unreasonable.

- Excessive settlement of the pier criterion:

If an excessive settlement criterion of 0.6 m (2 ft) is used,

$$\theta_{check} = \frac{H}{2\times S} = \frac{0.6\text{ m}}{2\times 45\text{ m}} = \frac{2\text{ ft}}{2\times 150\text{ ft}} = 6.67\times 10^{-3}\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta_{check} = 0.38^{\circ}$$

$$\theta_{close} = \frac{H}{S} = \frac{0.6\text{ m}}{45\text{ m}} = \frac{2\text{ ft}}{150\text{ ft}} = 1.33\times 10^{-2}\text{ radian}$$

Therefore, the criterion for closing the bridge is:

$$\theta_{close} = 0.76^{\circ}$$

The threshold for Tiltmeter1 and Tiltmeter2 on US59 over Guadalupe River Bridge is 0.38° for checking the bridge, 0.76° for closing the bridge. Data analysis on tiltmeters on US59 over Guadalupe River Bridge in Chapter 5 shows that the bridge has been safe.

Tiltmeter3 and Tiltmeter4 are installed on the top of pier (SB2) to measure the tilt angle of the pier around the flow direction axis and the traffic direction axis (perpendicular to the flow direction), respectively. The threshold for Tiltmeter3 and Tiltmeter4 on US59 over Guadalupe River Bridge can be obtained through Equation 7-2 and Equation 7-3.

- Loss of the deck criterion:

$$\theta_{check} = \frac{1}{4}\times\frac{L}{D} = \frac{1}{4}\times\frac{0.45\text{ m}}{13.8\text{ m}} = \frac{1}{4}\times\frac{1.5\text{ ft}}{46\text{ ft}} = 8.15\times 10^{-3}\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta_{check} = 0.46^{\circ}$$

$$\theta_{close} = \frac{1}{2}\times\frac{L}{D} = \frac{1}{2}\times\frac{0.45\text{ m}}{13.8\text{ m}} = \frac{1}{2}\times\frac{1.5\text{ ft}}{46\text{ ft}} = 0.016\text{ radian}$$

Therefore, the criterion for closing the bridge is:

$$\theta_{close} = 0.93^{\circ}$$

The threshold for Tiltmeter3 and Tiltmeter4 on US59 over Guadalupe River Bridge is 0.46° for checking the bridge, 0.93° for closing the bridge. Data analysis on tiltmeters on US59 over Guadalupe River Bridge in Chapter 5 shows that the bridge has been safe.

CASE FOR SH80 AT SAN ANTONIO RIVER BRIDGE

There are four tiltmeters installed on SH80 over San Antonio River Bridge (Figure 7-15).

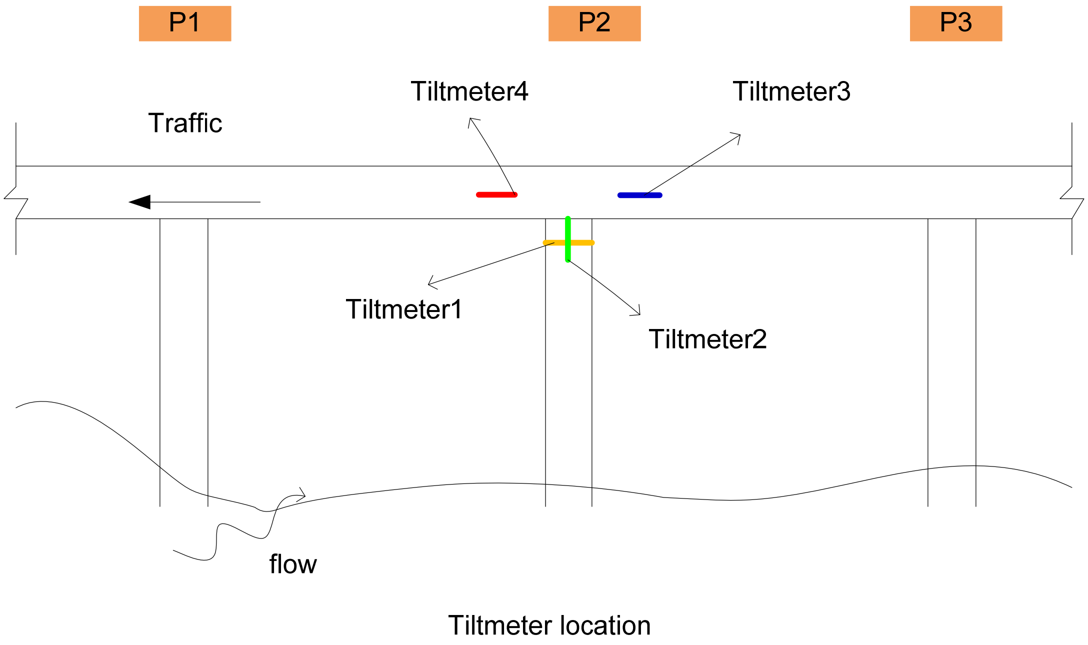


Figure 7-15. Layout of the Tiltmeter Location on SH80 over San Antonio River Bridge.

Tiltmeter1 and Tiltmeter2 are installed on the top of pier (P2) to measure the tilt angle of the pier around the flow direction axis and the traffic direction axis, respectively. The threshold for Tiltmeter1 and Tiltmeter2 on SH80 over San Antonio River Bridge can be obtained through Equation 7-2 and Equation 7-3.

- Loss of the deck criterion:

$$\theta_{check} = \frac{1}{4} \times \frac{L}{D} = \frac{1}{4} \times \frac{0.45\text{ m}}{12.9\text{ m}} = \frac{1}{4} \times \frac{1.5\text{ ft}}{43\text{ ft}} = 8.72 \times 10^{-3}\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta_{check} = 0.5^{\circ}$$

$$\theta_{close} = \frac{1}{2} \times \frac{L}{D} = \frac{1}{2} \times \frac{0.45\text{ m}}{12.9\text{ m}} = \frac{1}{2} \times \frac{1.5\text{ ft}}{43\text{ ft}} = 0.017\text{ radian}$$

Therefore, the criterion for closing the bridge is:

$$\theta_{check} = 1^{\circ}$$

The threshold for Tiltmeter1 and Tiltmeter2 on SH80 over San Antonio River Bridge is 0.5° for checking the bridge, 1° for closing the bridge. Data analysis on tiltmeters on SH80 over San Antonio River Bridge in Chapter 6 shows that the bridge has been safe.

Tiltmeter3 and Tiltmeter4 are installed on the deck to measure the tilt angle of the deck around the flow direction axis. The threshold for Tiltmeter3 and Tiltmeter4 on SH80 over San Antonio River Bridge can be obtained through Equation 7-5, Equation 7-6, and Equation 7-7.

- Loss of the deck criterion:

$$\theta = \sqrt{\frac{L}{S}} = \sqrt{\frac{0.45\text{ m}}{22.8\text{ m}}} = \sqrt{\frac{1.5\text{ ft}}{76\text{ ft}}} = 0.14\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta = 8^{\circ}$$

Obviously, 8° is an unacceptable criterion.

- Excessive settlement of the pier criterion:

If an excessive settlement criterion of 0.6 m (2 ft) is used,

$$\theta_{check} = \frac{H}{2 \times S} = \frac{0.6\text{ m}}{2 \times 22.8\text{ m}} = \frac{2\text{ ft}}{2 \times 76\text{ ft}} = 0.013\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta_{check} = 0.75^{\circ}$$

$$\theta_{close} = \frac{H}{S} = \frac{0.6\text{ m}}{22.8\text{ m}} = \frac{2\text{ ft}}{76\text{ ft}} = 0.026\text{ radian}$$

Therefore, the criterion for checking the bridge is:

$$\theta_{close} = 1.5^{\circ}$$

The threshold for Tiltmeter3 and Tiltmeter4 on SH80 over San Antonio River Bridge is 0.75° for checking the bridge, 1.5° for closing the bridge. Data analysis on tiltmeters on SH80 over San Antonio River Bridge in Chapter 6 shows that the bridge has been safe.

CONCLUSIONS

The threshold for tiltmeters can be established based on two points of view: the pier point of view and the deck point of view. The threshold for Tiltmeter1 and Tiltmeter2 on US59 over Guadalupe River Bridge is 0.38° for checking the bridge, 0.76° for closing the bridge. The threshold for Tiltmeter3 and Tiltmeter4 on US59 over Guadalupe River Bridge is 0.46° for checking the bridge, 0.93° for closing the bridge. Data analysis on tiltmeters on US59 over Guadalupe River Bridge in Chapter 5 shows that the bridge has been safe.

The threshold for Tiltmeter1 and Tiltmeter2 on SH80 over San Antonio River Bridge is 0.5° for checking the bridge, 1° for closing the bridge. The threshold for Tiltmeter3 and Tiltmeter4 on SH80 over San Antonio River Bridge is 0.75° for checking the bridge, 1.5° for closing the bridge. Data analysis on tiltmeters on SH80 over San Antonio River Bridge in Chapter 6 shows that the bridge has been safe.

CHAPTER 8:
GUIDELINES FOR SCOUR MONITORING

WHY WOULD YOU CHOOSE TO MONITOR A BRIDGE, CIRCUMSTANCES; AND WHEN?

Typically monitoring occurs to monitor a bridge for a shorter period of time, prior to the installation of more permanent scour countermeasures or bridge replacement. Scour monitoring is also used to monitor scour countermeasures and when scour calculations seem excessive compared to the observed scour, and data are required prior to final decisions on scour countermeasures or bridge replacement.

Scour monitoring of bridges using fixed instrumentation has been used as a scour countermeasure in the United States since the early 1990s. There are five types of devices currently recommended in the Federal Highway Administration's guidance on scour countermeasures, HEC-23 (Lagasse et al., 2009). These scour monitors include sonars, sliding collars, float-out devices, tilt meters, and Time Domain Reflectometers. This TxDOT project developed and tested a new device, TBS, and also tested motion sensors. Some of the fixed instruments measure scour at or near a bridge, while others measure movement of the bridge that may be caused by scour.

There is no scour monitor that works under all circumstances. The selection of a scour monitoring system for a bridge is site-specific and consideration needs to be given to numerous factors to help ensure the success of a system. Appendix C, *Guidelines for the Selection, Design and Implementation of a Fixed Scour Monitoring Program,* provides guidance for the evaluation of bridges for potential scour monitoring systems. The selection matrix, developed for the NCHRP's synthesis on *Monitoring Scour Critical Bridges* (Hunt, 2009) and included in the FHWA's HEC-23 on scour countermeasures (Lagasse et al., 2009), provides parameters to be considered when choosing a bridge scour monitoring system. It also documents which states have used or are using the different types of scour monitors. The selection matrix and a discussion of the factors may be found in Appendix C.

Various factors need to be considered when designing a bridge scour monitoring system. Factors include the bridge construction and geometry, waterway, soil and extreme conditions, data acquisition and analysis, cost, initial and long-term funding, and maintenance, repairs and inspections. The available scour monitoring technologies have strengths and disadvantages, and the decision to use a particular instrument or combination of instruments should be carefully evaluated. The extreme conditions in Texas including the high temperatures, floating debris, and floods need to be considered in selecting a scour monitoring system for a particular bridge site. Scour monitors are still in development and there is a need to make them less expensive, easier to install, more robust, and to optimize the remote and wireless data collection and warning system.

The use of fixed instrumentation as a scour countermeasure is a process that begins with the evaluation of the scour countermeasure alternatives for a particular bridge site, includes the design and installation of the instrumentation and the development of a scour monitoring protocol, and can continue for many years with the scour monitoring program for the bridge. Appendix C provides information to help TxDOT anticipate both the advantages and responsibilities of a successful scour monitoring system and program. The information was gathered during this TxDOT scour monitoring project and the NCHRP Synthesis 396, *Monitoring Scour Critical Bridges* (Hunt, 2009). Appendix C includes the best practices and the lessons learned with the use of fixed scour monitoring instrumentation at bridges.

Following is an outline of the chapters in Appendix C, *Guidelines for the Selection, Design and Implementation of a Scour Monitoring Program*:

1. Introduction.
2. Scour Monitoring Alternatives.
3. Design of the Fixed Scour Monitoring System and Program.
4. Installation of Fixed Scour Monitoring Instrumentation.
5. Implementation of the Scour Monitoring Program.
6. Conclusions and Recommendations.
7. Useful References and Bibliography.

CHAPTER 9:
THE SCOUR MONITORING PROTOCOLS

The protocol for the implementation of the scour monitoring program is a critical aspect for the success of the monitoring system. The Scour Monitoring Protocols developed for US59 over Guadalupe River and SH80 over San Antonio may be found in Appendix D and E.

The protocol for each bridge includes a description of the bridge and its' scour monitoring system; details of the installation of the system including photographs and plans; data collection; routine and emergency monitoring; data analysis; the chain of command to make decisions during an emergency situation; emergency procedures to follow in case a "scour event" has occurred; access to the system; and maintenance, inspection and repairs to the system. The information as documented in the scour monitoring protocol for each bridge may change. The protocols should be updated on a regular basis to reflect any changes in the program.

The NCHRP synthesis (Hunt, 2009) found that the problems with maintenance of the fixed scour monitoring system and program were the main concern expressed by bridge owners. It is important for TxDOT to identify the group(s) and individuals that will be responsible for the scour monitoring program and to update them as necessary.

The protocol includes a clear set of detailed instructions for those responsible for the routine and emergency monitoring of the bridge. There should be a chain of command so that responsibility is transferred when those who are responsible are on vacation, sick, unable to monitor, or are no longer in their particular position. The routine and emergency procedures are very site-specific. Often an owner will start with a conservative program with high frequencies for routine and emergency monitoring. After a period, the records will be reviewed and the frequency of monitoring may be adjusted.

A clear chain of command of those responsible for emergency situations also needs to be in place. Those responsible for analyzing the data should have instructions as to whom they should contact round-the-clock should the scour readings indicate a problem. This should include possible procedures to follow, which may include closure of the bridge, land monitoring, underwater inspections, or the emergency installation of contingency countermeasures such as riprap, etc.

Changes in the watershed or at the bridges may also affect the data. Those responsible for analyzing and interpreting the data should keep informed as to new developments, construction, mining, or other situations that might cause scour or siltation at the bridges with scour monitors.

A clear protocol detailing responsibilities can help to provide proper maintenance to prevent a sensor or system failure. If the person(s) responsible for monitoring are transferred to other positions, or if they retire, new person(s) need to be given the responsibility and training for the system. There have been instances where the telephone service has been interrupted due to non-payment of the telephone bill.

It is important to develop a regular maintenance and inspection program. TxDOT maintenance crews may be responsible for routine, above-water maintenance. Checklists and forms to guide the inspectors may be found in Appendix D. During the inspections, it is advisable that a member of the TxDOT scour monitoring team coordinate with the inspection crew to ensure that all important components are inspected and to help interpret their findings. If possible, this person would be on-site. The streambed elevations recorded during diving inspections and fathometer surveys may also be used as ground truth measurements to check the accuracy of the scour monitoring devices.

Following is an outline of the chapters for each bridge that are contained in the Appendix D: Scour Monitoring Protocol for US59 over Guadalupe River Bridge and Appendix E: Scour Monitoring Protocol for SH80 over San Antonio River Bridge.

1. Introduction.
2. Description of the Bridge and the Scour Monitoring System.
3. Installation of the Monitoring System.
4. Programming of the System.
5. Data Acquisition.
6. Analysis of Data.
7. Access to the Scour Monitoring System.
8. Maintenance of the Scour Monitoring System.
9. Inspection of the Scour Monitoring System.
10. Construction Work at the Bridges
11. System Malfunction.
12. Contacts

ATTACHMENT A – Bridge Plans

ATTACHMENT B – Sample Data

ATTACHMENT C– TxDOT Contact List and Protocols

ATTACHMENT D – Inspection Checklists

CHAPTER 10:
CONCLUSIONS AND RECOMMENDATIONS

GENERAL

The experiments performed in the laboratory show that the accelerometer and tiltmeter can be used in scour monitoring events since both give a warning of impending bridge failure successfully. However, the instrumentation of two bridges (US59 over Guadalupe River Bridge and SH80 over San Antonio River Bridge in Texas) does not show great hope for the use of accelerometers to predict the bridge scour because of lack of efficient excitation from traffic. Another issue with the accelerometer is the high power consumption during the transmission of the data, which cannot be satisfied with an ordinary solar panel. The tiltmeter can provide the integral behavior of the bridge in the field, therefore the tiltmeter is recommended for scour monitoring.

Besides accelerometer and tiltmeter, sonar sensor, water stage sensor, float-out device, and tethered buried switches are also used in the project. Of all those instruments, the tethered buried switches are recommended as a complement to the tiltmeters because they are reliable, relatively low cost to purchase, but costly to install.

LARGE SCALE LABORATORY EXPERIMENTS

Two large scale laboratory experiments were performed in the Haynes Coastal Engineering Laboratory at Texas A&M University. In the shallow foundation experiment, one column, 0.45 m (1.5 ft) in diameter and 4 m (13.1 ft) long, was embedded to a depth of 0.3 m (1 ft) in fine silica sand in a two-dimensional flume. Two concrete slabs, each roughly 0.53 m (1.75 ft) wide by 2 m (6.75 ft) long, placed end-to-end on the column simulated the bridge deck. In the deep foundation experiment, the bottom of the column was reconstructed to form a pile foundation. The column was embedded to 0.45 m (1.5 ft) in the sand with 0.15 m (0.5 ft) of column and 0.3 m (1 ft) of pile foundation. Accelerometer, tiltmeter, water stage sensor, float-out device, tethered buried switch, and sonar sensor were installed to monitor the simulated bridge. An acoustic doppler velocimeter was mounted in the flume to provide the water velocity. Both the shallow foundation experiment and deep foundation experiment indicated that the accelerometer can be used to predict impending bridge failure as well as tiltmeter and sonar sensor. The FFT approach as well as ratio of Root Mean Square approach was proven to be effective to analyze the accelerometer data as they showed a significant change when the scour depth reached the bottom of the column and the column started to settle and rock. The tiltmeter was reliable, stable, and robust. Both float-out device and tethered buried switch worked very well during the experiment; both of them showed great potential to be applied in the field to monitor scour event. The sonar sensor worked well as long as the minimum water depth of 0.6 m (2 ft) was met. Note that the sonar sensor cannot predict scour depth if the sonar sensor is attached to the column and the column starts to settle. Indeed, then the sonar sensor also settles. If this is not a problem, the sonar sensor can be used to monitor scour depth at that location. The water stage did not work very well in these two experiments. The two laboratory experiments indicated which monitors to use in the field scour monitoring experiments.

SCOUR MONITORING OF US59 OVER GUADALUPE RIVER BRIDGE

The monitoring system was installed on the southbound part of the US59 over Guadalupe River Bridge on May 28, 2009. The hardwired and wireless motion sensors installed on the US59 over Guadalupe River Bridge recorded good data for one week after installation. Then the connection with the bridge was lost after June 8, 2009, and was fixed on October 15, 2009. The two accelerometers recorded good data again until late November 2009. Due to the high power demand from the accelerometers on the system and unfavorable weather condition for the solar power system, the bridge scour monitoring system shut down automatically when the battery voltage dropped below 12 volts. Therefore, data from late December 2009 to early February 2010 was sparse.

With respect to the accelerometers, the frequency domain analysis and the acceleration ratio approach require a lot of data to be collected and stored. Therefore accelerometers require a lot of power to acquire and transmit the data. The two approaches (frequency and acceleration ratio) worked well for the model bridge because the structure and its vibration were simple. The response to vibrations of full scale bridges is much more complex and requires controlled and large excitation for useful data to be collected. The frequency content of the response is complex and the accelerations ratio is not consistent. The noise level can impact the true content of the transmitted signal. Accelerometers are a good idea that requires much more work, which is beyond the time and budget of this project. Therefore they were abandoned as a viable solution in this project on March 11, 2010.

All the sensors and the master station give consistent data since the initial installation on May 28, 2009, including the water stage sensor, tiltmeters, flout-out devices, and tethered buried switches. The water stage sensor is fixed to the bridge parapet at the bottom of the deck and is measuring the water surface elevation of the US 59 over Guadalupe River Bridge. The water stage sensor readings are comparable to the USGS database. The tiltmeters give us very good information about the tilt angle of the bridge. The tilt of the bridge is influenced by changes in daily temperature. Two float-out devices (Float-out1 and Float-out2) are buried in the soil near Pier SB2. Float-out1 is buried 16.2 m (54 ft) below top of deck, and Float-out2 is buried 18.9 m (63 ft) below top of deck. Two tethered buried switches (TBS1 and TBS2) are buried in the soil near Pier SB3. TBS1 is buried 7.2 m (24 ft) below top of deck. TBS2 is buried 10 m (34 ft) below top of deck. The two tethered buried switches were working properly until the cables were ripped due to construction on the bridge. The temperature of the system matches with the weather history in Victoria very well.

SCOUR MONITORING OF SH80 OVER SAN ANTONIO RIVER BRIDGE

The monitoring system was installed on SH80 over San Antonio River Bridge on October 16, 2009. The hardwired accelerometer gave much better information than the wireless accelerometer did in this case. Good sets of data were obtained from the hardwired accelerometer in December 2009. We could not get good data from October 20, 2009, to October 26, 2009, and after December 23, 2009. For the wireless accelerometer, only one group of good data (on October 20, 2009) was collected. The connection with the bridge was lost for one and a half month, from late October to early December 2009. The wireless accelerometer was removed from the SH80 over San Antonio River Bridge on December 9, 2009. On March 11, 2010, the hardwired accelerometer was removed from the bridge and four tiltmeters were installed instead. Tiltmeters are giving stable and reasonable reading now. The tilt readings show a slight but clear variation correlated to the system temperature.

The tethered buried switches are working well and give good information about corresponding scour depth at the bridge if the depth of the instruments is reached. Two tethered buried switches (TBS1 and TBS2) are buried in the soil near Pier P1. TBS1 is buried 12.3 m

(41 ft) below the top of deck. TBS2 is buried 11.4 m (38 ft) below the top of deck. Both TBS1 and TBS2 have given an almost constant value of 1 during this project, which means the sensors are working properly and not floated out. The monitoring system also gives the reading of temperature and battery. The reading of temperature matches very well the recorded weather history in Karnes City, Texas.

THRESHOLD FOR TILTMETERS

The threshold for tiltmeters can be established based on two points of view: the tilt of the pier and the tilt of the deck. The threshold for Tiltmeter1 and Tiltmeter2 on the deck of the US59 over Guadalupe River Bridge is 0.38° for checking the bridge, 0.76° for closing the bridge. The threshold for Tiltmeter3 and Tiltmeter4 on the pier of the US59 over Guadalupe River Bridge is 0.46° for checking the bridge, 0.93° for closing the bridge. Data analysis on tiltmeters on US59 over Guadalupe River Bridge in Chapter 5 shows that the bridge has been safe.

The threshold for Tiltmeter1 and Tiltmeter2 on the pier of the SH80 over San Antonio River Bridge is 0.5° for checking the bridge, 1° for closing the bridge. The threshold for Tiltmeter3 and Tiltmeter4 on the deck of the SH80 over San Antonio River Bridge is 0.75° for checking the bridge, 1.5° for closing the bridge. Data analysis on tiltmeters on SH80 over San Antonio River Bridge in Chapter 6 shows that the bridge has been safe.

RECOMMENDATIONS

With respect to the accelerometers, the frequency domain analysis and the acceleration ratio approach require a lot of data to be collected and stored. Therefore accelerometers require a lot of power to acquire and transmit the data in the field. The two approaches (frequency and acceleration ratio) worked well for the model bridge in the laboratory experiment because the structure and its vibration were simple. The response to vibrations of full scale bridges is much more complex and requires controlled and large excitation for useful data to be collected. The frequency content of the response is complex and the acceleration ratios are not consistent. So accelerometers are a good idea for bridge scour monitoring but require much more work. Small wind turbines or electrical grid can be considered as alternatives for power generation.

Tiltmeters are reliable, simple, and relatively inexpensive to purchase and to install. They are recommended as sensors that integrate the overall behavior of the bridge and can give warnings when failure approaches. They can be helpful for other than scour distress of the bridge including earthquake.

Tethered buried switches are new, likely helpful, inexpensive to purchase, but relatively costly to install. They can cover only one scour location chosen by the engineer. They are recommended for early warning but in combination with tiltmeters.

Cameras are a very good idea; they indicate water stage, the presence of debris, large bridge movements, and their use should be pursued. At night, infrared still photos can be used. The power required for movies to be transmitted is likely too large for solar panels or turbines. Still photos are sufficient and require much less power including transmission. A smart way to install them and secure them needs to be developed. The future scour monitoring system should be reliable during extreme events such as hurricanes, high floods, and long rain period.

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APPENDIX A:
BUDGET FOR US59 OVER GUADALUPE RIVER BRIDGE

Budget for US59 over Guadalupe River Bridge

Item	Personnel	Cost ($)	Item cost	Comments
Instrumentation system design	graduate student, Jerry	3000	**3000**	$75 /hr* 40 hrs=$3000
Equipment and preparation			**26250**	
tilt sensor (4)		1800		$450 *4 = $1800
stage sensor (1)		1900		
float-out device (2)		1700		$850* 2= $1700
tethered buried switch (2)		1000		$500*2=$1000
hardwired motion sensor (1)		2000		
wireless motion sensor (1)		2000		
master station:				
enclosure		100		
data logger		1900		
cellular modem		500		
antenna, cellular		100		
power supply		200		
solar power system - 3 *20 (watt)		3000		$1000 *3=$3000
testing before installation		10000		
shipping		50		
System installation	Alpha Testing, Inc., TAMU group (6)		**22700**	
screws,conduits, etc.		200		
drilling		6000		
man power		9000		$75/hr* 10hrs/day*2days*6persons=$9000
traffic control		4000		$2000/day*2days=$4000

snooper truck		3000		$1500/day*2 days=$3000
loggernet software		500		
System maintenance (1 year)	4 site-visiting		**6760**	
man power		6000		$75*10*2*4=$6000
screws, conduits , etc		200		
Cellular service for 1 year		360		$30/month *12months=$360
shipping equipments		200		
Data analysis			**9000**	
computer		1000		
analysis	graduate student	4000		$20/hr* 200hrs=$4000
super computer resource	graduate student	4000		$20/hr*200hrs=$4000
Web-site design and maintenance			**4000**	
initial design	graduate student	1600		$20/hr*80hrs=$1600
maintenance	weekly	400		$20/hr*20hrs=$400
development on the website	graduate student	2000		$20/hr*100hrs=$2000
Engineering oversight	Professional Engineers	9000	**9000**	$75/hr*60hrs*2persons=$9000
Travel expense	Jerry, Bea, TAMU group		**15000**	
	round trip air-flight	5000		
	hotel	6000		
	dining	2000		
	traffic	2000		
Total cost			**95710**	

APPENDIX B:
BUDGET FOR SH80 OVER SAN ANTONIO RIVER BRIDGE

Budget for SH80 over San Antonio River Bridge

Item	Personnel	Cost ($)	Item cost ($)	Comments
Instrumentation system design	graduate student, Jerry	3000	**3000**	$75/hr * 40 hrs=$3000
Equipment and preparation			**19650**	
tilt sensor (4)		1800		$450 *4=$1800
tethered buried switch (2)		1000		$500*2=$1000
hardwired motion sensor (1)		2000		
wireless motion sensor (1)		2000		
master station:				
enclosure		100		
data logger		1900		
cellular modem		500		
antenna, cellular		100		
power supply		200		
solar power system - 2*20 (watt)		2000		$1000 *2=$2000
testing before installation		8000		
shipping		50		
System installation	TAMU group (7)		**18000**	
screws,conduits, etc.		500		
man power		10500		$75/hr* 10hrs*2days*7persons=$10500
traffic control		4000		$2000/day*2days=$4000
snooper truck		3000		$1500/day*2days=$3000
System maintenance (1 year)	2 site-visiting		**3760**	
man power		3000		$75/hr*10hrs*2days*2persons=$3000

screws, conduits, etc.		200		
Cellular service for 1 year		360		$30/month *12months=$360
shipping equipments		200		
Data analysis			**6000**	
analysis	graduate student	4000		$20/hr*200hrs=$4000
super computer resource	graduate student	2000		$20/hr*100hrs=$2000
Web-site design and maintenance			**4200**	
initial design	graduate student	1600		$20/hr*80hrs=$1600
maintenance	weekly	600		$20/hr*30hrs=$600
development on the website	graduate student	2000		$20/hr*100hrs=$2000
Engineering oversight	Professional Engineers	9000	**9000**	$75/hr*60hr*2persons=$9000
Travel expense	Jerry, Bea, TAMU group		**7500**	
	round trip air-flight	2000		
	hotel	3000		
	dining	1000		
	traffic	1500		
Total cost			**71110**	

APPENDIX C:
GUIDELINES FOR THE SELECTION, DESIGN, AND IMPLEMENTATION OF A FIXED SCOUR MONITORING PROGRAM

TABLE OF CONTENTS

INTRODUCTION

PURPOSE

WHY WOULD YOU CHOOSE TO MONITOR A BRIDGE, UNDER WHAT CIRCUMSTANCES, AND WHEN? Typically monitoring is used to monitor a bridge for a shorter period of time, prior to the installation of permanent scour countermeasures, or the bridge replacement. Scour monitoring is also used to monitor scour countermeasures, and when scour calculations seem excessive compared to the observed scour and data are required prior to final decisions on scour countermeasures or bridge replacement.

Bridge scour is the number one cause of bridge collapse. Improvements in prediction methods, scour countermeasures, and scour monitoring are needed. Scour at bridges has been exceedingly difficult to predict as well as quantify. Channel profile measurements are taken during routine inspections and often after extreme flood events, but both of these cases are outside the window of the event. Observations and research have shown that the ultimate scour limit during an event may differ from the scour limit post event by several feet, depending on the channel type and bed load. Attempts have been made to measure the channel profile during the actual flood event but the success of those measurements has been somewhat mixed. Devices usually require that personnel be on site manipulating the equipment or reading the equipment after the event. The safety of the personnel during and even after the event may prevent access and reliable readings. With variables such as the duration of the event, drift load, channel velocity, and bed load, the life expectancy of these devices is usually very short and the measurements taken may not be very accurate. With the advent of remote monitoring systems for electronic instrumentation, research needs to be conducted to develop devices for real time scour measurement at bridges subject to catastrophic failure due to scour.

In 2007 TxDOT sponsored a project, *Realtime Monitoring of Scour Events Using Remote Monitoring Technology.* The purpose was to explore the option of fixed scour monitoring at bridges. This was done as a useful approach to improving the safety of the traveling public while minimizing the expense. Fixed scour monitoring consists of placing instruments on or around the bridge monitoring the depth of the scour hole that may develop around bridge supports during high flow events or monitoring any movement of the bridge due to scour. Warnings are sent to the authorities in time to shut down the bridge in case of an emergency. Scour monitors are still in development and there is a need to make them less expensive, easier to install and more robust, and to optimize the remote and wireless data collection and warning system.

The use of fixed instrumentation as a scour countermeasure is a process that begins with the evaluation of the scour countermeasure alternatives for a particular bridge site, includes the design and installation of the instrumentation and the development of a scour monitoring program, and can continue for many years with the scour monitoring program for the bridge. These guidelines provide information to help TxDOT anticipate both the advantages and responsibilities of a successful scour monitoring system and program. The information in this document was gathered during this TxDOT scour monitoring research project and the NCHRP Synthesis 396, *Monitoring Scour Critical Bridges* (Hunt, 2009). These guidelines are on the best practices and the lessons learned with the use of fixed scour monitoring instrumentation at bridges.

BACKGROUND

The most recent guidelines on bridge scour countermeasures may be found in the FHWA Hydraulic Engineering Circular 23 (HEC-23), *Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance – Third Edition* (Lagasse et al., 2009). Scour countermeasures, as defined in HEC-23, are "measures incorporated into a highway-stream crossing system to monitor, control, inhibit, change, delay, or minimize stream instability and bridge scour problems."

Based on their functionality, HEC-23 categorizes scour countermeasures into four general groups—hydraulic, structural, biotechnical, and monitoring. Hydraulic countermeasures include both river training structures that modify the flow, and also armoring countermeasures that resist erosive flow. Structural countermeasures consist of modifications of the bridge foundation. These may be classified as foundation strengthening or pier/abutment geometry modification. Biotechnical countermeasures combine vegetation with structural (hard) elements for streambank protection. Monitoring countermeasures may be fixed instrumentation, portable instrumentation, or visual monitoring.

This report was prepared to include a general background and the resources relative to the state-of-the-art in bridge scour monitoring technology. The most recent guidance from FHWA on scour monitoring instrumentation may be found in HEC-23. Detailed information on bridge scour monitoring may be found in the NCHRP Synthesis 396, *Monitoring Scour Critical Bridges* (Hunt, 2009). This study assessed the state of knowledge and practice for fixed scour monitoring of scour critical bridges. It included a survey of the United States transportation agencies and bridge owners to obtain their experience with fixed scour monitors. More information on the earlier types of fixed scour monitors may be found in the NCHRP Report 396 for Project 21-3, *Instrumentation for Measuring Scour at Bridge Piers and Abutments* (Lagasse et al., 1997) and the corresponding installation, operation, and fabrication manuals (Schall et al., 1997a and 1997b).

According to the FHWA guidelines, existing bridges found to be vulnerable to scour, should be monitored and/or have scour countermeasures installed. FHWA's HEC-18 (Richardson and Davis, 2001) first recommended the use of fixed instrumentation and sonic fathometers (depth finders) as scour monitoring countermeasures in their Second Edition (1993). Two of the fixed scour monitoring instruments discussed in this report were recommended in TRB NCHRP Project 21-3, *Instrumentation for Measuring Scour at Bridge Piers and Abutments* (Lagasse et al., 1997). The purpose of that project was to study devices that measure and monitor maximum scour at bridges. The project developed, tested, and evaluated methods both in the laboratory and in the field. The NCHRP project extensively tested and recommended two systems—the sonic fathometer and the magnetic sliding collar devices. Each of these fixed instruments measures and monitors scour. Additional fixed scour monitoring systems that were tested under this project included sounding rods and other buried devices. Subsequent to the NCHRP project, three additional fixed monitors were developed and installed—float-out devices, tiltmeters, and Time Domain Reflectometers. These were documented in the 2009 publications of HEC-23 and the Synthesis Report. The float-out and tiltmeters are now being used extensively. Currently bridge owners are taking these research recommendations to custom-design scour monitoring systems to meet difficult site-specific requirements and to develop programs for the monitoring of scour critical bridges to satisfy FHWA and state criteria.

Scour monitoring using fixed instrumentation may also be part of a bridge Plan of Action. The Federal requirements for bridge inspection are set forth in the National Bridge Inspection Standards (NBIS). The NBIS require bridge owners to maintain a bridge inspection program that includes procedures for underwater inspection. This information may be found in the FHWA Federal Register, Title 23, Code of Federal Regulations, Highways, Part 650, Bridges, Structures, and Hydraulics, Subpart C, National Bridge Inspection Standards (23 CFR 650, Subpart C). The most recent ruling was enacted on January 13, 2005. The revisions underscore actions required for bridges that are determined to be scour critical. These include the preparation of a Plan of Action to monitor known and potential deficiencies and to address critical findings, and monitoring of bridges in accordance with the plan for bridges that are scour critical (23 CFR 650.313).

MANUAL ORGANIZATION

Chapter 1 introduces the subject of fixed scour monitoring instrumentation for bridges and includes the purpose of the guidelines, the background of scour monitoring, and the manual organization. Chapter 2 includes a general overview of scour monitoring, and a description of the scour monitoring alternatives.

Chapter 3 outlines guidance for the design of a fixed scour monitoring system and program. It discusses options that should be considered during the design in order to ensure the success of the scour monitoring system. Chapter 4 discusses guidance on the installation of the scour monitoring system.

Chapter 5 reviews the implementation of the scour monitoring program once installed in order to ensure that it provides useful data and remains operational. It includes discussions on the protocol, plans of action, routine and emergency monitoring, data collection and analysis, and maintenance, inspection, and repairs to the systems. Chapter 6 is a summary of conclusions and recommendations. Chapter 7 includes useful current and historic references on scour monitoring and bridge scour.

SCOUR MONITORING ALTERNATIVES

SCOUR MONITORING AND INSTRUMENTATION

FHWA HEC-23 contains the most recent guidance on scour monitoring, and defines it as "activities used to facilitate early identification of potential scour problems. Monitoring could also serve as a continuous survey of the scour progress around the bridge foundations." There are limited funds to replace or repair all the scour critical and unknown foundation bridges, therefore HEC-23 states that an alternative solution is to monitor and inspect the bridges following high flows and storms. A well-designed monitoring program aims at providing an efficient and cost-effective short-term alternative to hydraulic and structural scour countermeasures. Monitoring can also be used in conjunction with hydraulic and/or structural countermeasures.

Recommended in HEC-23 are three types of scour monitoring: fixed instrumentation, portable instrumentation, and visual monitoring. Fixed monitors may be placed on a bridge structure, or in the streambed or on the banks near the bridge. Portable instrumentation monitoring devices can be manually carried, used along a bridge, and transported from one bridge to another. Visual inspection monitoring may be performed at standard regular intervals and may include increased monitoring during high flow events (flood watch), land monitoring, and/or underwater inspections. A bridge may have one or more types of scour monitoring techniques that also can be used in combination with other hydraulic and/or structural scour countermeasures. Scour monitoring may be a permanent or a temporary interim countermeasure.

The various fixed instrumentation devices are either mounted on the bridge or installed in the streambed or on the banks in the vicinity of the bridge. Each scour monitoring device transmits data to a data logger at its remote unit. The data from any of these fixed instruments may be downloaded manually at the sight, or it can be telemetered to another location. The early scour monitoring devices measured streambed elevations using simple units mounted on-site and read manually. Almost all of the more recent installations use remote technology. Each bridge may have one or more remote sensor units that transmit data to a master unit on or near the bridge. The scour monitoring data are then transmitted from the master unit to a central office and/or posted on the Internet.

Portable Scour Monitors

Portable instruments are more cost-effective in monitoring an entire bridge or multiple bridges than fixed instruments; however, they do not offer a continuous watch over the structures. It is often dangerous for individuals to go to a bridge to take measurements during a storm event. The allowable level of risk affects the frequency of data collection using portable instruments. Examples of portable instruments are sounding rods, sonars on floating boards, scour boats, and scour trucks.

Visual Inspection

Similar to portable monitoring, there are limitations on when inspectors can visit the bridges during storms. The scour hole that forms during a high-flow event is often filled in during the receding stage as the stream flow returns to normal. This “scour-and-infill” cycle is not commonly detected using portable devices, nor during measurements taken by divers after a storm.

Fixed Scour Monitors

The use of scour monitoring technology in the United States has led to the development of several fixed instruments suitable for different types of sites and structures. The fixed monitors recommended in the FHWA guidelines include sonars, magnetic sliding collars, float-out devices, tiltmeters, and Time Domain Reflectometers (TDRs). These are summarized in Table C-1 and described in detail in the following sections.

Table C-1. Fixed Instrumentation Summary

Type of Fixed Instrumentation	Best Application	Advantages	Limitations
Sonar	Coastal regions	Records infilling; time history; can be built with off the shelf components	Debris, high sediment loading and air entrainment can interfere with readings; records scour only at the sensor location
Magnetic Sliding Collar	Fine bed channels	Simple, mechanical device	Vulnerable to ice and debris impact; only measures maximum scour; unsupported length, binding; records scour only at the sensor location
Tiltmeter	All	May be installed on the bridge structure and not in the streambed and/or underwater; may detect scour in more than one location	Provides bridge movement data that may or may not be related to scour
Float-Out Device	Ephemeral channels	Lower cost; ease of installation; buried portions are low maintenance and not affected by debris, ice, or vandalism	Does not provide continuous monitoring of scour; limited battery life; records scour only at the sensor location
Time Domain Reflectometer	Riverine ice channels	Robust; resistance to ice, debris, and high flows	Limit on maximum lengths for signal reliability of both cable and scour probe; records scour only at the sensor location

TYPES OF FIXED SCOUR MONITORING INSTRUMENTATION

Sonars

The sonar scour monitors are mounted onto the pier or abutment face (Figure C-1 and Figure C-2) to take streambed measurements, and each is connected to a data logger. The sonar instrument measures the distance from the sonar head to the treambed and back based on the travel time of a sound wave through water. The data logger controls the sonar system operation and data collection functions. The data logger is programmed to take measurements at prescribed intervals. Sonar sensors normally take a rapid series of measurements and use an averaging scheme to determine the distance from the sonar transducer to the streambed. These instruments can track both the scour and refill (deposition) processes. The early sonar monitors used existing fish finders. Currently new sonar monitors range from the fish finders to smart sonar transducers, both of which are commercially available.

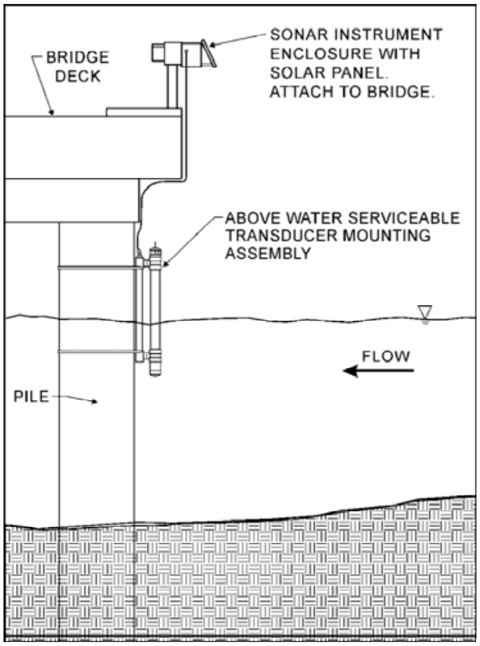

Figure C-1. Schematic of Sonar Scour Monitoring System (FHWA HEC-23).

