Concrete Box Culvert Earth Pressure Monitoring

Final Report
March 2022

Sponsored by
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16. Abstract

Earth pressure on concrete box culverts is a key component of design and load rating decisions. Currently, the Iowa Department of Transportation (DOT) Office of Bridges and Structures uses the maximum and minimum lateral earth pressure of 36/18 lb/ft^3 specified for load factor design (LFD) and allowable stress design (ASD) and 60/30 lb/ft^3 for load and resistance factor design (LRFD).

The objective of this project was to analyze collected data to determine the actual earth pressures associated with Iowa soil conditions to determine which load pressures are more realistic for typical Iowa soil conditions and construction methods for concrete box culverts.

A brief literature review was conducted to identify potential factors related to the vertical and lateral earth pressures. To gain a better understanding of actual pressures on concrete box culverts in Iowa, a culvert in Ida County was instrumented in 2016. Two concrete box culverts—the one in Ida County and the other in Crawford County—were monitored for more than 2.5 years and 1 year, respectively, to identify the realistic design soil pressure for Iowa soil conditions.

The captured pressure, strain, and temperature data were analyzed to find the relation between the temperature and earth pressure experienced by the culverts. The measured vertical and lateral pressures were compared with specified design pressure loading.

The monitoring results from both culverts led to the consistent conclusion that the earth pressure experienced by the culverts were 2 to 6 times that of the design values with the LRFD and LFD/ASD methods. Extensive longitudinal cracks (parallel to the flow) were observed at the bottom surface of the top slab on both culverts.

Given the findings from this research, further research is recommended, as outlined at the end of this report.

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CONCRETE BOX CULVERT EARTH PRESSURE MONITORING

Final Report
March 2022

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Earth pressure on concrete box culverts is a key component of design and load rating decisions. Currently, the Iowa Department of Transportation (DOT) Office of Bridges and Structures uses the maximum and minimum lateral earth pressure of 36/18 lb/ft^3 specified for load factor design (LFD) and allowable stress design (ASD) and 60/30 lb/ft^3 for load and resistance factor design (LRFD).

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The monitoring results from both culverts led to the consistent conclusion that the earth pressure experienced by the culverts were 2 to 6 times that of the design values with the LRFD and LFD/ASD methods. Extensive longitudinal cracks (parallel to the flow) were observed at the bottom surface of the top slab on both culverts.

Given the findings from this research, further research is recommended to determine a realistic soil pressure design and the relation between the soil weight and the culvert vertical/lateral pressures for Iowa. This would require the instrumentation of additional culverts.

Once the improved design soil pressure and the relation between the soil weight and the culvert vertical/lateral pressures are identified, a new culvert is recommended to be designed, constructed, and monitored following the updated design for vertical and lateral pressures.

CHAPTER 1. INTRODUCTION

1.1 Background and Problem Statement

Earth pressure on concrete box culverts is a key component of design and load rating decisions. The accurate determination of these pressures is thereby critical, as soil conditions vary greatly from state to state.

The American Association of State Highway and Transportation Officials (AASHTO) has revised the design guidelines over the years to impose greater design/rating earth pressures for buried structures. This is one of the major reasons that many older culverts that were designed based on allowable stress design (ASD) or load factor design (LFD) guidelines do not pass load and resistance factor design (LRFD) ratings, although the culverts have performed satisfactorily for many years.

Currently, the Iowa Department of Transportation (DOT) Office of Bridges and Structures uses the maximum and minimum lateral earth pressure of 36/18 lb/ft^3 specified for the LFD and ASD methods and 60/30 lb/ft^3 for the LRFD method.

It would be helpful to understand which load pressure is more realistic for Iowa soil conditions and typical construction methods. This understanding is very important for culvert load ratings to avoid unnecessary load postings of many older culverts, and it was the motivation behind this project.

1.2 Objective

The objective of this project was to determine which load pressure (36/18 lb/ft^3 or 60/30 lb/ft^3) is more realistic for Iowa soil conditions and typical construction methods.

1.3 Research Work Overview

To achieve the objective of this project, several tasks were performed. Initially, a brief literature review was conducted to identify additional potential factors related to the vertical and lateral earth pressures on culverts. To gain a better understanding of actual pressures on concrete box culverts in Iowa, two newly constructed culverts were selected for field monitoring.

The first monitored culvert, in Ida County, consisted of multiple 8 ft by 12 ft concrete boxes. The monitoring system, which consisted of six strain gauges and five pressure cells, was installed on July 26, 2016. After two full seasonal cycles, and with the amount of accumulated data, the data were collected and analyzed to determine actual earth pressures associated with Iowa soil conditions for use during both the design and load rating of box culverts. The data from that culvert showed that the recorded pressures were actually 2 to 4 times greater than the LRFD and LFD/ASD design values, indicating a potentially concerning situation.

Because of these surprising results on the first monitored culvert, the instrumentation of an additional culvert was proposed to gain a deeper understanding of the pressure data. The second culvert, in Crawford County, was monitored with heavier instrumentation. Three instrumentation sections with different buried depths were identified and instrumented with 11 pressure cells and 10 strain gauges per section. The culvert was monitored for more than one year, from August 3, 2020 until October 7, 2021.

In both phases of this research, the data collection began during construction to collect earth pressures and accompanying fill heights during compaction. The field-collected data were analyzed to find reliable correlations between the earth pressure and other factors (such as construction situation, soil temperature, etc.). The measured vertical and lateral pressures were compared with specified design loads. Based on the analysis results, the recommended Iowa-specific earth pressures were determined and can be used by bridge designers and load rating engineers when designing or load rating concrete box culverts.

In addition to instrumentation and data analysis efforts, the research team documented the contractors' compaction activity, paying close attention to the equipment and methods used. An emphasis on crack inspections was included throughout the duration of the project, including the culvert condition when it arrived on site, during compaction, and once the culvert was in-service after construction was completed.

1.4 Report Overview

The remainder of this report presents the details and findings from this project as follows:

Chapter 2. Literature Review
Chapter 3. Field Study Instrumentation and Measurement
Chapter 4. Ida County Field Monitoring
Chapter 5. Crawford County Field Monitoring
Chapter 6. Summary, Conclusions, and Further Research Recommendations

CHAPTER 2. LITERATURE REVIEW

2.1 Background and Specification Overview

Culvert structures include small-sized pipe culverts and reinforced concrete box culverts. For this chapter, a brief literature review was conducted to understand the determination of design earth loads in the AASHTO code and to identify the potential factors that may influence the pressure experienced by a culvert structure and the pressure measurement.

AASHTO has revised their design guidelines over the years to impose larger earth pressure requirements for buried structures. In the 1980s, the earth pressure in the AASHTO (1983) code was specified as 120 lb/ft^3 in the vertical direction and 30 lb/ft^3 in the horizontal direction. AASHTO (1987) doubled the horizontal pressure to 60 lb/ft^3 and removed a load reduction factor for the vertical earth pressure prediction (Lawson et al. 2010).

Later, AASHTO (1992) introduced a modification coefficient of F_e as a soil-structure interaction factor, based on the Marston theory, for the vertical pressure prediction. This modification coefficient is a function of culvert width and overburden height and should not be taken as greater than 1.15 for installations with compacted fill and not greater than 1.40 for installations with un-compacted fills.

AASHTO (1996) defined maximum and minimum horizontal earth pressures as 60 lb/ft^3 and 30 lb/ft^3, respectively.

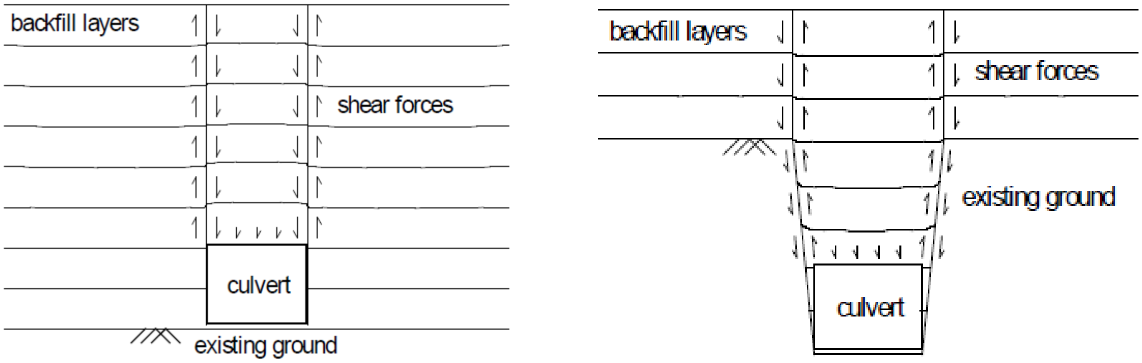
The current Iowa DOT Office of Bridges and Structures uses the lateral earth pressure of 36/18 lb/ft^3 specified with LFD and ASD and the 60/30 lb/ft^3 with LRFD.

2.2 Measured Pressure and Interpretation Based on Effects

To determine the actual soil pressure acting on buried structures, one of the most commonly used approaches is to install a few pressure cells on the existing culvert structure to collect the in situ pressure data. However, the pressure readings could be influenced by two major factors: the soil arching effect and the culvert deformation.

The soil arching effect depends on the relative movement of soil near the structure. Lawson et al. (2010) gave a detailed illustration of the vertical soil arching effect. In general, the two types of vertical soil arching effect are negative effect and positive effect.

Negative arching occurs on the embankment culvert installation, where the combined column of the culvert and the soil is stiffer than the surrounding soil. As the surrounding soil settles more than the soil over the culvert, the shear force transfers from the surrounding soil to the soil over the culvert and results in greater pressure on the culvert (as shown in Figure 1-a).



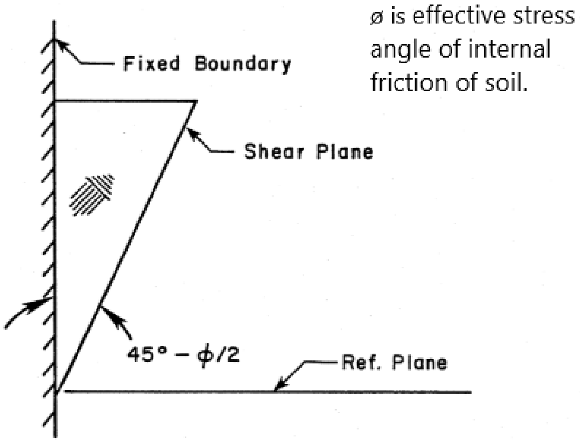
a. Negative arching b. Positive arching

Lawson et al. 2010, Texas Tech

Figure 1. Soil arching effect

Positive arching occurs on a trench culvert installation, where the soil above the culvert settles more than the surrounding soil and the shear force helps carry part of the soil weight over the culvert (as shown in Figure 1-b). Positive arching results in a reduction of the earth pressure on the culvert.

Horizontal pressure readings can also be influenced by the soil arching effect. James et al. (1986) measured the soil pressure on an 8×8×44 ft culvert unit. The lateral pressure was measured by a few pressure cells installed at different heights. The results indicated that the pressure measured at a lower level is less than the pressure at a higher level. This is because of the soil configuration, such that the soft soil over the stiff soil with a fixed boundary creates a shear plane (as shown in Figure 2).

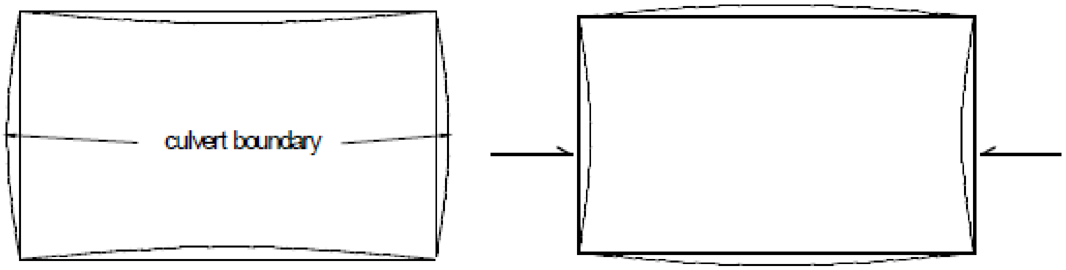


James et al. 1986, Texas Transportation Institute

Figure 2. Sliding wedge of soil adjacent to rigid boundary

The shear plane carries part of the soil weight and reduces the lateral pressure near the bottom of the culvert.

In addition to the soil arching effect, the way the culvert deflects is another factor that may influence the measured pressure on the culvert (Lawson et al. 2010). For example, as the weight of the soil on the culvert increases and the mid-span of the top slab deflects (as shown in Figure 3-a), the soil transfers the load away from the center of the span.



a. Vertical pressure dominate b. Horizontal pressure dominate

Lawson et al. 2010, Texas Tech

Figure 3. Culvert deformation

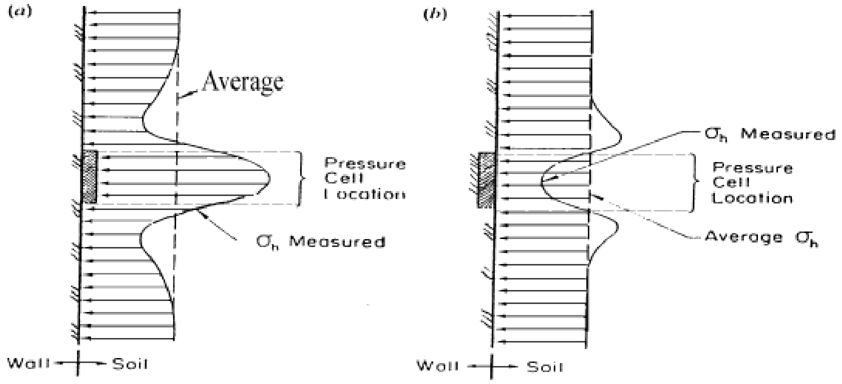
This effect reduces the moment in the top slab but may increase the lateral pressure experienced by the wall. When the lateral pressure load dominates, the culvert can deform in a way as shown in Figure 3-b. This effect can reduce the lateral pressure on the wall but increase the pressure experienced by the top slab.

Awwad et al. (2000/2012) indicated that the lateral pressure induces the box culvert to deflect in an opposite manner and negate the deflections caused by the vertical pressure. This effect causes another decrease in moment in the top and bottom slab.

Dasgupta and Sengupta (1991) and Katona and Vittes (1982) indicated that the actual pressure distribution on the top slab of a culvert is parabolic instead of uniform. Oswald (1996) indicated that the load redistribution might continue due to creep. Yang (2000) and Wood (2000) studied the factors that may affect the earth pressures acting on buried box culverts under deep embankments.

The results from field monitoring and numerical analyses indicated that the level of compaction could influence the earth pressure distribution, and especially the horizontal earth pressure acting on the culvert wall. The results also suggested that AAHSTO (1977) significantly underestimated both vertical and horizontal earth pressures; whereas, AASHTO (1996) provides more appropriate simplified earth pressures.

With respect to the instrumentation, Seed et al. (1991) illustrated the two most common types of systematic soil pressure measurement errors, as shown in Figure 4.



(a) Over-registration of soil pressure (b) Under-registration of soil pressure

Seed et al. 1991, CRC Press

Figure 4. Systematic errors in the measurement of soil pressures

In general, a protruding pressure cell attached on the rigid structure may result in an over-registration of pressure, while an embedded pressure cell may result in an under-registration of soil pressure. These errors could be avoided by using a rigid (non-deformable) pressure cell.

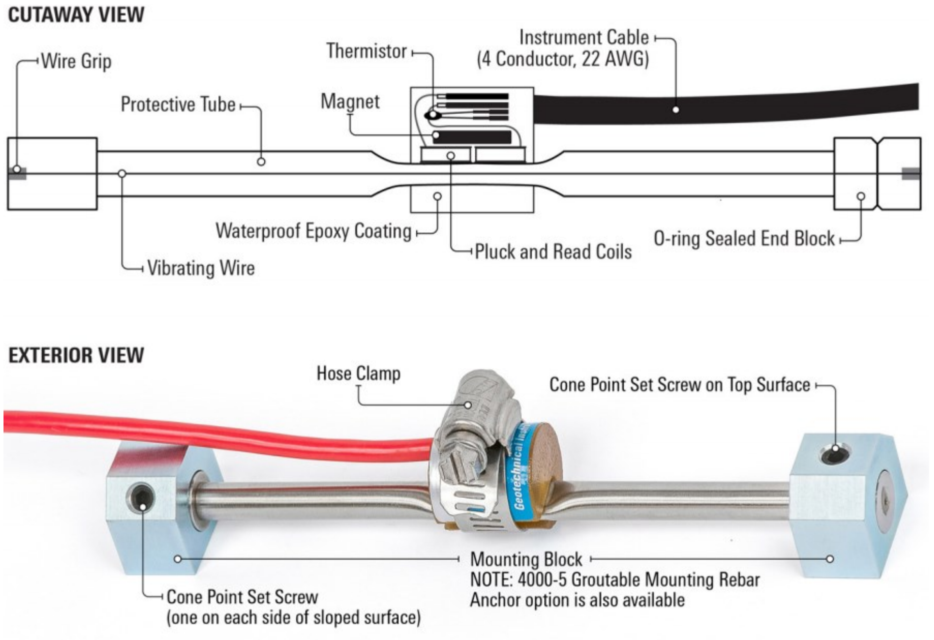
Yang (2000) pointed out that the fixity condition of the pressure cell may influence the accuracy of the thermal factors in the user's manual provided by the manufacturer. This is because these thermal factors are calibrated under laboratory conditions when the pressure cell is free from constraint. The field condition, on the other hand, has the pressure cell fixed on the structure. As such, the constraint on the cell is different from the laboratory calibration condition, and significant temperature effect is produced due to this constraint.

CHAPTER 3. FIELD STUDY INSTRUMENTATION AND MEASUREMENT

The project objective was to observe the soil pressures of the two culverts. To achieve this goal, two types of sensors—strain gauges and pressure cells—were used to capture the culvert behavior subject to the soil weight. The details of the strain gauges and pressure cells that were used are described in Section 3.1 and 3.2, respectively.

3.1 GEOKON Model 4000 Vibrating Wire Strain Gauges (VWSGs)

GEOKON Model 4000 vibrating wire strain gauges (VWSGs) were used during the fieldwork to monitor the strain behavior of the culverts. Figure 5 shows the design of the strain gauge, with mounting blocks for the installation.



GEOKON 2021 (and various prior years)

Figure 5. Vibrating wire strain gauge

The strain gauge has a working strain range of 0 to 4,000 microstrain. Before installation, each strain gauge was checked for its initial reading, and the results indicated that all of them fell into the range of 3,000 to 3,500 microstrain.

After collecting the reading, the strain must be corrected for thermal effect utilizing Equation 1 (GEOKON 2019).

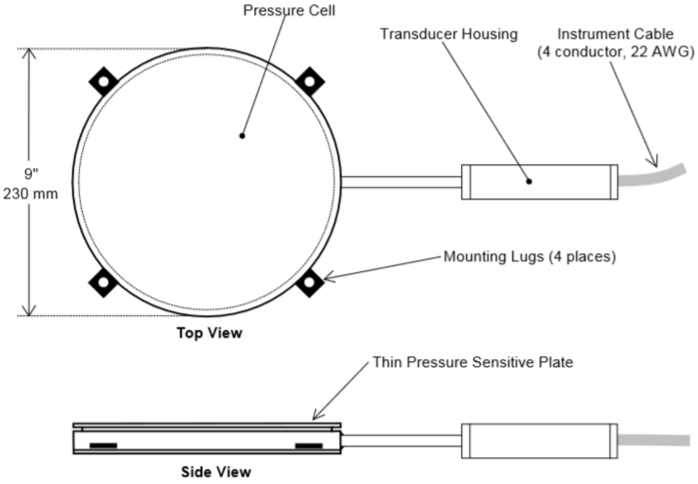
$$\mu\varepsilon_{corrected} = (R_1 - R_0) + (T_1 - T_0) \times (CF_1 - CF_2) \tag{1}$$

where, R_1 is the current reading, R_0 is the initial reading, T_1 is the temperature at any time point, T_0 is the initial temperature, CF_1 is the coefficient of expansion of steel (6.5×10^{-6} in/in/°F), and CF_2 is the coefficient of expansion of concrete (5.5×10^{-6} in/in/°F).