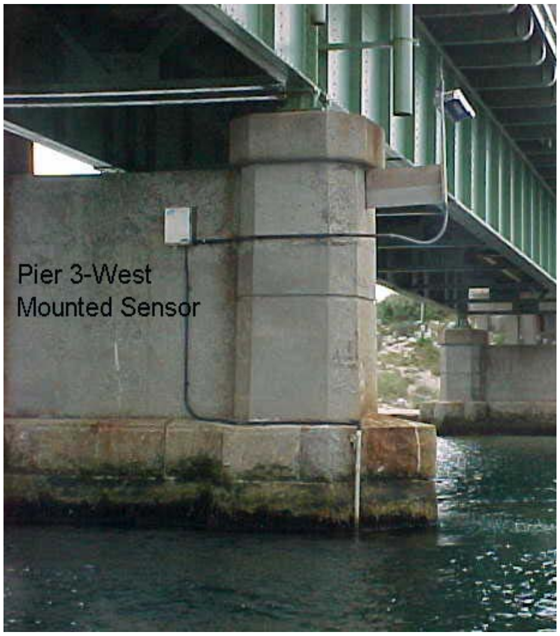

Figure C-2. Sonar Scour Monitor, Data Logger and Solar Panel (NYSDOT).

Magnetic Sliding Collars

Magnetic sliding collars (Figures C-3 and Figure C-4) are rods or masts that are attached to the face of a pier or abutment and driven or augered into the streambed. A collar with magnetic sensors is placed on the streambed around the rod. If the streambed erodes, the collar moves or slides down the rod into the scour hole. The depth of the collar provides information on the scour that has occurred at that particular location.

The early version of the sliding magnetic collar used a battery operated manual probe that was inserted down from the top and a buzzer sounded when the probe tip sensed the level of the magnetic collar. More recent collars have a series of magnetically activated switches at known distances. Magnets in the steel collar come into proximity with the switches as it slides into the scour hole, the switches close and their position is sensed by the electronics. The data logger reads the level of the collar via the auto probe and senses scour activity. While sonar scour monitors may be used to provide the infill scour process at a bridge, magnetic sliding collars can only be used to monitor the maximum scour depth.

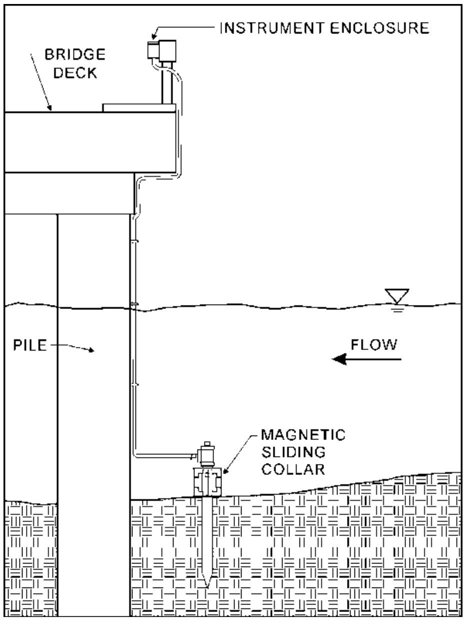

Figure C-3. Schematic of Sonar Scour Monitoring System (FHWA HEC-23)

Figure C-4. Magnetic Sliding Collar Installation (Caltrans).

Float-Out Devices

Buried devices may be active or inert buried sensors or transmitters. Float-out devices (Figures C-5 and Figure C-6) are buried transmitters. This device consists of a radio transmitter buried in the channel bed at pre-determined depth(s). If the scour reaches that particular depth, the float-out device floats to the stream surface and an onboard transmitter is activated. It transmits the float-out device's digital identification number with a radio signal. The signal is detected by a receiver in an instrument shelter on or near the bridge. The receiver listens continuously for signals emitted by an activated float-out device. A decoded interface decodes the activated float-out device's unique digital identification number that will determine where the scour has occurred. A data logger controls and logs all activity of the scour monitor. These are particularly easy to install in dry streambeds, during the installation of an armoring countermeasure such as riprap, and during the construction of a new bridge. The float-out device is a small low powered digital electronics position sensor and transmitter. The electronics draws zero current from a lithium battery, which, according to the manufacturer, provides a 9-year life expectance when in the inactive state buried in the streambed.

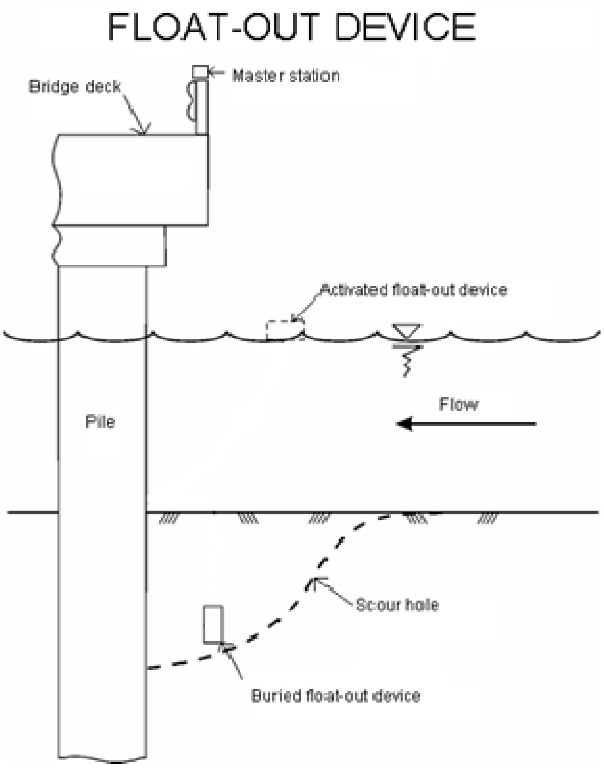

Figure C-5. Schematic of Float-Out Device (Texas Transportation Institute).

Figure C-6. Float-Out Devices Color Coded and Numbered for Identification (ETI Instrument Systems).

Tiltmeters

Tiltmeters (Figures C-7 and Figure C-8) measure movement of the bridge itself. A pair of tiltmeters or clinometers will monitor the position of the bridge. One monitors bridge position parallel to the direction of the traffic (longitudinal direction of the bridge), and the second monitors the position perpendicular to traffic (usually parallel with the stream flow). Should the bridge be subject to scour causing one of the support piers to settle, one or both of the tiltmeters would detect a change in position. Should the change in bridge position as detected by the dual-axis tiltmeter exceed a programmable limit, the data system would send out an alert status message.

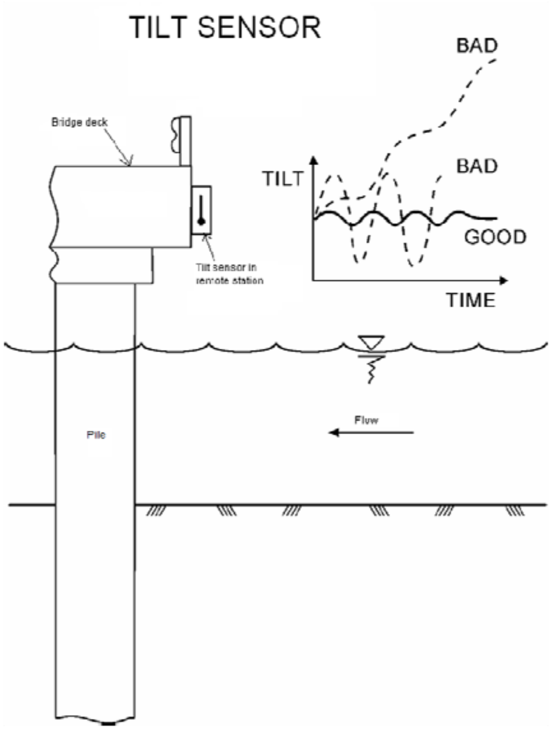

Figure C-7. Schematic of Tiltmeter (Texas Transportation Institute).

Figure C-8. Tiltmeter Installation (Caltran).

Caltrans (Avila et al., 1999) notes that the tiltmeters monitor the ever-changing position that normally occurs because bridges must be redundant enough to withstand some amount of movement without failure. It is difficult to set the magnitude of the angle at which the bridge is in danger. Bridges are not rigid structures and movement can be induced by traffic, temperature, wind, hydraulic and earthquake loads. It is necessary to observe the "normal" movement of the bridge and then determine the "alarm" angle that would provide sufficient time for crews to travel to the bridge to inspect and close the bridge to traffic, if necessary. Caltrans has accomplished this by installing the tiltmeters and monitoring normal changes in bridge position for several months and setting the "alarm" angle based on the unique signature of each pier monitored on any given bridge.

Time Domain Reflectometry

In Time Domain Reflectometry, an electromagnetic pulse is sent down one pipe and returns through a parallel pipe, both of which are buried vertically in the streambed (Figures C-9 and Figure C-10). When the pulse encounters a change in the boundary conditions (i.e., the soil-water interface), a portion of the pulse's energy is reflected back to the source from the boundary. The remainder of the pulse's energy propagates through the boundary until another boundary condition (or the end of the probe) causes part or all of the energy to be reflected back to the source. By monitoring the round-trip travel time of a pulse in real time, the distance to the respective boundaries can be calculated and this provides information on any changes in streambed elevation. Monitoring travel time in real time allows the processes affecting sediment transport to be correlated with the change in bed elevation. Using this procedure, the effects of hydraulic and ice conditions on the erosion of the streambed can be documented.

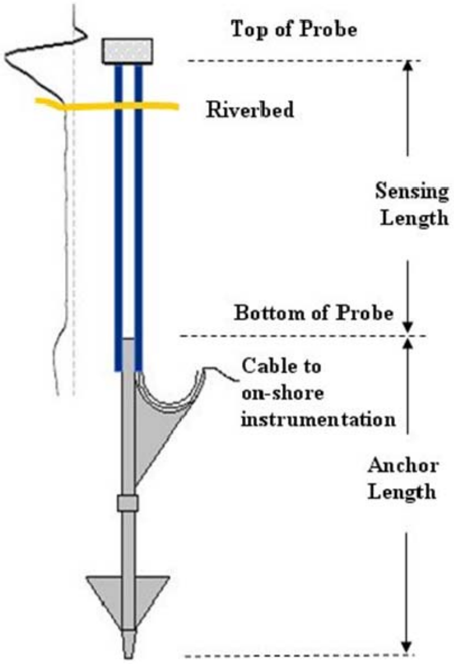

Figure C-9. Schematic of Time Domain Reflectometry Probe (USCOE CRREL).

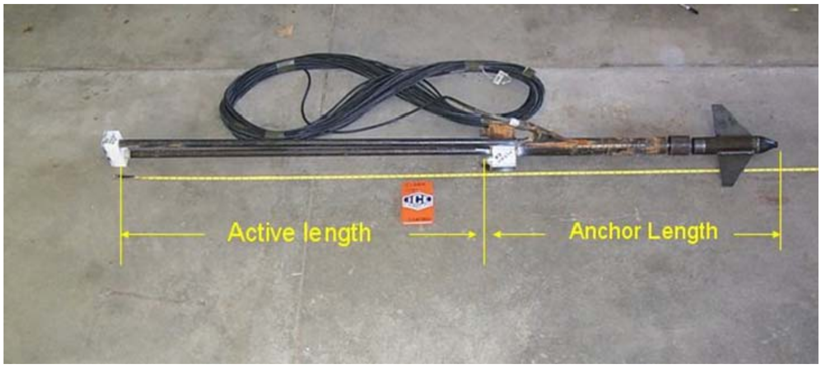

Figure C-10. Time Domain Reflectometry Probe (USCOE CRREL).

Tethered Buried Switches

This is a buried device that is tethered to the bridge piers or abutments and incorporates tilt switches (Figure C-11). When activated by scour, the tilt switches inside sense the change in physical orientation and alert the bridge data system. Being tethered permanently to the bridge structure, these devices continue to provide data to the system data logger. Life span is in excess of up 20 years for the tethered sensors.

These devices were first developed and installed during this TxDOT research project. Information from the case studies using these switches may be found in Chapter 3 of the project report.

Figure C-11. Tethered Buried Switch Prior to Installation.

Accelerometers

As the bridge pier moves in the *x*, *y*, and *z* planes, the accelerometers or accelerometers measure the frequency at which the structure moves and the magnitude of movement (tilt) in each of the three perpendicular planes (Figure C-12). These devices are mounted inside the bridge system's electronics enclosures. The electronics enclosures are installed directly onto the surface of the bridge pier. Accelerometer data downloaded from the system may be analyzed by Fast Fourier Transforms to provide the natural frequency of the bridge as it responds to normal environmental conditions. The same analysis is useful to detect changes as the bridge responds to scour disturbance to supporting soil around the piers. These devices were installed during this TxDOT research project. Information from the case studies using these sensors may be found in Chapter 3 of the project report.

(a) (b)

Figure C-12. Accelerometers: (a) Mounted in the Field and (b) Mounted in the Flume Lab Tests.

Additional Instrumentation

The stage sensor is an acoustic sounding device that measures the distance from its mounting on the bridge to the water surface (see Figure C-13). The elevation of the water surface is determined by subtracting the measured distance from the sensor transducer to the water from the known elevation of the transducer. Rising stage may indicate the need for closer analysis of the other system sensors that are measuring the scour or the movement of the bridge.

Velocity meters may be installed at bridge sites to measure velocities in the vicinity of the piers or abutments (see Figure C-14). The acoustic doppler velocimeter device measures instantaneous velocity components at a single point. It has three acoustic receivers to measure velocity in three directions. The largest challenge with velocity meters is selecting appropriate locations to mount the meters in order to obtain useful data. If they are too close to the piers or abutments, then the measured velocities are influenced by the obstruction of the substructure units. Finding a location to install the velocity meter that is not affected by the substructure units or other obstructions needs to be considered during the selection and design of the velocity meters. Due to the location restrictions, the velocity meters may be difficult to protect and subject to damage from impact from debris, ice, marine traffic, or any construction.

Figure C-13. Water Stage Sensor Mounted on Pier Cap (NYSDOT).

Figure C-14. Velocitymeter Mounted on Bridge Fender (MSHA).

DESIGN OF THE FIXED SCOUR MONITORING SYSTEM AND PROGRAM

The development of a scour monitoring program for bridges incorporates the guidance from the FHWA for scour at bridges, resulting in a solution to fulfill these requirements. An interdisciplinary team of geotechnical, hydraulic, structural, and electrical engineers design the scour monitoring system. There are several steps in the development of the scour monitoring system and program. There may be some variation in the order in which these steps are completed, depending on the work previously done, the available information, and if it is an emergency installation.

REVIEW OF AVAILABLE DATA

A review of all available data to assess the historic, current, and potential scour conditions should be undertaken. These data include aerial photographs; bridge plans; diving inspection reports; biennial and in-depth above-water inspection reports; fathometer surveys; topographic maps; FEMA Flood Insurance Studies; details on any scour countermeasure installations; soils data and boring reports; bridge scour evaluations; observations from those familiar with the site including bridge maintenance engineers, county and district officials, and local residents; and scour information on any nearby bridges.

HYDRAULIC, SCOUR, AND STABILITY ANALYSES OF THE BRIDGE

The hydraulic engineer would conduct a hydraulic analysis, compute the potential scour, and evaluate the observed scour conditions. If these results indicate that the bridge is scour critical, the stability of the bridge would need to be evaluated. A geotechnical engineer would conduct the pier and/or abutment stability analyses for the substructure units that are scour critical. This would provide information as to whether the foundation is stable under the observed or potential scour conditions. This analysis would be conducted to determine the critical depth for a bridge failure, as well as investigate potential failure mechanisms. It would also provide guidance to establish a second scour depth to be used as the trigger (alert) elevation. If this elevation is reached, certain prescribed actions would be taken in order to prevent further scour (i.e., the installation of hydraulic or structural countermeasures) or to protect the traveling public (i.e., closure of the bridge or increased visual monitoring and survey alert).

SELECTION OF SCOUR MONITORING INSTRUMENTATION

Selection Criteria

Scour monitoring is often the preferred alternative for a variety of reasons. For bridges that are scheduled to be replaced, scour monitors may be selected because they may be less expensive than traditional structural or hydraulic countermeasures. In addition, armoring of the channel bottom may interfere with the construction of the new bridge. The placement of armoring in a waterway may also result in environmental concerns and complicated permitting issues.

Fixed instrumentation is also being used on scour critical bridges where there are no bridge replacement plans. Scour monitors may be installed at these bridges as an interim countermeasure, prior to the installation of other hydraulic and/or structural countermeasures that may take longer to design and install. The fixed monitors may also be installed in conjunction with other types of hydraulic and/or structural countermeasures, to confirm that they are functioning to protect the bridge. For example, if riprap is installed for pier protection, the FHWA HEC-23 (Lagasse et al., 2009) guidance states that it should be monitored.

The scour monitoring system is custom-designed for each bridge site. The selection, location, and design are dependent on many factors. These include cost, environmental, construction, and maintenance considerations. The type of monitoring instrument employed depends on the geometry of the bridge substructure and on the channel characteristics. Guidance on the selection of a scour monitoring system is provided in FHWA HEC- 23. Factors such as the depth of the water, the size of the bridge, the geometry of the substructure unit, the frequency with which readings will be taken, and the extent of debris, ice, air entrainment and/or turbidity in the channel need to be considered in the selection of a scour monitoring system.

Some advantages of scour monitoring systems cited in the synthesis surveys (Hunt, 2009) include:

- Provides safety for the traveling public.
- Continuous monitoring of streambed elevations and scour conditions.
- May be quickly designed and installed.
- A cost-effective system relative to other hydraulic and structural scour countermeasures.
- Remote downloading of data reduces required visits to the bridge.

- Reduction in the number of diving inspections and/or fathometer surveys due to the information provided by the monitors.
- Capability of measuring both scour and the refill processes.
- Development of a prescribed Plan of Action to guide decision-making during a flood event.
- Appropriate for large bridges and deep water conditions.
- May be used to extend the life of a bridge.
- May be used in combination with other scour countermeasures.
- Provide data useful for replacement bridges.
- Provide data for scour research.

The various types of fixed instrument devices are summarized in Table C-1. The best type of applications as well as some of the advantages and disadvantages of each type of device are listed in Table C-1.

Selection Matrix

The fixed instrumentation selection matrix, Table C-2 was developed to complement the countermeasure selection matrix in FHWA HEC-23, Chapter 2. If fixed instrumentation is to be used to monitor a bridge, this table provides additional items to be considered in deciding between the various fixed instrument options. It was developed based on the results of the synthesis study state survey and literature search. Table C-2 includes the following categories for suitable river environment for the various fixed instruments:

- Type of waterway – riverine/tidal.
- Flow habit.
- Water depth.
- Bed material.
- Extreme condition.

The functional applications and bridge geometry include information on the characteristics of the bridges for the different types of instruments:

- Substructure monitored.
- Foundation type.

The table includes additional items regarding the monitoring system capabilities which may be mandatory or desirable criteria for a particular bridge site:

- Continuous monitoring.
- Remote technology.

The last two columns include the installation experience by state for each type of fixed monitor for those that responded to the synthesis survey and also from the literature search.

Table C-2. Fixed Instrumentation Selection Matrix

	FUNCTIONAL APPLICATIONS					SUITABLE RIVER ENVIRONMENT [2]													
	Local Scour		Contraction Scour	Stream Instability		Waterway Type		Flow Habit	Water Depth	Bed Material	Extreme Conditions	Foundation Type	Capabilities		Maintenance	Survey Respondents		Installation Experience	
Type of Fixed Instrumentation	Abutments [1]	Piers	Floodplain and Channel	Vertical	Lateral	Tidal	Riverine	E=Ephemeral I=Intermittant P=Perennial PF=Perennial/ Flashy	A = < 3 ft B = 10-30 ft C = 31-50 ft D = 51-75 ft E = 76-100 ft	F = Fine bed S = Sand bed C = Coarse bed R = Riprap	D=Debris T=Temperatures S=Sediment loads I=Ice flows V=High Velocity Flows	P=Piles SF=Spread Ftg DS=Drilled Shafts U=Unknown	Continuous Monitoring	Remote Technology	H = High M = Moderate L = Low	No. of Bridge Sites	No. of Instruments	Installation Experience by State from Surveys *(Note: States in **bold** have indicated they plan to use fixed instrumentation in the future)*	Additional Installation Experience by State Other Sources
Sonar	◗	●	●	●	◗	●	●	✓	✓	✓	T, I, V	✓	Yes	Yes	M - H	48	164	**AK**, AR, **CA**, **FL**, GA, **HI**, IN, KS, MD, NC, NJ, NV, **NY**, **TX**, **VA**, **WA**	CO, NM, OR, RI, WI
Magnetic Sliding Collar	●	●	●	●	◗	◗	●	✓	A, B	F, S, C	✓	✓	Yes	Yes	M	8	22	**CA**, **HI**, IN, **MN**, NJ, **NY**	CO, FL, ME, MI, NM, RI, TX, WI
Tilt Sensors	●	●	●	●	●	●	●	✓	✓	✓	✓	✓	Yes	Yes	L	4	35	**CA**, **WA**	
Float Out Device	●	●	●	●	●	○	●	E, I	A, B	F, S	✓	✓	No	Yes	L	3	35	AL, **CA**, NV	AZ
Sounding Rods [1]	◗	●	●	●	◗	◗	●	✓	A, B	C	T, S	SF	Yes	No	H	0	0		AR, IA, NY
Time Domain Reflectometers [1]	◗	●	●	●	●	○	●	P, PF	A, B	F, S, C	✓	✓	Yes	Yes	M	1	2	**VT**	

●	well suited/primary use
◗	possible application/secondary use
○	unsuitable/rarely used
N/A	not applicable
✓	suitable for the full range of the characteristics/conditions

[1] There were limited survey replies for monitoring of abutments, sounding rods and time domain reflectometers, therefore information from the literature was used for this table.

[2] The following items listed in the FHWA HEC-23 countermeasure matrix are applicable to the full range of the characteristics for fixed instrumentation and were not included in the survey:

River type: braided, meandering, straight
Stream size: wide, moderate, small
Bend radius: long, moderate, short
Bank condition: vertical, steep, flat
Floodplain: wide, moderate, narrow/none

Purchase, Installation, Maintenance, and Repair Costs

For the NCHRP synthesis study, the bridge owners provided information on the costs of the scour monitoring systems. A summary of estimated cost information based on the survey results may be found in Table C-3. This information was used to update the new edition of FHWA HEC-23 (Lagasse et al., 2009).

The costs of the scour monitoring installations varied widely due to different site conditions, the type of contract, and the method of installation. The survey question on installation costs asked the respondents to provide information on the cost of materials, the labor, cost per monitor location, and/or the total cost. Cost information was provided by 11 different states representing 41 bridge sites.

Table C-3. Estimated Cost Information

Typed of Fixed Instrumentation	Instrument Cost with Remote Technology ($)[1]	Instrument Cost for Each Additional Location ($)	Installation Cost	Maintenance/ Operation Costs
Sonar	12,000–18,000	10,000–15,500	Medium to high; 5 to 10-person days to install	Medium to High
Magnetic Sliding Collar	13,000–15,500	10,500–12,500	Medium, minimum 5-person days to install	Medium
Tiltmeters	10,000–11,000	8,000–9,000	Low	Low
Float-Out Device	10,100–10,600	1,100–1,600	Medium; varies with number installed	Low
Sounding Rods	7,500–10,000	7,500–10,000	Medium; minimum 5-person days to install	High
Time Domain Reflectometers	5,500–21,700	500	Low	Medium

(1)Cost per device will decrease when multiple devices share remote stations and/or the master station.

The cost information for materials was the data most often provided by the survey respondents. The installation, operation, maintenance, and repair costs are more difficult to ascertain.

Instrument costs generally include the basic scour monitoring instrument and mounting hardware, as well as power supply, data logger, and instrument shelter/enclosure, where applicable. This cost may not include miscellaneous items to install the equipment such as electrical conduit, brackets, and anchor bolts that may be included as part of the contractor installation cost. Some of the material costs included other devices such as water stage and one bridge included monitoring, maintenance, and repairs during a two-year period that the bridge is expected to be monitored.

The installation costs were often not available because the labor was provided by students or state maintenance groups, or the cost was included with other construction items. Scour monitors may be installed at certain sites by the state maintenance group with equipment they own. More complicated installations and sites may require specialized contractors and construction equipment to install the scour monitoring devices.

Maintenance and repair costs were only given by one respondent, Florida DOT, District 7. For their sonar scour monitoring system the operation and maintenance was estimated at $18,000, and inspection and repairs were about $9,000. They stated that these were necessary due to durability problems with the sensors and vandalism. The respondents provided numerous comments on maintenance and repairs. The general comments on the cost of maintenance ranged from modest to expensive. Repair costs were estimated to be expensive, particularly when underwater divers were required for the reinstallation underwater components. The installation of the monitors may be funded with bridge rehabilitation, research, or a routine or emergency project. When that project is over and the funding ends there may be no mechanism under which to fund long-term maintenance and repairs. Survey comments included the need for a commitment to maintain the equipment and also a maintenance contract with a firm familiar with the equipment that can make repairs in an expedient manner. Traffic conditions and lane closures were also cited as difficulties in maintaining the monitoring system. Contractor installation and repair costs also vary greatly in different regions of the United States.

The cost of the scour monitoring installations can vary dramatically due to different factors such as site conditions, the experience of the personnel installing the equipment, the type of contract, and the installation requirements. Larger bridges and deeper waterways are more expensive to instrument than smaller bridges in ephemeral or low water crossings. Scour monitors may be installed at certain sites by the state maintenance group, or other bridge owners with equipment they own or rent, or by university professors and students. More complicated installations and sites may require specialized contractors and construction equipment to install the scour monitoring devices.

Factors that contribute to increased scour monitoring installation, inspection, maintenance, and repair costs include: larger bridges; complex pier geometries; bridges with large deck heights off the water; deeper waterways; long distance electrical conduit runs; more durable materials required for underwater tidal installations; the type of data retrieval required (i.e., Internet, satellite); lane or bridge closures and maintenance-of-traffic; and installation and access equipment such as boats, barges, snooper trucks, drills and diving teams.

Most recent installations of fixed instrumentation have used remote technology to download data to avoid repeated visits to the bridge site. Although this increases the initial equipment cost, it can substantially reduce the long-term operational costs of data retrieval. Site data retrieval involves sending crews to the bridge and access may include security clearance, lane or bridge closures, and equipment such as snooper trucks or boats. Remote technology can also increase safety to the traveling public because it permits real-time monitoring during the storm events that may result in earlier detection of scour.

DESIGN OF THE SCOUR MONITORING PROGRAM

The scour monitoring program is custom designed for each bridge site. The data may be taken at programmed intervals and downloaded any time, and it can also be programmed to automatically alert the bridge owner of emergency situations. The type of monitoring instrument employed depends on the geometry of the bridge substructure and on the channel characteristics. The location of the monitors on the substructure units are selected in consideration of accessibility for servicing, protection against vandalism, and any potential debris, marine traffic or ice forces. The heightened security at the bridges in the past few years has made accessibility a major issue. Severe environmental conditions that can interfere with the functioning of the monitors, such as debris, extreme temperatures, tidal waters or ice, need to be considered when choosing the materials for the fixed instruments.

The system can provide round-the-clock monitoring, even during storms; scour data for bridge scour research, velocity, and water stage records; and the integration of the newest scour prediction techniques with physical data collection. The system helps to ensure the safety of the traveling public, and it is a cost-efficient solution to a potentially costly remediation utilizing conventional technology.

There are a variety of options to consider in the design of a fixed scour monitoring system for a particular bridge site. Careful evaluation of the bridge and site conditions can help ensure that the system will provide the necessary data and is robust enough to function for the intended duration of the scour monitoring.

The location of the monitors on the bridge is selected in consideration of accessibility, protection against vandalism, and any potential debris or ice debris forces. The heightened security at the bridges in the past few years has made accessibility a major issue. Traffic safety, lane closures, and traffic detours for servicing the monitors also need to be considered.

The location and number of the monitors will vary depending on the extent of the existing and potential scour problem, the amount of risk the owner is willing to take, and the funding available for the scour monitors. For the monitors that measure scour holes, the monitors are generally placed in the locations where maximum scour is expected to occur. This location should be studied carefully on a case-by-case basis while taking advantage of existing knowledge. In sands, it is likely that the location extends fairly broadly in front and to the side of the pier; in clays that is not necessarily the case. Laboratory experiments indicate that in clay the scour hole around a cylindrical pier can be non-existent in front of the pier, although it is significant on the side of the pier where the mean shear stress is maximum and behind the pier where the turbulence intensity is high (Briaud et al. 2003). Placing the scour monitor in front of the pier in this case would indicate no scour when the scour holes would be significant around the sides and in the back of the pier. The shape of the pier is also a factor. Long rectangular piers develop a scour hole in the front of the pier, but little scour behind the pier because the flow is streamlined by the time it gets to the back of the pier. A second problem associated with locating the scour monitor is that the scour hole around the bridge support cannot be the same depth all around the pier. Considering all factors, it appears that the best place for placing the monitor is to the side of the pier or abutment immediately behind the front edge. This can also help in reducing the impact of debris. Nonetheless, it is important to consider each case independently.

Accessibility is important to ensure access to the monitoring system when maintenance is required. It is necessary for servicing the system, inspection, and repairs. The daily data record produced by the system can also provide information on the health and operational status of the scour monitoring system. There are instances, however, where the data appear reasonable, yet one of the sensors is not functioning properly. Regularly scheduled routine maintenance and inspections help to ensure that the system is functioning properly and the streambed or movement readings are accurate.

The design of the monitoring instrument and the method with which it is attached to the bridge is site-specific. As-built plans and diving inspections may provide information on the geometry of the underwater and above-water portions of the pier or abutment. When there are uncertainties regarding underwater dimensions and clearances, adjustable arms may be designed for the sonar mounting bracket. During installation, the contractor can then adjust these brackets so that the sonar device projects out sufficiently to clear the footing and take streambed readings. Once the location of the device and the spot to be monitored are selected, the design engineer should work with the structural and electrical engineers to detail the mounting and the conduit for the monitoring system. Items such as types of materials, bolts, and their embedment depths, and conduit routing and attachments are best detailed by these specialists. Using robust, though often more expensive materials and methodologies, will most likely result in improved sensor integrity as well as significant savings in future repair costs, especially on bridges over deep waters. This is due to the high costs associated with underwater installations, inspections, maintenance, and repairs.

Severe environmental conditions that may interfere with the functioning of the monitors, such as debris, extreme temperatures, ice, and tidal waters, need to be considered when choosing the materials and type of mountings for the fixed instruments. The equipment needs to be adequate to operate and withstand the high temperatures that occur in Texas. Many fixed monitors will not operate under frozen water conditions. Due to the cold weather and tidal waterways in northeast installations, ASTM Grade 316 stainless steel has been used. A lower grade of stainless steel (ASTM Grade 304) was employed during an emergency installation in New York, and a few years later the mountings had extensive corrosion. On one Alaska bridge installation there were instances where floating debris ripped the sonar sensor from the substructure. In Alaska they have developed a “retractable arm,” which lowers the sonar into the water at designated times to take readings, and then retracts back to a designated location under the bridge.

The power source will vary depending on what is available and most reliable for a particular bridge site. The monitoring system may be solar powered or connected to electrical power at the bridge, if available. With the exception of accelerometer sensors, the monitoring systems require low power; therefore, solar power may be used if there is adequate regular sunlight. Initially in the early monitoring installations there was concern regarding the use of solar panels due to potential vandalism. Numerous panels have been installed and there have been few reports of vandalism. The monitoring systems that use solar panels have performed better than the locations using traditional electrical power. The locations powered by alternating current have required replacement float chargers, most likely due to power surges.

Remote monitoring has been installed using cellular telephone, telephone landline, or satellite technology. The telephone lines have proved to be the most reliable. They do not require power and are continuously available. Cellular telephones are also reliable, but they are not continuous, and need to be turned on and off at regular intervals using solar panels. Satellite service has been used when the other two options were not available. Satellite service, although less expensive than cellular systems, has a disadvantage—it can provide only one-way communication from the bridge. The system can send data from the bridge, however, incoming commands to examine, modify, or repair the system cannot be transmitted to the bridge, as is done with the other methods. More recent monitoring systems transmit data to a server and it is posted on the Internet so those with authorized passwords may access the data. This provides greater flexibility because the data can be retrieved and analyzed from any location with a computer and Internet access.

The funding mechanism for the design and installation of the scour monitoring instrumentation and the program may be accomplished under numerous types of contracts. The plans and specifications may be developed as part of a larger bridge rehabilitation program. In this case, careful attention is required for the timing of the installation of the scour monitors, as well as the protection of the monitors during the construction. Consideration should be given to retaining a portion of the installation cost to ensure that the contractor keeps the scour monitoring system operational through the duration of the construction. The scour monitors may be installed as a stand-alone contract, accomplished under emergency conditions or if funding is available for this type of scour countermeasure system. Numerous monitoring systems have been installed as part of research projects as was the case in the TxDOT project. These often include devices that measure scour and other hydraulic variables that can provide data useful for scour research. One problem with the research installations is that they are often limited by the duration of the project, which is often two to four years. Provisions for funding the continued operation of the scour monitoring system may be made so that the bridge owner is able to continue to retrieve the data and maintain the monitoring system upon the completion of the research.

The data from the monitors may be taken at programmed intervals and downloaded at any time. The data can be set up to automatically alert the owner or designated others of emergency situations. The systems can provide round-the-clock monitoring, even during storms.

INSTALLATION OF FIXED SCOUR MONITORING INSTRUMENTATION

Scour monitoring systems are a relatively new technology. Electrical and underwater contractors most often install the system. On larger bridges in deep waters, the contractor installation costs often equal or exceed the cost of the manufacture of the scour monitoring system. Most likely, the contractor has not performed this type of work, so the plans and specifications should be very detailed to ensure the successful installation of the system. The inclusion of good details can also aide in keeping the bid prices reasonable because the contractor will better understand the extent of the work. It is also advisable to have one of the designers of the monitoring system "on-site" or in close contact with the contractor throughout the installation. There are often many unknowns both in the underwater conditions and in the as-built geometry of the substructure unit. New site information on existing scour may result in changes to the location of the scour monitors. Having the system designer available during the installation ensures the proper changes are made in the field.

There may be numerous unknowns for underwater installations. If the underwater contractor is not receiving a lump sum payment, but the work is based on the time to install (time and materials), the designer should specify the means and method of installation. For example, installation equipment such as the type of drill the contractor uses to install the underwater components should be specified. A pneumatic drill has been used effectively to minimize the time it takes for the installation of anchor bolts into concrete substructure units. There could be extensive time delays when the contractor uses drills that are not appropriate for underwater construction.

Since the construction inspector cannot view the underwater components, it is advisable to have these components of the installation inspected by an independent contractor prior to completion of the contract. This will ensure that all bolts and attachments are in place and that the mounting is properly secured to the substructure unit. Underwater installation photographs should be required of the contractors in order to ensure the proper installation and also to provide as-built information for future inspections, maintenance, and repairs.

In smaller waterways and in areas of installation that are less complicated, there have been cases where the DOT maintenance group or others have installed the scour monitoring system. Here also, it is recommended that a member of the monitoring design team work with these groups. As with all bridge reconstruction projects, it is good practice to develop a set of as-built plans following the installation of the system. This is particularly true for the underwater components of the system. This will aid in future maintenance, inspections, and repairs to the system.

IMPLEMENTATION OF THE SCOUR MONITORING PROGRAM

The implementation of the scour monitoring program is a critical aspect of the program. Due to the interdisciplinary nature of scour monitoring, and perhaps due in part to the newness of the FHWA bridge scour program and of these devices, it is not always obvious which division of the bridge management will be responsible for the scour monitoring program. It is important during the design process for the owner to identify the group(s) that will be responsible for the scour monitoring program. This could be the bridge owner or it may be outsourced. The process includes the design of the system protocol; routine and emergency monitoring; analysis of the data and determination of the safety of the bridge; the chain of command to make decisions during an emergency situation; maintenance, inspection, and repairs to the system; and the funding for the continued operation of the scour monitoring system. This information should be documented in the scour monitoring protocol manual and Plan of Action for the bridge. The manual needs to be updated on a regular basis to reflect any changes in the program. The responsibility for the monitoring system has been the most difficult aspect in the implementation of the scour monitoring programs reported in the synthesis report. A thorough and systematic plan developed prior to the installation of the scour monitoring system will result in a program that is successful to ensure the safety of the bridge and of the traveling public.

SCOUR MONITORING PROTOCOL AND PLAN OF ACTION

The recently published FHWA guidance on the Plan of Action should be useful in the development of a detailed, hands-on protocol for emergency actions for scour monitoring programs for scour critical or unknown foundation bridges.

FHWA HEC-23 contains guidance on the development of a Plan of Action. The two primary components of the Plan of Action are instructions regarding the type and frequency of inspections to be made at the bridge, and a schedule for the timely design and construction of scour countermeasures. A Plan of Action includes the following: (1) management strategies, (2) inspection strategies, (3) bridge closure instructions, (4) countermeasure alternatives and schedule, and (5) miscellaneous information. Scour monitoring programs with flood, portable and/or fixed monitoring are important components of a Plan of Action. In 2006, the FHWA posted a revised Plan of Action standard template on their website. The section on Monitoring Programs includes items for detailed documentation of regular/increased inspections, fixed scour devices and flood monitoring. In 2007, a new NHI course (FHWA-NHI-135085) entitled “Plan of Action (POA) for Scour Critical Bridges” was developed. The course provides guidance on developing a POA and case studies for the development of a POA. One case study uses fixed instrumentation for monitoring. The course and Standard Template may be downloaded from the FHWA and NHI websites.

ROUTINE AND EMERGENCY MONITORING AND DATA COLLECTION AND ANALYSIS

The development of a clear set of detailed instructions for those responsible for the routine and emergency monitoring of the bridge is essential. A chain of command of those responsible for emergency situations needs to be in place. Those responsible for analyzing the data should have instructions as to who they should contact “round-the-clock” should the scour readings indicate a problem. The Plan of Action would indicate possible procedures to follow, which may include closure of the bridge, land monitoring, underwater inspections, the emergency installation of contingency countermeasures such as riprap, etc.

The chain of command needs to include information so that responsibility is transferred when those who are responsible are on vacation, sick, unable to monitor, or are no longer in their particular position. The routine and emergency procedures are very site-specific. Often an owner will start with a conservative program with high frequencies for routine and emergency monitoring. After a period, the records will be reviewed and the frequency of monitoring may be adjusted.

The scour monitoring systems that are continuous are capable of producing a large amount of data. Consideration needs to be given to the intervals at which the data should be recorded and collected. Data reduction methods using computer spreadsheet programs provide valuable assistance for analyzing and storing the data. They help identify trends and may be useful when comparing data with other bridge sites.

Changes in the watershed may also affect the data. Those responsible for analyzing and interpreting the data should keep informed as to new developments, construction, dredging, mining, or other situations that might cause scour or siltation at the bridge.

If a clear protocol detailing responsibilities is in place, this can help to provide proper maintenance to prevent a sensor or system failure. If the person(s) responsible for monitoring are transferred to other positions, or if they retire, new person(s) need to be given the responsibility and training for the system. There have been instances where the telephone service has been interrupted due to non-payment of the telephone bill. This was due to job transfers, and in one case, the invoice was being sent to someone not involved in the scour program. In one situation, the area code in a city changed and the data could not be accessed because the new area code needed to be programmed into the new monitoring system.

MAINTENANCE, INSPECTIONS, AND REPAIRS

It is important to develop a regular maintenance and inspection program. The maintenance crews for the bridge owner may be responsible for routine, above-water maintenance. The frequency of underwater and structural inspections and fathometer surveys at each bridge will vary. The owner may add inspection and maintenance requirements for the scour monitoring system to the underwater and structural inspection contracts. If the bridge is a movable bridge and there are also electrical inspectors, these can aide in the above-water inspection of the electrical components of the system. The inspection guidelines and requirements should include detailed checklists and sketches to guide the inspectors, and to ensure that the scour monitoring system is examined periodically. Maintenance and inspection forms for the two TxDOT bridges in this research project may be found in Appendices D and E. Provisions may be made in the inspection contracts for minor cleaning and repairs as well. During the inspections, it is advisable that a member of the scour monitoring team coordinate with the inspection crew to ensure that all important components are inspected, and to help interpret their findings. If possible, this person would be on-site during the inspection. The streambed elevations recorded during diving inspections and fathometer surveys may also be used as ground truth measurements to check the accuracy of the scour monitoring devices for the instruments that measure streambed elevations and to confirm the measurements of the instruments that measure bridge movement.

CONCLUSIONS AND RECOMMENDATIONS

Scour monitoring used fixed instrumentation has been used in 32 states and the District of Columbia. A scour monitoring program can be an efficient, cost-effective alternative, or complement to traditional scour countermeasures. The system and program are custom-designed for each bridge and site. There have been many innovations in scour monitoring technology and this report outlines some of the lessons learned in installations in a wide variety of locations.