The equation accounts for the initial reading of the gauge, the thermal expansion of concrete, and the thermal expansion of steel.

3.2 GEOKON Model 4810 Earth Pressure Cells

The fieldwork used earth pressure cells to capture the pressure experienced by the concrete culvert. The pressure cell used in this project was the GEOKON Model 4810 earth pressure cell. It is designed to measure the earth pressure on structures. One of the plates is thick and designed to bear against the external surface of the structure in a way that will prevent flexure of the cell. The other plate is thin and reacts to the earth pressure. Figure 6 shows a the GEOKON Model 4810 earth pressure cell.



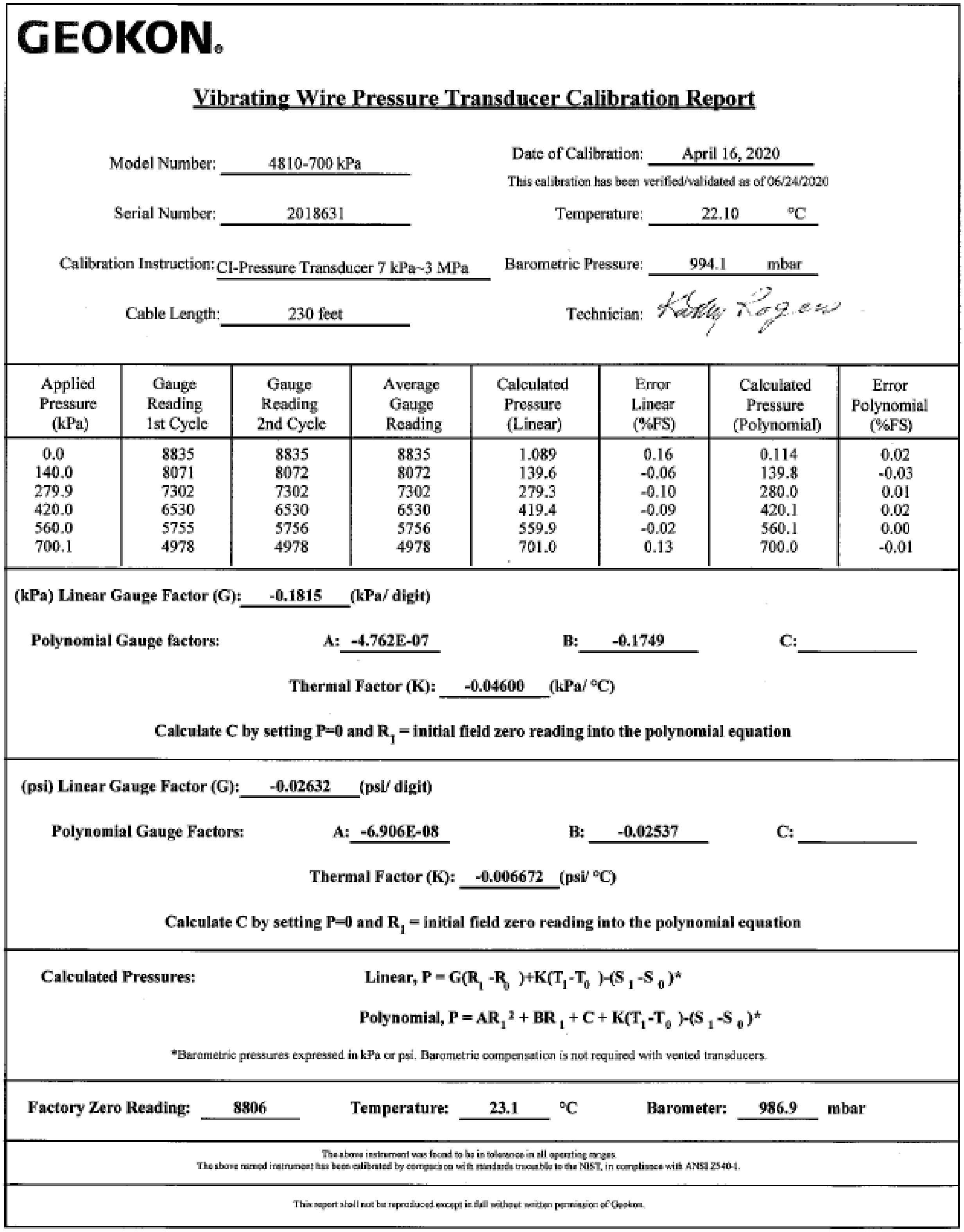
GEOKON 2021 (and various prior years)

Figure 6. Earth pressure cell

According to the GEOKON Instruction Manual, all the pressure data needs to be thermally corrected, following Equation 2, using the temperature data collected by the thermal gauge embedded in the transducer housing.

$$P_{corrected} = (P_1 - P_0) + (T_1 - T_0)K \tag{2}$$

where, P_1 is the pressure data at any time point, P_0 is the initial pressure, T_1 is the temperature at any time point, T_0 is the initial temperature, and K is the thermal factor. Each pressure cell was supplied with calibration sheets, as shown in Figure 7.



GEOKON

Vibrating Wire Pressure Transducer Calibration Report

Model Number: 4810-700 kPa

Date of Calibration: April 16, 2020

This calibration has been verified/validated as of 06/24/2020

Serial Number: 2018631

Temperature: 22.10 °C

Calibration Instruction: CI-Pressure Transducer 7 kPa~3 MPa

Barometric Pressure: 994.1 mbar

Cable Length: 230 feet

Technician: Kathy Rogers

Applied Pressure (kPa)	Gauge Reading 1st Cycle	Gauge Reading 2nd Cycle	Average Gauge Reading	Calculated Pressure (Linear)	Error Linear (%FS)	Calculated Pressure (Polynomial)	Error Polynomial (%FS)
0.0	8835	8835	8835	1.089	0.16	0.114	0.02
140.0	8071	8072	8072	139.6	-0.06	139.8	-0.03
279.9	7302	7302	7302	279.3	-0.10	280.0	0.01
420.0	6530	6530	6530	419.4	-0.09	420.1	0.02
560.0	5755	5756	5756	559.9	-0.02	560.1	0.00
700.1	4978	4978	4978	701.0	0.13	700.0	-0.01

(kPa) Linear Gauge Factor (G): -0.1815 (kPa/ digit)

Polynomial Gauge factors: A: -4.762E-07 B: -0.1749 C: ________

Thermal Factor (K): -0.04600 (kPa/ °C)

Calculate C by setting P=0 and R_1 = initial field zero reading into the polynomial equation

(psi) Linear Gauge Factor (G): -0.02632 (psi/ digit)

Polynomial Gauge Factors: A: -6.906E-08 B: -0.02537 C: ________

Thermal Factor (K): -0.006672 (psi/ °C)

Calculate C by setting P=0 and R_1 = initial field zero reading into the polynomial equation

Calculated Pressures:

Linear, $P = G(R_1 - R_0) + K(T_1 - T_0) - (S_1 - S_0)^*$

Polynomial, $P = AR_1^2 + BR_1 + C + K(T_1 - T_0) - (S_1 - S_0)^*$

*Barometric pressures expressed in kPa or psi. Barometric compensation is not required with vented transducers.

Factory Zero Reading: 8806 Temperature: 23.1 °C Barometer: 986.9 mbar

The above instrument was found to be in tolerance in all operating ranges.
The above named instrument has been calibrated by comparison with standards traceable to the NIST, in compliance with ANSI Z540-1.

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GEOKON 2011

Figure 7. Sample calibration sheet

To determine the reasonable thermal compensation with the correct thermal factor, the researchers conducted a laboratory study on the pressure cells. Since Yang (2000) indicated that the fixed condition in the field may influence the accuracy of the thermal factor (K) provided on the gauge data sheet, the laboratory study was used to find the correct thermal factor (K) by either verifying the thermal factor (K) provided by the manufacturer or calibrating each gauge to obtain the real thermal factor (K) subject to the fixity condition.

Before installation, three of the pressure cells were tested to determine if they were properly functioning. Table 1 shows the unique thermal factor (K) for each pressure cell provided in the product data sheets.

Table 1. Pressure cell thermal factors

	Pressure-1	Pressure-2	Pressure-3
Thermal factor (K)	-0.009489	-0.02200	-0.01269

Two tests were performed, and the results are shown in Section 3.2.1 and 3.2.2 respectively.

3.2.1 First Test

To simulate the field restraint condition, two pressure cells (Pressure-1 and Pressure-3) were attached to a concrete slab using the same approach as that used in the field (see Figure 8 for the gauge locations).

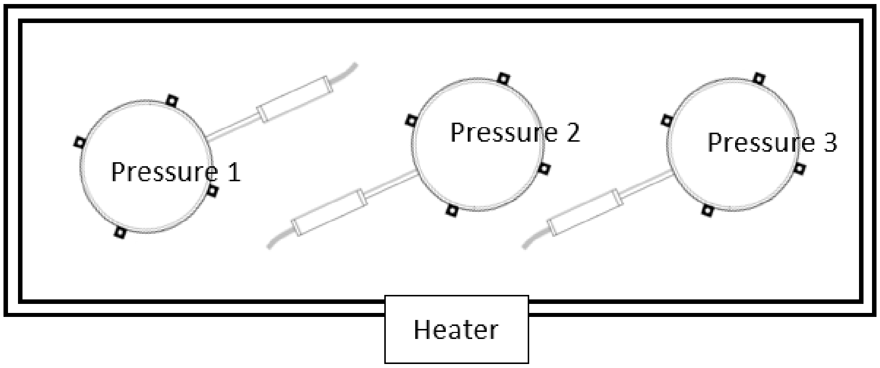
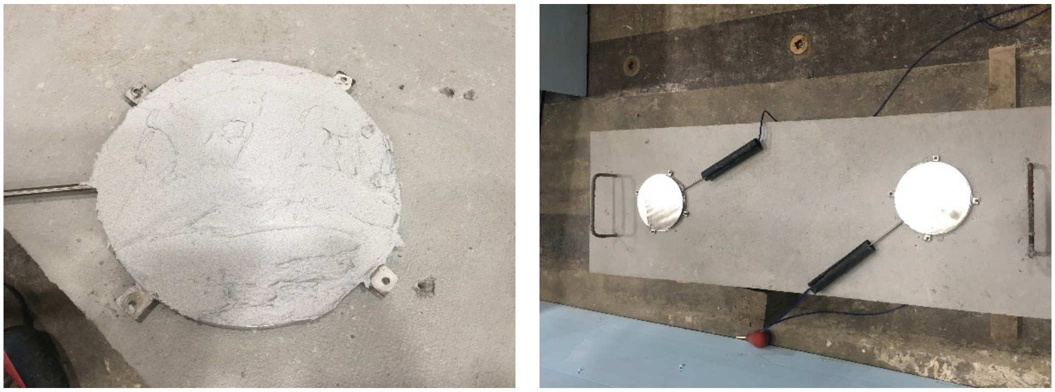


Figure 8. First test setup (plan view in isolation room)

As shown in Figure 9-a, a layer of mastic grout was first placed between the concrete slab and pressure cell to provide close contact.



a) Mastic Grout b) Restrained Pressure Cells

Figure 9. Restraint condition on the pressure cells

After the pressure cell was placed on the concrete slab, it was restrained using screws at four locations (shown in Figure 9-b).

Another pressure cell (Pressure-2) was placed between Pressure-1 and Pressure-3 without any restraint, as shown previously in Figure 8. Four concrete slabs, with a total weight of about 8,500 lb, were placed on top of Pressure-1 and Pressure-3, as shown in Figure 10.

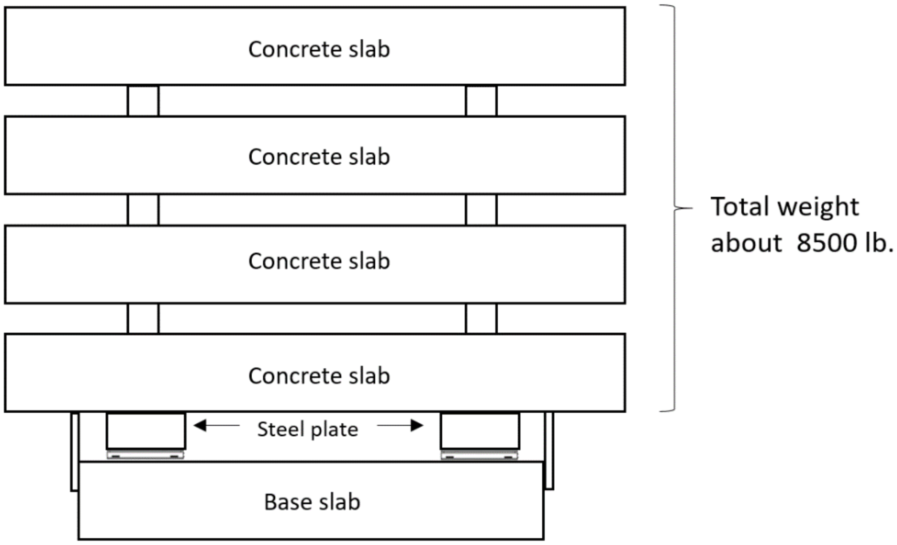
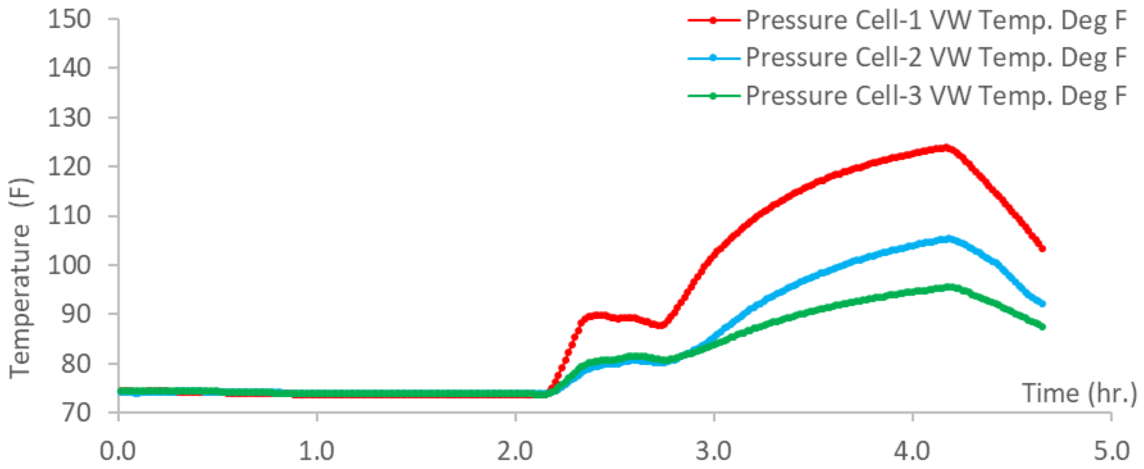


Figure 10. First test setup (elevation view)

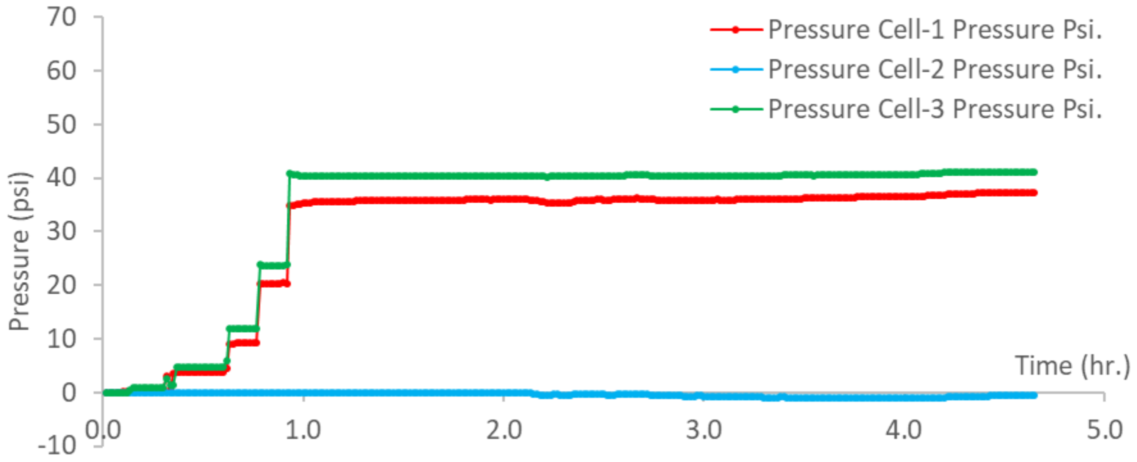
Note that, the slab weight was carried only by Pressure-1 and Pressure-3, and there was no load applied on Pressure-2.

An isolation room was built utilizing polythene foam. One heater was used to blow hot air into the isolation room. The temperature around the three pressure cells was changed by turning the heater on or off.

Figure 11-a and 11-b plot the temperature and pressure data versus time for the first test.



a) Temperature vs. time in the first test



b) Pressure vs. time in the first test

Figure 11. First test data

The pressure data shown in Figure 11-b have been corrected for the thermal compensation using the previous Equation 1 and the unique thermal factor (*K*) provided by the manufacturer. During the first hour, the temperature in the isolation room was constant and similar to the room temperature (Figure 11-a). The four concrete slabs were put on top of the pressure cells. Figure 11-b shows that Pressure-1 and Pressure-3 experienced a sudden pressure increase when each of the concrete slabs were placed.

From the second to fifth hour, the temperature in the isolation room was adjusted, as shown in Figure 11-a. Although the thermal gauge embedded in the transducer housing showed a different temperature distribution, all three pressure cells showed constant pressure data. This matches with the fact that the load on the pressure cells was unchanged from the second to the fifth hour.

3.2.2 Second Test

To gain a better understanding of the thermal distribution on the pressure cells, a second test was performed. The two differences between the first and second test were as follows: 1) two fans and one more heater were used to create a more evenly distributed temperature field in the isolation room (shown in Figure 12) and 2) two thermal couples were attached on the pad of Pressure-1 and Pressure-3.

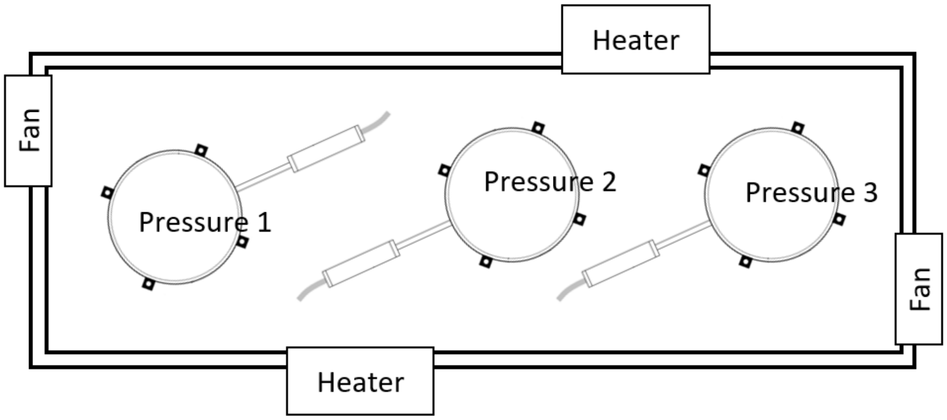
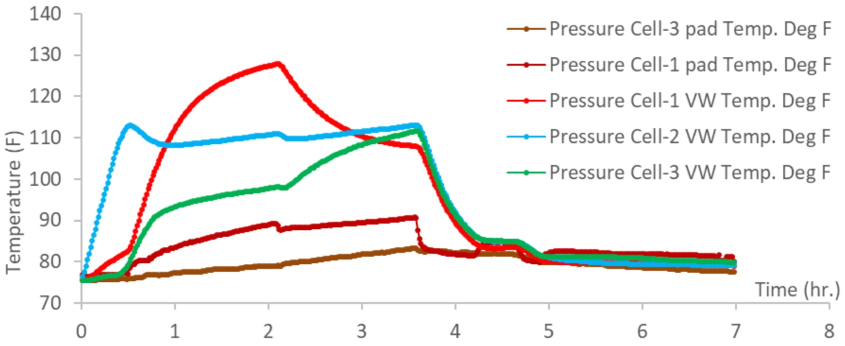