The systems can provide round-the-clock monitoring, even during storms, scour data for bridge scour research, velocity, and water stage records, and the integration of the newest scour prediction techniques with physical data collection. The data traditionally collected by the majority of scour monitoring systems are in the form of streambed elevations. More recent installations include tilt meters that measure movement of the bridge due to scour or other causes.

The main problems reported by the states in the use of fixed scour instrumentation include the maintenance and repairs to the systems and the funding to continue the operation and scour monitoring program. A thorough and systematic plan developed prior to the installation of the scour monitoring system will result in a program that is successful to ensure the safety of the bridge and of the traveling public.

The advancements that bridge owners would like to see for future fixed scour monitoring technology include the development of durable instrumentation, with increased reliability and longevity, decreased costs, and minimum or no maintenance. This equipment would include instrumentation that measures scour, and also water elevations and velocities.

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APPENDIX D:
SCOUR MONITORING PROTOCOL FOR US59 OVER GUADALUPE RIVER BRIDGE

TABLE OF CONTENTS

INTRODUCTION

The US59 Bridge crosses the Guadalupe River southwest of Victoria, Texas. It consists of two twin bridges that carry traffic in the southbound and northbound directions. A scour monitoring system was installed in 2009 on the southbound of US59 Bridge as part of a TxDOT project on scour monitoring using fixed instrumentation. Fixed scour monitors may be placed on a bridge structure or in the streambed or on the banks near a bridge. They can measure bridge movements or changes in streambed elevations due to scour.

The US59 Bridge installation includes two types of fixed scour monitoring instruments and a water stage. These consist of four tiltmeters, two float-out devices, and one water stage. The tiltmeters measure the movement of the bridge in two directions. The float-out devices are buried in the streambed, and should they be exposed due to scour, they will be released in the water, float to the top, and transmit a signal. The water stage measures the elevation of the water surface at the bridge.

The monitoring system was first installed at the southbound of US59 over Guadalupe River Bridge on May 2009. The sensors transmit data to a master station that transmits data to a server. The data are posted on website and may be retrieved directly from the server.

DESCRIPTION OF THE BRIDGE AND SCOUR MONITORING SYSTEM

Figures D-1 and D-2 show the location of the US59 Bridge (Google Earth). In Figure D-1, SB0 represents the North Abutment, SB1 and SB2 represent the bents/piers that are in the Guadalupe River, and SB3 represents the South Abutment of the southbound bridge.

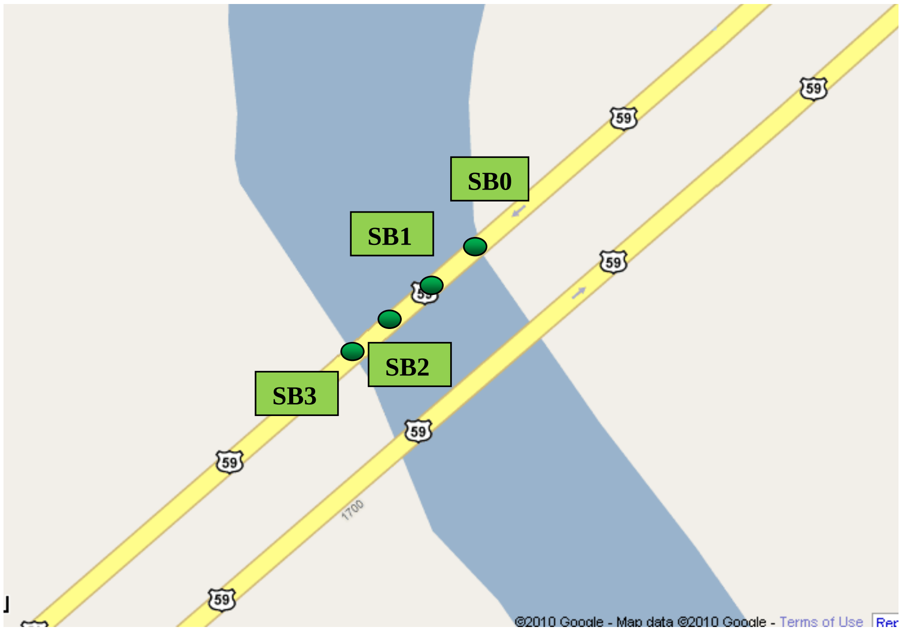


Figure D-1. Layout of US59 Showing Substructure Convention for the Southbound Bridge (Source: Google Earth).

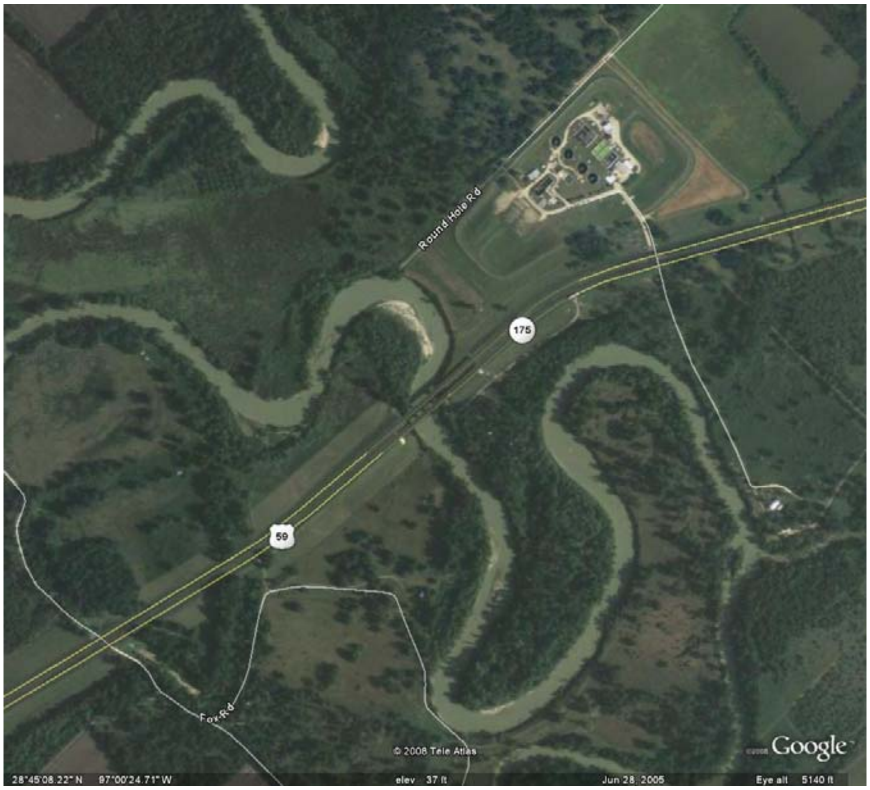


Figure D-2. Meandering Guadalupe River in the Vicinity of the US59 (Source: Google Earth).

GUADALUPE RIVER

The Guadalupe River flows from Kerr County, Texas, to San Antonio Bay in the Gulf of Mexico. The Guadalupe River has several dams along its length, the most notable of which forms Canyon Lake located northwest of New Braunfels.

The US59 over Guadalupe River Bridge is experiencing erosion problems in the form of stream migration and bridge scour. This has resulted in a threat to the integrity of the bridge structure. During the period between 1987 and 2002, the river bend upstream of the bridge on US59 migrated approximately 81 m (270 ft) toward the North Abutment. The river continues to migrate in that direction and has become a threat to the bridge and adjoining highway.

THE BRIDGE STRUCTURE

The existing US59 over Guadalupe River Bridge was originally two twin structures, each three spans with pre-cast multiple beams built in 1967. Each bridge was 111 m (333 ft) long and included two web-wall river bents/piers. The river pier foundations are H-piles extending to a depth of approximately 9 m (27 ft) below the pile caps. The pile caps are about 1 m (3 ft) below the riverbed. An elevation and plans of the bridge may be found in Attachment A.

In October 1998, the northbound bridge was lengthened by one span to the southwest as a protective measure after the record flood that year. In 2001, both northbound and southbound bridges were lengthened to the northeast by two spans as the river channel continued eroding in that direction. TxDOT was constructing the extension for both eastern and western sides on the southbound bridge at the time that the scour monitoring system was installed. The datum used for the bridge and the scour monitoring system is the National Geodetic Vertical Datum (N.G.V.D.) 1929, elevation 0.0 ft, which is also Mean Sea Level.

THE SCOUR MONITORING SYSTEM

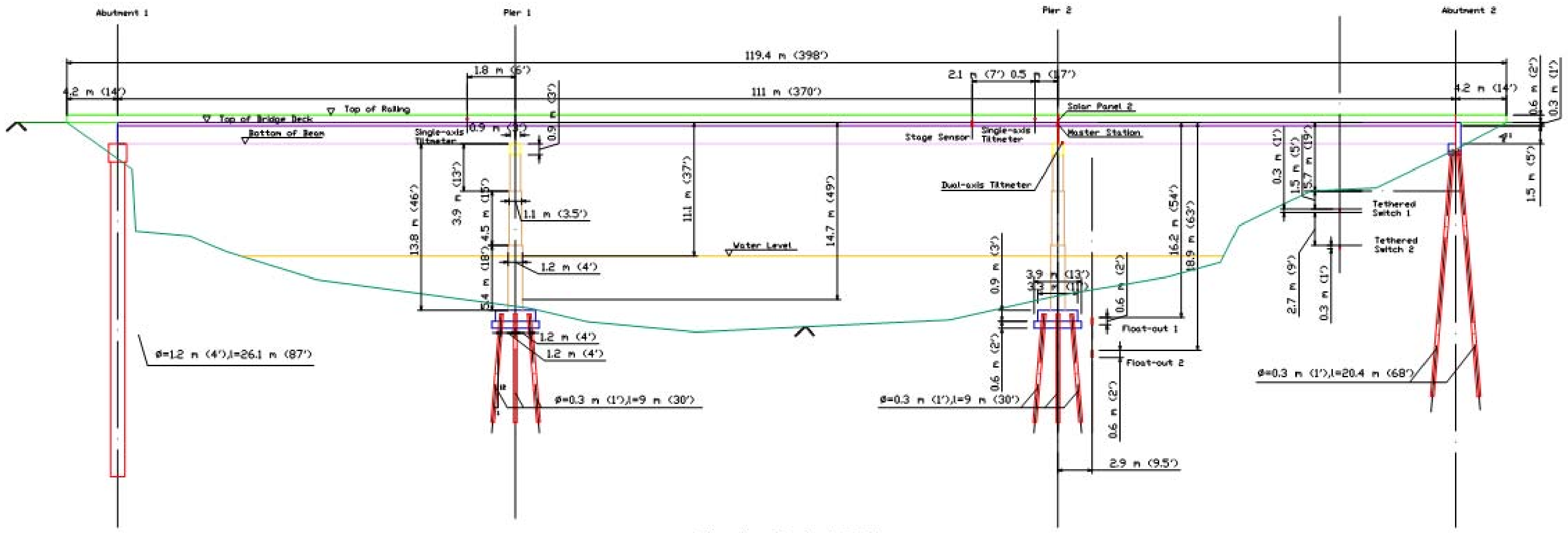
The fixed scour monitoring system employs tiltmeters and float-out devices to detect scour at the piers. The system at the bridge consists of one master control station, four tiltmeters in three enclosures, two buried float-out devices, a water stage sensor, and a temperature sensor (see Figure D-3). A remote server may be set-up at the TxDOT designated office to retrieve and store the data, and to transmit it to Internet website for the project. The tiltmeters measure the movement of the bridge and are programmed to take measurements at specified intervals.

The master control station contains the data acquisition module that collects and stores the data in the programmed format. The data are transmitted via modem from the master control station to the server/computer at the designated TxDOT district office. Solar panels that maintain battery power were installed to power the scour monitors. The number and locations of the current scour monitoring sensors at the US59 Bridge may be found in Figure D-15 and Figure D-16.

The tiltmeters provide information about the tilt angle of the bridge. The tilt of the bridge may be correlated to the temperature. Two float-out sensors are buried in the soil near Pier SB2.

The Float-out1 is buried 16.2 m (54 ft) beneath from the top of the deck, and the Float-out 2 is buried 18.9 m (63 ft) beneath the top of the deck. The water stage sensor is fixed to the bridge parapet at the height of deck bottom and is measuring the water surface elevation of the US59 over Guadalupe River Bridge. The water stage sensor readings are compatible with USGS database. Two TBS equipments are buried in the soil near the Pier SB3. The TBS1 is buried 7.2 m (24 ft) away from the top of the deck. The TBS2 is buried 10 m (34 ft) away from the top of the deck. The two TBS equipments have lost connection due to the reconstruction of the bridge. The temperature of the system matches with the weather history in Victoria. The master station provides the data for the monitoring system for US59 over Guadalupe River Bridge.

This scour monitoring program is state-of-the-art, using equipment and concepts recommended by the Federal Highway Administration and the Transportation Research Board. TTI makes no guarantee that the program will provide complete notification of a scour failure. However, it does exceed all current inspection and monitoring programs currently established for scour. The program that follows is a guideline to establish a baseline for analyzing and reacting to various scour levels.



Elevation (Scale: 1:500)

Figure D-3. Layout of the Scour Monitoring System at US59 over Guadalupe River Bridge.

INSTALLATION OF THE SYSTEM

The bridge scour monitoring system was installed on US59 over Guadalupe River Bridge in May 2009 and modified in June 2010. Several parties participated in the installation. TxDOT was responsible for the traffic control. The TxDOT traffic inspection team provided deck coring and the snooper truck for below-deck access. The drilling contractor installed the two float-out devices and tethered buried switches in the soil with the aid of researchers from Texas A&M University. Texas A&M University researchers and consultants from ETI and STV were responsible for the drilling, screwing, gluing, and the wiring of the instruments to the bridge.

INSTALLATION OF THE MASTER STATION

The master station was mounted on the bridge fascia on the outside of the concrete parapet. It is on the same fixture as the solar panels. Two solar panels were installed near the master station to provide the power. One more solar panel was installed near the wireless accelerometer to provide power for the wireless accelerometer, which is on the cap beam of the pier with debris (SB1). Figures D-4 to D-5 show the installation of the master station and solar panels.

Figure D-4. Mounting the Master Station.

Figure D-5. Solar Panel on the Pier SB1 (with Debris).

INSTALLATION OF THE TILTMETERS

Four tiltmeters were installed on the US59 Bridge as shown in Figure D-6. They are housed in three enclosures that are bolted and glued to the concrete bridge at three locations. All the tiltmeters are wired to the data logger CR1000 located in the master station. A snooper truck was used for the installation. Figures D-7 to D-10 show the installation process of the tiltmeters on the bridge.

One dual-axis tiltmeter was installed on the pier cap of Pier SB2 to measure simultaneously the tilt angle of the bridge pier around two axes. It measures the tilt angle of the pier in the flow direction axis and the tilt angle of the pier in the traffic direction axis (perpendicular to the flow direction). One single-axis tiltmeter was located at the back of the enclosure on the deck, measuring the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction). It is located at a distance of 0.5 m (1.7 ft) horizontally east of the master station. A second single-axis tiltmeter was installed at the back of an enclosure approximately 47 m (154.3 ft) from the first single-axis tiltmeter location. It is measures the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction). Figures D-11 to D-16 show the tiltmeters installed on the bridge.

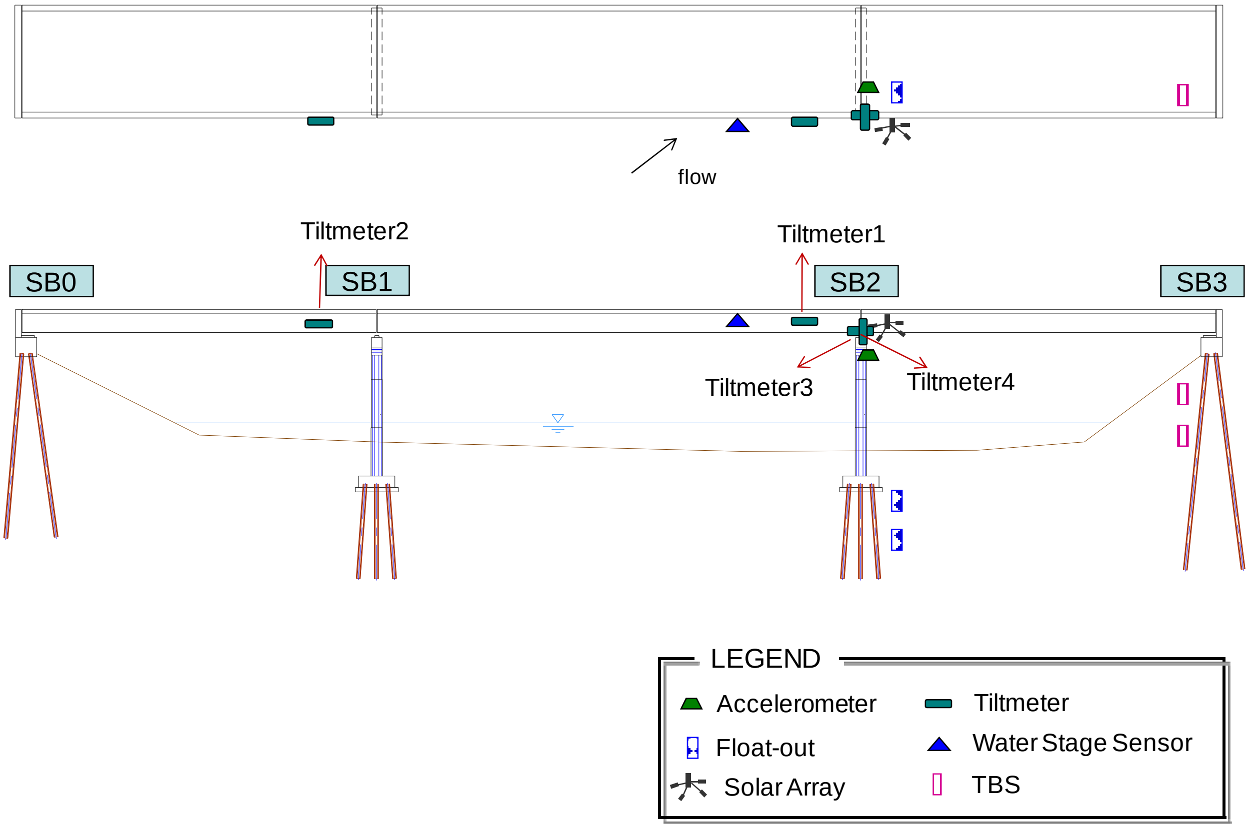


Figure D-6. Schematic of the Scour Monitoring System on US59 over Guadalupe River.

Figure D-7. Working on a Snooper Truck (SB1 is front pier with debris).

Figure D-8. Drilling a Hole in the Tiltmeter Enclosure to Install the Bolt.

Figure D-9. Positioning the Tiltmeter.

Figure D-10. Applying Glue to the Tiltmeter Enclosure.

Figure D-11. The Installed Tiltmeter, Master Station, and Solar Panels.

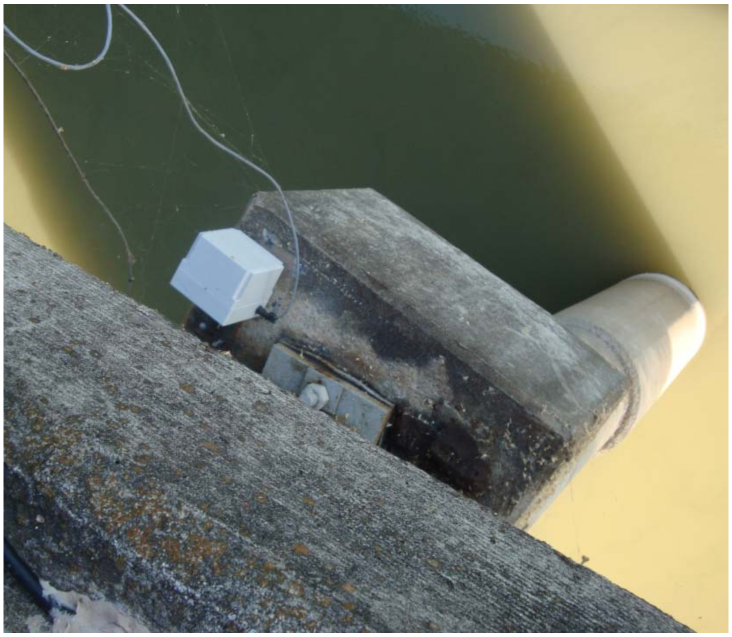


Figure D-12. Dual-Axis Tiltmeter on the Pier SB2.

Figure D-13. Single-Axis Tiltmeter 1 on the Deck Adjacent to Master Station at Pier SB2.

Figure D-14. Single-Axis Tiltmeter 2 on the Deck at Pier SB1.

Figure D-15. Bridge Scour Monitoring System (View from South Side of the Bridge).

Figure D-16. Bridge Scour Monitoring System (View from North Side of the Bridge).

INSTALLATION OF THE WATER STAGE SENSOR

The water stage sensor was mounted in a bracket to the parapet of the bridge at the height of bottom of the deck. It measures the water surface elevation at the US59 over Guadalupe River Bridge. It is about 2.1 m (7 ft) horizontally away from the single-axis tiltmeter at Pier SB2. The bracket was fixed on the bridge deck by three screws. The water stage sensor was installed vertically to give correct readings. The wire of the stage sensor was connected into the master station after installation. Figures D-17 to D-18 show the installation of the water stage sensor.

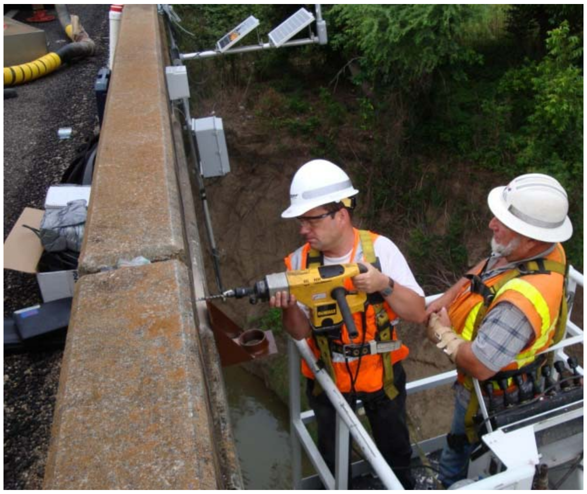


Figure D-17. Bracket for Water Stage Sensor.

Figure D-18. Installed Water Stage Sensor.

INSTALLATION OF FLOAT-OUT DEVICES

The float-out devices installed at the bridge are 0.6 m (2 ft) in length and 89 mm (3.5 inches) in diameter (see Figure D-21). To install the two float-out devices, one hole was drilled through the bridge deck. The hole was about at a distance of 2.4 m (8 ft) away from the edge of the deck parapet and 2.85 m (9.5 ft) away from the center of the Pier SB2. The TxDOT inspection team drilled the hole through the deck. The contractor Alpha Testing was responsible for the installation of float-out devices. Figures D-19 to D-22 depict the installation process of the float-out devices.

Figure D-19. Drilling the Hole through the Bridge Deck.

Figure D-20. Close-Up of the Drilled Hole in the Deck.

Figure D-21. Float-Out Devices prior to Second and Final Installation.

The first attempt at installation of the float-out devices was not successful. In order to ensure that the float-out devices are installed at the right position, a rebuilt PVC pipe was used as an extension of the device (Figures D-22 to D-26).

Figure D-22. PVC Pipe as an Extension of the Float-Out Device.

Figure D-23. View Looking inside the PVC Pipe.

05/28/2009 13:06

Figure D-24. Float-Out Device Mounted in the PVC Pipe.

05/28/2009 13

Figure D-25. Ready to Go.

Figure D-26. Refilling the Drilled Hole after the Installation of the Float-Out Devices.

The final as-built elevations for the float-out devices were measured relative to the top of the bridge deck and the existing streambed. The Float-out1 was buried 1.5 m (5 ft) below the streambed at a distance of 16.2 m (54 ft) from the top of the bridge deck. The Float-out2 was buried at a distance of 2.7 m (9 ft) below the Float-out1 and at a distance of 18.9 m (63 ft) from the top of the deck.

PROGRAMMING OF THE SYSTEM

The data collection system is programmed to take measurements at specified intervals. The settings at the time of the completion of the TxDOT project in August 2010 are for the master station to collect data every 20 minutes and to transmit the data to the server every hour.

DATA ACQUISITION

COMPUTER SET-UP

1. To collect the data, the Campbell Scientific LoggerNet software shall be installed and properly set-up on the TxDOT server designated for the scour monitoring system.
2. The designated computer shall be connected to a telephone line, capable of receiving incoming telephone calls.
3. The computer may be left on at all times to ensure immediate retrieval of data should a scour event occur.
4. The computer shall be properly secured against theft or damage.

NORMAL CIRCUMSTANCES: DOWNLOADING OF DATA

The system is programmed such that the data are automatically downloaded to the designated computer once every hour. If there is a concern and data are needed immediately or more frequently, the data may also be retrieved at any time by calling the data collection system using a computer that contains the Campbell Scientific LoggerNet software. Sample data can be reviewed in the following Attachment B.

SPECIAL FLOOD EVENTS

The TxDOT district engineer responsible for the scour monitoring program shall integrate the scour monitoring system into the flood, storm, and hurricane watch programs and emergency protocols currently in place in the district. This program would include information on what triggers an emergency in the district, what emergency actions are taken, and what increased scour monitoring should be employed at the US59 Bridge. This would include the frequency with which data will be taken and the identification of those responsible for retrieving and analyzing the data for the duration of the event, and for a designated time after the event.

HOW TO CONNECT AND DOWNLOAD THE DATA

The website link to download the raw data collected from sensors on US59 over Guadalupe River Bridge is: http://scour.civil.tamu.edu/us59_sensors.dat.

Below is a sample of the data collected from the website:

```
"TOA5","US59","CR1000","22594","CR1000.Std.16","CPU:US59GuadalupeRiverJun10.CR1","43046","Sensors"
"TIMESTAMP","RECORD","Alarm","Stage","X1Tilt","Y1Tilt","X2Tilt","Y2Tilt","MasTemp","TBS1Stat","TBS2Stat","FO1Stat","FO2Stat","MasBatt"
"TS","RN","","","","","","","","","","","",""
"","","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp"
"2010-10-06 08:20:00",1003,9,61,-1.35,-4.47,0.3,-0.4,14.54,3,3,0,0,13.51
"2010-10-06 08:40:00",1004,9,61,-1.28,-4.03,0.31,-0.41,15.63,3,3,0,0,13.85
"2010-10-06 09:00:00",1005,9,61,-1.28,-4.01,0.3,-0.39,16.74,3,3,0,0,13.88
"2010-10-06 09:20:00",1006,9,61,-1.28,-4.04,0.29,-0.37,17.87,3,3,0,0,13.87
"2010-10-06 09:40:00",1007,9,61,-1.28,-3.93,0.29,-0.37,19,3,3,0,0,13.89
"2010-10-06 10:00:00",1008,9,61,-1.25,-3.81,0.28,-0.34,20.05,3,3,0,0,14.24
"2010-10-06 10:20:00",1009,9,61,-1.24,-3.73,0.27,-0.31,20.91,3,3,0,0,14.12
"2010-10-06 10:40:00",1010,9,61,-1.24,-3.68,0.27,-0.29,21.67,3,3,0,0,13.52
```

THE WEBSITE

The Scour Monitoring Center website address is currently on the TTI server at: http://scour.civil.tamu.edu. Those who have not used the TTI website for scour monitoring will need to obtain a login name and password in order to access the website.

The website contains three projects on the project list: Laboratory Experiments, US59 over Guadalupe River, and SH80 at San Antonio River. Also shown are one photo and one schematic of the instrumentation for each project. Clicking on the name or the photo of the US59 Bridge will lead to the webpage containing the plots of data collected from the bridge sensors. The data logger on the bridge transmits data every 20 minutes. Hence the monitoring website shows the real-time plots every 20 minutes. The webpage should be refreshed every 20 minutes. The webpage shows the data for a period of 20 hours for the bridge.

INTERPRETATION OF US59 OVER GUADALUPE RIVER BRIDGE WEBSITE PLOTS

The instrumentation includes one dual-axis tiltmeter (two plots showing the tilt angle of the pier in both the flow and traffic directions) on the bridge pier, two single-axis tiltmeters on the deck (two plots showing the tilt angle of the deck in the flow direction axis), one water stage (water level), two float-out devices (scour level reached) and two TBS (scour level reached). Note that the TBS units were disconnected due to the construction of the extension of the bridge. In addition to the above data, the master station records the temperature and the battery condition for the monitoring system. A total of 11 figures are shown on the webpage.

1. "Tiltmeter3 on the pier – around the flow direction axis," "Tiltmeter4 on the pier – around the traffic direction axis" plots show the tilt angle of the pier around the flow direction axis and around the traffic direction (perpendicular to the flow direction) respectively. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is degrees.
2. "Tiltmeter1 on the deck – around the flow direction axis," "Tiltmeter2 on the deck – around the flow direction axis" plots show the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction) for two single-axis tiltmeters. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is degrees.
3. "Water Stage" plot shows the water stage sensor reading at the bridge. It gives the water elevation above the mean sea level. The unit is ft.
4. "Float-out1" plot shows the status of Float-out1 located at the bridge. The Float-out1 was buried 1.5 m (5 ft) below the soil surface at a distance of 16 m (54 ft) below the top of the deck. "Float-out2" plot shows the status of Float-out2 located at the bridge. The Float-out2 was buried 2.7 m (9 ft) below Float-out1 at a distance of 19 m (63 ft) below the top of the deck.
    - If the float-out device is in the vertical position, and has not floated out, the plot will show a smiling face (Figure D-27a).
    - If the float-out device has floated out, the plot will show a danger sign (Figure D-27b).

5. "Tethered Buried Switch 1" plot shows the status of TBS1 located at the bridge. The TBS1 was buried 1.5 m (5 ft) below the ground surface near the southwest abutment at a distance of 7.2 m (24 ft) below the top of the deck. "Tethered Buried Switch 2" plot shows the status of TBS2 located at the bridge. The TBS2 was buried 3 m (10 ft) below TBS1 at a distance of 10 m (34 ft) below the top of the deck.
   - If the TBS is in the vertical position, and has not floated out, the plot will show a smiling face (Figure D-27a).
   - If the TBS has floated out, the plot will show a danger sign (Figure D-27b).
   - If the wire of the switch is broken, the plot will show a disconnection logo (Figure D-27c).
6. "Temperature" plot shows the temperature in the master station. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is °C.
7. "Battery" plot shows the battery condition in the master station. The readings are taken every 20 minutes and are presented over a 20-hour period. The unit is volts.

(a) (b) (c)

Figure D-27. Logos for Website: (a) Smiling Face, (b) Danger Sign, and (c) Disconnection.

RECOMMENDATIONS FOR COMMUNICATION WITH THE SYSTEM

The website shows the real-time plot of all the sensor readings for a 20-hour window. Routine data monitoring consists of daily checking of the website and weekly analysis of the data collected by the monitoring system, which is currently stored on the server located at Texas A&M University, College Station, Texas. Also an on-site bridge inspection every year is recommended. On-site bridge inspection includes visual inspection of the bridge and the installed instruments.

Another option for data monitoring is using the “emailsend” program in LoggerNet, which can help to monitor the installed system easily. When the reading exceeds the set threshold or reading changes value for the float-out devices, the software will send an email to the person in charge of the monitoring system. The frequency of the email may be increased in a storm season to actively monitor the system.

DATA ANALYSIS

The monitoring system is set so that the data are collected by the data logger every 20 minutes and transmitted to the server every hour.

The data format for the scour monitoring system for the bridge scour is shown below:

"2010-06-16 02:40:00",747,0,11.2,2.84,2.42,-2.27,-2.39,27.47,3,3,0,0,12.9

"2010-06-16 03:00:00",748,0,11.2,2.84,2.42,-2.27,-2.39,27.37,3,3,0,0,12.89

"2010-06-16 03:20:00",749,0,11.2,2.84,2.41,-2.27,-2.39,27.31,3,3,0,0,12.88

"2010-06-16 03:40:00",750,0,11.21,2.84,2.41,-2.27,-2.39,27.18,3,3,0,0,12.88

The first column is the timestamp, including the date and time of the corresponding data collected; the second column is the counter; the third column is the alarm; the fourth column is the reading from the stage sensor (in units of feet); the fifth column is the reading from Tiltmeter1 on the deck (degrees); the sixth column is the reading from Tiltmeter2 on the deck (degrees); the seventh column is the reading from Tiltmeter3 on the top of pier (degrees); the eighth column is the reading from Tiltmeter4 on the top of pier (degrees); the ninth column shows the temperature of master station (°C); the tenth column is the reading from the first TBS located at 7.2 m (24 ft) from the bridge deck; the eleventh column is the reading from the second TBS located at 10.2 m (34 ft) from the bridge deck; the twelfth column is the reading from the first float-out sensor located at 16.2 m (54 ft) from the bridge deck; the thirteenth column is the reading from the second float-out sensor located at 18.9 m (63 ft) from the bridge deck; and the last column is the master station battery reading (volts).

Recommendations and comments on the nature of data observed are as follows:

1. If the tilt angle goes beyond the threshold, and immediately drops back, the data should be closely monitored. It does not necessarily require any action. If the tilt angle goes beyond the threshold, and lasts for 40 minutes (2 data points), an on-site inspection of the bridge is recommended and may also lead to the decision about the closure of the bridge.
2. If the Float-out1 reading is showing 1, it means that the scour depth under Pier SB2 is at least 2.1 m (7 ft). If the Float-out2 reading is showing 1, it means that the scour depth under Pier SB2 is at least 4.8 m (16 ft). When the float-out device floats out, maintenance of the bridge to mitigate scour is recommended.

3. The water stage sensor shows the water elevation of the river at the location of the water stage sensor on the US59 over Guadalupe River Bridge. During the flood season, the water level will be very high. Checking the data every hour is recommended during emergency events. If the water level reaches up to the level of the bridge deck, i.e., 18 m (60 ft), the closure of the bridge is recommended.

TILTMETERS

During the course of the research project, the data from the tiltmeters was collected from 9:50 a.m. May 28, 2009, to 7:00 a.m. August 9, 2010. The four tiltmeters each provide one reading every 20 minutes. The data collected are labeled as follows: X1Tilt, Y1Tilt, X2Tilt and Y2Tilt. The unit of the collected data is in degrees. X1Tilt records the data obtained from Tiltmeter1, measuring the tilt angle of the deck in the flow direction axis (perpendicular to the traffic direction). Y1Tilt records the data obtained from Tiltmeter2, measuring the tilt angle of the deck in the flow direction axis (perpendicular to the traffic direction) at the other location. X2Tilt records the data obtained from Tiltmeter3, measuring the tilt angle of the pier in the flow direction axis. Y2Tilt records the data obtained from Tiltmeter4, measuring the tilt angle of the pier in the traffic direction axis (perpendicular to the flow direction). Figure D-28 shows the location of the tiltmeters on US59 over Guadalupe River Bridge. Here, Tiltmeter2a represents the sensor that measures the tilt angle of the deck around the traffic direction axis and was relocated on June 5, 2010. Tiltmeter2b represents the reinstalled tiltmeter that measures the tilt angle of the deck in the flow direction axis (perpendicular to the traffic direction) after June 5, 2010.

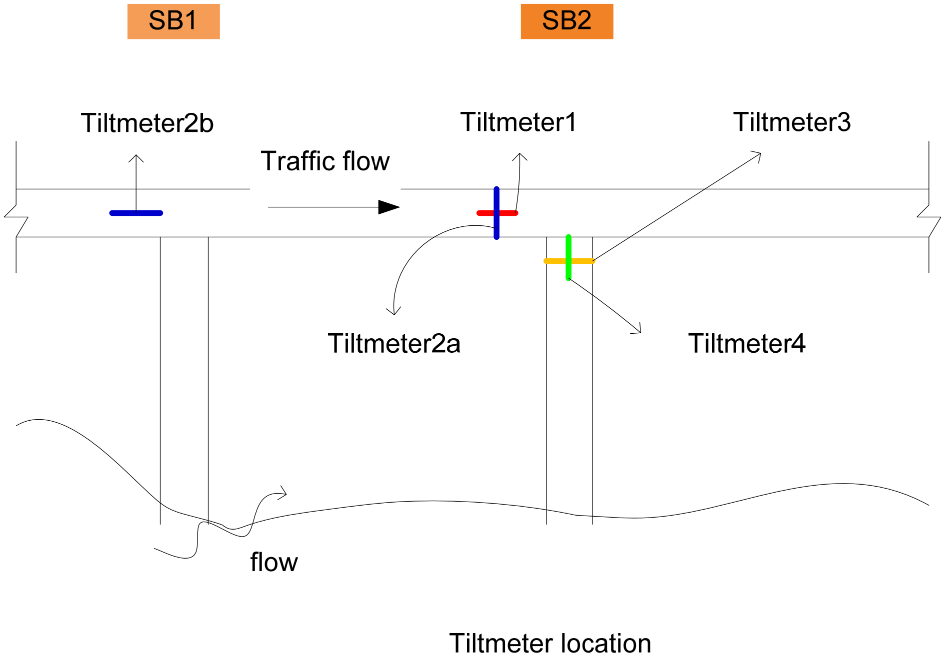


Figure D-28. Schematic Layout of the Tiltmeter Locations on US59 over Guadalupe River Bridge.

The following is a discussion of the data obtained from Tiltmeter 1 from May 28, 2009 till August 9, 2010. Additional data and discussions of the data from the other tiltmeter may be found in Attachment B.

Figure D-29 shows the time history plot of the data obtained from Tiltmeter1 located on the deck near the master station. It measures the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction).

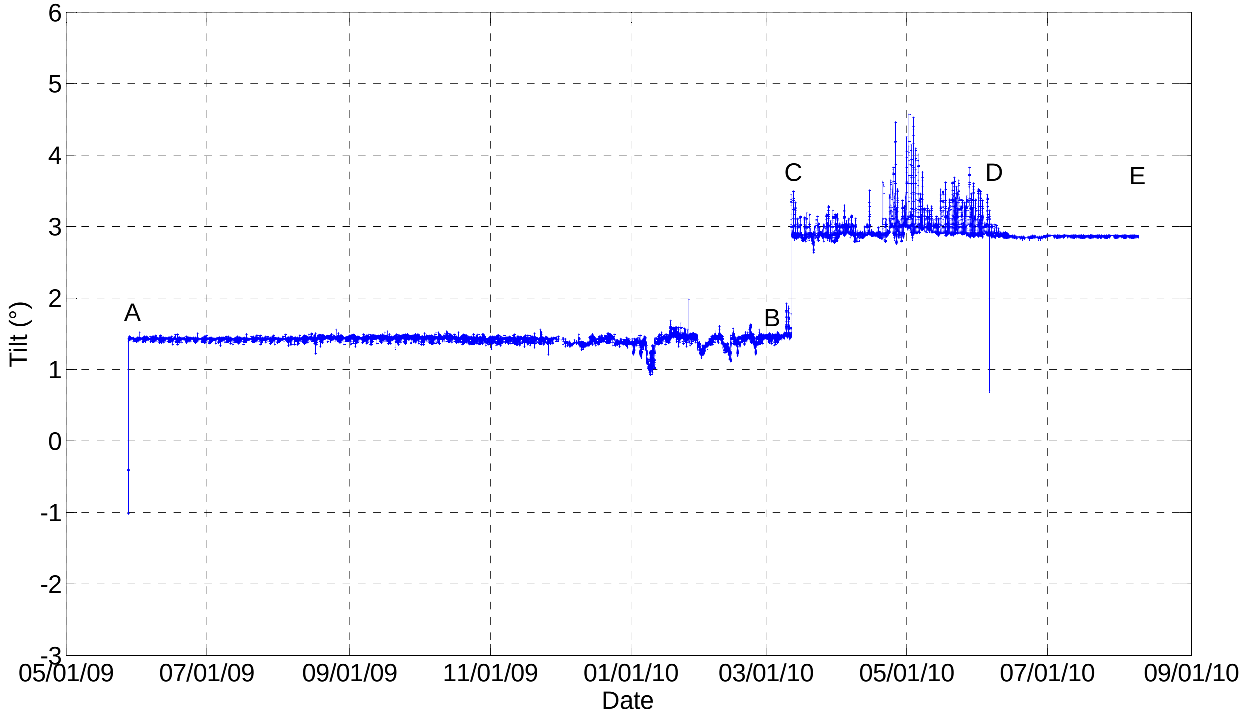


Figure D-29. Tiltmeter1 Time History Plot on US59 over Guadalupe River Bridge.

The data collected from Tiltmeter1 are categorized into different phases according to the maintenance and modifications that were performed on the scour monitoring system.

Phase A-B (May 28, 2009–March 11, 2010)

Figure D-30 shows the time history plot of all the data collected from Tiltmeter1 and the temperature recorded before the system was modified in March 2010. The blue line shows the tilt angle of the deck in the flow direction axis (perpendicular to the traffic direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the two curves of the deck's rotation and temperature are correlated. This is due to the response of the bridge deck, on which Tiltmeter1 is mounted, to changes in temperature.