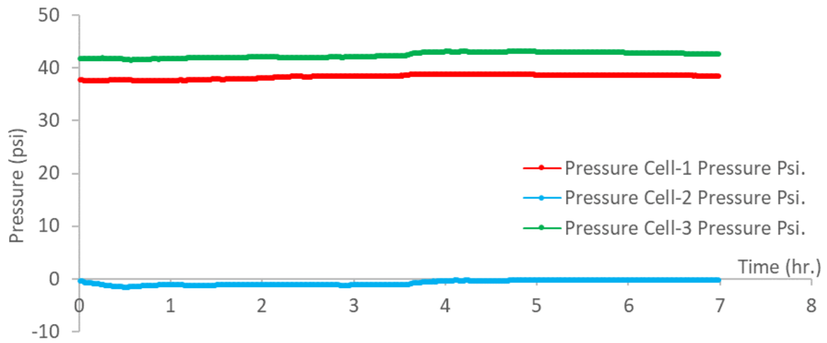
Figure 12. Second test barrel cross-section view

The goal of using the thermal couples was to capture the temperature change on the pad of the pressure cells. The temperature data collected from the thermal couples should be distinguished from the date collected from the thermal gauge embedded in the transducer housing, since the latter was near the vibrating wire and about 1 ft from the pressure cell (see the previous Figure 6).

Figure 13-a and 13-b show the temperature and pressure data versus time for the second test.



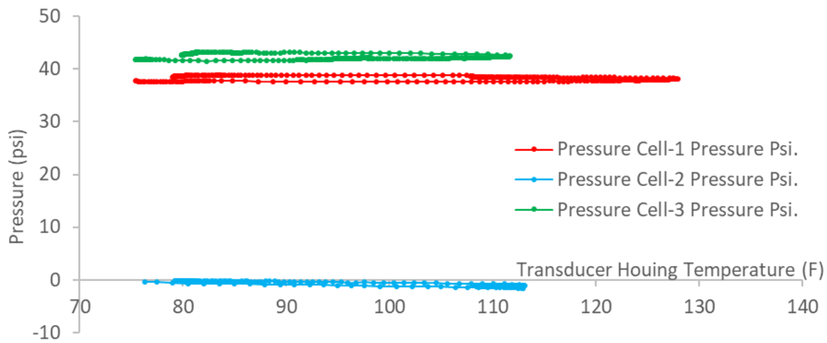
a) Temperature vs. time in the second test



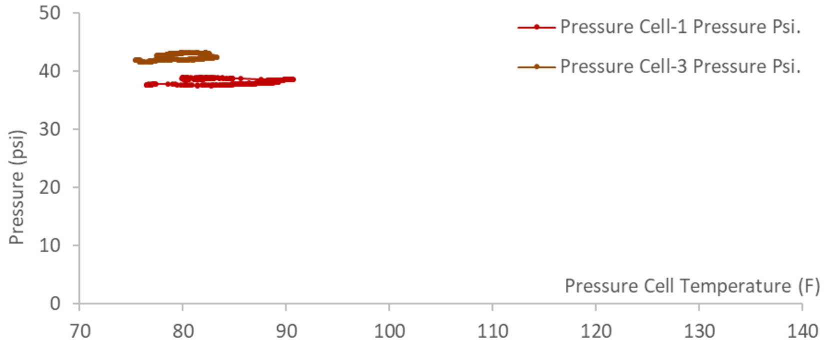
b) Pressure vs. time in the second test

Figure 13. Second test Data-1

The results showed the same conclusion as the first test in that the pressure on all three pressure cells was constant although the maximum temperature in the isolation room experienced about a 50° F change. The same conclusion also appears in Figure 14-a and –b, which show the pressure data vs. transducer housing temperature and pressure cell temperature, respectively.



a) Pressure vs. WV temperature



b) Pressure vs. pressure pad temperature

Figure 14. Second test Data-2

3.2.3 Earth Pressure Cell Thermal Laboratory Test Conclusions

The results from both laboratory tests indicated that the pressure readings were constant despite changes in temperature. Given this conclusion, the manufacturer-provided thermal factor (*K*) was found to be valid even if the pressure cell was restrained with a fixed condition and subject to significant temperature changes.

CHAPTER 4. IDA COUNTY FIELD MONITORING

4.1 Culvert Information

A concrete box culvert on US 20 in Ida County, constructed in 2016, was selected for the first field monitoring. Figure 15 shows the dimensions of a typical cross section view of the culvert with a 12 in. thick top and bottom slab and 9 in. wide web.

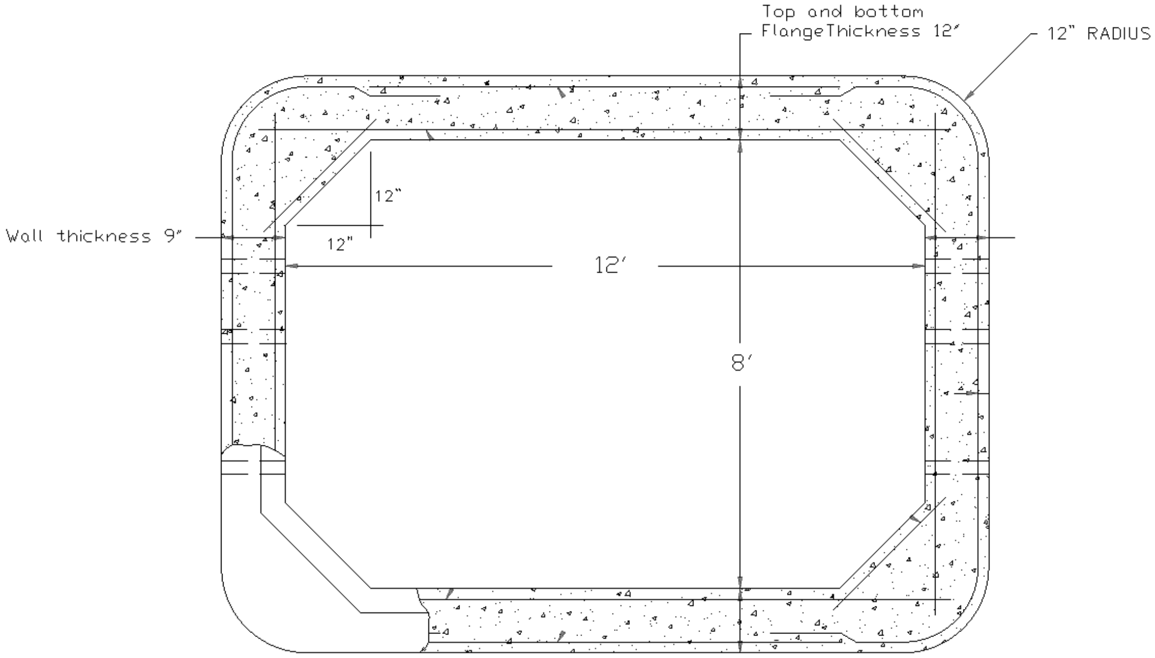
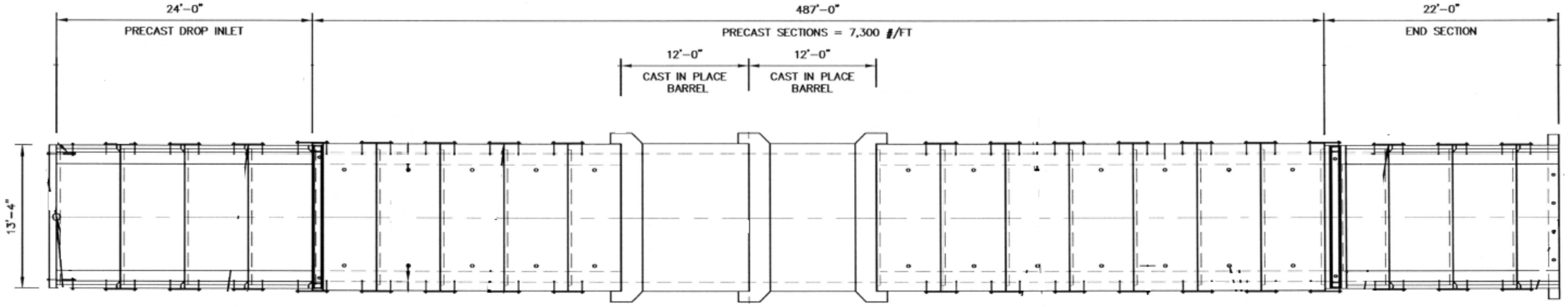
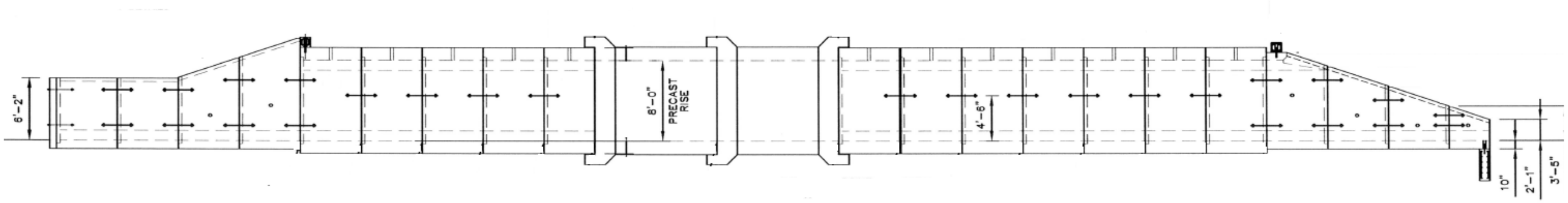


Figure 15. Ida County barrel cross-section view

The exterior of the culvert was 10 ft high and 13.5 ft wide. Figure 16 shows the plan view and elevation view of the whole culvert.



a) Plan view



b) Elevation View

Figure 16. Ida County culvert plan view and elevation view

The complete underground structure was 533 ft long with a 24 ft precast drop inlet, 487 ft long concrete box culvert, and 22 ft long end sections. The 487 ft concrete box culvert consisted of 27 6 ft long precast culvert sections next to the precast drop inlet, two 12 ft long cast-in-place barrels, and another 46 6 ft long precast culvert sections next to the end sections. According to the design calculations, the size of the culvert was designed for a vertical load of the unit soil weight (γ_s=120 lb/ft^3). The lateral earth pressure was not shown in the calculation book.