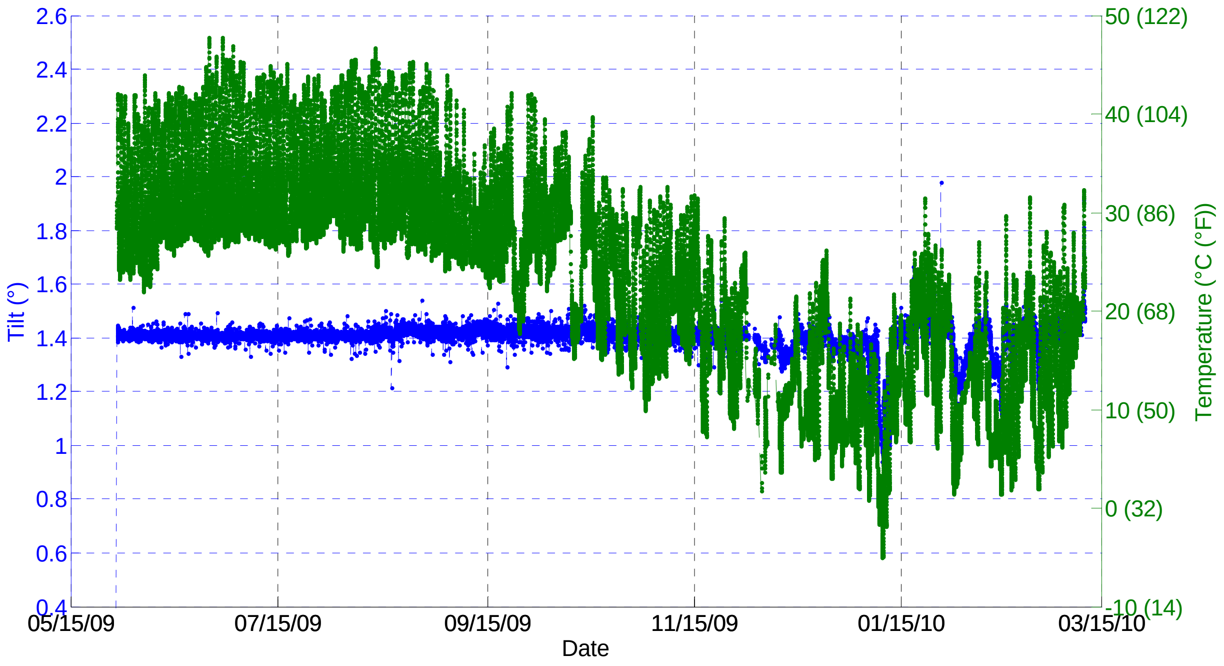


Figure D-30. Tiltmeter1 and Temperature Response Plot for Period AB.

Phase C-D (March 11, 2010–June 5, 2010)

Figure D-31 shows the time history plot of all the data collected from Tiltmeter1 and the temperature recorded after the system was modified in March 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

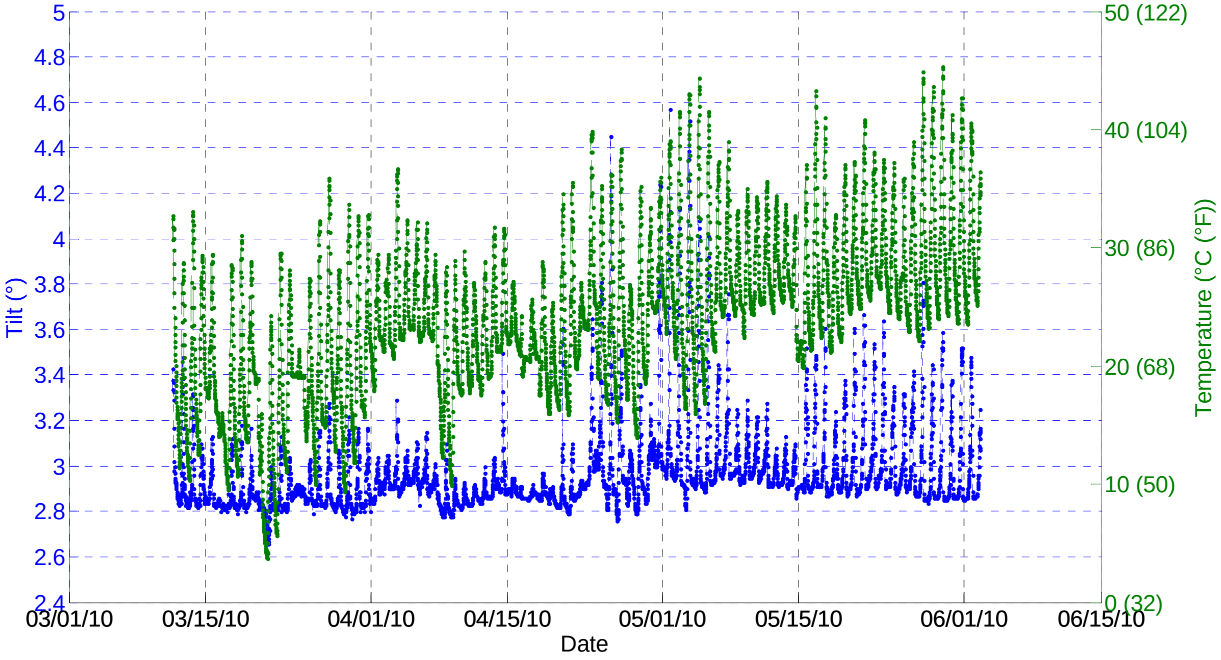


Figure D-31. Tiltmeter1 and Temperature Response Plot for Period CD.

Phase D-E (June 5, 2010–August 9, 2010):

Figure D-32 shows the time history plot of all the data of Tiltmeter1 and the temperature recorded after maintenance was performed on the system in June 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

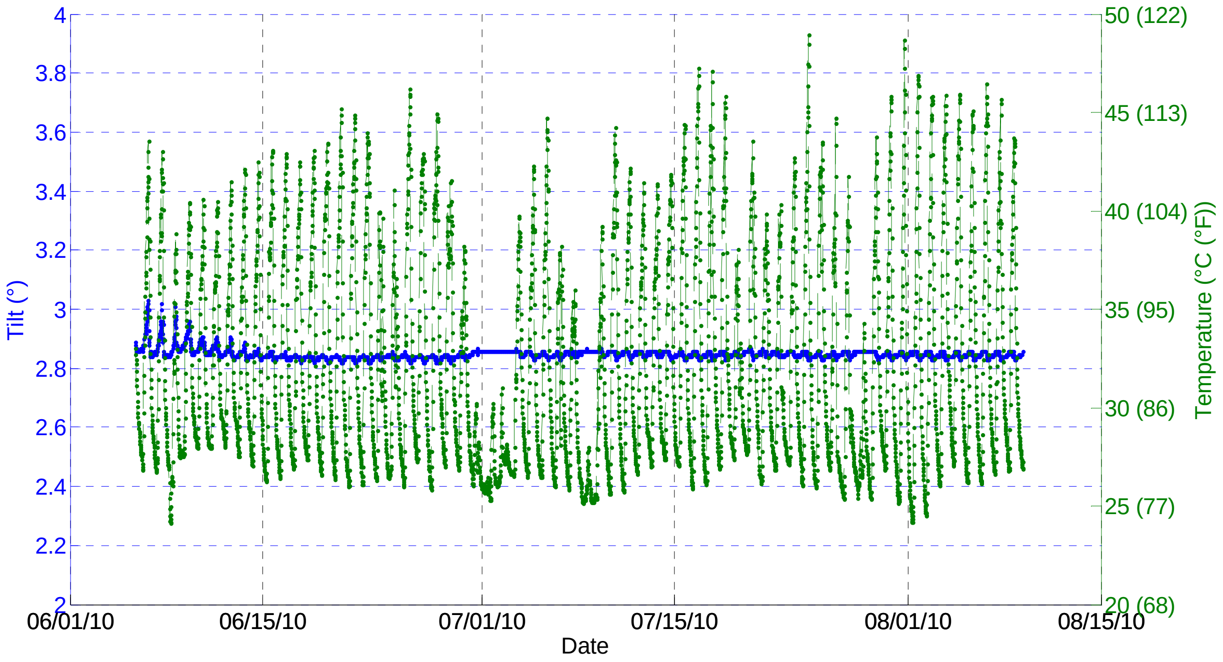


Figure D-32. Tiltmeter1 and Temperature Response Plot for Period DE.

FLOAT-OUT DEVICES

The float-out devices give output in the form of two discrete values, 0 and 1. A value of 0 will be transmitted to the data acquisition system if the float-out device is vertical and buried in the streambed, has not floated out, and does not transmit a signal. The radio transmitter will transmit a value of 1 to the data acquisition system if the float-out device is released, floats out, and becomes horizontal. Figure D-33 shows the data collected from the two float-out devices installed on US59 over Guadalupe River Bridge. Float-out1 is buried 1.5 m (5 ft) below the soil surface at a distance of 16 m (54 ft) below the top of the deck. Float-out2 is buried 2.7 m (9 ft) below Float-out1 at a distance of 19 m (63 ft) below the top of the deck.

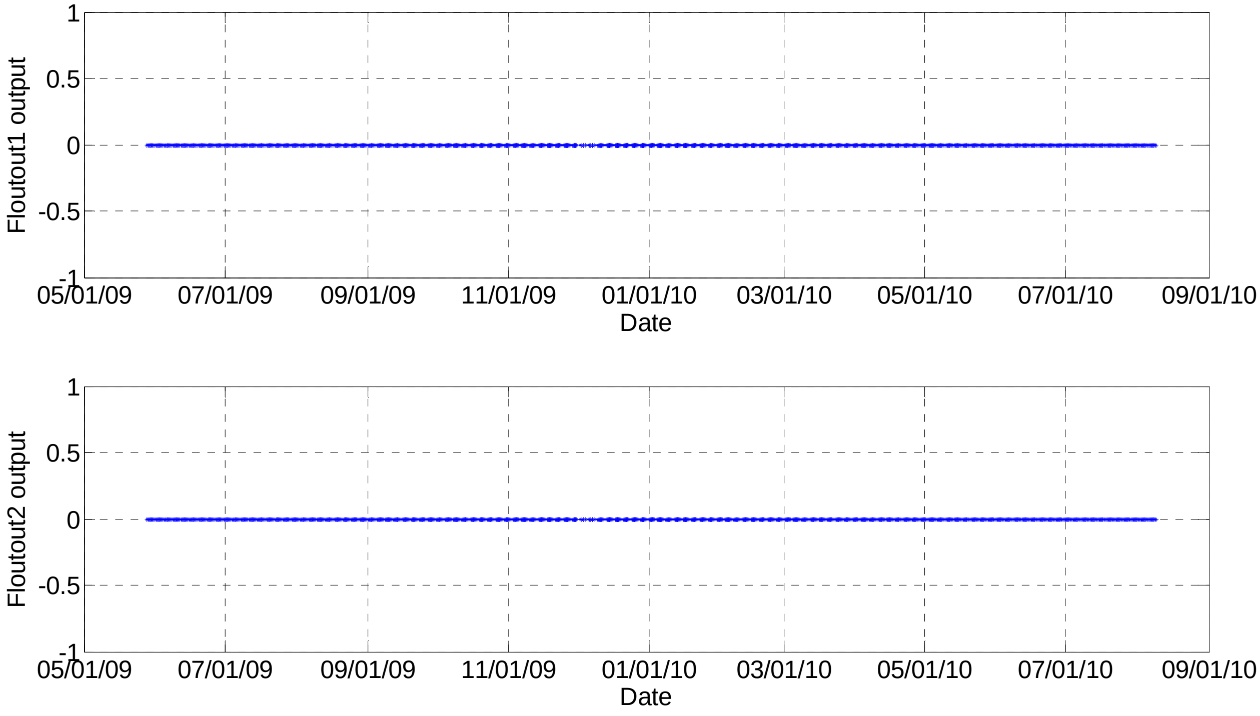


Figure D-33. Float-Out Device Response at US59 over Guadalupe River Bridge.

Figure D-33 shows that the float-out devices have both transmitted a value of 0 since their installation in May 2009 indicating that the devices are vertical, have not floated out, and have not been subject to scour.

WATER STAGE SENSOR

The water stage sensor provides data on the elevation of the water level at the US59 over Guadalupe River Bridge. The datum is Mean Sea Level. The elevation of the top surface of the bridge deck is 18.3 m (61 ft) above the datum. The elevation of the bottom of the deck is 18 m (60 ft) above the datum. The water stage sensor was installed at the level of the bridge deck so that the water stage sensor is at a height 18 m (60 ft) above the datum. The elevation of the water level was obtained by subtracting the distance between the sensor and the water surface from the elevation of the deck 18.3 m (61 ft).

The water gage readings from the USGS were used to validate the data collected from the US59 water stage sensor. The USGS station number USGS 08176500 is located 10 km (6.4 miles) upstream of the US59 over Guadalupe River Bridge. The data collected at the USGS site was compared to the water stage sensor reading. The gage height historic data may be obtained from USGS website. The gage height measures the water elevation above the gage datum, which is 8.74 m (29.15 ft) above the mean sea level NGVD 29. An adjustment was made for the offset of the USGS gage reading in order to compare US59 the water stage reading with the USGS gage reading. Figure D-34 depicts the method that the measurements are taken from the water stage sensor. Figure D-35 shows the location of project and USGS gages.

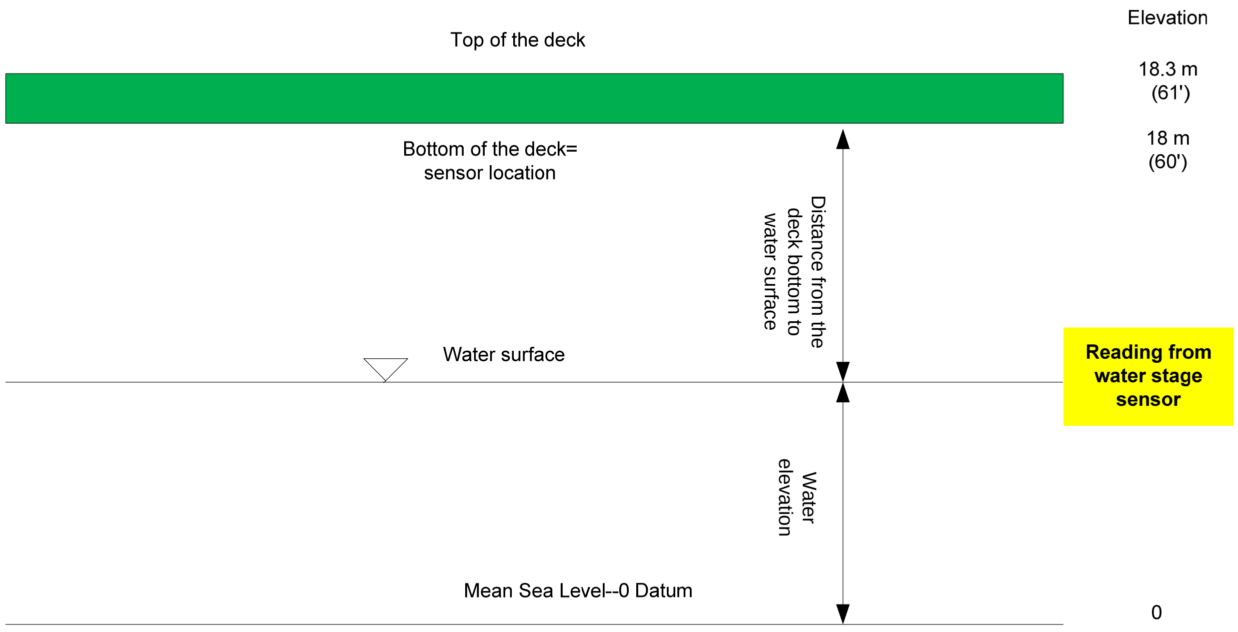


Figure D-34. Description of the Measurement from the Water Stage Sensor.

Figure D-35. Location of USGS Gage Sensors.

Figure D-36 shows the comparison of the readings obtained from the US59 water stage sensor with the readings obtained from USGS gage sensor. The two readings compare well in some portions of the data and there are discrepancies in other parts. The reason for the discrepancy is that the water stage sensor lost power due to large consumption by the accelerometers during the first phase of the research project. During those periods it recorded default values and not the actual water surface elevations. Hence these values could not be evaluated with respect to the USGS gage readings.

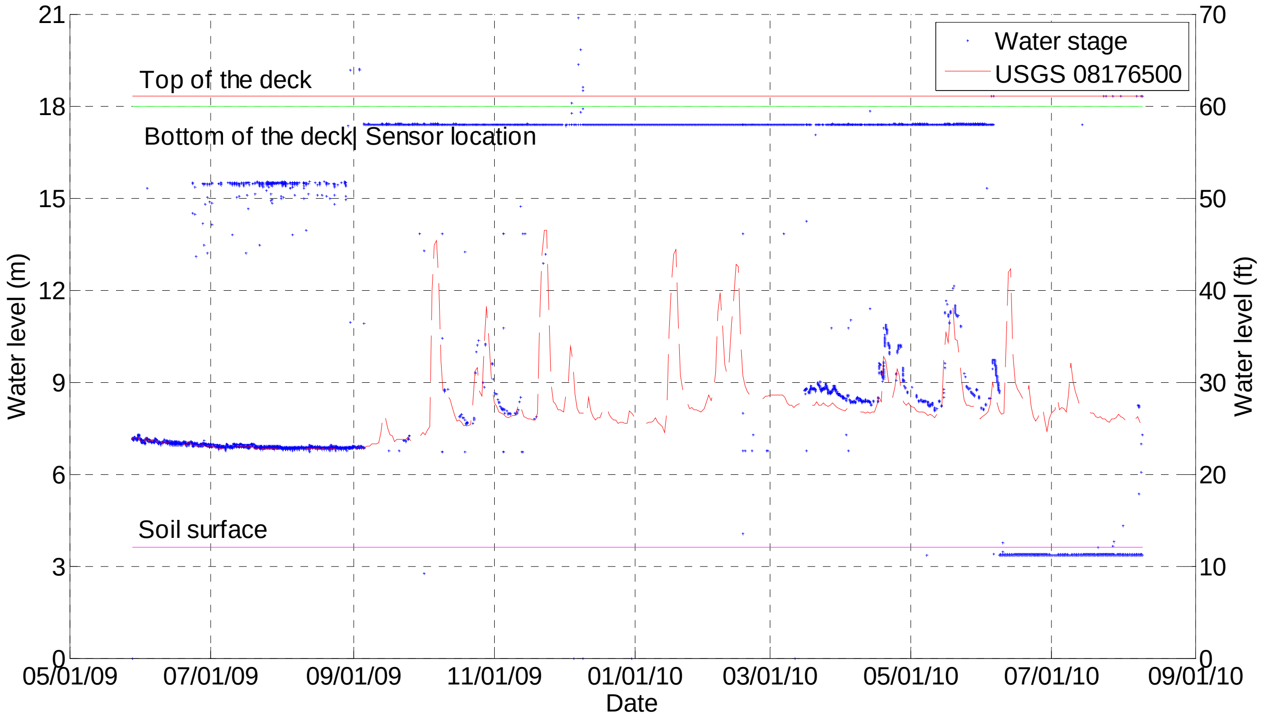


Figure D-36. Comparison of Water Stage Sensor and USGS08176500 Gage Readings.

OTHER READINGS

In addition to the data from the installed instruments at the US59 over Guadalupe River Bridge, the scour monitoring system also records battery voltages and the reading from the temperature sensor located in the master sensor enclosure. The units for the battery readings are volts and for temperature degrees Centigrade.

Figure D-37 shows the temperature reading for the system. The daily mean temperature in Victoria is also plotted in the figure for comparison. The temperature data from the monitoring system compares well with the daily mean temperature in Victoria. Figure D-38 shows the battery reading for the system. The battery voltage is also correlated with the temperature data. This is due to the fact that the battery is charged using solar panel, which is dependent on the temperature.

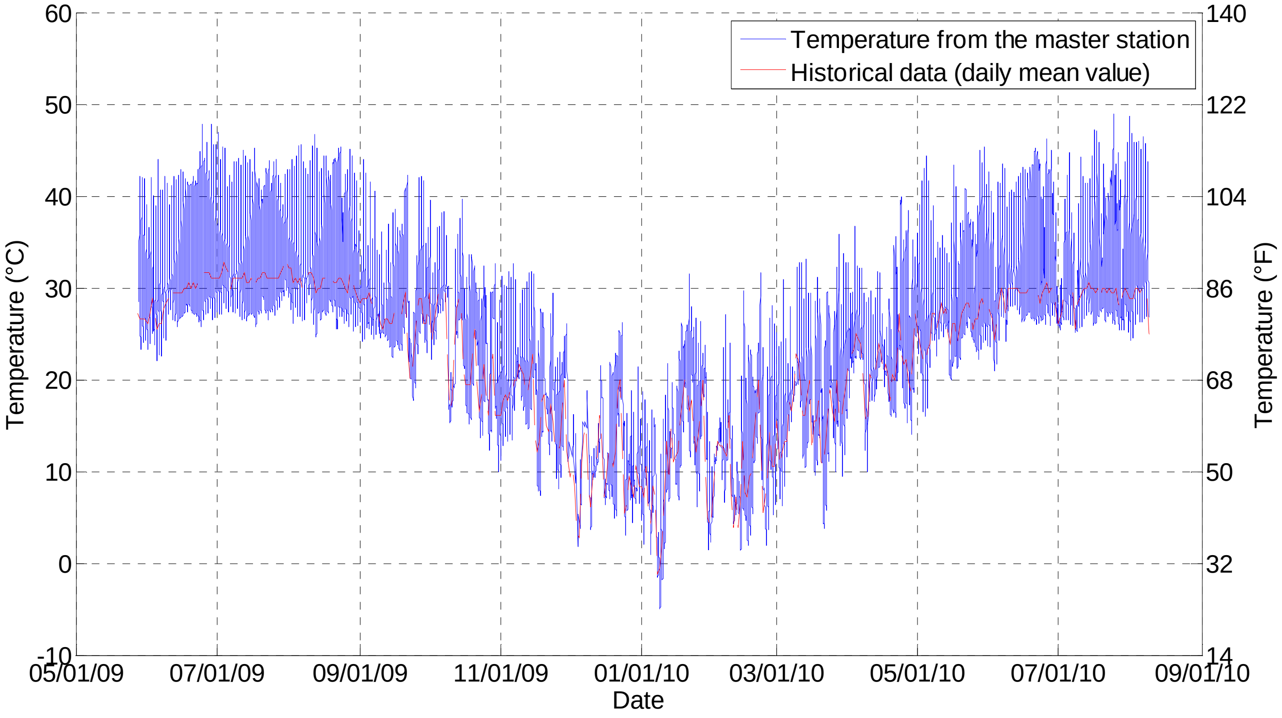


Figure D-37. Temperature Readings for US59 over Guadalupe River Bridge.

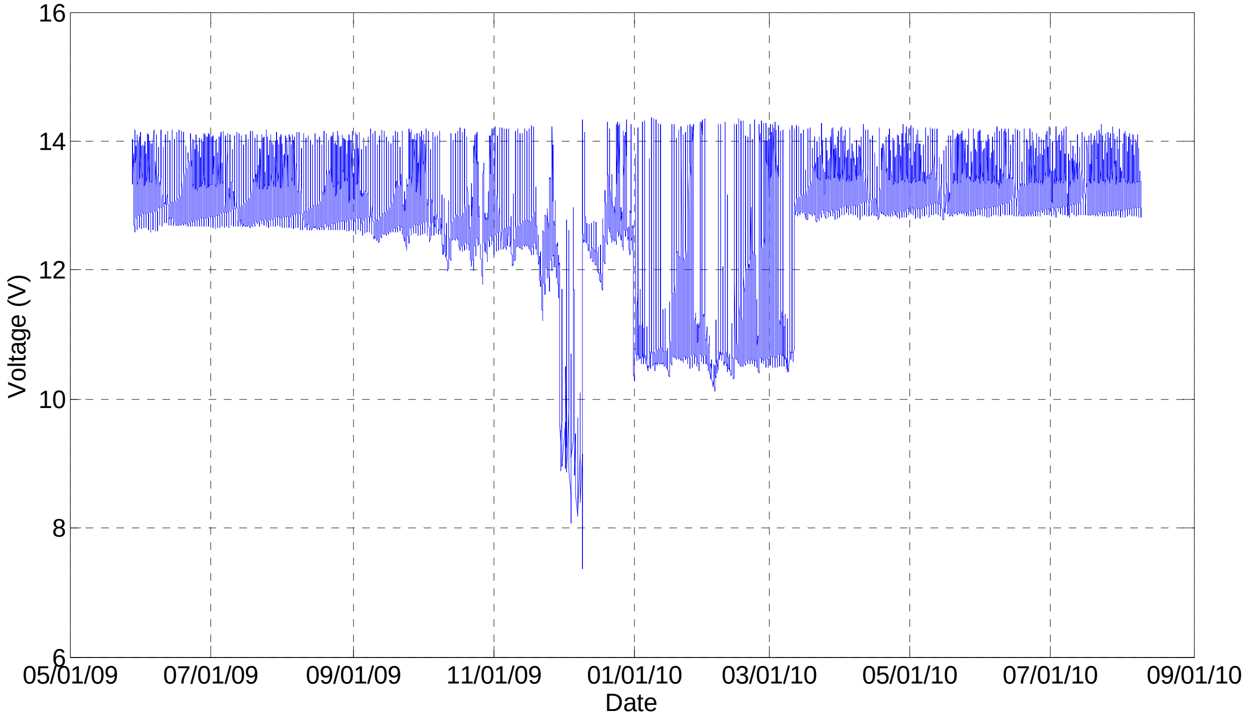


Figure D-38. Battery Readings for US59 over Guadalupe River Bridge.

INTERPRETATION OF THE DATA

Following are some guidelines to interpret the data from the scour monitoring system.

TILTMETERS

There are four tiltmeters installed on US59 over Guadalupe River Bridge (Figure D-39). The tiltmeters record the tilt angles at different locations on the bridge in both the flow and traffic directions. A consistent reading indicates that the bridge is stable and significant scour has not been detected. If the reading exceeds a preset threshold value, then a warning should be issued and consideration given to closure of the bridge.

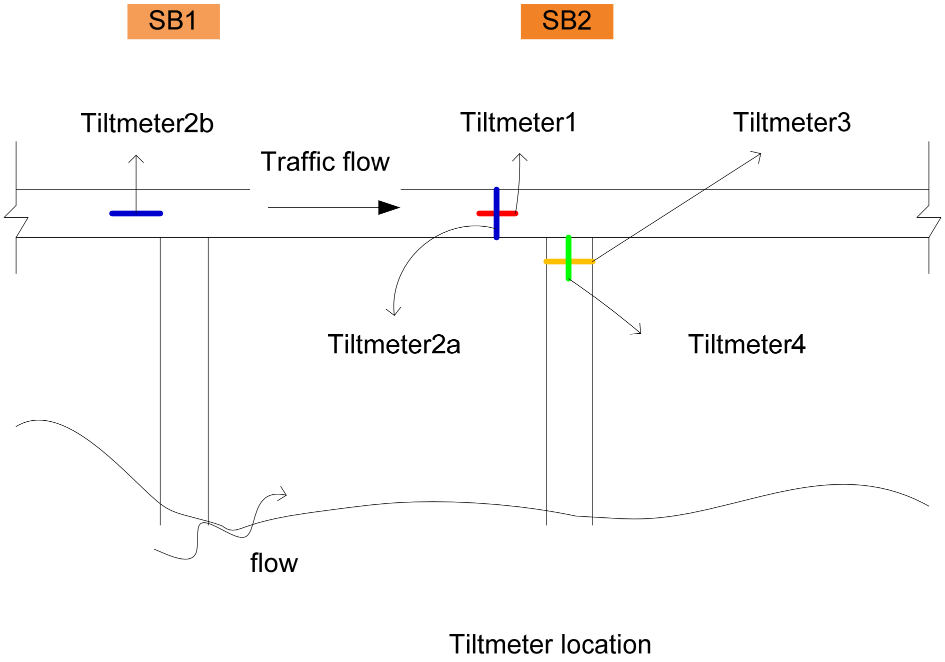


Figure D-39. Layout of the Tiltmeter Locations on US59 over Guadalupe River Bridge.

The threshold values of the tilt angle for the US59 over Guadalupe River Bridge needs to be studied and established. The threshold values for tiltmeters can be established based on two points of view: the pier point of view and the deck point of view. Analysis and recommendations for thresholds for special inspection and bridge closure are discussed in the TxDOT research report. The recommended thresholds for the US59 are summarized below.

Tiltmeter1 and Tiltmeter2 are installed on the deck to measure the tilt of the deck around the flow direction axis (perpendicular to the traffic direction). The thresholds for Tiltmeter1 and Tiltmeter2 are 0.38° for alert/checking the bridge, 0.76° for critical/closing the bridge. Tiltmeter3 and Tiltmeter4 are installed on the top of Pier (SB2) to measure the tilt angle of the pier in the flow direction axis, and the traffic direction axis (perpendicular to the flow direction) respectively. The thresholds for Tiltmeter3 and Tiltmeter4 are 0.46° for alert/checking the bridge, 0.93° for critical/closing the bridge.

FLOAT-OUT DEVICES

The reading of 0 obtained from the flout-out sensor means that it is buried in the streambed, and a reading of 1 means it has been exposed due to scour and has floated out. Float-out1 was buried 1.5 m (5 ft) below the soil surface, and Float-out2 was buried 2.7 m (9 ft) below Float-out1. The floating out of float-out device means that the scour depth has reached the depth at which the instrument was buried.

WATER STAGE SENSOR

The water stage sensor gives the water surface elevation at the location of the sensor, which is located at a distance of 2.25 m (7.5 ft) from Pier SB2 (Figure D-3).

SYSTEM RECOMMENDATIONS

If the tiltmeters indicate movement in excess of the checking/alert and closing/critical angles and/or the float-out devices float to the top and transmit a signal, TxDOT shall review the data and consider the necessary steps, if any, to be taken. The district may alert the authorities so that the public is diverted from using the bridge or the bridge may be closed. If the alert tiltmeter readings are obtained or the Float-out1 is activated, TxDOT shall immediately convene a meeting to discuss the installation of scour countermeasures. Interim mitigation measures may be taken, which may include the following:

1. Check the scour monitoring data every hour for a period of 12 hours. After that time, the data shall be checked every 12 hours for the next 72 hours.
2. Confirm these scour depths with alternate methodologies.
3. Implement or increase the frequency of the land field monitoring of the piers.

4. Conduct a Diving Inspection of the problem pier(s) and adjacent pier.
5. Consideration should be given to increasing the frequency of Diving Inspections and underwater surveys.
6. Consider the addition of pier protection.
7. Consider the addition of pier strengthening.

CLOSURE OF THE BRIDGE

If a bridge closure is recommended, TxDOT forces shall be responsible for a complete shutdown of the roadways as per TxDOT procedures. In the event of closure, the TxDOT instructions may be found in Attachment C of this protocol. Once a bridge closure has occurred, it shall be necessary to confirm the measurements of the devices through above and/or underwater inspections.

BRIDGE INSPECTIONS BASED ON SCOUR DATA

TxDOT shall ensure that the department sends engineers to the bridge(s) for a visual inspection as soon as it is deemed safe to do so to confirm the measurements taken by the fixed monitoring devices. If the inspectors confirm the scour critical measurements that were taken by the fixed devices, the bridge shall remain closed and a Diving Inspection shall be conducted. If the inspectors determine that the streambed elevations that are higher those reported by the fixed devices, the elevations shall be reported to the Department, and a decision shall be made regarding the necessity of a Diving Inspection.

A Diving Inspection may be required after the report of a critical scour depths or movement of the bridge. The Diving Consultant for the emergency Diving Inspection contract shall do this work. If there is an event that requires a Diving Inspection, the Diving Consultant Project Manager shall be contacted.

ACCESS

Access to the scour monitoring system is limited. It is recommended that the items listed below, as well as those discussed in the following sections be considered before performing maintenance, repairs, or inspections.

- Keys may be required to open instrumentation boxes or doors.
- A snooper, manlift, or a climber is required to access portions of the instrumentation mounted on the pier and bridge fascia.
- Lane closures may be required. Proper maintenance and protection of traffic as well as inspection/repair crew safety will be needed.
- Security clearance may be required to access parts or all of the bridge. Contact the appropriate authorities and notify them when and where the work is scheduled to take place.

MAINTENANCE

One set of instruments, the float-out devices at SB2, will need to be retrieved periodically in order to replace batteries and ensure that the instrument is functioning properly. The maintenance period can be either after a flood washes the float-out loose, or at two-year intervals after installation. While batteries nominally last 10 years, field results are typically well shy of that time.

The TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate TxDOT Bridge maintenance group for the routine maintenance of the system. The following items are included as maintenance requirements for the bridge:

- "Contact Information" in Attachment C shall be updated annually (i.e., January 31) to ensure that all names, addresses, and contact numbers are current. The Group responsible for this update shall contact all the individuals listed in Attachment C to make them aware or remind them of their responsibilities regarding the scour monitoring program.
- Indoor instrument boxes and electrical conduit shall be visually inspected for corrosion, overheating, insects, moisture, etc.
- The thermostat reading or temperature reading shall be recorded for areas containing instruments.

A Scour Monitoring Maintenance Checklist has been included in Attachment D. This form shall be completed after all routine maintenance and kept on file in the TxDOT district office.

GENERAL INSPECTION

The above-water instruments need to be checked during biennial or other bridge inspections. Because all of the instruments are sealed, the inspection will simply require checking of the instrument for visible damages. Routine monitoring provides the best chance of catching any irregularities.

The TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate group for the inspection of the monitoring system components. This work shall be performed by the appropriate bridge maintenance group or the consultant retained for the inspection of the bridge. The following items are included in the list of required work:

- Inspect all outdoor instruments boxes for corrosion, damage, vandalism, leaks, etc.
- Inspect the outdoor/above water conduit and cable for corrosion, damage, vandalism, leaks, etc.
- Remove any spiders, mice nests, bird droppings, etc. from all outdoor instrument boxes.
- Check the door gasket and/or seal.
- Check and clean the solar panels.

A Scour Monitoring General Inspection Checklist has been included in Attachment D. This form shall be completed after all general inspections and kept on file in the TxDOT district office.

TTI may be contacted should there be any questions with regard to the general inspection of the system or new parts are required for the system. If the general inspection reveals that the system requires maintenance and/or repair, this work shall be performed by TxDOT maintenance, an electrical contractor, or other appropriate group.

CONSTRUCTION WORK AT THE BRIDGE

If any construction work is done near the fixed scour monitors, including work unrelated to the bridge, provisions shall be made to protect the scour monitoring system. Upon completion of the work, the monitors shall be checked to ensure the monitors had not been damaged. If they are damaged, they shall be repaired at the expense of the Contractor. Figure D-40 depicts the current construction for the extension of the both bridges.

Figure D-40. Construction on the Extension of the Southbound Lane of US59 over Guadalupe River Bridge.

Due to the construction of the extension to the bridge, the two TBS originally installed at the bridge at the south abutment (SB3) were disconnected and are no longer active.

SYSTEM MALFUNCTION

In the event of a scour monitoring system malfunction, the TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate groups for troubleshooting of the scour monitoring devices. Depending on the nature of the work, it may be done by the TxDOT maintenance group, a general contractor, or an electrical contractor.

If the system cannot be repaired using the suggestions outlined below, TxDOT may contact TTI. If the problem cannot be resolved via instructions given by telephone, arrangements may be made for TTI to visit the site.

The following are recommendations for troubleshooting various system malfunctions:

1. If the instruments do not turn on at the scheduled sample intervals:

- Check the battery voltage and all power connections.
- Review the past data and look for anomalies in the daily battery voltages. If there are anomalies, see if there have been any events (i.e., a power outage or damage to the system) that might have caused the problem.
- If the battery voltage is less than 12.2 volts, this is an indication that there is a problem.
- If the battery voltage is low (less than 11 volts), check the output of the solar panel, if applicable, with the sun shining, and make sure it is producing at least 15 volts before the regulator, and about 13.5 volts after the regulator.
- If the solar panel is functioning properly, either (1) the battery is faulty or was drawn down by lack of solar energy for recharging (e.g., an extended period of overcast weather), or (2) the data logger staying turned on too long, or cycling too frequently, either from an error in programming or a faulty data logger.
- In either case, replace the battery with a fully charged battery and evaluate the data logger functioning for a short sample interval (e.g., 5 minutes). If the data logger appears to be functioning properly, re-program for the regular sample interval and periodically check the battery voltage (e.g., every week) to ensure proper operation.
- If the data logger appears to be malfunctioning, check the programming and/or follow the troubleshooting instructions from the manufacturer.

2. If the tiltmeter readings are erratic:

- Check for high (14.0+ volts) battery readings.
- Check to make sure the charger is functioning properly.

3. If the tiltmeter readings remain fixed at a single elevation for a prolonged period of time:

- Check the battery voltage and all power connections (see Item 1).
- Check the tiltmeter to ensure that it is still securely connected. Check all wiring.

4. If a call to the automated telephone service results in a busy signal, no dial tone, or if it rings but there is no answer:

- Contact the local telephone provider's service department. Ask the telephone service representative to check the line to determine whether it is an internal or external problem. A technician will be sent to the site if the problem is external.
- If it is determined that it is a problem with an outside line, schedule a repair.
- If it is determined that it is a problem with an inside line, check connections with the telephone line and modem.

5. If a call to the automated telephone service results in "0" elevation readings:

- Wait a few minutes and try again. The system may have been in the process of downloading data.

The initial monitoring system worked well for 10 days. After that the connection with the bridge was lost due to the loss of IP address with Verizon. The problem was fixed in October 2009.

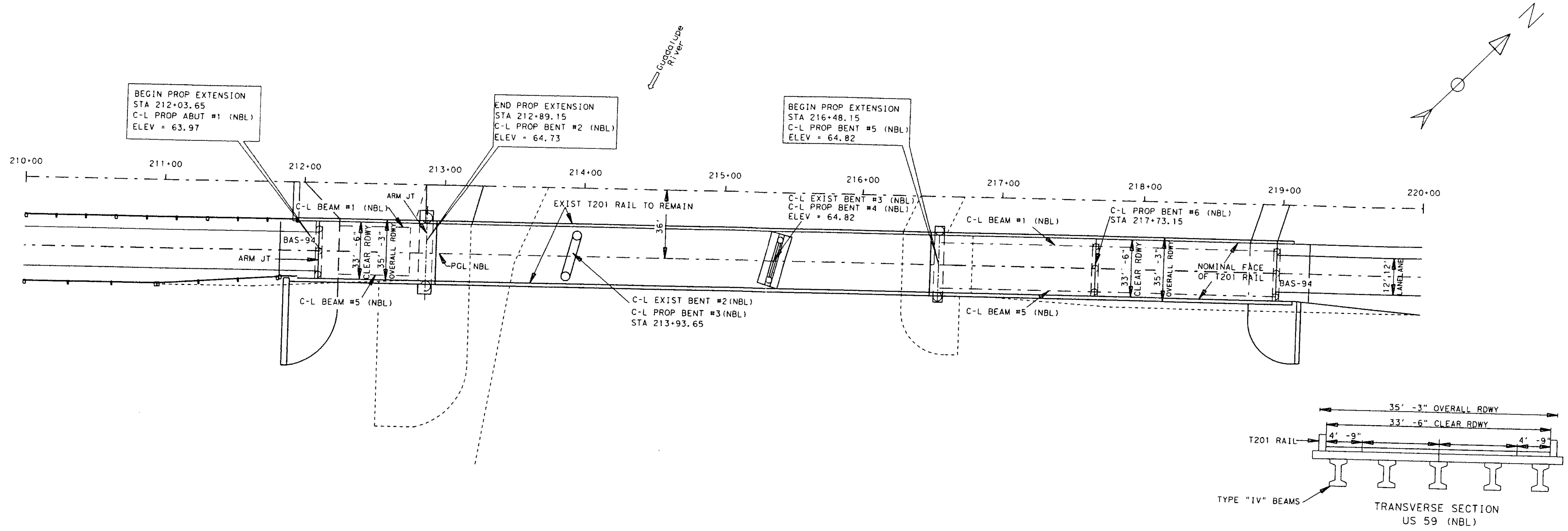
RESPONSIBILITY AND CONTACT LIST

Those responsible for the scour monitoring system and/or implementation of emergency procedures should be included in Attachment C: TxDOT Contact List. TxDOT district emergency protocols including flood watch and bridge closure may also found in Attachment C. The contact list shall be updated once a year by January 31 to reflect any changes.

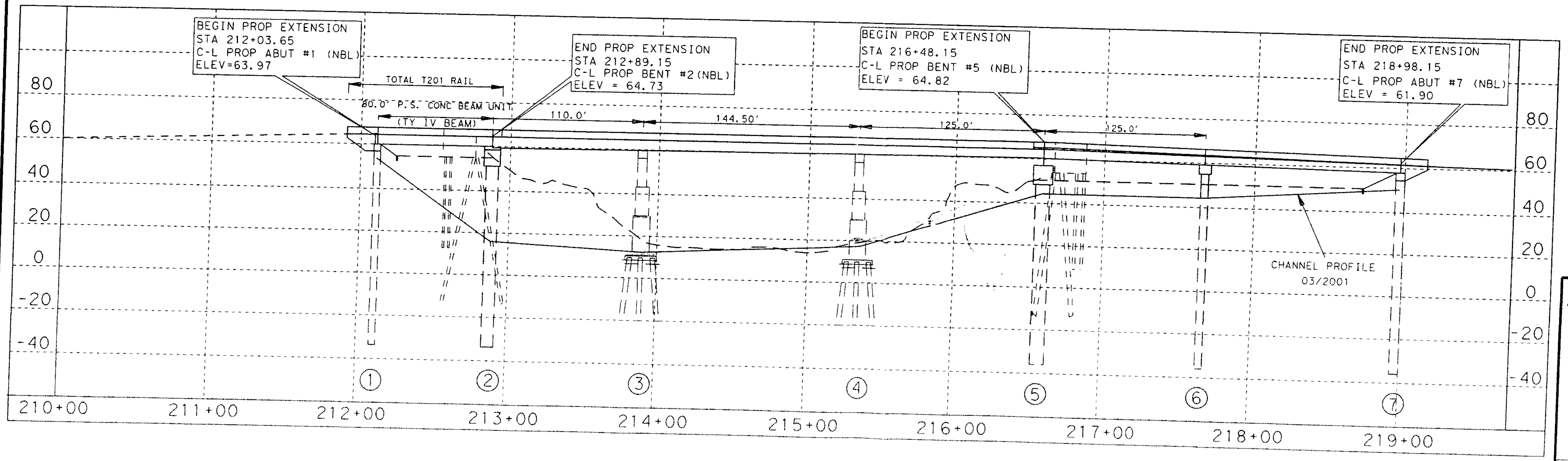
This document shall be revised to reflect any changes resulting from field conditions, new information obtained with future testing or analyses, and/or new technology. A distribution list shall be maintained by the TxDOT engineer in charge of the scour monitoring system. That person shall be sent all future revisions. The revisions shall be incorporated and distributed as necessary.

ATTACHMENT A:
BRIDGE PLANS

ORIGINAL Plan set and details



TRANSVERSE SECTION
US 59 (NBL)

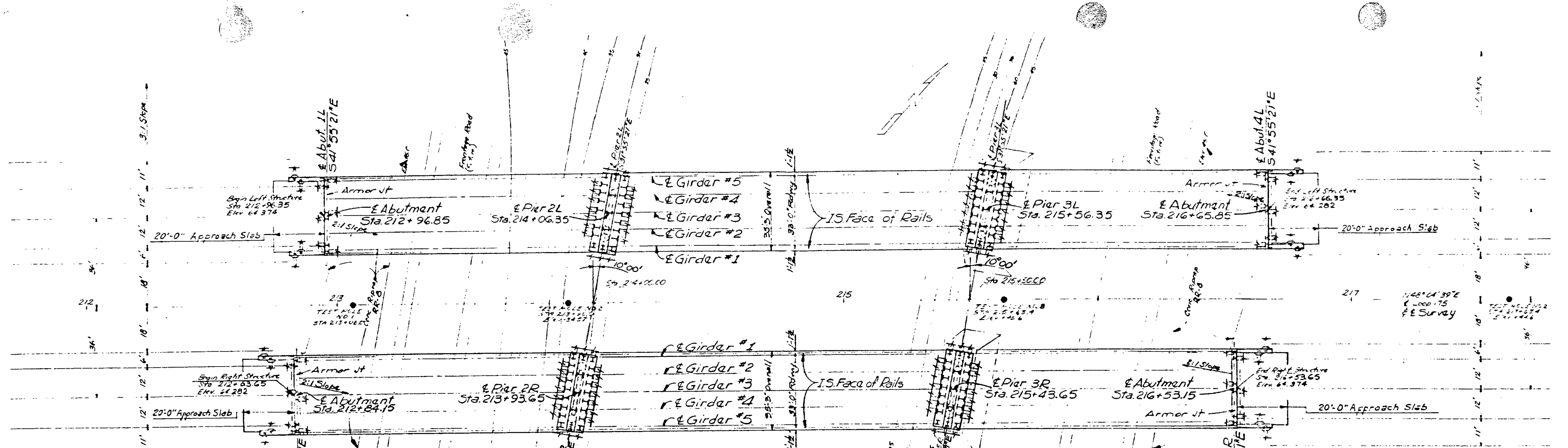


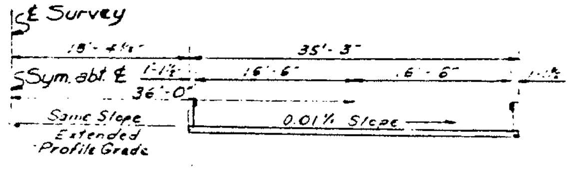
Texas Department of Transportation
Design Division (Bridge)

BRIDGE LAYOUT
GUADALUPE RIVER BRIDGE
US 59
NORTHBOUND LANES
(STRUCTURE NO. =
13235008805050)

DN:	CK:	DW:	CK:

DIST	FED REG	FEDERAL AID PROJECT ●	SHEET
13	6		





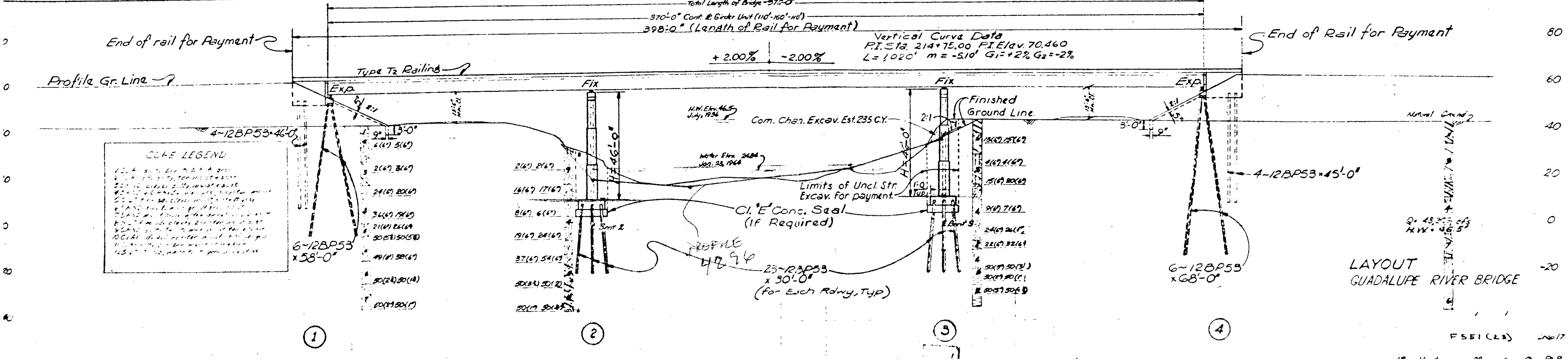
TYPICAL HALF SECTION

TABLE OF ESTIMATED QUANTITIES

ITEM	Uncl. Str. Excav.	Piling 12BP53	Class "A" Conc. Bents & Piers	Class "A" Conc. Slabs	Class E Conc. Seals	Riprap RR-8 Cl. B Conc.	Reinf. Steel	Structural Steel H.Y.C.	Structural Steel Armor Jt. & Shoes	Railing Ty. T2
	C.Y.	L.F.	C.Y.	C.Y.	C.Y.	C.Y.	Lbs.	Lbs.	Lbs.	L.F.
Abutment Bents	148	2,240	128.4	~	~	385	12,764	~	~	112.0
Interior Piers	2,190	2,760	519.2	~	118.0	~	65,756	~	~	~
Cont. Pl. Gird. Units	~	~	~	563.2	~	~	134,390	806,300	9,340	1480.0
Totals	2,338	5,000	647.6	563.2	118.0	385	212,910	806,300	9,340	1592.0

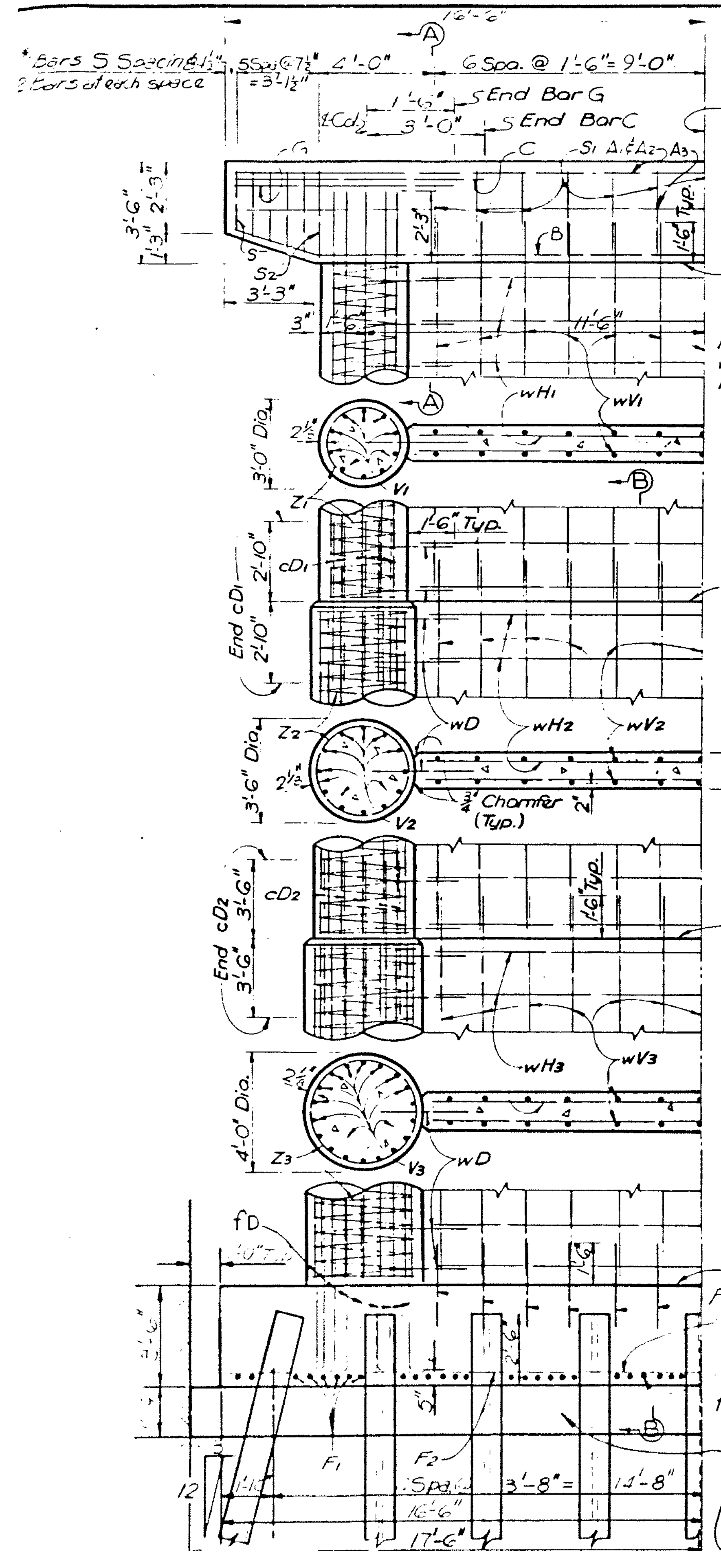
BEARING SEAT ELEVATIONS

Girder	BEARING Abut #1 Lt. Str.	Abut #1 Rt. Str.	Pier #2 Lt. Str.	Pier #2 Rt. Str.	Pier #3 Lt. Str.	Pier #3 Rt. Str.	Abut #4 Lt. Str.	Abut #4 Rt. Str.
1	57.860	57.768	59.035	59.013	59.013	59.035	57.768	57.860
2	57.787	57.695	58.966	58.936	58.936	58.966	57.695	57.787
3	57.715	57.623	58.897	58.860	58.860	58.897	57.623	57.715
4	57.642	57.550	58.828	58.783	58.783	58.828	57.550	57.642
5	57.570	57.478	58.759	58.707	58.707	58.759	57.478	57.570

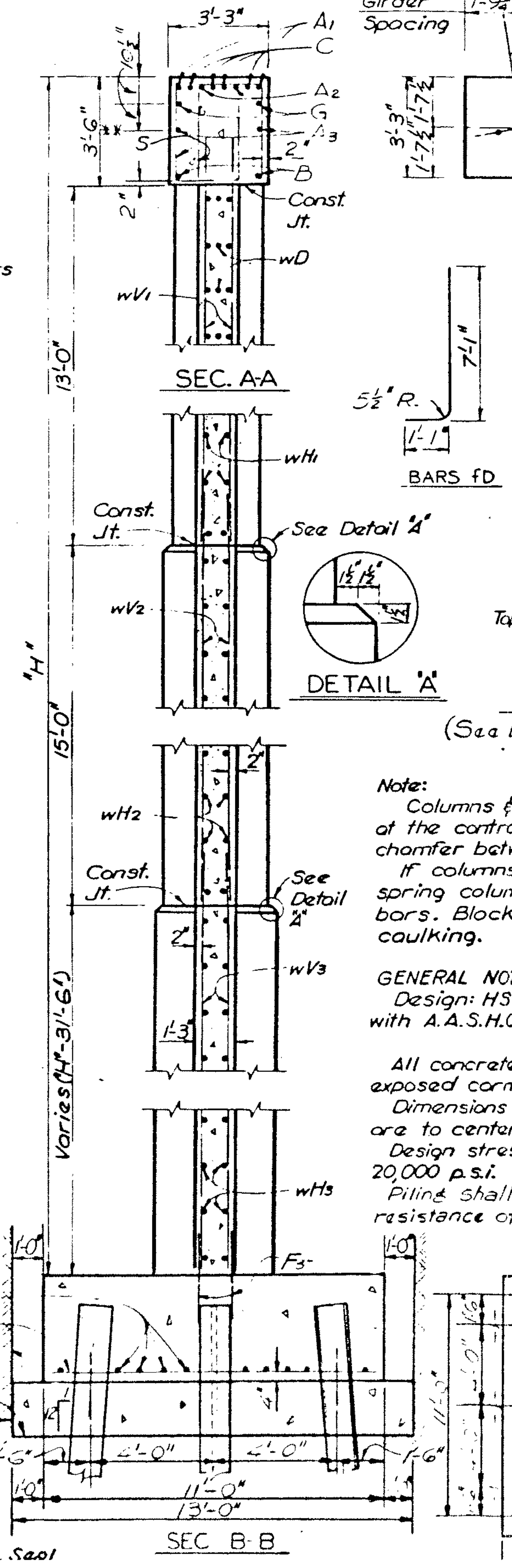


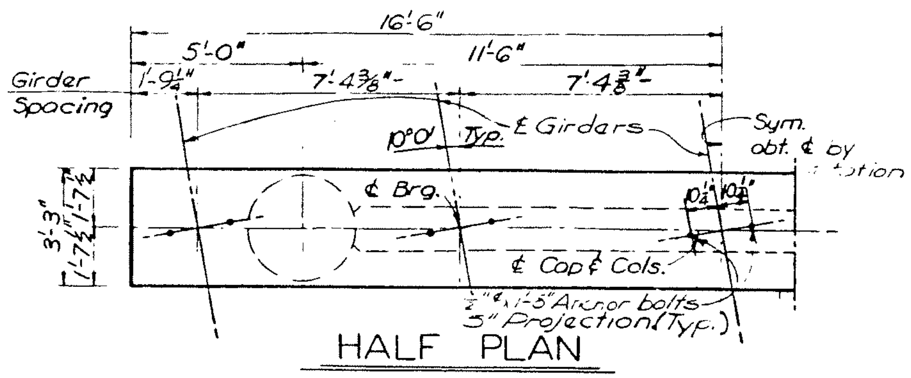
LAYOUT
GUADALUPE RIVER BRIDGE

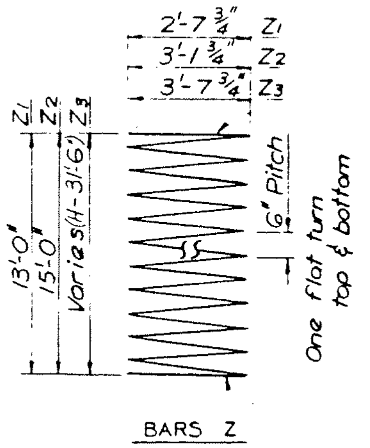
F551 (23)

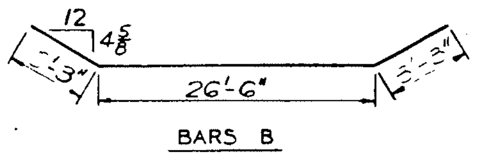


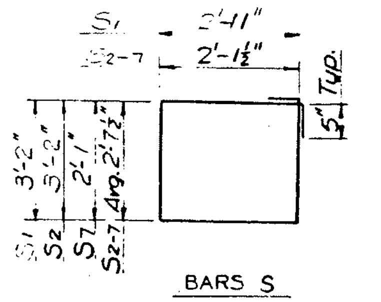
** Double Bars S2-S7 on Cantilever
Single bars S1 between Columns.

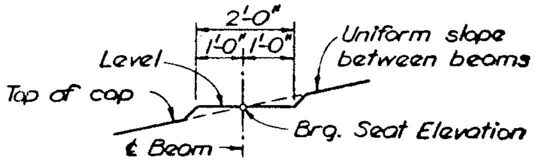












BEARING SEAT DETAIL
(See Layout for Table of Brg. Seat Elevs.)

Note:

Columns & webwall may be placed monolithically at the contractors option, in which case the ¾" chamfer between columns & webwall shall be omitted.

If columns & webwall are placed separately, spring column forms enough to insert #6 dowel bars. Block between with wood strips or caulking.

GENERAL NOTES:

Design: HS 20-44 Loading in accordance with A.A.S.H.O. 1961 Standard Specifications.

All concrete shall be Class "A". Chamfer all exposed corners ¾" unless otherwise noted.

Dimensions relating to reinforcing steel are to centers of bars.

Design stress for reinforcing steel = 20,000 p.s.i.

Piling shall be driven to a min. resistance of 48 T/pile.

BILL OF CONSTANT REINFORCING STEEL

Bar	No.	Size	Length	Weigh
A1	2	#11	32'-6"	345
A2	2	#10	32'-6"	230
A3	2	#5	32'-6"	68
B	2	#10	33'-0"	284
C	3	#[illegible]	7'-9"	267
CD1	20	#9	5'-8"	385
CD2	24	#11	7'-0"	693
F1	52	#10	10'-6"	2,349
F2	10	#6	32'-6"	488
F3	26	#6	3'-0"	117
fD	36	#11	8'-0"	1,530
G	4	#5	6'-3"	26
S	13	#5	13'-0"	176
S2-7 [illegible]	24	#5	10'-4"	259
[illegible]	20	#9	5'-3"	1,037
[illegible]	24	#11	14'-9"	1,881
wD	36	#6	3'-0"	162
wH1	16	#5	19'-9"	330
wH2	20	#5	19'-3"	402
wV1	26	#5	14'-6"	393
wV2	26	#5	16'-6"	447
Z1	2	#3	233'-0"	176
Z2	2	#3	317'-0"	238
				12,53

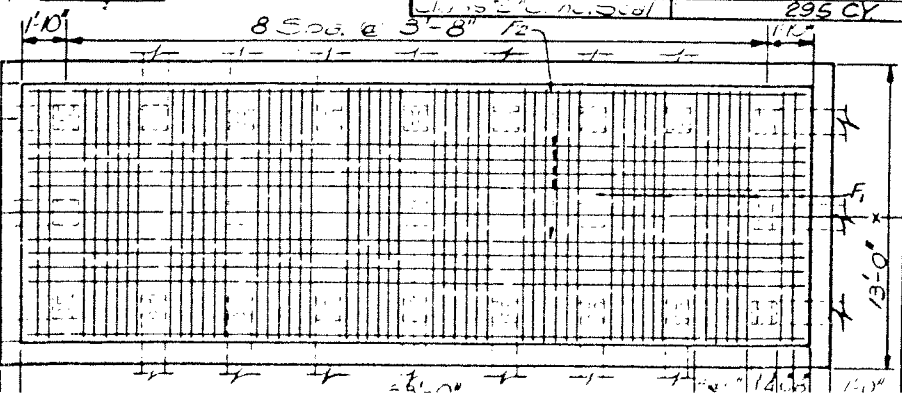
BILL OF VARIABLE REINFORCING STEEL

"H"	#5 Bars wH3 @ 18'-9" 1'-6" c.-c.		26 ~ #5 Bars wV3 1'-6" c.-c.		#6 Bars wD @ 3'-0" 1'-6" c.-c.		36 ~ #11 Bars V3		2 ~ #3 Bars Z3		Total Reim Stee Lbs.
	No.	Weight	Length	Weight	No.	Weight	Length	Weight	Length	Weight	
40	12	235	10'-0"	271	12	54	8'-3"	1,578	[illegible]	[illegible]	2,30
41	12	235	11'-0"	298	12	54	9'-3"	1,769	241'	182	2,53
42	14	274	12'-0"	325	14	63	10'-3"	1,959	264'	198	2,81
43	16	313	13'-0"	353	16	72	11'-3"	2,151	287'	216	3,10
44	16	313	14'-0"	380	16	72	12'-3"	2,343	309'	232	3,34
45	18	352	15'-0"	407	18	81	13'-3"	2,533	332'	250	3,62
46	20	391	16'-0"	434	20	90	14'-3"	2,725	355'	266	3,90
47	20	391	17'-0"	461	20	90	15'-3"	2,916	378'	284	4,14
48	22	430	18'-0"	488	22	99	16'-3"	3,107	401'	302	4,42

TOTAL ESTIMATED QUANTITIES (For One Pier)

Item	"H" Dimension										Unit
	40'	41'	42'	43'	44'	45'	46'	47'	48'		
Class "A" Concrete	118.9	120.7	122.5	124.4	126.2	128.0	129.8	131.6	133.4		C.Y
Reinforcing Steel	14,835	15,071	15,352	15,638	15,873	16,156	16,439	16,675	16,959		Lbs

	[illegible] #2	[illegible] #3
Uncl. Str. Excav.	438 C.Y.	657 C.Y.
Class "B" Conc. Seal	295 C.Y.	295 C.Y.



TEXAS HIGHWAY DEPARTMENT
BRIDGE DIVISION

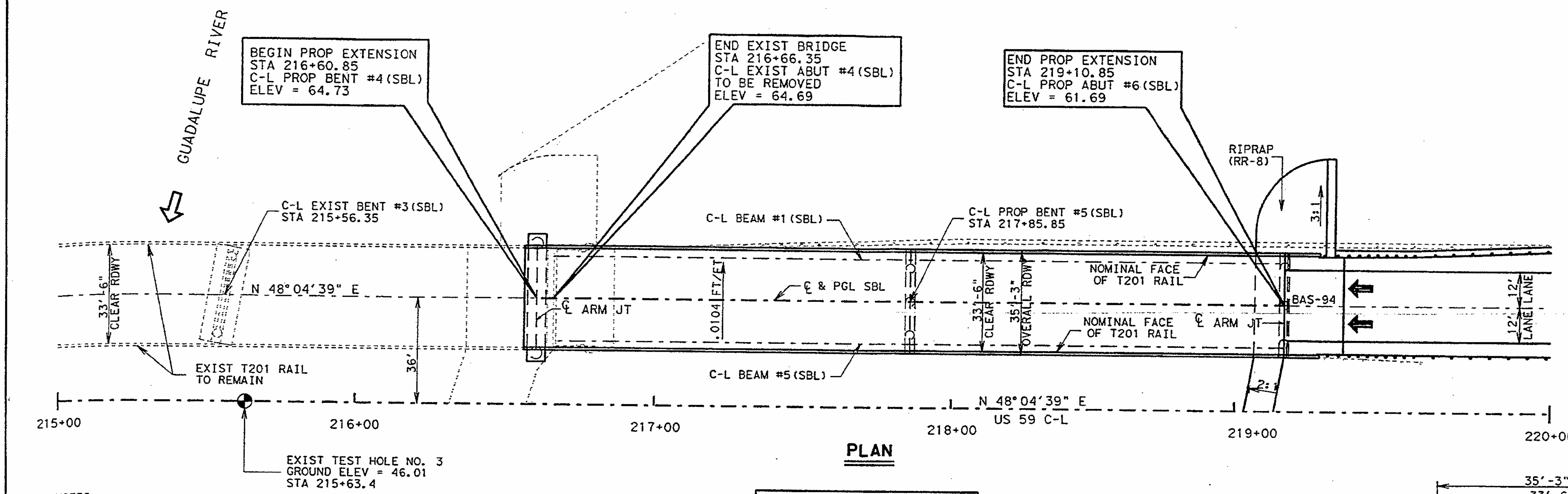
INTERIOR PIERS

33'-0" ROADWAY 10° L.F. SKEW

GUADALUPE RIVER BRIDGE

ORIGINAL DRAWING DATE	STATE DISTRICT	FEDERAL REGION	FEDERAL AID PROJECT	SHEE
Dec. 1964				

1st Lengthening Project



PLAN

NOTES:

CONTRACTOR SHALL VERIFY ALL EXISTING DIMENSIONS AND ELEVATIONS IN THE FIELD.

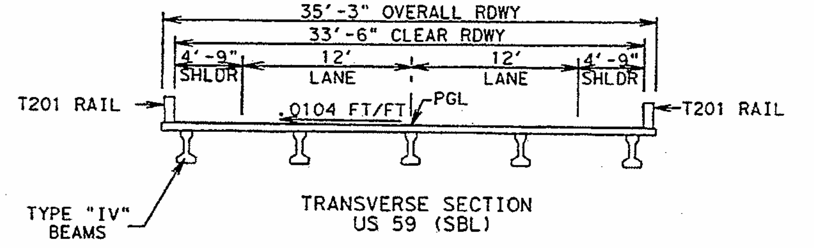
DESIGN SPEED: 70 MPH
EXIST ADT: 13,000 VPD
FUNCT CLASS: RURAL PRINCIPAL ARTERIAL

PROFILE ELEVATIONS ARE TOP OF CONC DECK.

STRUCTURE NO: 13235008805049

ALL EXIST ABUTMENTS AT BEARING N 41 55'21" W

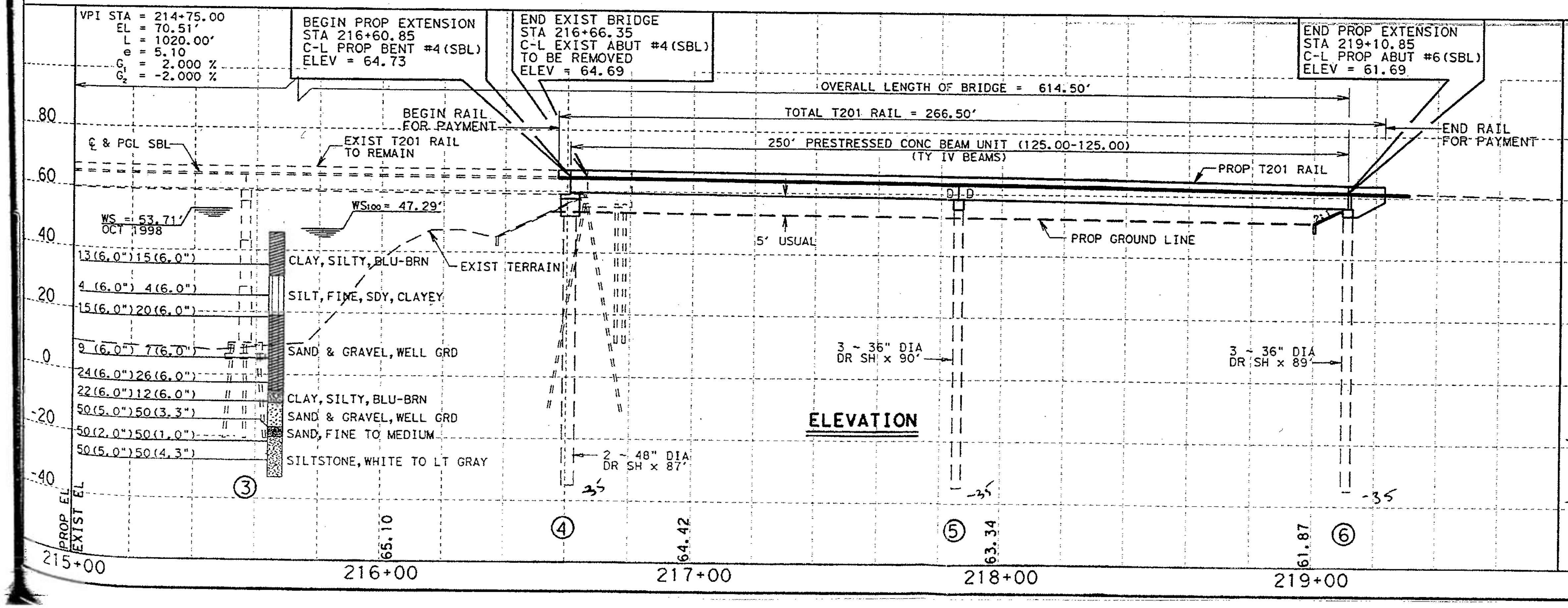
ALL PROP BENTS AND ABUTMENTS AT BEARING N 41 55'21" W



TRANSVERSE SECTION
US 59 (SBL)

DAVID P. HOHMANN 60983
David Hohmann 10/11/99

MARK P. McCLELLAND 60710
Mark McClelland 10/11/99



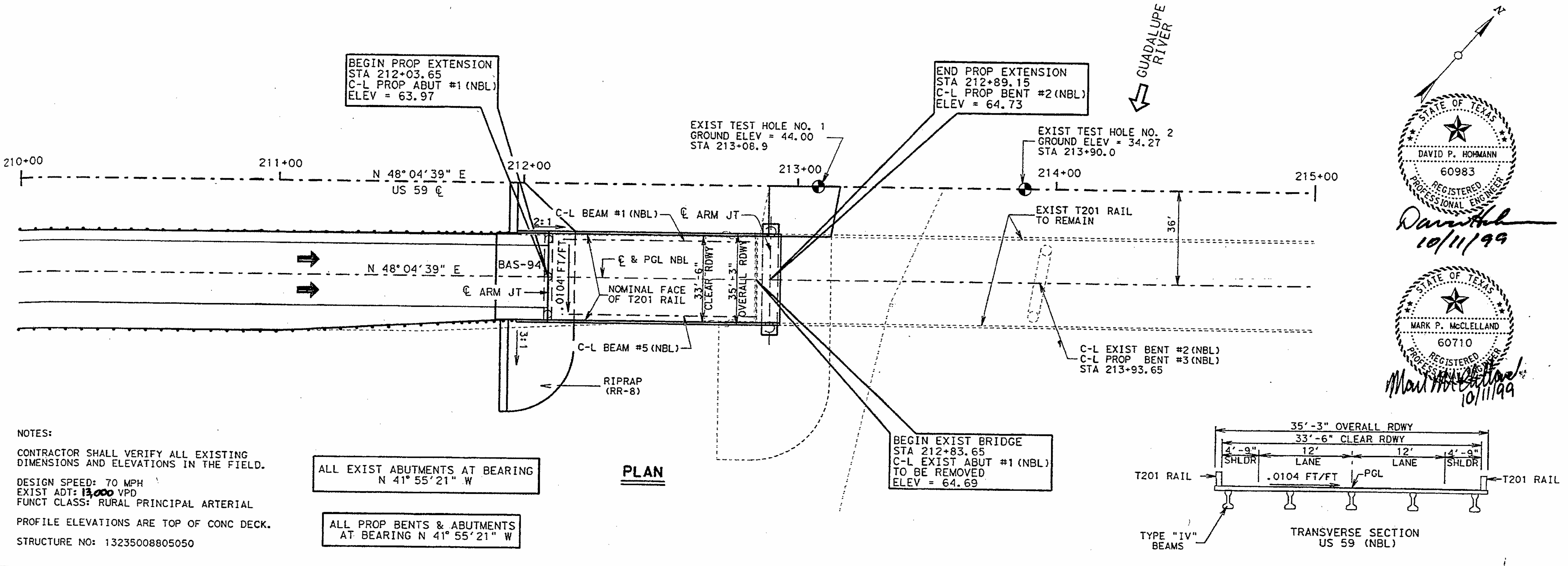
ELEVATION

Texas Department of Transportation
©1999 TxDOT

BRIDGE LAYOUT
GUADALUPE RIVER BRIDGE
US 59
SOUTHBOUND LANES
(STRUCTURE NO. = 13235008805049)

BLAISE H. DREITNER 65843
Blaise H. Dreitner, P.E.
11-5-99

FED. RD. DIV. NO.	FEDERAL AID PROJECT NO.		SHEET NO.
6	ER 99(693)		50
STATE	DIST.	COUNTY	
TEXAS	YKM	VICTORIA	
CONT.	SECT.	JOB	HIGHWAY NO.
0088	05	075	US 59



PLAN

TRANSVERSE SECTION
US 59 (NBL)

NOTES:

CONTRACTOR SHALL VERIFY ALL EXISTING DIMENSIONS AND ELEVATIONS IN THE FIELD.

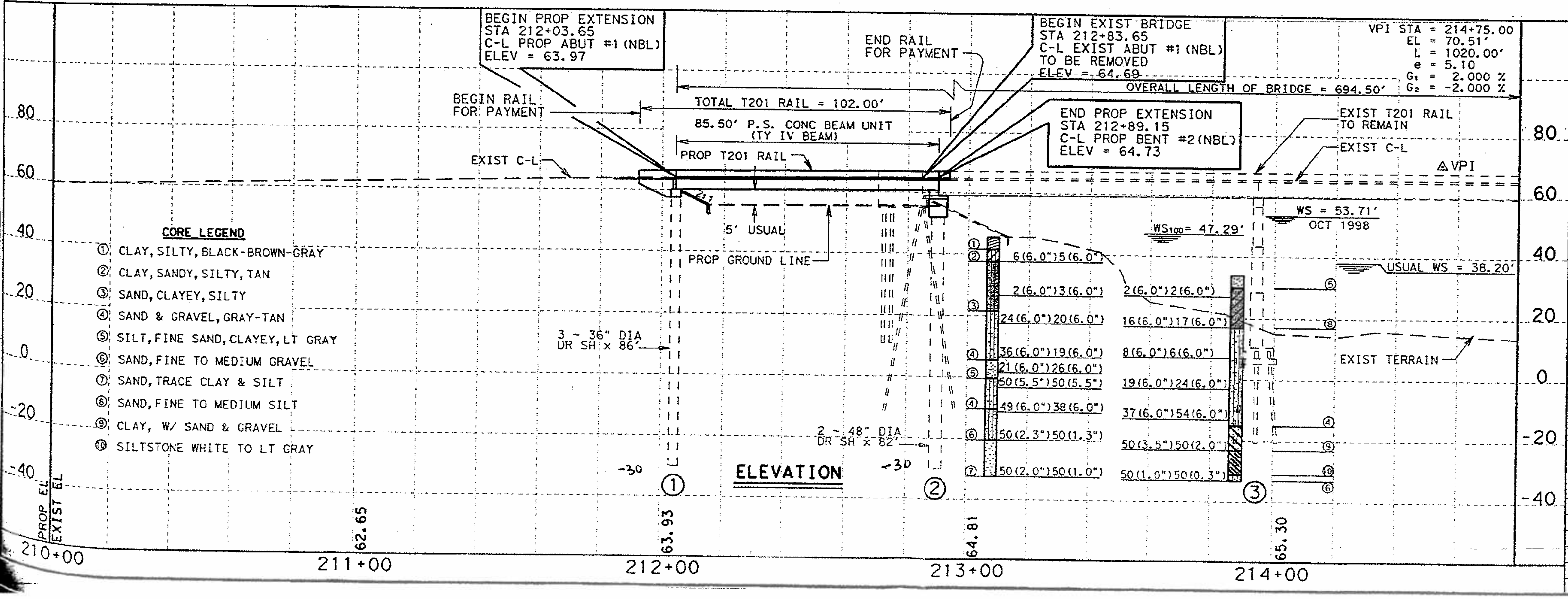
DESIGN SPEED: 70 MPH
EXIST ADT: 13,000 VPD
FUNCT CLASS: RURAL PRINCIPAL ARTERIAL

PROFILE ELEVATIONS ARE TOP OF CONC DECK.

STRUCTURE NO: 13235008805050

ALL EXIST ABUTMENTS AT BEARING N 41° 55′ 21" W

ALL PROP BENTS & ABUTMENTS AT BEARING N 41° 55′ 21" W



CORE LEGEND

- ① CLAY, SILTY, BLACK-BROWN-GRAY
- ② CLAY, SANDY, SILTY, TAN
- ③ SAND, CLAYEY, SILTY
- ④ SAND & GRAVEL, GRAY-TAN
- ⑤ SILT, FINE SAND, CLAYEY, LT GRAY
- ⑥ SAND, FINE TO MEDIUM GRAVEL
- ⑦ SAND, TRACE CLAY & SILT
- ⑧ SAND, FINE TO MEDIUM SILT
- ⑨ CLAY, W/ SAND & GRAVEL
- ⑩ SILTSTONE WHITE TO LT GRAY

ELEVATION

DAVID P. HOHMANN
60983
10/11/99

MARK P. McCLELLAND
60710
10/11/99

Texas Department of Transportation
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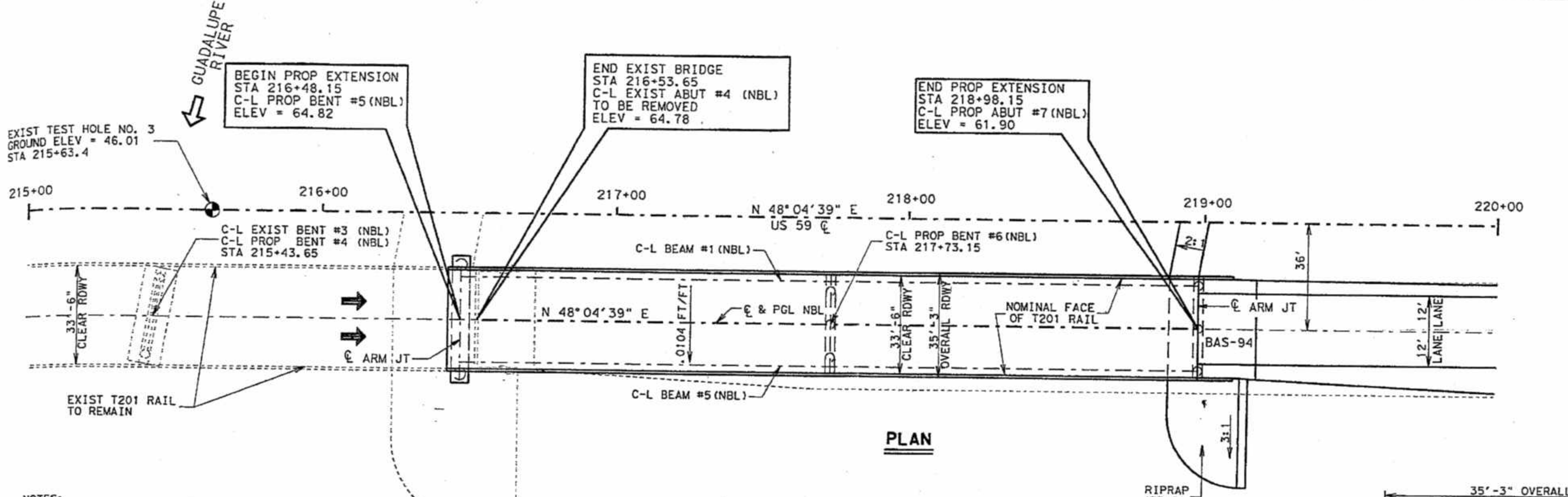
BRIDGE LAYOUT
GUADALUPE RIVER BRIDGE
US 59
NORTHBOUND LANES
(STRUCTURE NO. = 13235008805050)

BLAISE H. DREITNER
65843
Blaise H. Dreitner, P.E.
11-5-99

SHEET 1 OF 2 SHEETS

FED. RD. DIV. NO.	FEDERAL AID PROJECT NO.		SHEET NO.
6	ER 99(693)		58
STATE	DIST.	COUNTY	
TEXAS	YKM	VICTORIA	
CONT.	SECT.	JOB	HIGHWAY NO.
0088	05	075	US 59



ALL EXIST ABUTMENTS AT BEARING N 41° 55' 21" W

ALL PROP BENTS AND ABUTMENTS AT BEARING N 41° 55' 21" W

DAVID P. HOHMANN
60983
David Hohmann
10/11/99

MARK P. McCLELLAND
60710
Mark McClelland
10/11/99

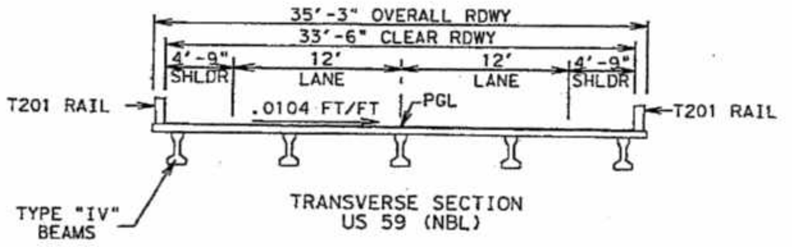
NOTES:

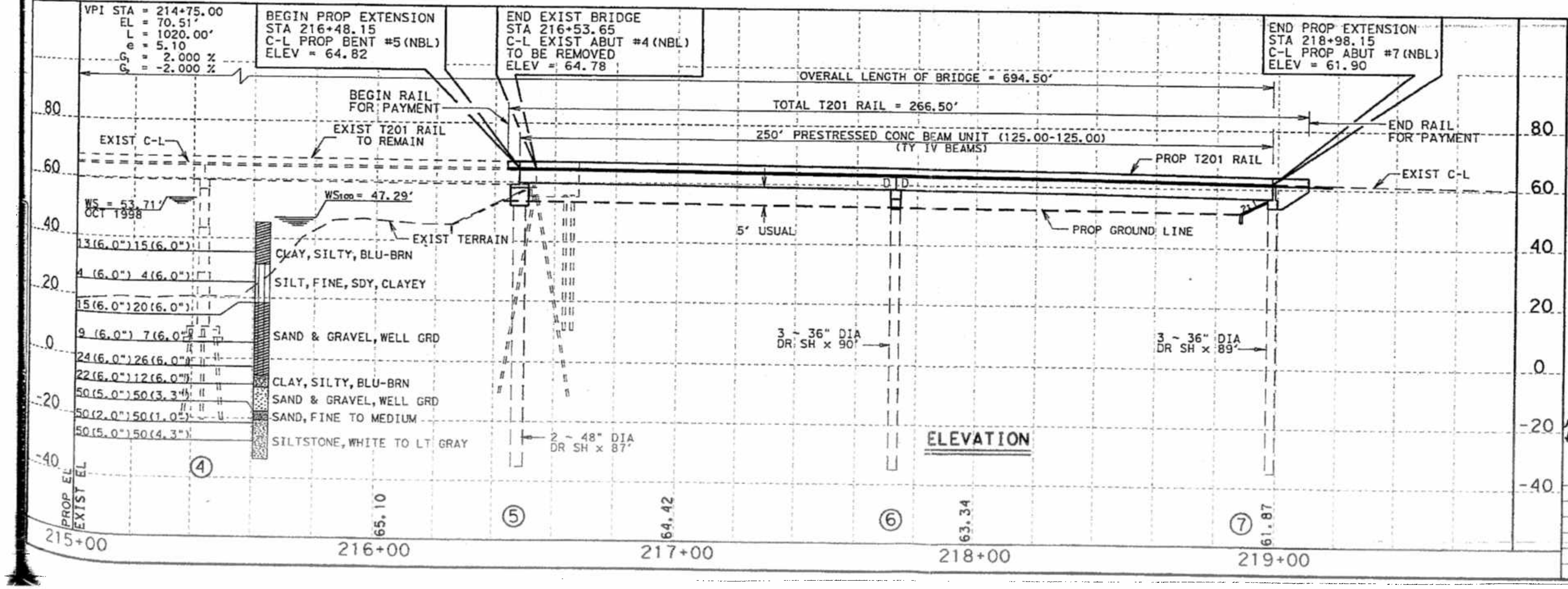
CONTRACTOR SHALL VERIFY ALL EXISTING DIMENSIONS AND ELEVATIONS IN THE FIELD.