4.2 Field Condition and Construction

The majority of the box was set on top of a 6 in. thick sand base. At differential settlement areas, a 12 in. Class I bedding was created under the sand layer (as shown in Figure 17).

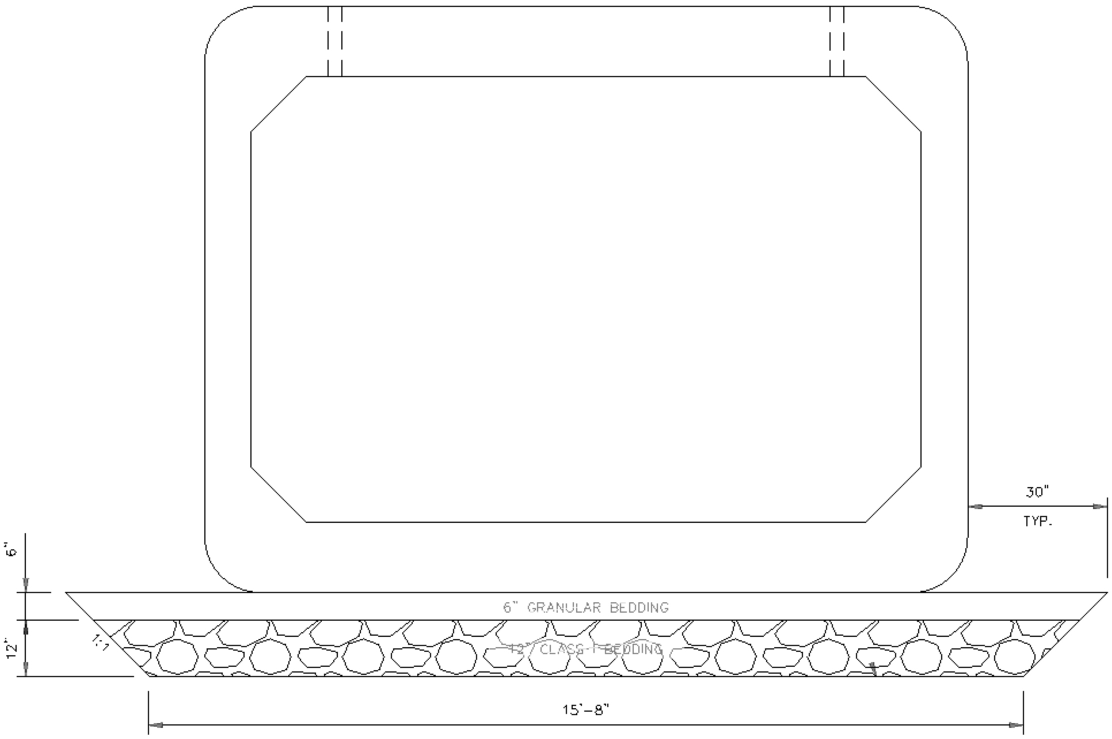


Figure 17. Ida Counting bedding detail at differential settlement area

Along the side of the box, the contractor used flooded backfill up to the top of the box. Sand was put in using 2 ft lifts. Class 10 fill above the box was placed in 8 in. lifts using a tractor and pans and a wedge foot roller for compaction. The first lift above the box was about 3 ft deep to protect the box from the weight of the construction equipment. Figure 18 shows the soil profile over the culvert.

The culvert was embedded under the embankment of US 20. The maximum depth of the soil over the top of the culvert was about 37 ft.

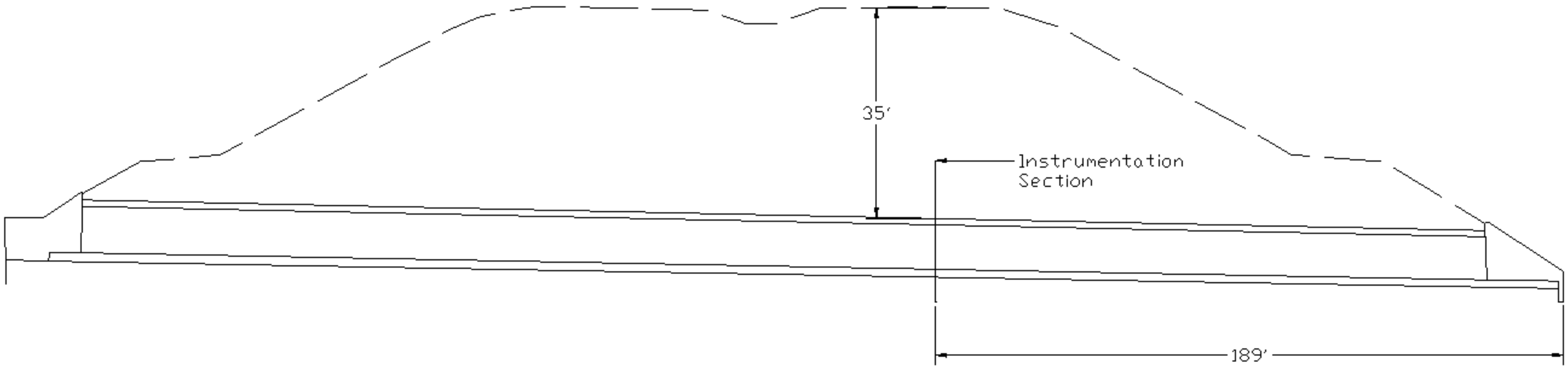


Figure 18. Ida County soil profile over the culvert

A web camera was installed in early April 2016 to collect general site information during construction. Figure 19 shows several video screenshots of the earthwork progress.

July 22, 2016 July 26, 2016

July 29, 2016 September 6, 2016

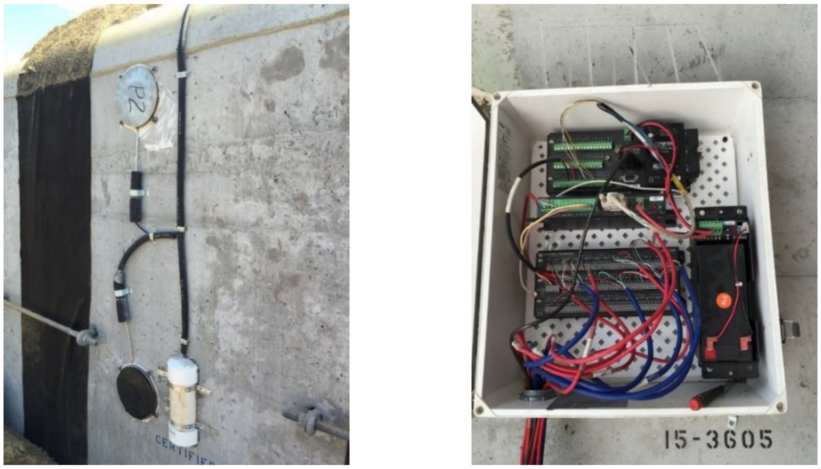
November 2, 2016 November 7, 2016

Figure 19. Ida County earthwork progress

The precast culvert units started to be placed in the field on July 22, 2016. The instrumentation work was finished right after the precast culvert units were placed in the field and finished on July 26, 2016. The backfill work started after the instrumentation work and reached to the height of the culvert by July 29, 2016. By November 7, 2016, most of the backfill work was completed.

4.3 Instrumentation Plan

The instrumented section was selected at about 189 ft from the end (see previous Figure 18) with a soil embankment of 35 ft. The earth pressure monitoring system consisted of five GEOKON Model 4810 earth pressure cells, six GEOKON Model 4000 VWSGs, and a Campbell CR-1000 data logger (see Figure 20-b).



a) Strain and earth pressure gauges b) CR 1000 data logger

Figure 20. Sensors and data logger

The system was powered by a 14 in. by 18 in. solar panel. Installation was completed on July 28, 2016 before the earth fill reached the height of the lowest sensors. Figure 21 shows the locations of the sensors.