DESIGN SPEED: 70 MPH
EXIST ADT: 13,000 VPD
FUNCT CLASS: RURAL PRINCIPAL ARTERIAL

PROFILE ELEVATIONS ARE TOP OF CONC DECK.

STRUCTURE NO: 13235008805050





Texas Department of Transportation
©1999 TxDOT

BRIDGE LAYOUT
GUADALUPE RIVER BRIDGE
US 59
NORTHBOUND LANES
(STRUCTURE NO. = 13235008805050)

BLAISE H. DREITNER
65843
Blaise H. Dreitner, P.E.
11-5-99

SHEET 2 OF 2 SHEETS

FED. RD. DIV. NO.	FEDERAL AID PROJECT NO.		SHEET NO.
6	ER 99 (693)		59
STATE	DIST.	COUNTY	
TEXAS	YKM	VICTORIA	
CONT.	SECT.	JOB	HIGHWAY NO.
0088	05	075	US 59

ATTACHMENT B:
SAMPLE DATA

(A). DATA ANALYSIS ON TILTMETER2 (MAY 28, 2009—AUGUST 9, 2010):

Figure D-B-1 shows the time history plot of the data obtained from Tiltmeter2 (including both Tiltmeter2a and Tiltmeter2b).

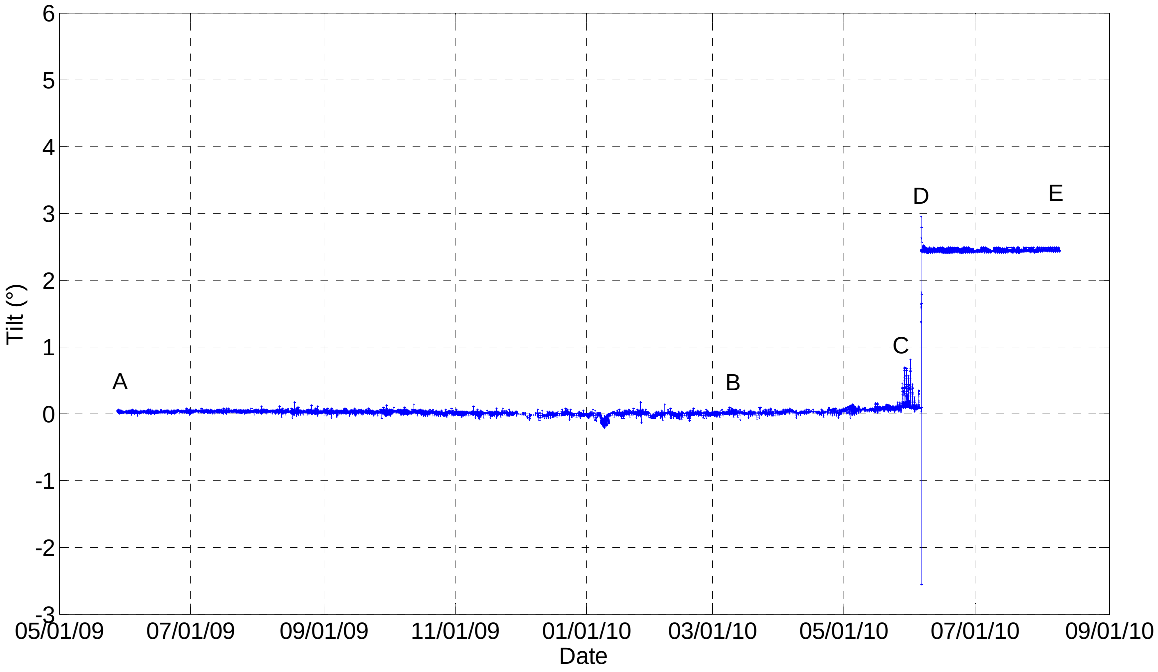


Figure D-B-1. Tiltmeter2 Time History Plot on US59 over Guadalupe River Bridge.

In Figure D-B-1, the point B represents the day when the system was reprogrammed. Point C represents the day when Tiltmeter2 was removed from the dual-axis tiltmeter enclosure to another location on the bridge deck.

Phase A-B (May 28, 2009–March 11, 2010)

Figure D-B-2 shows the time history plot of all the data collected from Tiltmeter2 and the temperature recorded before the system was reprogrammed in March 2010. The blue line in figure shows the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the data collected from Tiltmeter2.

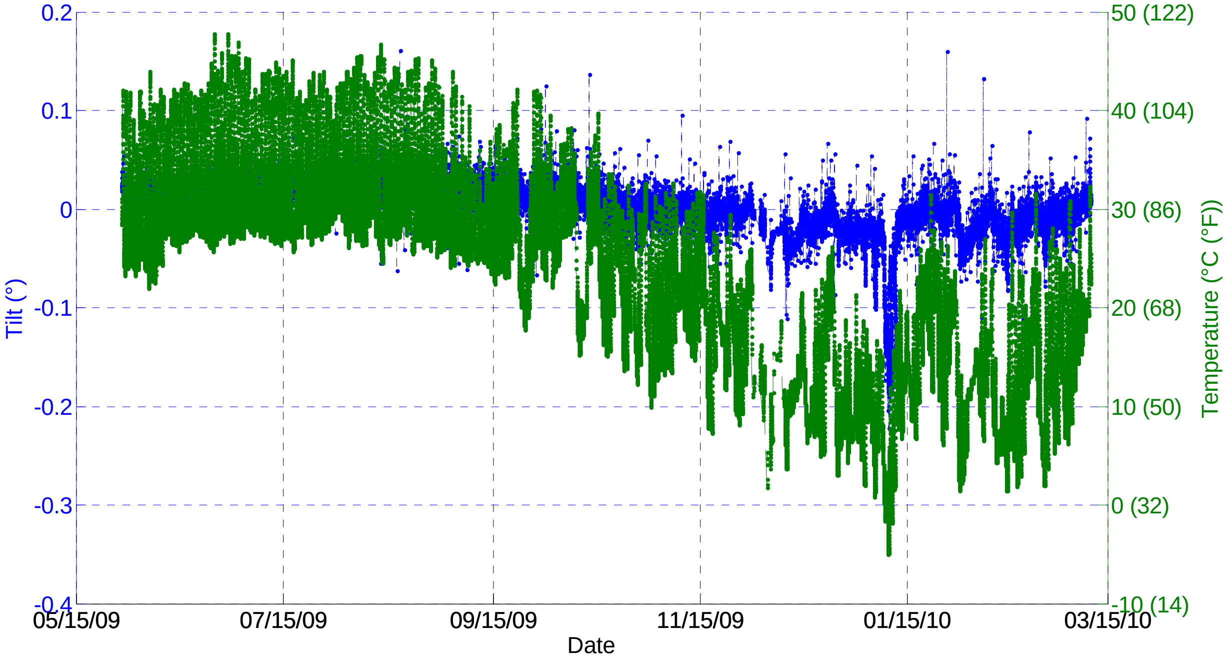


Figure D-B-2. Tiltmeter2 and Temperature Response Plot for Period AB.

Phase B-C (March 11, 2010–June 5, 2010)

Figure D-B-3 shows the time history plot of data collected from Tiltmeter2 and the temperature recorded after the system was reprogrammed in March 2010. The blue line shows the tilt angle of the deck around the flow direction axis (perpendicular to the traffic direction), and the green line in the figure shows the temperature in the master station box. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

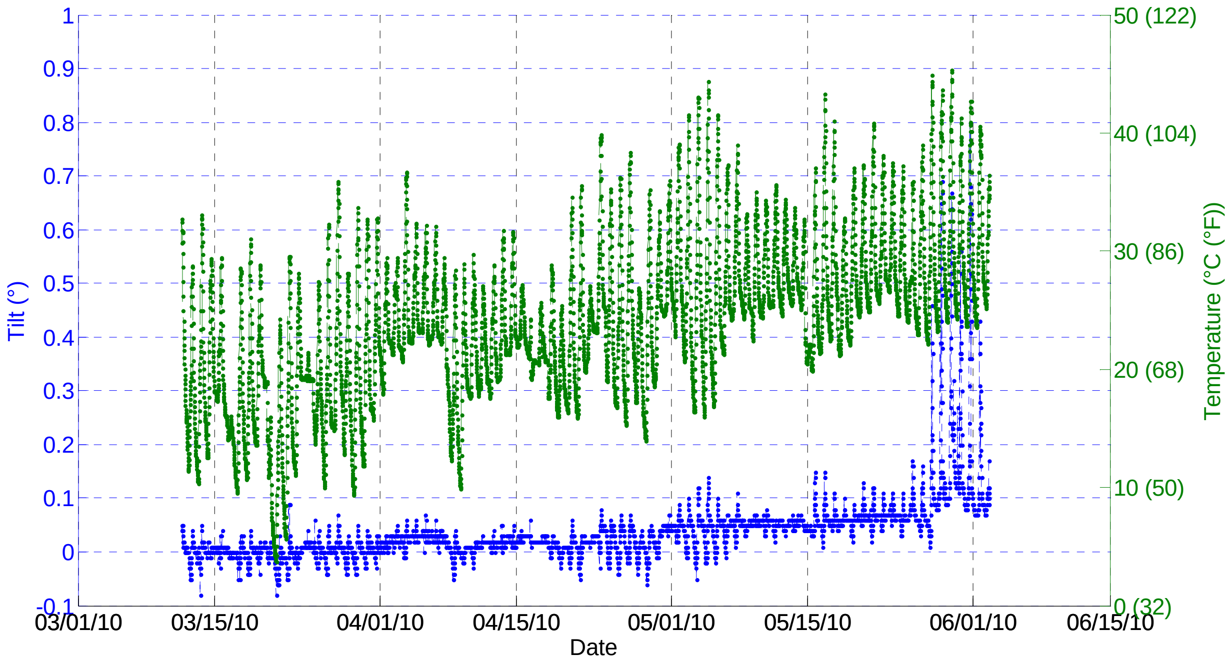


Figure D-B-3. Tiltmeter2 and Temperature Response Plot for Period BC.

Phase D-E (June 5, 2010–August 9, 2010)

Figure D-B-4 shows the time history plot of data collected from Tiltmeter2 and the temperature recorded in the modified monitoring system in June 2010. The correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

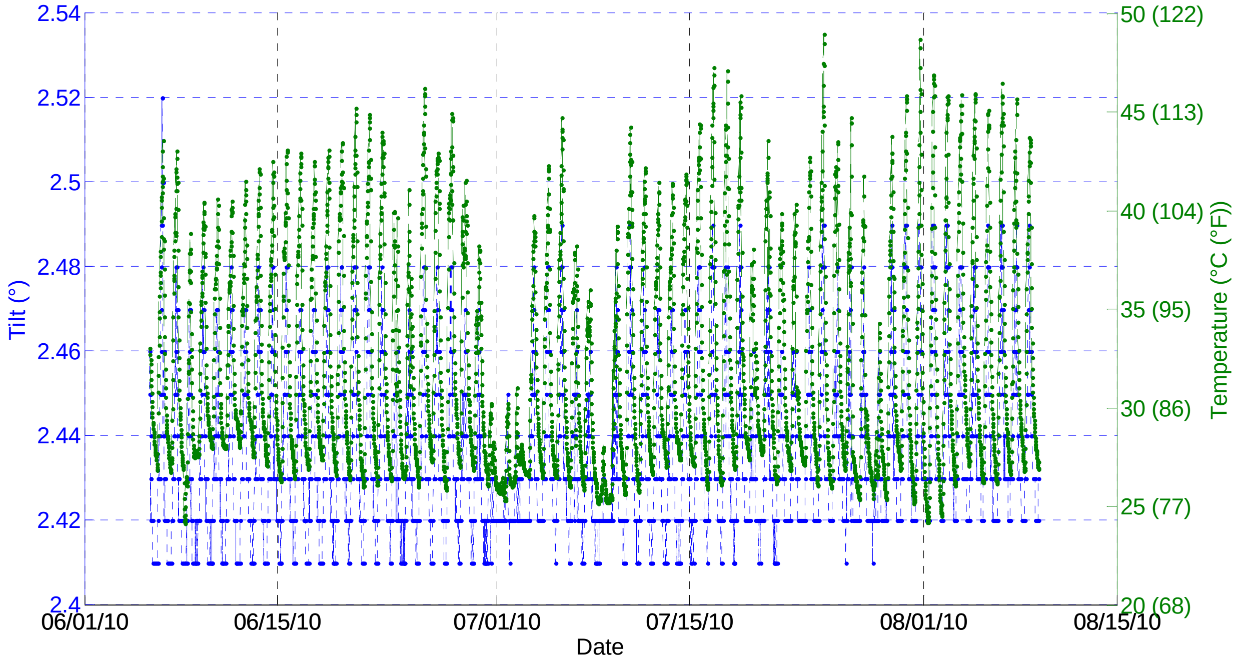


Figure D-B-4. Tiltmeter2 and Temperature Response Plot for Period DE.

(B). DATA ANALYSIS ON TILTMETER3 (MAY 28, 2009–AUGUST 9, 2010)

Figure D-B-5 shows the time history plot of the data collected from Tiltmeter3 located on the top of the pier measuring the tilt angle of the pier around the flow direction axis.

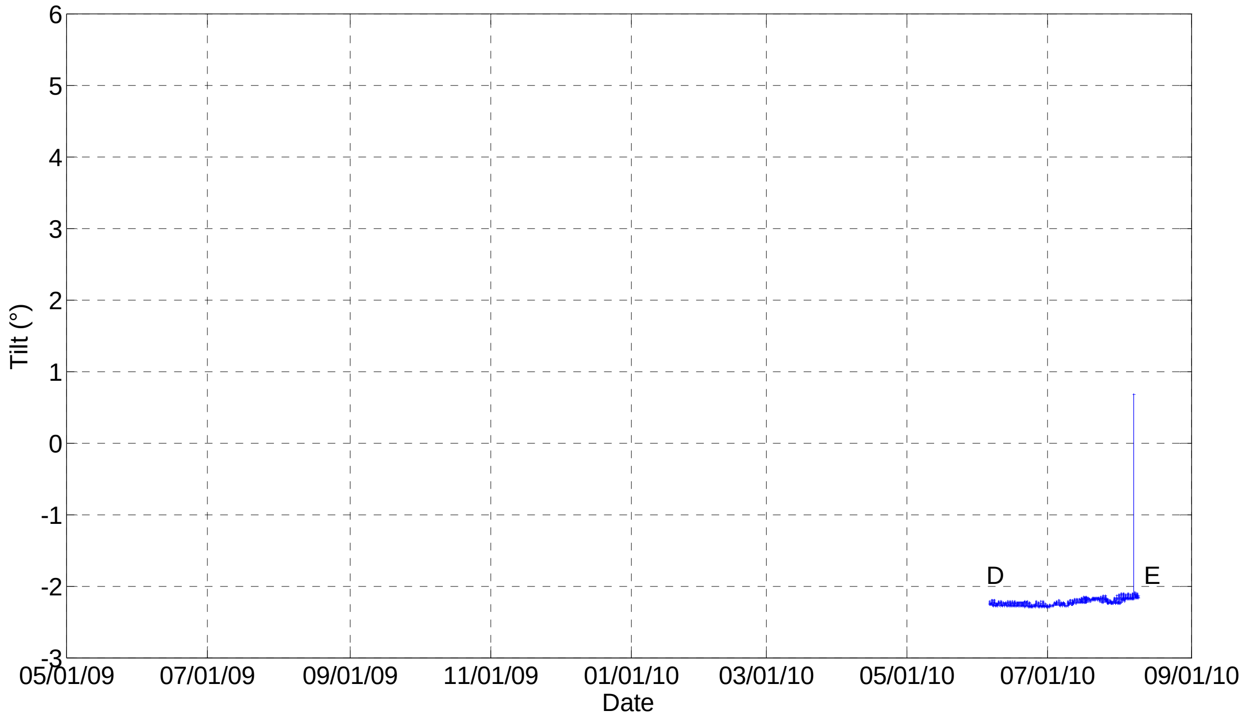


Figure D-B-5. Tiltmeter3 Time History Plot on US59 over Guadalupe River Bridge.

Figure D-B-5 shows all the data collected from Tiltmeter3 measuring the tilt angle of the pier around the flow direction axis. Tiltmeter3 was installed on June 5, 2010, therefore before June 5, 2010, no data points are present.

Phase D-E (June 5, 2010–August 9, 2010)

Figure D-B-6 shows the time history plot of all the data collected from Tiltmeter3 and the temperature recorded after the system was modified on June 5, 2010. The blue line shows the tilt angle of the pier around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the previous data collected from Tiltmeter3.

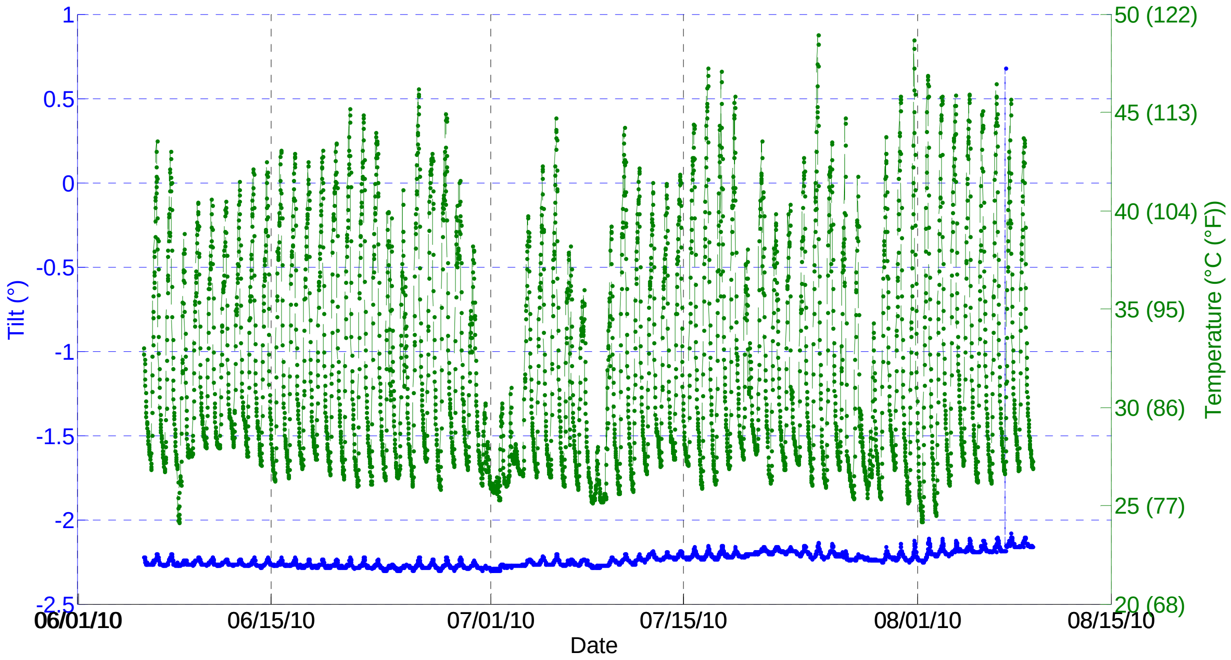


Figure D-B-6. Tiltmeter3 and Temperature Response Plot for Period DE.

(C). DATA ANALYSIS ON TILTMETER4 (MAY 28, 2009–AUGUST 9, 2010)

Figure D-B-7 shows the time history plot of the data collected from Tiltmeter4 located on the top of the pier measuring the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction).

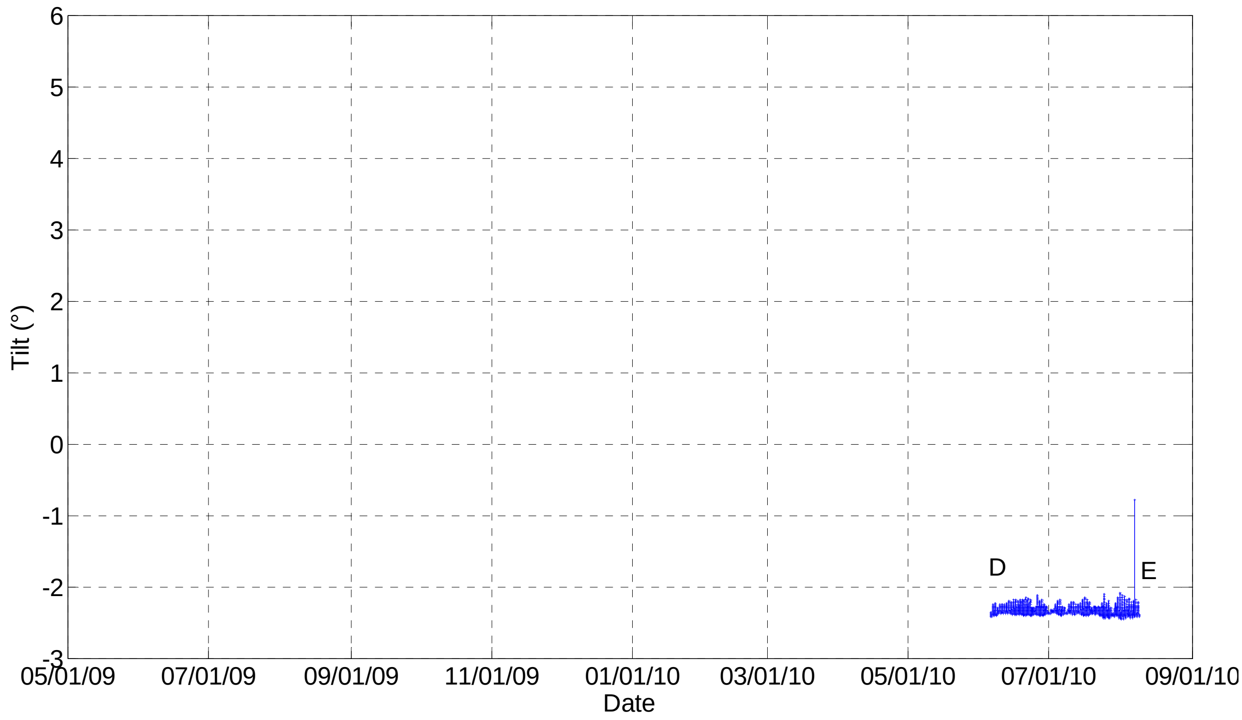


Figure D-B-7. Tiltmeter4 Time History Plot on US59 over Guadalupe River Bridge.

Figure D-B-7 shows all the data collected from Tiltmeter4 measuring the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction). Tiltmeter4 was installed on June 5, 2010, therefore before June 5, 2010, no data points are present.

Phase D-E (June 5, 2010–August 9, 2010)

Figure D-B-8 shows the time history plot of all the data collected from Tiltmeter4 and the temperature recorded after the system was modified on June 5, 2010. The blue line shows the tilt angle of the pier around the traffic direction axis (perpendicular to the flow direction), and the green line shows the temperature recorded by the sensor located in the master station enclosure. The positive correlation exists between the two quantities as observed in the previous data collected from Tiltmeter4.

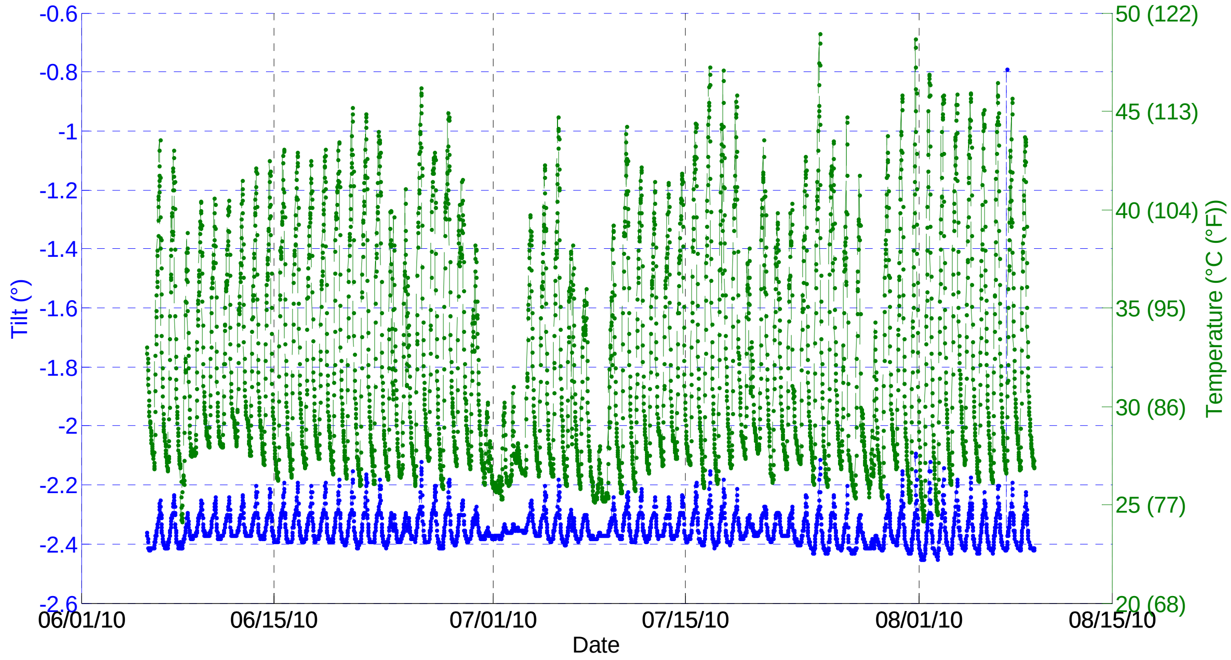


Figure D-B-8. Tiltmeter4 and Temperature Response Plot for Period DE.

ATTACHMENT C:
TXDOT CONTACT LIST AND PROTOCOLS

<u>TxDOT to insert:</u>

Contact list of those responsible for the scour monitoring system; to include name, title, telephone numbers (office, cell and home), email and pager (if applicable).

Any existing protocols for emergency including flood watch and bridge closure instructions for US59.

ATTACHMENT D:
INSPECTION CHECKLISTS

General Inspection Checklist for Scour Monitors

Bridge: ______________________________
Location: ______________________________
B.I.N.: ______________________________
Piers: ______________________________

Dates: ______________________________
____

Affiliation: ______________________________

Inspectors: ______________________________
____
____
____

Address: ______________________________
Telephone: ______________________________
Fax: ______________________________
E-mail:

Signature: ______________________________
Date: ______________________________

Bridge Name: ________________________
BIN # ___________________________

Scour Monitoring General Inspection Checklist

Sheet _____ of _____
Date:________
Inspector's Initials: ________

Bridge Information

1 Bridge Name ________________________

2 BIN # ________________________

3 Location of Scour Monitoring Equipment ________________________

(Please use a new sheet for each pier/abutment) ________________________

Inspection Checklist

4 Do any of the following show signs of damage, vandalism, corrosion, moisture exposure, insects, bird droppings, etc?

- **a) instrument boxes** ☐ Yes ☐ No ☐ Not Applicable
- **b) electrical conduits** ☐ Yes ☐ No ☐ Not Applicable
- **c) solar panels** ☐ Yes ☐ No ☐ Not Applicable
- **d) water stage** ☐ Yes ☐ No ☐ Not Applicable
- **e) antennas** ☐ Yes ☐ No ☐ Not Applicable
- **f) If "Yes" to any of the above, describe:** ________________________

Work Checklist

5 Have all the insides of the instrument boxes been cleaned of dust/debris? ☐ Yes ☐ No ☐ N/A

6 If moisture is present, has the moisure been removed? ☐ Yes ☐ No ☐ N/A

7 Have the faces of all solar panels been cleaned? ☐ Yes ☐ No ☐ N/A

Additional Comments and Final Conclusions

8 *(Please attach photographs and/or sketches if applicable)*

Inspector(s): ________________________
Title(s): ________________________
Agency/Company: ________________________
Address: ________________________
____
Telephone: ________________________
Fax: ________________________
E-mail: ________________________
Signature: ________________________
Date: ________________________

Maintenance Checklist for Scour Monitors

Bridge: ____________________
Location: ____________________
B.I.N.: ____________________
Piers: ____________________

Dates: ____________________
____

Affiliation: ____________________

Inspectors: ____________________
____
____
____

Address: ____________________
Telephone: ____________________
Fax: ____________________
E-mail:

Signature: ____________________
Date: ____________________

Bridge Name: ____________________
BIN # ___________________________

Scour Monitoring Maintenance Checklist

Sheet _____ of _____
Date:________
Inspector's Initials: ________

Bridge Information

1 **Bridge Name** ____________________
2 **BIN #** ____________________
3 **Location of Scour Monitoring Equipment** ____________________
(Please use a new sheet for each pier/abutment) ____________________

Maintenance Checklist

4 **Do any of the following show signs of damage, corrosion, moisture exposure, insects, etc?**
a) **Readily accessible instrument boxes** ☐ Yes ☐ No
b) **Readily accessible electrical conduit** ☐ Yes ☐ No
5 **What is the temperature inside of the area where the instrumentation is located?** ________ ^{o}F ______ ^{o}C

Work Checklist

6 **Have all the insides of instrument boxes been cleaned of dust, insects, etc?** ☐ Yes ☐ No ☐ N/A
7 **If moisture is present, has the moisture been removed?** ☐ Yes ☐ No ☐ N/A
☐ ☐

Additional Comments and Final Conclusions

9 *(Please attach photographs and/or sketches if applicable)*

Bridge Maintenance Personnel: ____________________
Title(s): ____________________
Agency/Company: ____________________
Address: ____________________
____
Telephone: ____________________
Fax: ____________________
E-mail: ____________________
Signature: ____________________
Date: ____________________

APPENDIX E:
SCOUR MONITORING PROTOCOL FOR
SH80 OVER SAN ANTONIO RIVER BRIDGE

TABLE OF CONTENTS

INTRODUCTION

The SH80 over San Antonio River Bridge crosses the San Antonio River northeast of the Karnes City, Texas. A scour monitoring system was installed in 2009 as part of a TxDOT project on scour monitoring using fixed instrumentation. Fixed scour monitors may be placed on a bridge structure, or in the streambed or on the banks near a bridge. They can measure bridge movements or changes in streambed elevations due to scour.

The SH80 Bridge installation includes two types of fixed scour monitoring instruments. These consist of four tiltmeters and two tethered buried switches. The tiltmeters measure the movement of the bridge in two directions. The tethered buried switches are buried in the streambed, and should they be exposed due to scour, they will be released in the water, float to the top, and transmit a signal.

The monitoring system was first installed at the SH80 over San Antonio River Bridge in October 2009. The sensors transmit data to a master station that transmits data to a server. The data are posted on website and it may be retrieved directly from the server.

DESCRIPTION OF THE BRIDGE AND SCOUR MONITORING SYSTEM

Figures E-1 and E-2 show the general location of the bridge in Google Earth and Google Map, respectively. In Figure E-1, P1 represents the compound web-wall on the northeast bank of the bridge. P2 represents the river pier. P3 and P4 are the two compound web-wall piers on the southwest bank of the bridge. SW abutment is the Southwest Abutment of the bridge.

Figure E-1. Layout of the SH80 Bridge Displaying Naming Convention for the Substructure Units (Source: Google Earth).

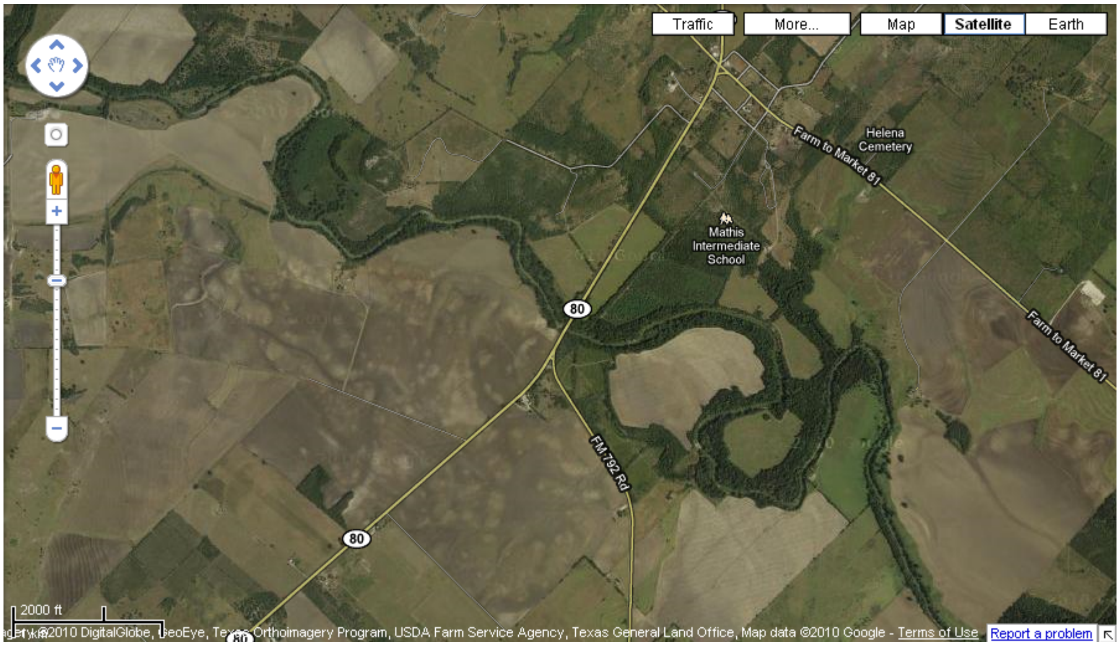


Figure E-2. Aerial View of the Meandering San Antonio River in the Vicinity of SH80 Bridge (Source: Google Map).

SAN ANTONIO RIVER

The San Antonio River is a major waterway that originates in central Texas in a cluster of springs in north central San Antonio, approximately 6.4 km (4 miles) north of downtown, and follows a southeastern path through the state. It eventually feeds into the Guadalupe River about 16 km (10 miles) from San Antonio Bay on the Gulf of Mexico. The river is 384 km (240 miles) long and crosses five counties, including Karnes County where the SH80 Bridge is located.

THE BRIDGE STRUCTURE

The bridge is a multi-span, 148 m (493 ft) long, two-lane bridge (Figure E-3). The main bridge consists of three spans, and is 63 m (207 ft 7 inches) long. It contains one river pier (P2), which has a concrete web-wall (Figure E-4). The second main span pier is a compound web-wall of cylindrical and trapezoidal bridge bents (P1) (Figure E-5). The supporting structure of the eastern bridge approach consists of a combination of cylindrical piers and square piers (Figure E-6). The datum used for the bridge and the scour monitoring system is the National Geodetic Vertical Datum (N.G.V.D.) 1929, elevation 0.0 ft, which is also Mean Sea Level. An elevation and plans of the bridge may be found in Attachment A.

Figure E-3. State Highway 80 over San Antonio River Bridge, Texas.

Figure E-4. River Pier with Concrete Web-Wall (P2).

Figure E-5. Compound Concrete Web-Wall Pier P1 on the Bridge Main Span.

Figure E-6. Eastern Approach Spans of SH80 over San Antonio River Bridge.

THE SOIL

The soil beneath the bridge foundation has large variations. The foundations of the piers rest on two types of soil, clay, and sand. Figure E-7 shows a riprap failure that occurred around Pier P1. This is the location where the TBS are buried. A soil sample was taken during the drilling process for the installation of the TBS. The soil beneath the Pier P3 is silty clay, which may be seen in Figure E-8.

(a) **(b)**

Figure E-7. Riprap Failure near Pier P1: (a) Elevation of Pier and (b) Close-Up View.

Figure E-8. Silty Clay at Pier P3.

THE SCOUR PROBLEM

The northern and southern banks downstream of the bridge are experiencing problems due to the meandering of the river. Vertical cut faces with layered soil with vegetation can be seen clearly in Figures E-9 and E-10. The river Pier P2, also has large accumulations of debris lodged at its upstream nose and this may contribute to scour (Figure E-4).

Figure E-9. Northern Bank of San Antonio River (Downstream of the Bridge).

Figure E-10. Southern Bank of San Antonio River (Downstream of the Bridge).

THE SCOUR MONITORING SYSTEM

The fixed sonar scour monitoring system employs tiltmeters and TBS to detect scour at the piers. The system at the bridge consists of one master control station, four tiltmeters in three enclosures, two TBS devices, and a temperature sensor (Figure E-11). A remote server may be set-up at the TxDOT designated office to retrieve and store the data, and to transmit it to Internet website for the project.

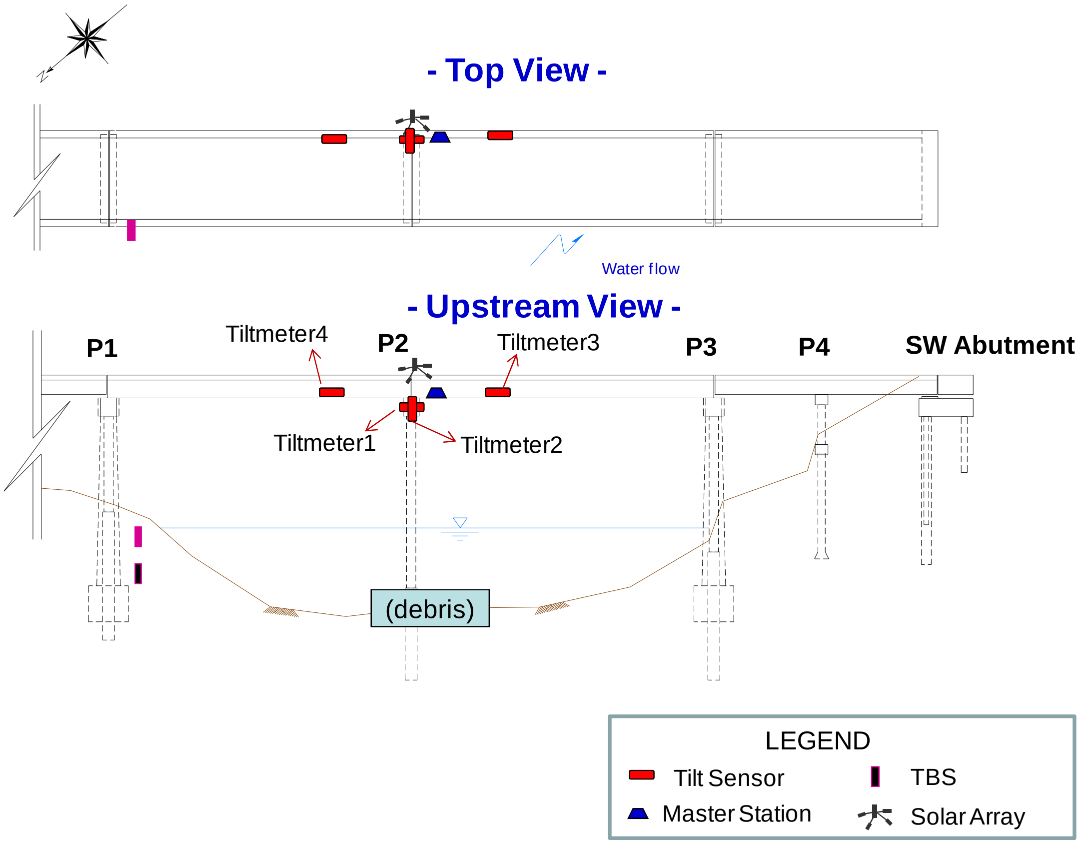


Figure E-11. Schematic Instrumentation on SH80 over San Antonio River Bridge.

The master control station contains the data acquisition module that collects and stores the data in the programmed format. The data are transmitted via modem from the master control station to the server/computer at the designated TxDOT district office. The solar panel maintains battery power to power the scour monitors. Photographs of the scour monitor system may be found in Section 3, Installation of the System.

The tiltmeters measure the movement of the bridge and are programmed to take measurements at specified intervals. The tiltmeters provide information about the tilt angle of the bridge. The tilt of the bridge may be correlated to the temperature. Two TBS devices are buried in the soil near Pier P1. The TBS1 is buried 12.3 m (41 ft) below the top of the bridge deck. The TBS2 is buried 11.4 m (38 ft) below the deck. The master station stores and transmits the data for the monitoring system for SH80 over San Antonio River Bridge.

This scour monitoring program is state-of-the-art, using equipment and concepts recommended by the Federal Highway Administration and the Transportation Research Board. TTI makes no guarantee that the program will provide complete notification of a scour failure. However, it does exceed all current inspection and monitoring programs currently established for scour. The program that follows is a guideline to establish a baseline for analyzing and reacting to various scour levels.

INSTALLATION OF THE SYSTEM

The bridge scour monitoring system was installed on SH80 over San Antonio River in October 2009, and modified in March 2010. Several parties participated in the installation. TxDOT was responsible for the traffic control. The TxDOT traffic inspection team was responsible for the snooper truck for below-deck access. Texas A&M University researchers and a consultant from ETI were responsible for the drilling, screwing, gluing, and the wiring of the instruments to the bridge.

INSTALLATION OF MASTER STATION

The master station is mounted near Pier P2. A solar panel was installed near the master station to provide power for monitoring system. Figure E-12 shows the installation of the master station at SH80 over San Antonio River Bridge.

(a) **(b)**

Figure E-12. Master Station on SH80 over San Antonio Bridge: (a) During Installation and (b) After Installation.

A data logger is programmed to receive data every 20 minutes and transmit the data by a cellular modem to a remote server. A monitoring website shows real time plots of the data.

INSTALLATION OF TBS EQUIPMENTS

Two TBS devices were installed in the soil near Pier P1. TBS1 was buried 2.4 m (8 ft) below the ground surface at a distance of 12.3 m (41 ft) below the top of the bridge deck. TBS2 was buried 0.9 m (3 ft) above TBS1 at a distance of 11.4 m (38 ft) below the top of the deck. A hand-auger was used to drill a hole into soil (Figure E-13). The drilled hole was 2.7 m (9 ft) deep.

The second step is to wire the TBS to the master station. The conduit that was connected with the TBS wire directly was fixed on Pier P1 vertically. The wire coming from the master station in the downstream side of the bridge was mounted in an “L” route along the bridge deck and Pier P1, covered by a cable-protection-pipe. Figure E-14 shows the photos after the installation of the TBS.

Figure E-13. Installation of the TBS Using a Hand-Auger.

(a) (b)

Figure E-14. Installed TBS Devices: (a) Conduit and (b) Close-Up View of Conduit.

INSTALLATION OF THE TILTMETERS

Four tiltmeters were installed on the SH80 Bridge as shown in Figure E-11. They are housed in three enclosures that are bolted and glued to the bridge at three locations. The sensors include one dual-axis tiltmeter and two single-axis tiltmeters. All the tiltmeters are wired to the data logger CR1000 located in the master station. The data logger is programmed to transmit data every 20 minutes. A snooper truck was used for the installation. Figures E-15 and E-16 show the tiltmeters installed on the bridge.

One dual-axis tiltmeter (Tiltmeter1 and Tiltmeter2) was installed on the pier cap of river Pier P2 to measure simultaneously the tilt angle of the bridge pier around two axes (Figure E-15). It measures the tilt angle of the pier in the flow direction axis and the tilt angle of the pier in the traffic direction axis (perpendicular to the flow direction). The two single-axis tiltmeters were installed on the bridge deck on the left and right side of river pier (P2), respectively. Both of them measure the tilt angle of the deck in the flow direction axis (perpendicular to the traffic direction). The horizontal distance between each single-axis tiltmeter and dual-axis tiltmeter is 3.75 m (12.5 ft).

(a) (b)

Figure E-15. Installed Dual-Axis Tiltmeter: (a) Side View and (b) Top View.

Figure E-16. Bridge Scour Monitoring System.

PROGRAMMING OF THE SYSTEM

The data collection system is programmed to take measurements at specified intervals. The settings at the time of the completion of the TxDOT project in August 2010 are for the master station to collect data every 20 minutes and to transmit the data to the server every hour.

DATA ACQUISITION

COMPUTER SET-UP

1. To collect the data, the Campbell Scientific LoggerNet software shall be installed and properly set-up on the TxDOT server designated for the scour monitoring system.
2. The designated computer shall be connected to a telephone line, capable of receiving incoming telephone calls.
3. The computer may be left on at all times to ensure immediate retrieval of data should a scour event occur.
4. The computer shall be properly secured against theft or damage.

NORMAL CIRCUMSTANCES: DOWNLOADING OF DATA

The system is programmed such that the data are automatically downloaded to the designated computer once every hour. If there is a concern and data are needed immediately or more frequently, the data may also be retrieved at any time by calling the data collection system using a computer that contains the Campbell Scientific LoggerNet software. See Section 6 for sample raw data output from the SH80 Bridge.

SPECIAL FLOOD EVENTS

The TxDOT district engineer responsible for the scour monitoring program shall integrate the scour monitoring system into the flood, storm, and hurricane watch programs and emergency protocols currently in place in the district. This program would include information on what triggers an emergency in the district, what emergency actions are taken, and what increased scour monitoring should be employed at the SH80 Bridge. This would include the frequency with which data will be taken and the identification of those responsible for retrieving and analyzing the data for the duration of the event, and for a designated time after the event.

HOW TO CONNECT AND DOWNLOAD THE DATA

The website link to download the raw data collected from sensors on SH80 over San Antonio River Bridge is shown below: http://scour.civil.tamu.edu/sh80_sensors.dat.

THE WEBSITE

The Scour Monitoring Center website address is currently on the TTI server at: http://scour.civil.tamu.edu. Those who have not used the TTI website for scour monitoring will need to obtain a login name and password in order to access the website.

The website contains three projects on the project list: Laboratory Experiments, US59 over Guadalupe River, and SH80 over San Antonio River. Also shown are one photo and one schematic of the instrumentation for each project. Clicking on the name or the photo of the SH80 Bridge will lead to the webpage containing the plots of data collected from the bridge sensors. The data logger on the bridge transmits data every 20 minutes. Hence the monitoring website shows the real-time plots every 20 minutes. The webpage should be refreshed every 20 minutes. The webpage shows the data for a period of 20 hours for the bridge.

INTERPRETATION OF SH80 OVER SAN ANTONIO RIVER BRIDGE WEBSITE PLOTS

The instrumentation on SH80 over San Antonio River Bridge includes one dual-axis tiltmeter on the pier (two plots showing tilt angle of the pier around both flow and traffic direction axes), two single-axis tiltmeters on the deck (two plots showing tilt angle of the deck around the flow direction axis), and two TBS devices (showing scour level reached). In addition to the above data, the master station records the temperature and the voltage battery condition for the monitoring system. A total of eight figures are shown on the webpage.

1. "Tiltmeter1 on the pier – around the flow direction axis," "Tiltmeter2 on the pier – around the traffic direction axis" plots show the tilt angle of the pier around the flow direction axis and traffic direction axis respectively. The unit is degrees.
2. "Tiltmeter3 on the deck –around the flow direction axis," "Tiltmeter4 on the deck – around the flow direction axis" plots show the tilt angle of the deck around the flow direction axis for two single-axis tiltmeters. The unit is degrees.
3. "Tethered Buried Switch 1" plot shows the status of TBS1 located at the bridge. The TBS1 was buried 2.4 m (8 ft) below the ground surface near the southwest abutment at a distance of 12.3 m (41 ft) below the top of the deck. "Tethered Buried Switch 2" plot shows the status of TBS2 located at the bridge. The TBS2 was buried 0.9 m (3 ft) above TBS1 at a distance of 11.4 m (38 ft) below the top of the deck.

  - If the TBS is in the vertical position, and has not floated out, the plot will show a smiling face (Figure E-17a).
  - If the TBS has floated out, the plot will show a danger sign (Figure E-17b).
  - If the wire of the switch is broken, the plot will show a disconnection logo (Figure E-17c).

4. “Temperature” plot shows the temperature in the master station. The unit is °C.
5. “Battery” plot shows the battery voltage in the master station. The unit is volts.

(a) **(b)** **(c)**

Figure E-17. Logos for the TBS Condition: (a) Smiling Face, (b) Danger Sign, and (c) Disconnection.

RECOMMENDATIONS FOR COMMUNICATION WITH THE SYSTEM

The website shows the real-time plot of all the sensor readings for a 20-hour window. Routine data monitoring consists of daily checking of the website and weekly analysis of the data collected by the monitoring system, which is currently stored on the server located at Texas A&M University, College Station, Texas. Also an on-site bridge inspection every year is recommended. On-site bridge inspection includes visual inspection of the bridge and the installed instruments.

Another option for data monitoring is using the “emailsend” program in LoggerNet, which can help to monitor the installed system easily. When the reading exceeds the set threshold or reading changes value for the tethered buried switches, the software will send an email to the person in charge of the monitoring system. The frequency of the email may be increased in a storm season to actively monitor the system.

DATA ANALYSIS

The monitoring system is set so that the data are collected by the data logger in the master station every 20 minutes and transmitted to the remote server every hour.

The data format for the scour monitoring system for the bridge scour is shown below:

"2010-06-25 21:20:00",7658,4,0.03,-0.06,0.1,-0.07,1,1,0,0,29.38,13.04

"2010-06-25 21:40:00",7659,4,0.03,-0.06,0.09,-0.07,1,1,0,0,28.95,13.04

"2010-06-25 22:00:00",7660,4,0.03,-0.06,0.09,-0.07,1,1,0,0,28.46,13.03

"2010-06-25 22:20:00",7661,4,0.03,-0.07,0.09,-0.07,1,1,0,0,28.1,13.03

The first column is the timestamp, including the date and time of the corresponding collected data; the second column is the counter; the third column is the alarm; the fourth column is the reading from Tiltmeter1 on the top of Pier P2 (degrees); the fifth column is the reading from Tiltmeter2 on the top of Pier P2 (degrees); the sixth column is the reading from Tiltmeter3 on the deck (degrees); the seventh column is the reading from Tiltmeter4 on the deck (degrees); the eighth column is the reading from TBS1 located at 12.3 m (41 ft) below the bridge deck; the ninth column is the reading from TBS2 located 11.4 m (38 ft) below the bridge deck; the tenth column is the reading of the first pulse; the eleventh column is the reading of the second pulse; the twelfth column is the temperature of the master station (°C); and the last column is the master station battery reading (volts).

Recommendations and comments on the nature of data observed during the research project are as follows:

1. If the tilt angle goes beyond the threshold, and immediately drops back, the data should be closely monitored. It does not necessarily require any action. If the tilt angle goes beyond the threshold, and lasts for 40 minutes (2 data points), an on-site inspection of the bridge is recommended and may also lead to the decision about the closure of the bridge.
2. If the TBS1 reading is 1, it means that the scour depth at Pier P2 is at least 2.1 m (7 ft). If the TBS2 reading is 1, it means that the scour depth at Pier P2 is at least 4.8 m (16 ft). When the TBS device floats out, maintenance of the bridge to mitigate scour is recommended.

Although no water stage sensor was installed on SH80 over San Antonio River Bridge, it is recommended that the USGS gages be used as part of the scour monitoring program, especially during the flood season. There are two USGS gages near the SH80 Bridge, one (USGS 08188500) is located in Goliad 56 km (35 miles) downstream from the bridge; the other (USGS 08183500) is located in Falls City 12.8 km (8 miles) upstream from the bridge.

TILTMETERS

The tiltmeters were installed on SH80 over San Antonio River Bridge in March 2010. The four tiltmeters are programmed to take readings every 20 minutes. The collected data are labeled as follows: X1Tilt, Y1Tilt, X2Tilt, and Y2Tilt. X1Tilt records the data collected from Tiltmeter1 on the pier cap of Pier P2, measuring the tilt angle of the pier in the flow direction axis. Y1Tilt records the data collected from Tiltmeter2 on the top of Pier P2, measuring the tilt angle of the pier in the traffic direction axis. X2Tilt records the data collected from Tiltmeter3 on the deck, measuring the tilt angle of the deck in the flow direction axis. Y2Tilt records the data collected from Tiltmeter4 on the deck, measuring the tilt angle of the deck in the flow direction axis at second location. Figure E-18 shows the location of tiltmeters on SH80 over San Antonio River Bridge.

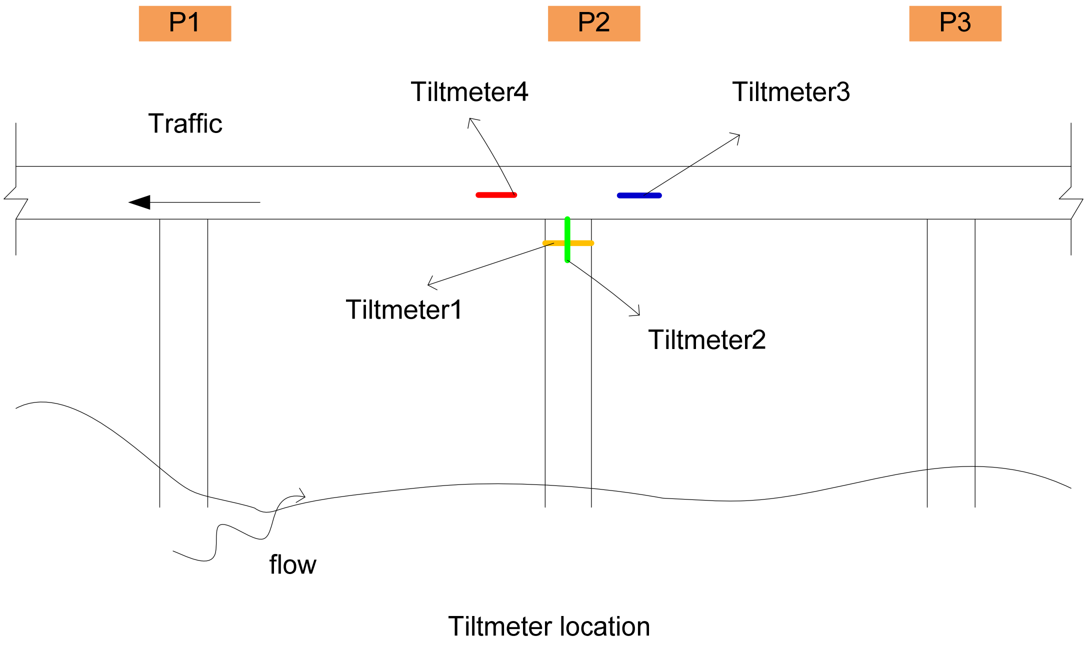


Figure E-18. Layout of the Tiltmeter Locations on SH80 over San Antonio River Bridge.

The following is a discussion of the data obtained from Tiltmeter1 from March 11, 2010 till August 9, 2010. Additional data and discussions of the data from the other tiltmeters may be found in Attachment B.

Figure E-19 shows the time history plot of the data collected from Tiltmeter1 located on the top of Pier P2 measuring the tilt angle of the pier in the flow direction axis.

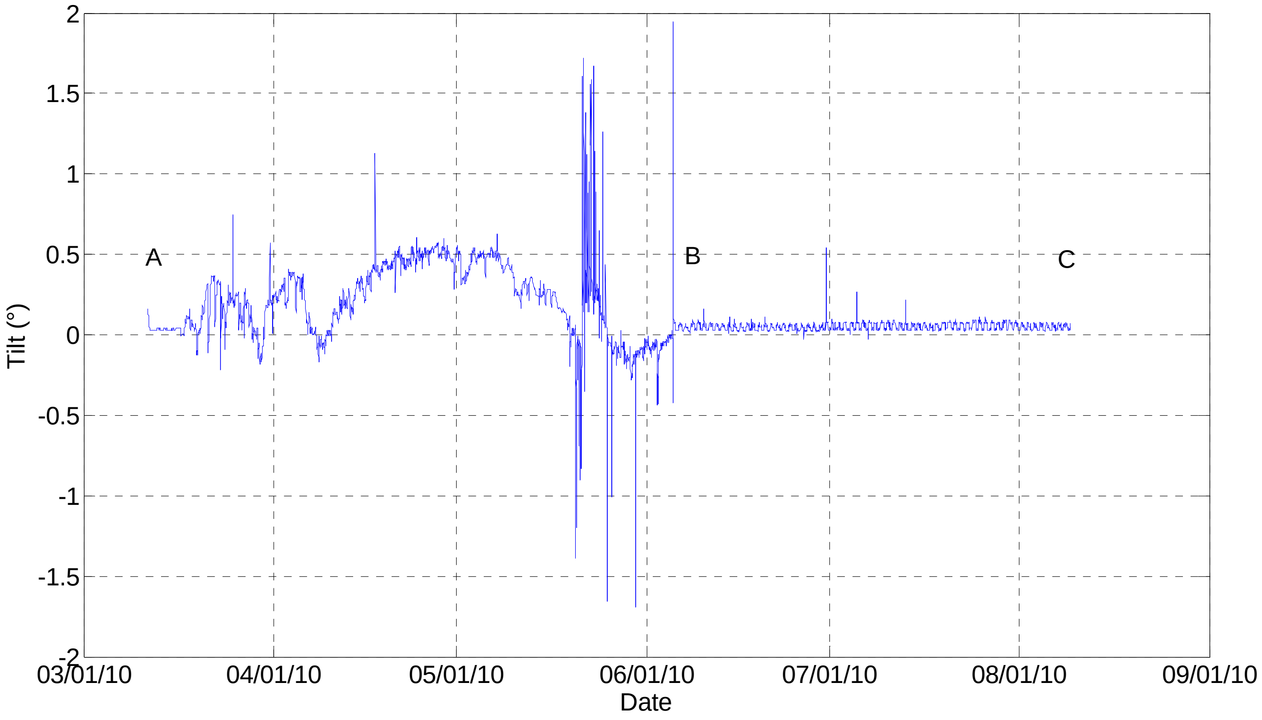


Figure E-19. Tiltmeter1 Time History Plot on SH80 over San Antonio River Bridge.

The data collected from Tiltmeter1 has been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter1 was installed on the bridge on March 11, 2010. Point B represents the day when TTI researchers adjusted the sensor on June 5, 2010. Point C represents the last day of data analysis for this research project report, August 9, 2010. From Figure E-19, it can be seen that Tiltmeter1 did not work properly before June 5, 2010, since the reading fluctuated from −1.5° to 1.5°. But after the replacement of Tiltmeter1, the output showed reasonable data.

The readings from Tiltmeter1 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure E-20 to study the correlation between these two quantities. The blue line shows the tilt angle of the pier in the flow direction axis, and the green line shows the temperature reading in the master station box. It can be inferred from the figure that the two curves of rotation of the pier and temperature are correlated. This is due to the response of the bridge pier, on which Tiltmeter1 is mounted, to the change in temperature.

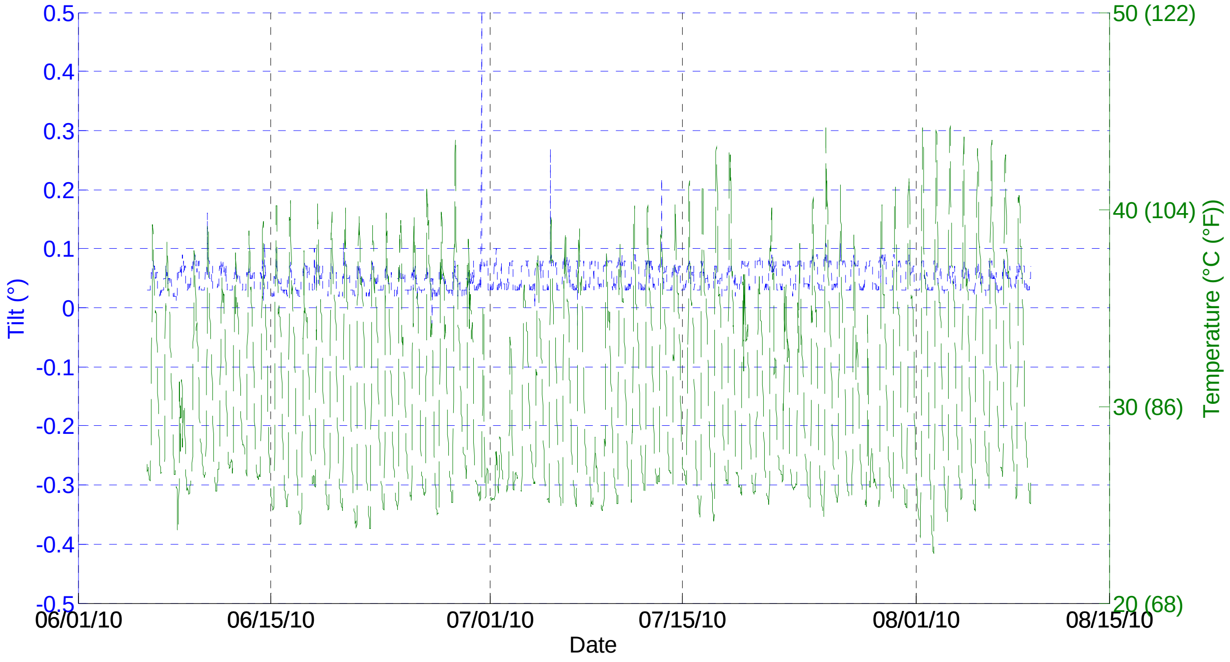


Figure E-20. Tiltmeter1 and Temperature Response Plot for Phase B-C.

TETHERED BURIED SWITCHES

The data for the two TBS devices was collected from 12:10 p.m. on October 16, 2009, to August 9, 2010. If the TBS is in the vertical position and the trigger has not been launched, the sensor will transmit a value of 1 to the data acquisition system. If the switch is triggered and the scour reaches the buried level, the sensor will transmit a value of 2 to the data acquisition system. If the wire of the switch is broken, the sensor will transmit a value of 3 to the data acquisition system. Figure E-21 shows the data collected from the two TBS devices installed on SH80 over San Antonio River Bridge. TBS1 was buried 2.4 m (8 ft) below the ground surface, near the southwest abutment at a distance of 12.3 m (41 ft) below the top of the deck. TBS2 was buried 0.9 m (3 ft) above TBS1 at a distance of 11.4 m (38 ft) below the top of the deck.

The connection was lost with the bridge for approximately one and a half months, from late October to early December in 2009. This is the reason for the gap in the data during this period Figure E-21.

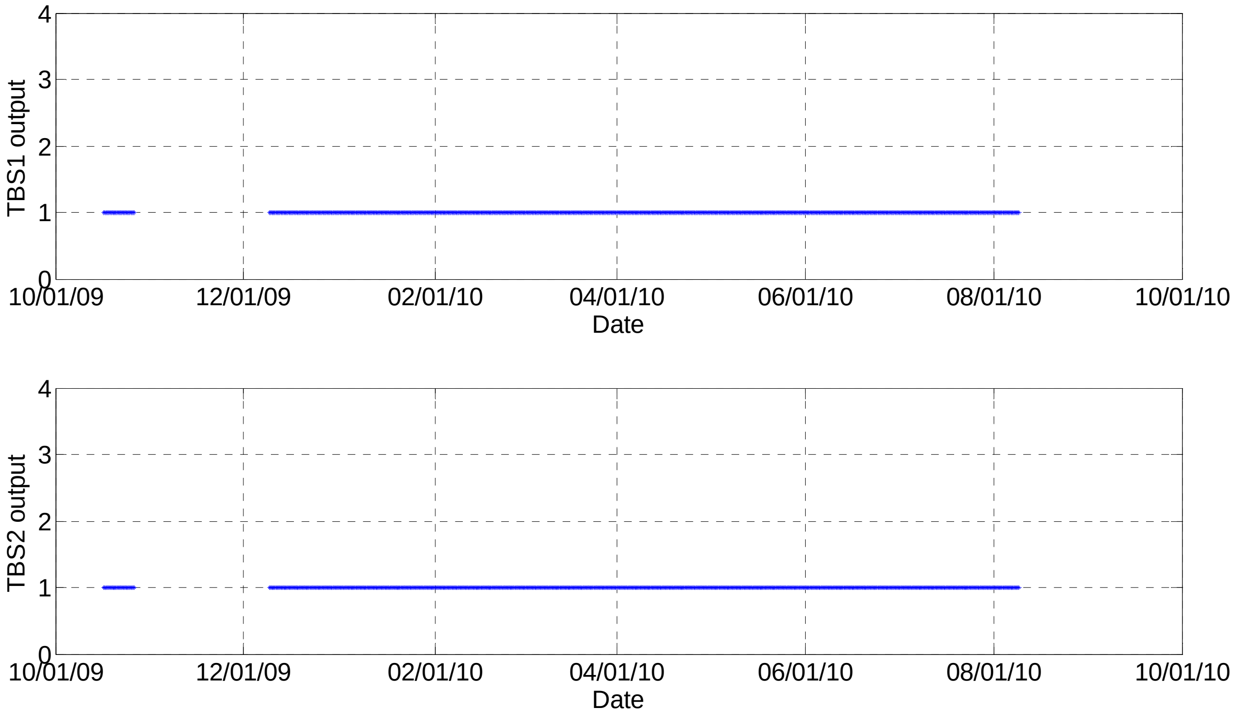


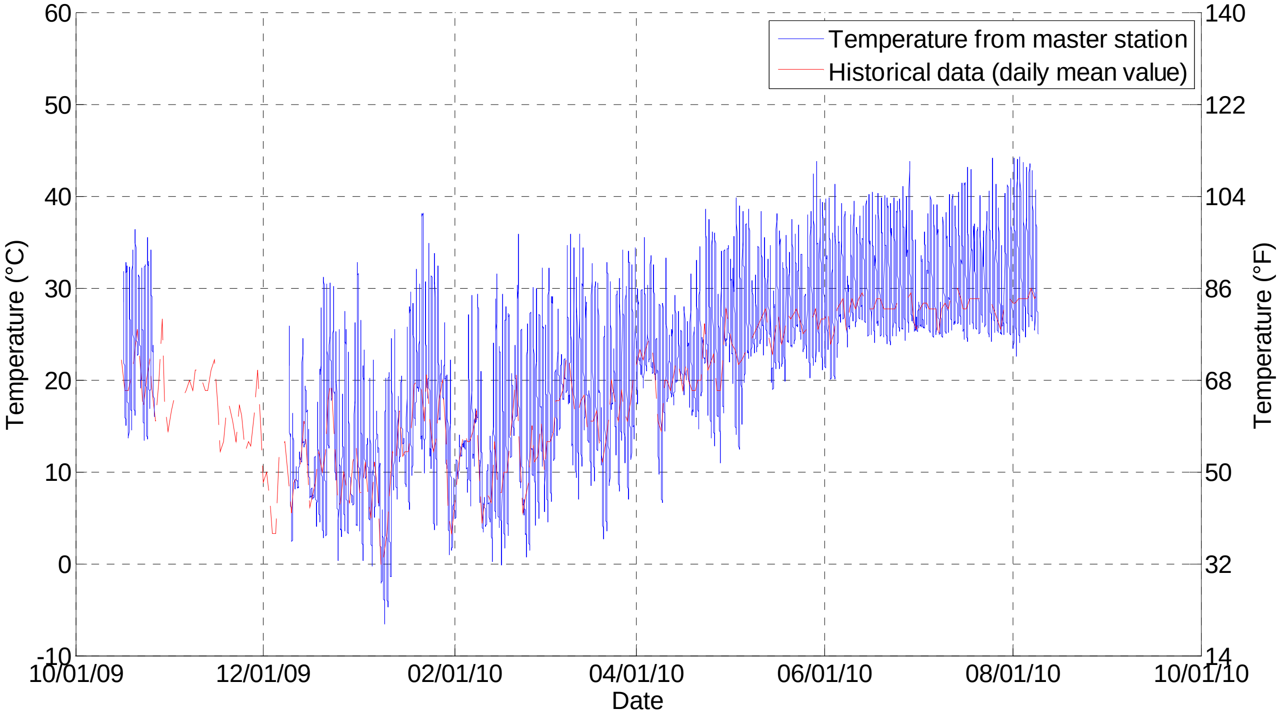
Figure E-21. TBS Response on SH80 over San Antonio River Bridge.

The TBS devices are giving a constant value of 1, which means that the scour depths have not reached the depths of the buried instruments.

OTHER READINGS

In addition to the data from the installed scour monitoring instruments on SH80 over San Antonio River Bridge, the system also records the readings from battery voltage and the temperature sensor located in the master sensor enclosure. Figure E-22 shows the temperature reading for the system. The daily mean temperature in Karnes City, Texas, is also plotted in the figure for comparison. The temperature data from the monitoring system correlates well with the daily mean temperature in Karnes City, Texas. Figure E-23 shows the battery voltage readings for the system. The battery voltage is also correlates with the temperature data.

The connection was lost with the bridge for approximately one and a half month, from late October to early December in 2009. This is the reason for gap in the data during that period in Figures E-22 and E-23.



*Historical data source:

http://www.wunderground.com/history/airport/KBEA/2009/10/16/CustomHistory.html?dayend=21&monthend=2&yearend=2010&req_city=NA&req_state=NA&req_statename=NA

Figure E-22. Temperature Readings for SH80 over San Antonio River Bridge.

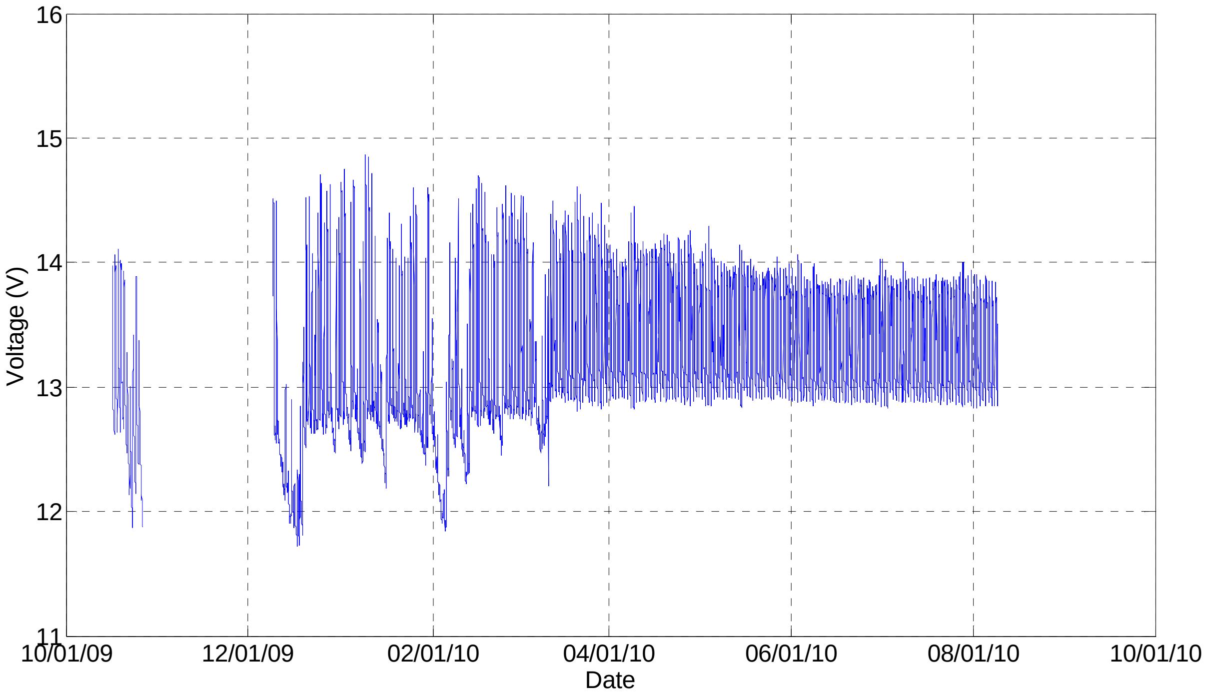


Figure E-23. Battery Readings for SH80 over San Antonio River Bridge.

INTERPRETATION OF THE DATA

Following are some guidelines to interpret the data from the scour monitoring system.

TILTMETERS

There are four tiltmeters installed on SH80 over San Antonio River Bridge (Figure E-18). The tiltmeters record the tilt angles at different locations on the bridge in both the flow and traffic directions. A consistent reading indicates that the bridge is stable and significant scour has not been detected. If the readings exceeds a preset threshold value, then a warning should be issued and consideration given to closure of the bridge.

The thresholds for Tiltmeter1 and Tiltmeter2 on SH80 over San Antonio River Bridge are 0.5° for checking the bridge, 1° for closing the bridge. The thresholds for Tiltmeter3 and Tiltmeter4 on SH80 over San Antonio River Bridge are 0.75° for checking the bridge, 1.5° for closing the bridge.

TETHERED BURIED SWITCHES

The reading of 1 means the TBS is in the vertical position and the trigger has not been launched; a reading of 2 means the switch is in the horizontal position, indicating the scour hole has reached the instrument level; and a reading of 3 means the wire of the switch is broken. The floating out of the TBS device means that the scour depth has reached the depth at which the instrument was buried.

SYSTEM RECOMMENDATIONS

If the tiltmeters indicate movement in excess of the checking/alert and closing/critical angles and/or the tethered buried switches float to the top and transmit a signal, TxDOT shall review the data and consider the necessary steps, if any, to be taken. The district may alert the authorities so that the public is diverted from using the bridge or the bridge may be closed. If the alert tiltmeter readings are obtained or the TBS2 is activated, TxDOT shall immediately convene a meeting to discuss the installation of scour countermeasures. Interim mitigation measures may be taken, which may include the following:

1. Check the scour monitoring data every hour for a period of 12 hours. After that time, the data shall be checked every 12 hours for the next 72 hours.
2. Confirm these scour depths with alternate methodologies.
3. Implement or increase the frequency of the land field monitoring of the piers.
4. Conduct a Diving Inspection of the problem pier(s) and adjacent pier.
5. Consideration should be given to increasing the frequency of Diving Inspections and underwater surveys.
6. Consider the addition of pier protection.
7. Consider the addition of pier strengthening.

CLOSURE OF THE BRIDGE

If a bridge closure is recommended, TxDOT forces shall be responsible for a complete shutdown of the roadways as per TxDOT procedures. In the event of closure, the TxDOT instructions may be found in Attachment C of this protocol. Once a bridge closure has occurred, it shall be necessary to confirm the measurements of the devices through above and/or underwater inspections as outlined in Section 6.

BRIDGE INSPECTIONS BASED ON SCOUR DATA

TxDOT shall ensure that the department sends engineers to the bridge for a visual inspection as soon as it is deemed safe to do so to confirm the measurements taken by the fixed sonar monitoring devices. If the inspectors confirm the scour critical measurements that were taken by the fixed devices, the bridge shall remain closed and a Diving Inspection shall be conducted. If the inspectors determine that the streambed elevations that are higher those reported by the fixed devices, the elevations shall be reported to the department, and a decision shall be made regarding the necessity of a Diving Inspection.

A Diving Inspection may be required after the report of a critical scour depths or movement of the bridge. The Diving Consultant for the emergency Diving Inspection contract shall do this work. If there is an event that requires a Diving Inspection, the Diving Consultant Project Manager shall be contacted.

ACCESS

Access to the scour monitoring system is limited. It is recommended that the items listed below, as well as those discussed in the following sections be considered before performing maintenance, repairs or inspections.

- Keys may be required to open instrumentation boxes or doors.
- A snooper, manlift, or a climber is required to access portions of the instrumentation mounted on the pier and bridge fascia (Figure E-24).
- Lane closures may be required. Proper maintenance and protection of traffic as well as inspection/repair crew safety will be needed.
- Security clearance may be required to access parts or all of the bridge. Contact the appropriate authorities and notify them when and where the work is scheduled to take place.

- **Figure E-24. Repairs Conducted by a Climber in Order to Avoid Lane Closures.**

MAINTENANCE

The TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate TxDOT Bridge maintenance group for the routine maintenance of the system. The following items are included as maintenance requirements for the bridge:

- "Contact Information" in Attachment C shall be updated annually (i.e., January 31) to ensure that all names, addresses, and contact numbers are current. The Group responsible for this update shall contact all the individuals listed in Attachment C to make them aware or remind them of their responsibilities regarding the scour monitoring program.
- Indoor instrument boxes and electrical conduit shall be visually inspected for corrosion, overheating, insects, moisture, etc.
- The thermostat reading or temperature reading shall be recorded for areas containing instruments.

A Scour Monitoring Maintenance Checklist has been included in Attachment D. This form shall be completed after all routine maintenance, and kept on file in the TxDOT district office.

GENERAL INSPECTION

The above-water instruments need to be checked during biennial or other bridge inspections. Because all of the instruments are sealed, the inspection will simply require checking of the instrument for visible damages. Routine monitoring provides the best chance of catching any irregularities.

The TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate group for the inspection of the monitoring system components. This work shall be performed by the appropriate bridge maintenance group or the consultant retained for the inspection of the bridge. The following items are included in the list of required work:

- Inspect all outdoor instruments boxes for corrosion, damage, vandalism, leaks, etc.
- Inspect the outdoor/above water conduit and cable for corrosion, damage, vandalism, leaks, etc.
- Remove any spiders, mice nests, bird droppings, etc. from all outdoor instrument boxes.
- Check the door gasket and/or seal.
- Check and clean the solar panels.

A Scour Monitoring General Inspection Checklist has been included in Attachment D. This form shall be completed after all general inspections and kept on file in the TxDOT district office.

TTI may be contacted should there be any questions with regard to the general inspection of the system or new parts are required for the system. If the general inspection reveals that the system requires maintenance and/or repair, this work shall be performed by TxDOT maintenance, an electrical contractor, or other appropriate group.

CONSTRUCTION WORK AT THE BRIDGE

If any construction work is done near the fixed scour monitors, including work unrelated to the bridge, provisions shall be made to protect the scour monitoring system. Upon completion of the work, the monitors shall be checked to ensure the monitors had not been damaged. If they are damaged, they shall be repaired at the expense of the contractor.

In the event that stone fill, riprap, or any type of armor protection is placed near or around piers or abutments with fixed monitoring devices, the contractor shall exercise reasonable care to avoid damaging these devices. The monitors shall be checked after the conclusion of the placement of the armor protection.

SYSTEM MALFUNCTION

In the event of a scour monitoring system malfunction, the TxDOT engineer in charge of the scour monitoring system shall be responsible for notifying the appropriate groups for troubleshooting of the scour monitoring devices. Depending on the nature of the work, it may be done by the TxDOT maintenance group, a general contractor, or an electrical contractor.

If the system cannot be repaired using the suggestions outlined below, TxDOT may contact TTI. If the problem cannot be resolved via instructions given by telephone, arrangements may be made for TTI to visit the site.

The following are recommendations for troubleshooting various system malfunctions:

1. If the instruments do not turn on at the scheduled sample intervals:

- Check the battery voltage and all power connections.
- Review the past data and look for anomalies in the daily battery voltages. If there are anomalies, see if there have been any events (i.e., a power outage or damage to the system) that might have caused the problem.
- If the battery voltage is less than 12.2 volts, this is an indication that there is a problem.
- If the battery voltage is low (less than 11 volts), check the output of the solar panel, if applicable, with the sun shining, and make sure it is producing at least 15 volts before the regulator, and about 13.5 volts after the regulator.
- If the solar panel is functioning properly, either (1) the battery is faulty or was drawn down by lack of solar energy for recharging (e.g., an extended period of overcast weather), or (2) the data logger staying turned on too long, or cycling too frequently, either from an error in programming or a faulty data logger.
- In either case, replace the battery with a fully charged battery and evaluate the data logger functioning for a short sample interval (e.g., 5 minutes). If the data logger appears to be functioning properly, re-program for the regular sample interval and periodically check the battery voltage (e.g., every week) to insure proper operation.
- If the data logger appears to be malfunctioning, check the programming and/or follow the troubleshooting instructions from the manufacturer.

2. If the tiltmeter readings are erratic:

- Check for high (14.0+ volts) battery readings.
- Check to make sure the charger is functioning properly.

3. If the tiltmeter readings remain fixed at a single elevation for a prolonged period of time:

- Check the battery voltage and all power connections (see Item 1).
- Check the tiltmeter to ensure that it is still securely connected. Check all wiring.

4. If a call to the automated telephone service results in a busy signal, no dial tone, or if it rings but there is no answer:

- Contact the local telephone provider's service department. Ask the telephone service representative to check the line to determine whether it is an internal or external problem. A technician will be sent to the site if the problem is external.
- If it is determined that it is a problem with an outside line, schedule a repair.
- If it is determined that it is a problem with an inside line, check connections with the telephone line and modem.

5. If a call to the automated telephone service results in "0" elevation readings:

- Wait a few minutes and try again. The system may have been in the process of downloading data.

The initial monitoring system worked well for 10 days. After that the connection with the bridge was lost due to the loss of IP address with Verizon. The problem was fixed in October 2009.

RESPONSIBILITY AND CONTACT LIST

Those responsible for the scour monitoring system and/or implementation of emergency procedures should be included in Attachment C: TxDOT Contact List. TxDOT District emergency protocols including flood watch and bridge closure may also found in Attachment C. The contact list shall be updated once a year by January 31 to reflect any changes.