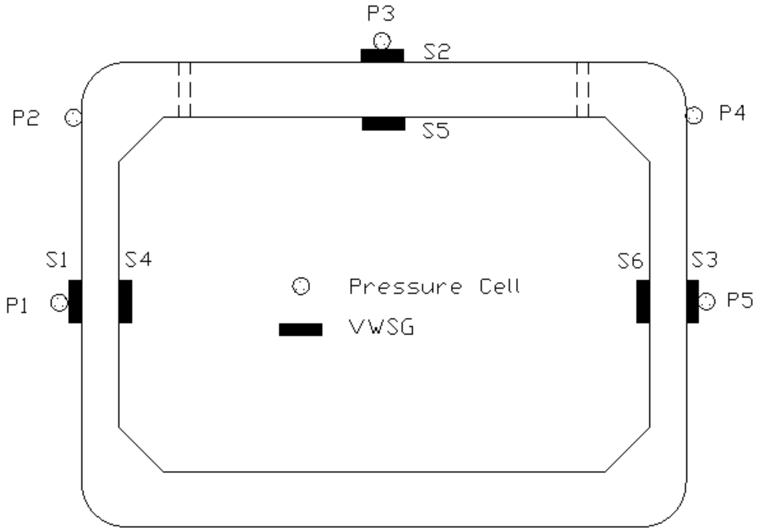


Figure 21. Ida County locations of pressure cells and strain sensors

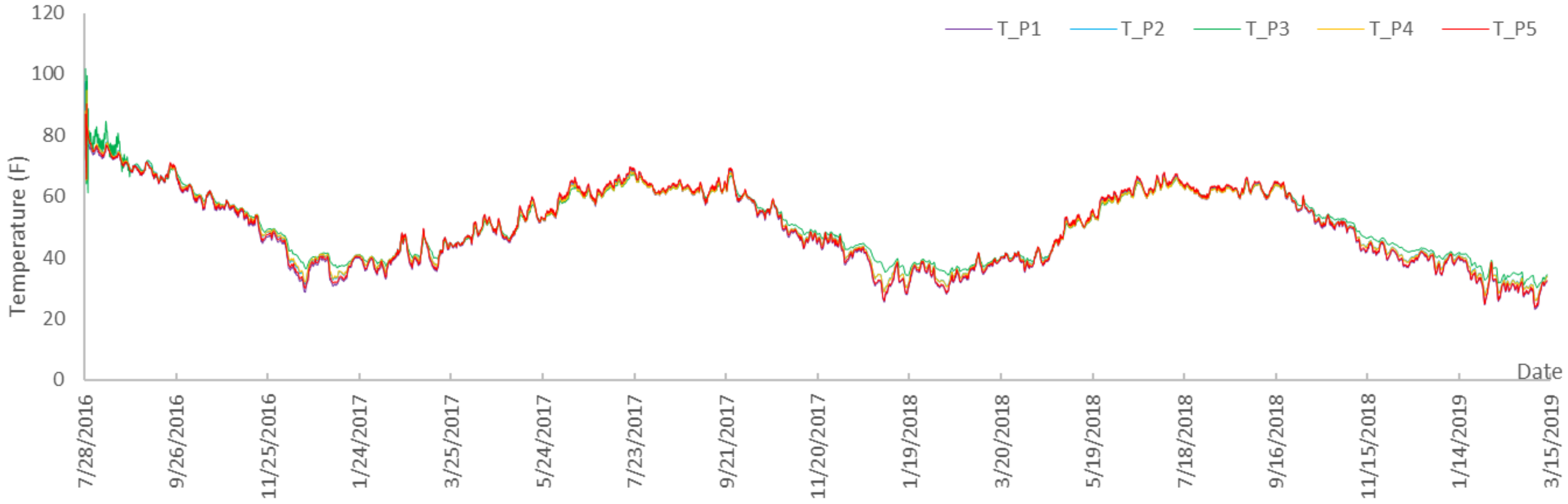
The pressure cells were covered by rubber, while the strain gauges on the exterior surface (S1, S2, and S3) were protected by covers made from polyvinyl chloride (PVC) pipe.

The previous Figure 20-a presents the sensors and covers. The other strain gauges (S4, S5, and S6) inside the culvert were left uncovered. The Campbell CR-1000 data logger worked with the sensors to collect earth pressure and strain data at a user-selected frequency of one reading per hour.

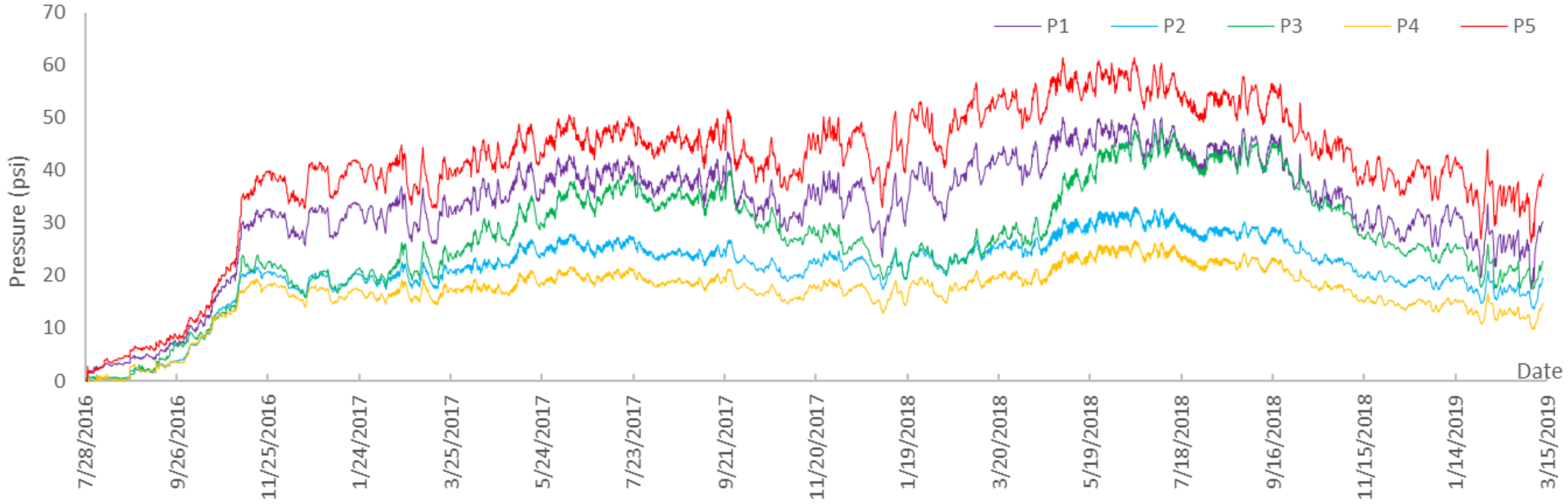
4.4 Pressure Results

The field monitoring took place from July 28, 2016 through March 15, 2019. Nearly 2 years and 8 months of data were collected at a frequency of one data point per hour. During this period, the culvert experienced the backfill load, construction load, and traffic load.

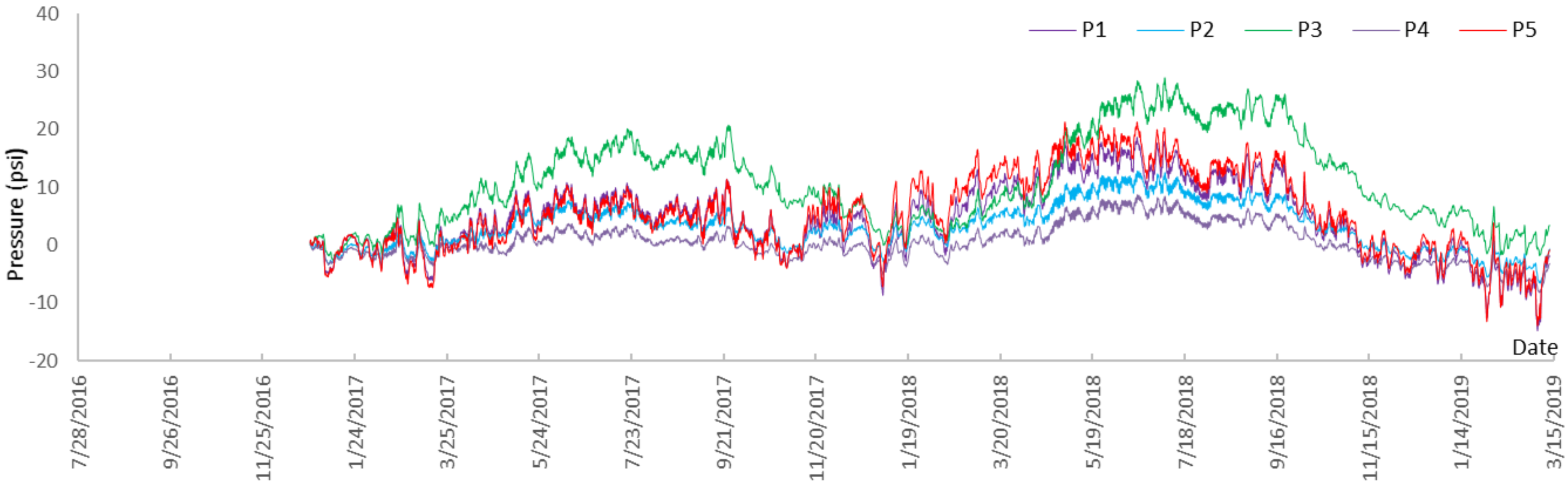
The pressure data from all pressure cells were thermally corrected utilizing the previous Equation 1 and the thermal factor provided on the gauge data sheet. Figure 22-a and -b present the field-collected pressure and temperature data from July 28, 2016 through March 15, 2019.



a) Temperature data



b) Pressure data (zeroed on July 28, 2016)



c) Pressure data (zeroed on December 26, 2016)

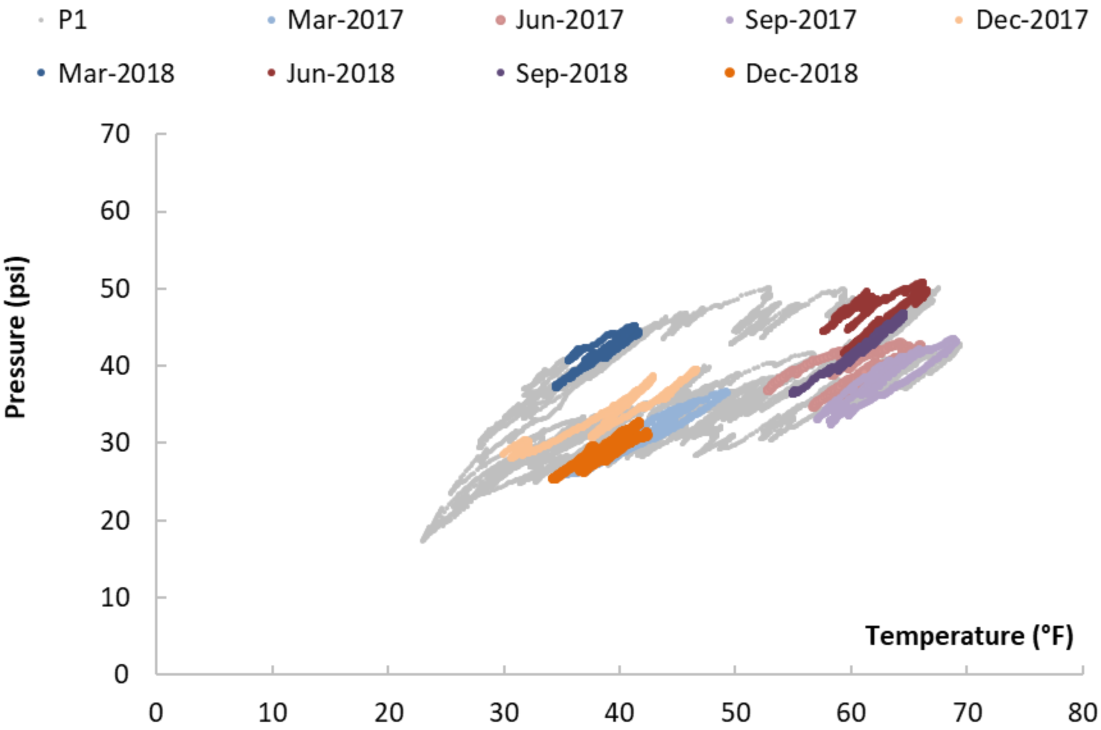
Figure 22. Ida County pressure and temperature data from pressure cells

During the first few months (July 28, 2016 through November 7, 2016), when most of the backfill work was underway, the data in Figure 22-b indicated that both the vertical and lateral earth pressures increased as the fill depth increased.