This document shall be revised to reflect any changes resulting from field conditions, new information obtained with future testing or analyses, and/or new technology. A distribution list shall be maintained by the TxDOT engineer in charge of the scour monitoring system. That person shall be sent all future revisions. The revisions shall be incorporated and distributed as necessary.

ATTACHMENT A:
BRIDGE PLANS

16	TEXAS	C 348-4-25	1
STATE DIST. NO.	COUNTY	STATE CONTROL NO.	HIGHWAY NO.
16	KARNES	348-4-25	SH 80

C/Chapman

#11

STATE OF TEXAS
STATE HIGHWAY DEPARTMENT

PLANS OF PROPOSED STATE HIGHWAY IMPROVEMENT

STATE PROJECT C 348-4-25

SCALES: PLAN 1 IN. = 100 FT.
PROFILE 1 IN. HOR. = 100 FT., 1 IN. VERT. = 10 FT.
CROSS SECTIONS 1 IN. HOR. AND VERT. = 5 FT.
OTHERS AS NOTED.

NET LENGTH OF PROJECT = 32,521.62 FT. = 6.158 MI.

ROADWAY =	31,814.87 FT. =	6.025 MI.
BRIDGES =	706.75 FT. =	0.133 MI.
TOTAL =	32,521.62 FT. =	6.158 MI.

KARNES COUNTY
STATE HIGHWAY NO. 80

FROM STATE HIGHWAY 123 IN KARNES CITY TO HELENA

GRADING, STRUCTURES, LIME STABILIZED SALVAGED BASE AND FOUNDATION COURSE, FLEXIBLE BASE, ONE COURSE SURFACE TREATMENT AND ASPHALTIC CONCRETE PAVEMENT

CERTIFICATION FOR FINAL PLANS
PROJECT WAS BUILT ACCORDING TO THE PLANS
AND [illegible] FINAL PLANS
[illegible] THE QUANTITIES
[illegible] FINAL ESTIMATE

James T. Chapman
RESIDENT ENGINEER

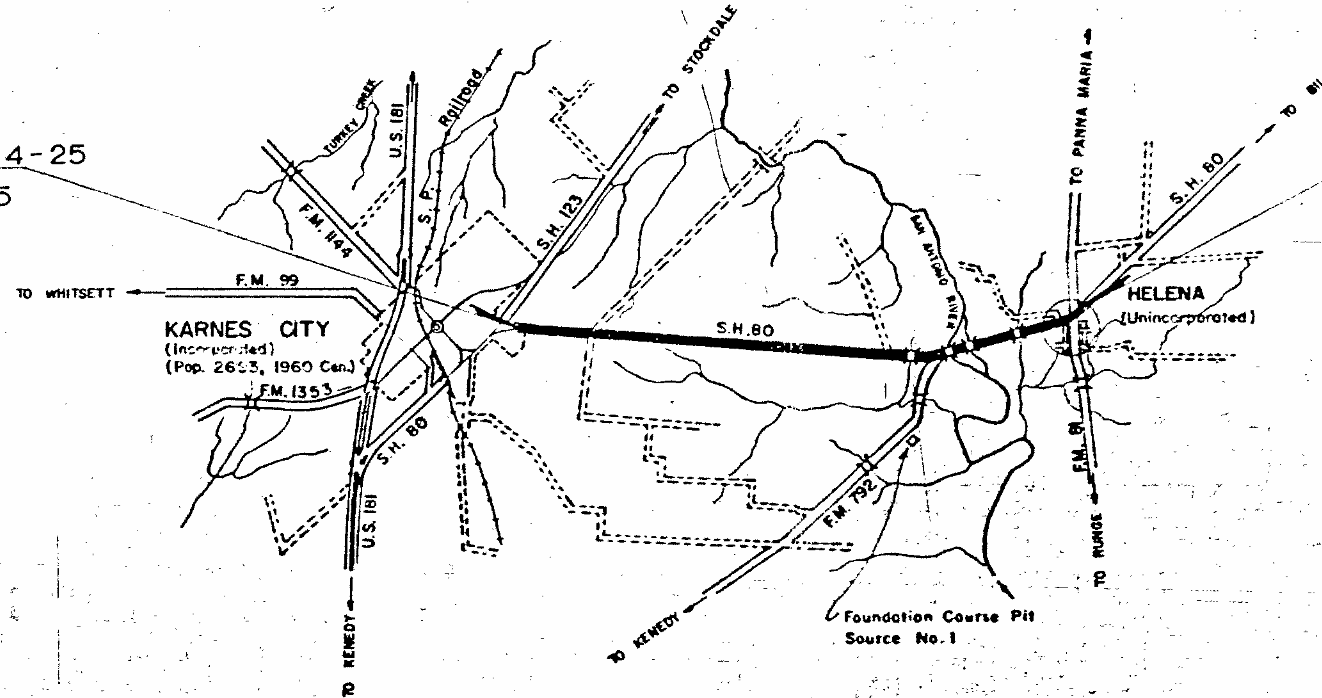
FINAL PLANS

129-0348-04-011

INDEX OF SHEETS

STA. 32+96.0
BEG. PROJ. C 348-4-25
CONTROL 348-4-25

STA. 358+15.42
END PROJ. C 348-4-25
CONTROL 348-4-25



NOTE:
Barricade "D", Signs D-34, D-35, W-155, D-57 & D-59 shall be used at the Beginning and End of Project.
Barricade "C", Signs D-34A, D-35 & W-155 shall be used on F. M. Hwy. 81 & 792.
Sign D-34 shall be used on all Side Roads.
Barricades "F" & "H" shall be used as directed by the Engineer.

THE CONTRACTOR SHALL MAKE HIS OWN INVESTIGATION AND DETERMINATION OF RAILROAD FACILITIES.

CONVENTIONAL SIGNS
- STATE OR NATIONAL LINE
- CITY OR VILLAGE LINE
- COUNTY LINE
- BASE OR SURVEY LINE
- RIGHT OF WAY LINE
- RIGHT OF WAY MARKERS
- FENCE LINE
- RAILROAD
- TRAVELLED WAY
- CULVERT OR BRIDGE
- POWER LINE
- TELEGRAPH OR TELEPHONE

SPECIFICATIONS ADOPTED BY THE STATE HIGHWAY DEPARTMENT OF TEXAS JANUARY 2, 1962 AND SPECIFICATION ITEMS LISTED AND DATED AS FOLLOWS SHALL GOVERN ON THIS PROJECT.
Special Labor Provisions for State Projects Adopted August 11, 1948

No Railroad Crossings
No Exceptions
One Equation
Sta. 274+28.98 Bk. = Sta. 274+26.78 Fwd. = +2.20 Ft.

LAYOUT SCALE: 1 IN. = 5,280 FT.

STATE HIGHWAY DEPARTMENT

CORRECT 7-30 19 69

James T. Chapman
RESIDENT ENGINEER

RECOMMENDED FOR APPROVAL 8-1 19 69

Louis A. Long
DISTRICT ENGINEER

APPROVED

CHIEF ENGINEER OF HIGHWAY DESIGN

DATE ACCEPTED

SUMMARY OF BRIDGES

PRM. STR. NO	SHEET NO.		STATION		LENGTH	DESCRIPTION AND DESIGN		EXTENSION	
	PLAN PROFILE	LAYOUT	BEGIN	END		EXISTING	PROPOSED	RT	LT
12	17	24	259+67.75	259+95.25	27'-6"	6-4x4x24 (MBC-7)	MC 5-1 (MOD) & MCW-P (MOD)	30'-3"	29'-9"
11	18	31 & 32	282+91.92	287+84.50	492'-7"	1-28'-6" I Beam Span, 1-27'-3" Slab & Girder Span, 1-151'-10" Truss Span and 10-28'-6" Slab & Girder Spans.	Remove 1-151'-10" Truss Span and Replace with 2-75'-11" Prestr. Conc Girder Spans. Widen Exist. Conc Spans 24' Rt. with 5-57' & 1-55'-9" Prestr. Conc. Girder Spans.	28'-0"	
18	18	46	301+28.54	302+88.54	160'-0"	2-80'-0" Continuous Slab Units with Steel Piling	2-80'-0" Continuous Slab Units, to be Widened to 48'-0" Rdwy. with Conc. Piling.	24'-0"	
10	19	24	317+95.00	318+21.67	26'-8"	3-8x8x28 (MBC-8)	MC 8-1 & MCW-P	16'-7"	39'-5"
TOTALS									

STR. NO	UNCL. STR. EXCAV.			CONC. PILING 15 IN SQ	DRILLED SHAFTS			PRESTR. CONC BEAMS	
	CULV CY	BRIDGES BENTS CY	BRIDGES ABUT CY	LF	18" LF	30" LF	36" LF	TY B LF	TY C LF
12	43								
11		58	36		34	576	119	1355.	1058.17
18			18	735					
10	276								
TOTALS	319	58	54	735	34	576	119	1355.	1058.17

STR. NO	CL. C CONC. FOR EXT. STR.				RIPRAP CONC. CL. B	REINF. STL.	STR. STL. ARMOR JOINT	RAILING		
	CULV. CY	BRIDGES SLABS CY	BRIDGES BENTS CY	BRIDGES ABUT CY	CY	LB	LB	TY T-1 LF	RAIL (SP) CONC POST LF	RAIL (SP) STL POST LF
12	101.85					15,924				
11		439.6	232.90	26.10	102.09	129,363	4,834	507.66	489.96	
18		161.8	22.00	10.00	43.71	39,032		162.50		162.50
10	137.35				4.79	20,013				
TOTALS	239.20	601.4	254.90	36.10	150.59	204,332	4,834	670.16	489.96	162.50

Continuation

STR. NO.	SALV. STR. STL. (Credit Item) LS.	CONC. SURF. TREAT. SY.			
12					
11	1	829			
18					
10					
TOTAL	*1	829			

*Truss Contains Approx. 183,000 Lbs. Steel

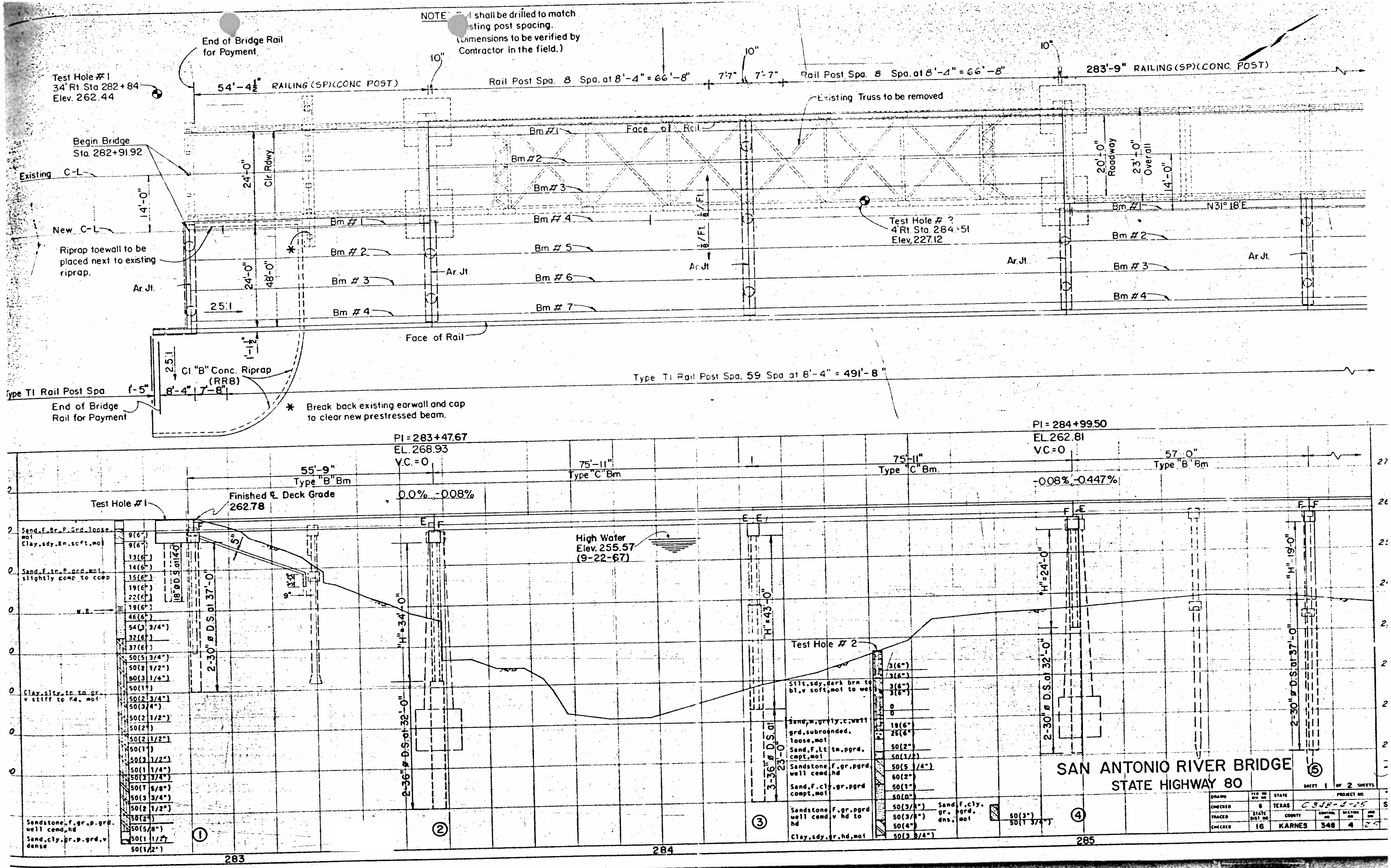
28
24
52

STRUCTURE SUMMARY

SHEET 2 OF 2

6

6		C 348-4-25			6
16	KARNES	348	4	25	67.00

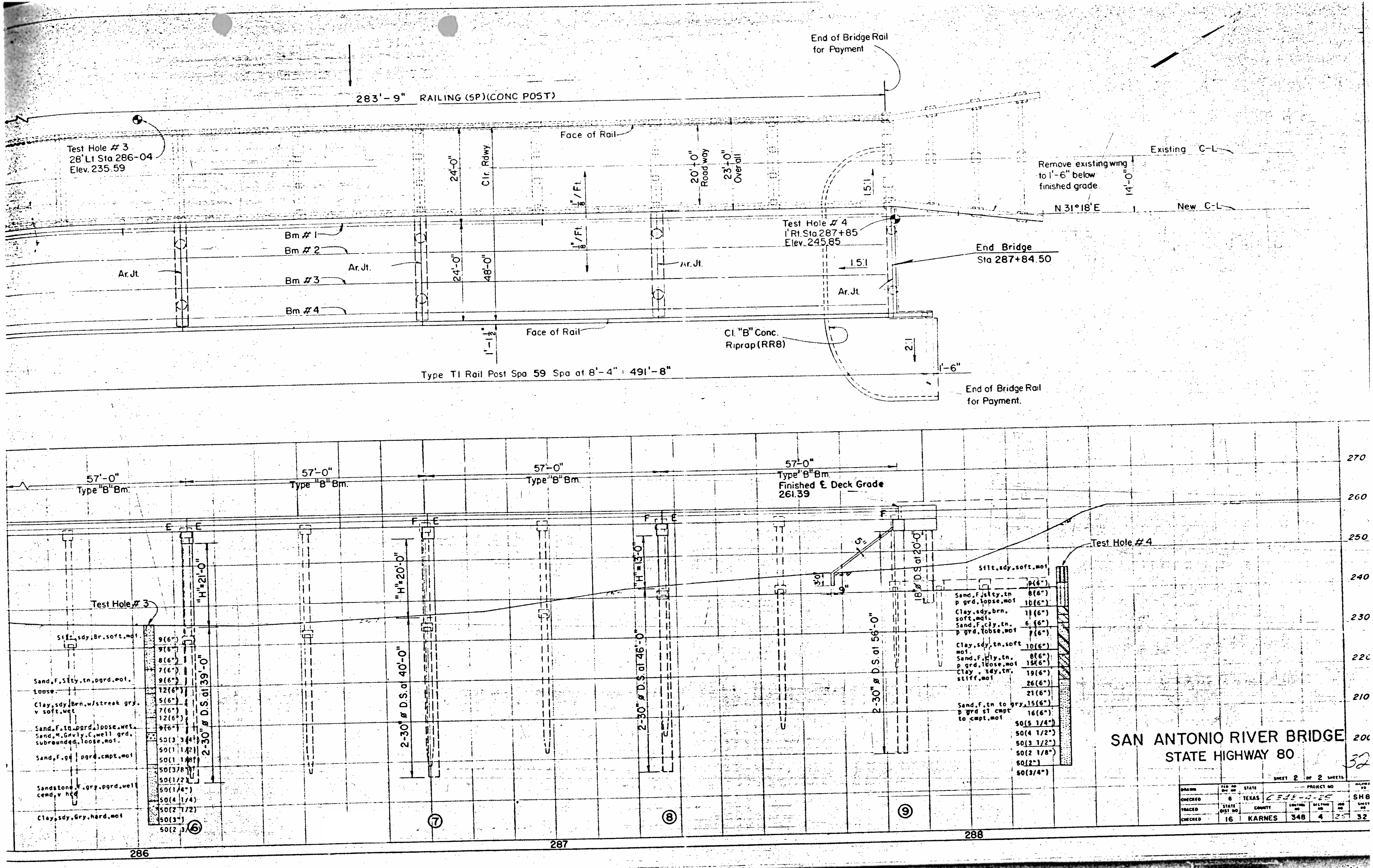


SAN ANTONIO RIVER BRIDGE

STATE HIGHWAY 80

SHEET 1 OF 2 SHEETS

DRAWN	FED RD DIV NO	STATE	PROJECT NO	
CHECKED	6	TEXAS	C 348-4-25	
TRACED	STATE DIST NO	COUNTY	CONTROL NO	SECTION NO	JOB NO
CHECKED	16	KARNES	348	4	25



SAN ANTONIO RIVER BRIDGE
STATE HIGHWAY 80

32

SHEET 2 OF 2 SHEETS

DRAWN	FED RD DIV NO	STATE	PROJECT NO				HIGHWAY NO
CHECKED	6	TEXAS	C 348-4-25				SH 8
TRACED	STATE DIST NO	COUNTY	CONTROL NO	SECTION NO	JOB NO		SHEET NO
CHECKED	16	KARNES	348	4	25		32

ATTACHMENT B:
SAMPLE DATA

(A). DATA ANALYSIS ON TILTMETER2

Figure E-B-1 shows the time history plot of the data obtained from Tiltmeter2 on the SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter2 is located on top of Pier P2 and measures tilt angle of the pier around the traffic direction axis.

The data collected from Tiltmeter2 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter2 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers adjusted the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. From Figure E-B-1, it can be seen that Tiltmeter2 did not work properly before June 5, 2010, since the reading fluctuated from −1.3° to 0.4°. But after the replacement of Tiltmeter2, Tiltmeter2 showed reasonable data.

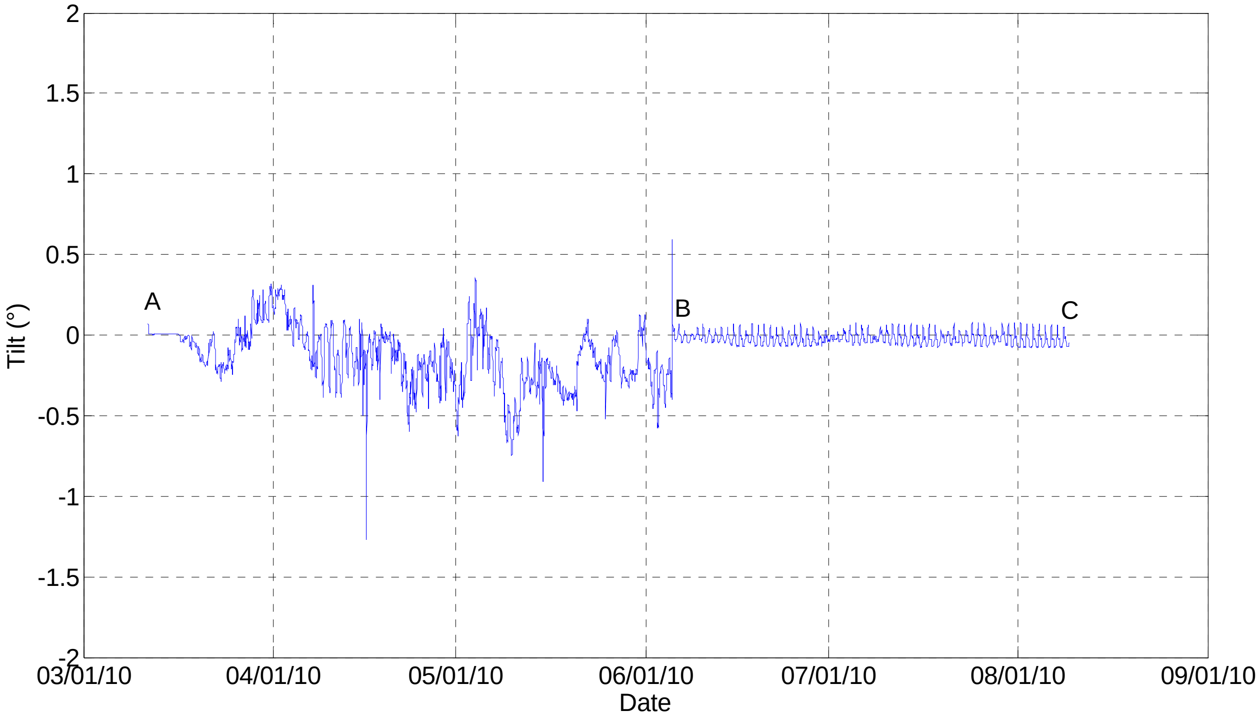


Figure E-B-1. Tiltmeter2 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter2 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure E-B-2 to study the correlation between these two quantities.

The blue line shows the tilt angle of the pier around the traffic direction axis, and the green line in the figure shows the temperature reading in the master station box. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

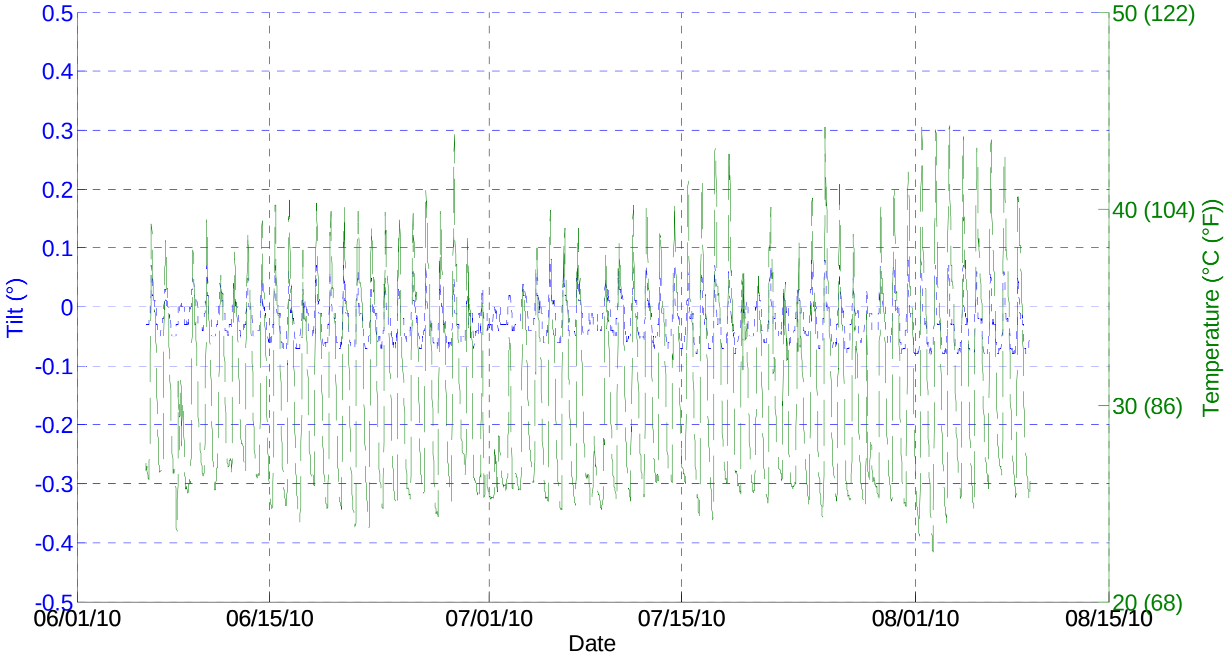


Figure E-B-2. Tiltmeter2 and Temperature Response Plot for Phase B-C.

(B). DATA ANALYSIS ON TILTMETER3

Figure E-B-3 shows the time history plot of the data collected from Tiltmeter3 on SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter3 is located on the deck of the bridge 3.8 m (12.5 ft) away from Tiltmeter2 and measures tilt angle of the deck around the flow direction axis.

The data collected from Tiltmeter3 has been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter3 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers replaced the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. Tiltmeter3 works well during the monitoring process.

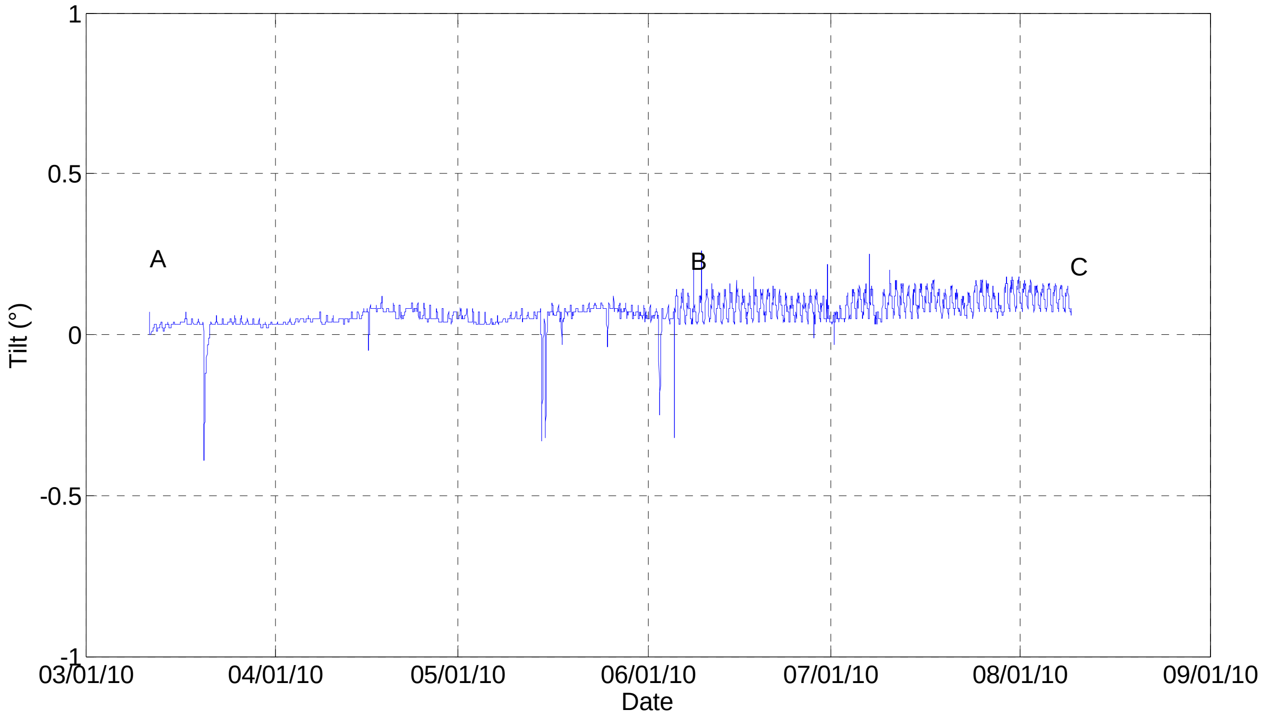


Figure E-B-3. Tiltmeter3 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter3 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure E-B-4 to study the correlation between these two quantities. The blue line shows the tilt angle of the deck around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

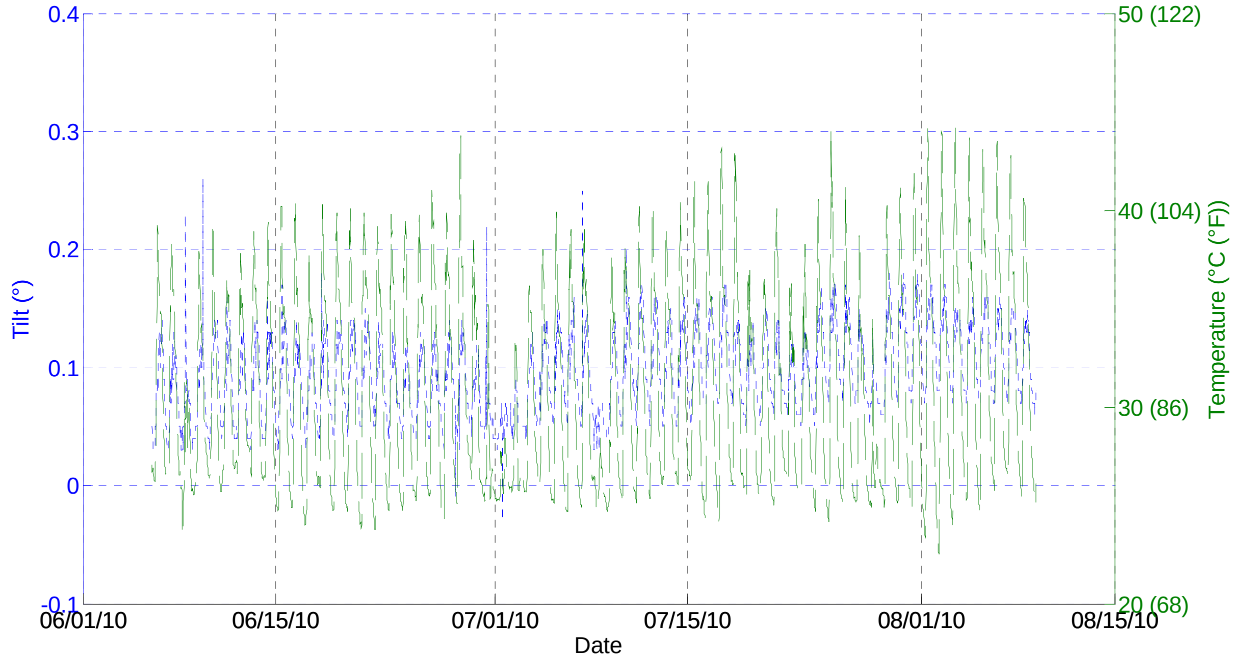


Figure E-B-4. Tiltmeter3 and Temperature Response Plot for Phase B-C.

(C). DATA ANALYSIS ON TILTMETER4

Figure E-B-5 shows the time history plot of the data collected from Tiltmeter4 on SH80 over San Antonio River Bridge from March 11, 2010, to August 9, 2010. Tiltmeter4 is located on the deck of the bridge 3.8 m (12.5 ft) away from Tiltmeter2 and measures the tilt angle of the deck around the flow direction axis.

The data collected from Tiltmeter4 have been categorized into different phases according to the maintenance and modifications done on the bridge scour monitoring system on SH80 over San Antonio River Bridge. Point A represents the day when Tiltmeter4 was installed on the bridge, which was March 11, 2010. Point B represents the day when TTI researchers replaced the sensor, which was June 5, 2010. Point C represents the last day on data analysis in this report, which was August 9, 2010. Tiltmeter4 works well during the monitoring process.

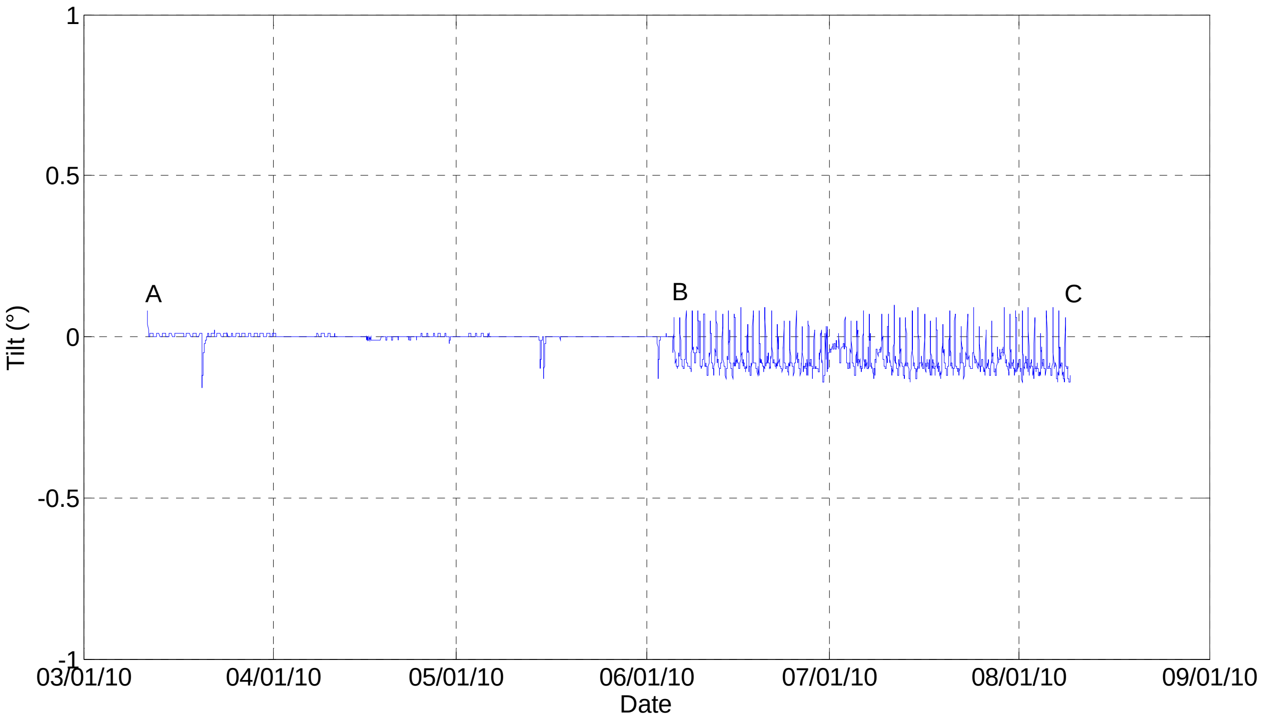


Figure E-B-5. Tiltmeter4 Time History Plot on SH80 over San Antonio River Bridge.

The reading from Tiltmeter4 and the temperature recorded by the sensor in the enclosure in Phase B-C is plotted in Figure E-B-6 to study the correlation between these two quantities. The blue line shows the tilt angle of the deck around the flow direction axis, and the green line shows the temperature recorded by the sensor located in the master station enclosure. It can be inferred from the figure that the correlation between the tilt data and the temperature follows the same trend as before. The two quantities are positively correlated.

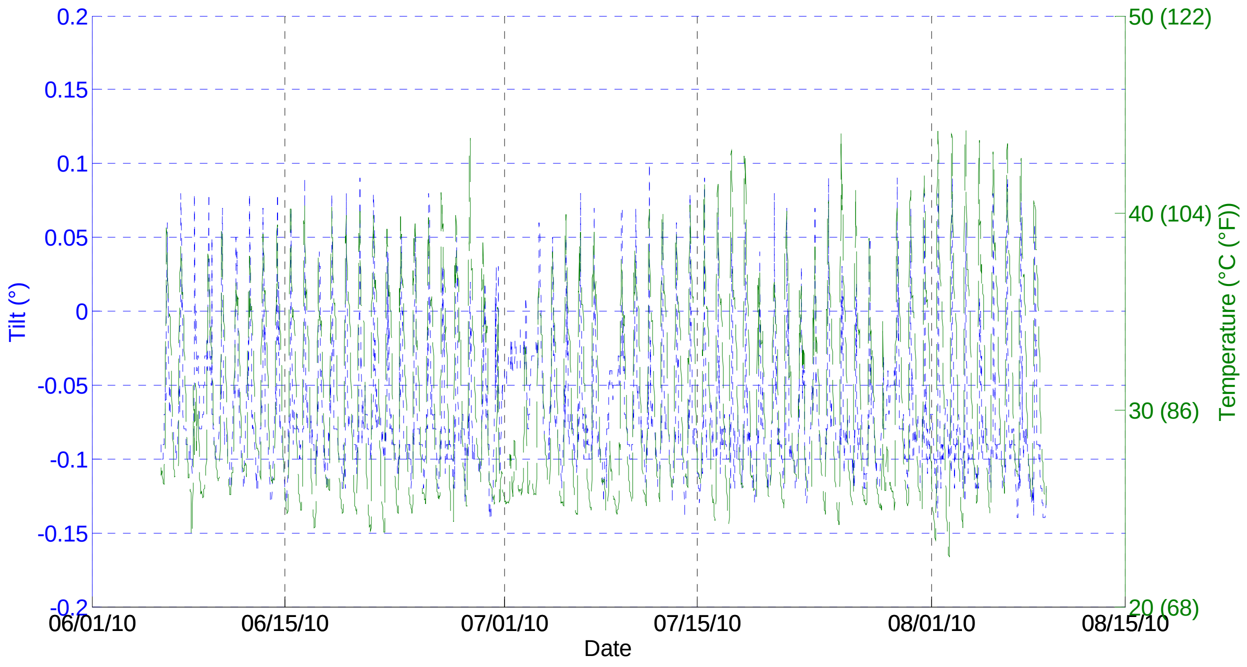


Figure E-B-6. Tiltmeter4 and Temperature Response Plot for Phase B-C.

ATTACHMENT C:
TXDOT CONTACT LIST AND PROTOCOLS

TxDOT to insert:

Contact list of those responsible for the scour monitoring system; to include name, title, telephone numbers (office, cell and home), email and pager (if applicable).

Any existing protocols for emergency including flood watch and bridge closure instructions for SH80.

ATTACHMENT D:
INSPECTION CHECKLISTS

General Inspection Checklist for Scour Monitors

Bridge:
Location:
B.I.N.:
Piers:

Dates:

Affiliation:

Inspectors:

Address:
Telephone:
Fax:
E-mail:

Signature:
Date:

Bridge Name: ________________________
BIN # ___________________________

Scour Monitoring General Inspection Checklist

Sheet _____ of _____
Date:________
Inspector's Initials: ________

Bridge Information

1 Bridge Name ________________________
2 BIN # ________________________
3 Location of Scour Monitoring Equipment ________________________
(Please use a new sheet for each pier/abutment) ________________________

Inspection Checklist

4 Do any of the following show signs of damage, vandalism, corrosion, moisture exposure, insects, bird droppings, etc?

a)	**instrument boxes**	☐ Yes	☐ No	☐ Not Applicable
b)	**electrical conduits**	☐ Yes	☐ No	☐ Not Applicable
c)	**solar panels**	☐ Yes	☐ No	☐ Not Applicable
d)	**water stage**	☐ Yes	☐ No	☐ Not Applicable
e)	**antennas**	☐ Yes	☐ No	☐ Not Applicable

f) If "Yes" to any of the above, describe: ________________________

Work Checklist

5	**Have all the insides of the instrument boxes been cleaned of dust/debris?**	☐ Yes	☐ No	☐ N/A
6	**If moisture is present, has the moisure been removed?**	☐ Yes	☐ No	☐ N/A
7	**Have the faces of all solar panels been cleaned?**	☐ Yes	☐ No	☐ N/A

Additional Comments and Final Conclusions

8 *(Please attach photographs and/or sketches if applicable)*

Inspector(s): ________________________
Title(s): ________________________
Agency/Company: ________________________
Address: ________________________
____
Telephone: ________________________
Fax: ________________________
E-mail: ________________________
Signature: ________________________
Date: ________________________

Maintenance Checklist for Scour Monitors

Bridge: ______________________________
Location: ______________________________
B.I.N.: ______________________________
Piers: ______________________________

Dates: ______________________________
____

Affiliation: ______________________________

Inspectors: ______________________________
____
____
____

Address: ______________________________
Telephone: ______________________________
Fax: ______________________________
E-mail:

Signature: ______________________________
Date: ______________________________

Bridge Name: ____________________
BIN # ___________________________

Scour Monitoring Maintenance Checklist

Sheet _____ of _____
Date:________
Inspector's Initials: ________

Bridge Information

1 Bridge Name ____________________
2 BIN # ____________________
3 Location of Scour Monitoring Equipment ____________________
(Please use a new sheet for each pier/abutment) ____________________

Maintenance Checklist

4 Do any of the following show signs of damage, corrosion, moisture exposure, insects, etc?
a) Readily accessible instrument boxes ☐ Yes ☐ No
b) Readily accessible electrical conduit ☐ Yes ☐ No
5 What is the temperature inside of the area where the instrumentation is located? ________ °F ______ °C

Work Checklist

6 Have all the insides of instrument boxes been cleaned of dust, insects, etc? ☐ Yes ☐ No ☐ N/A
7 If moisture is present, has the moisture been removed? ☐ Yes ☐ No ☐ N/A
☐ ☐

Additional Comments and Final Conclusions

9 *(Please attach photographs and/or sketches if applicable)*

Bridge Maintenance Personnel: ____________________
Title(s): ____________________
Agency/Company: ____________________
Address: ____________________
____
Telephone: ____________________
Fax: ____________________
E-mail: ____________________
Signature: ____________________
Date: ____________________