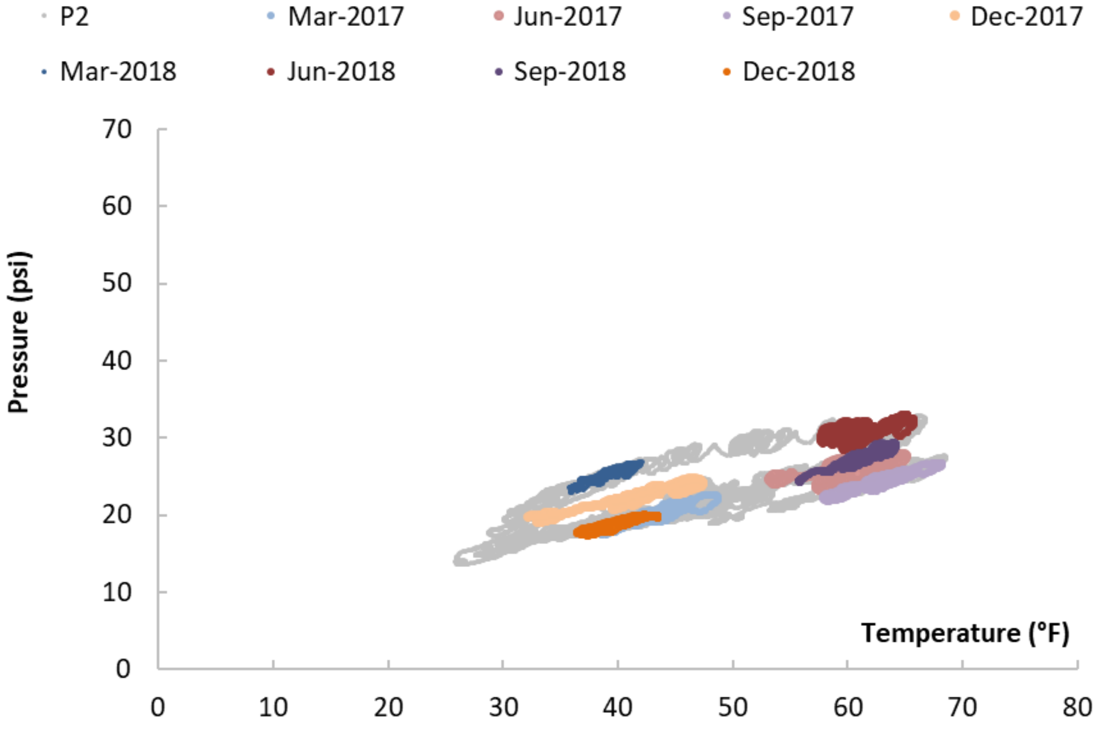
Data inspections indicated that a correlation between soil temperature and earth pressure existed. The relationship seen was that, as temperature increased, the pressure tended to increase. This was because the culvert tended to expand when the temperature increased and, hence, increased the pressure between the soil and the culvert exterior surface.

Figure 22-c zeroed the pressure data on December 26, 2016 when most of the backfill work was accomplished. The results indicated that the pressure-temperature relation for P3 (measuring vertical pressure) was more obvious than the other pressure cells (measuring the lateral pressure).

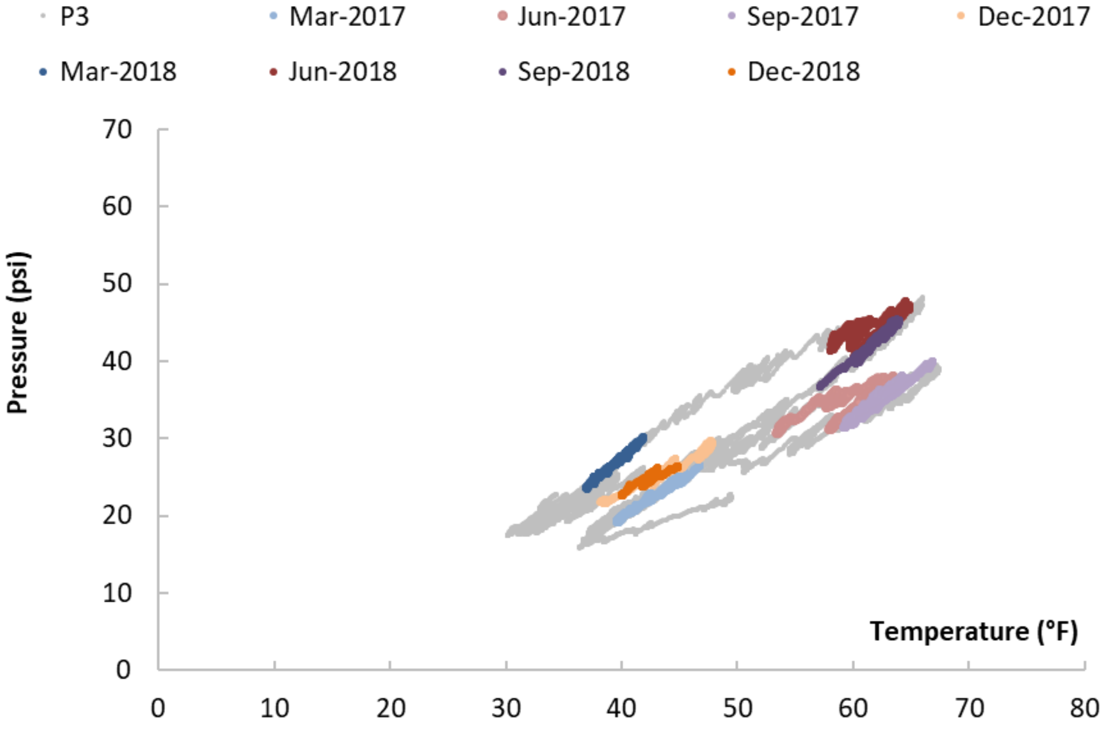
To better illustrate the relation between the pressure and temperature data, Figure 23 plots the pressure versus temperature for each pressure cell.



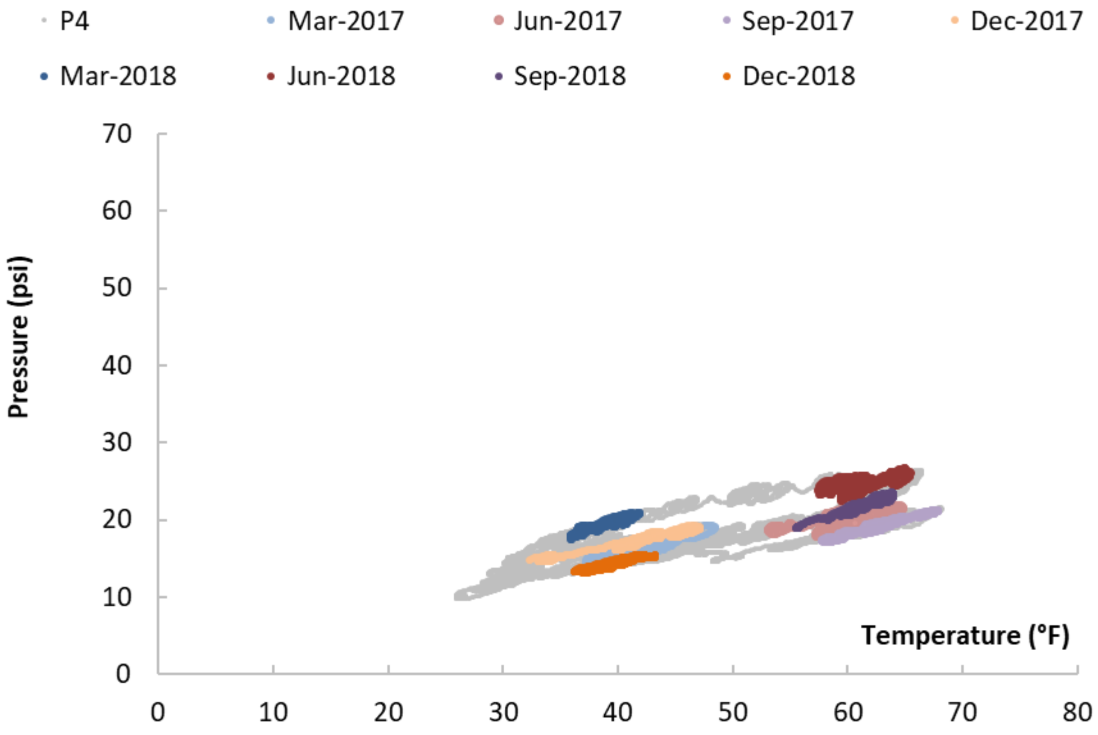
a) P1


P2
Mar-2017
Jun-2017
Sep-2017
Dec-2017
Mar-2018
Jun-2018
Sep-2018
Dec-2018
Pressure (psi)
Temperature (°F)
0
10
20
30
40
50
60
70
80

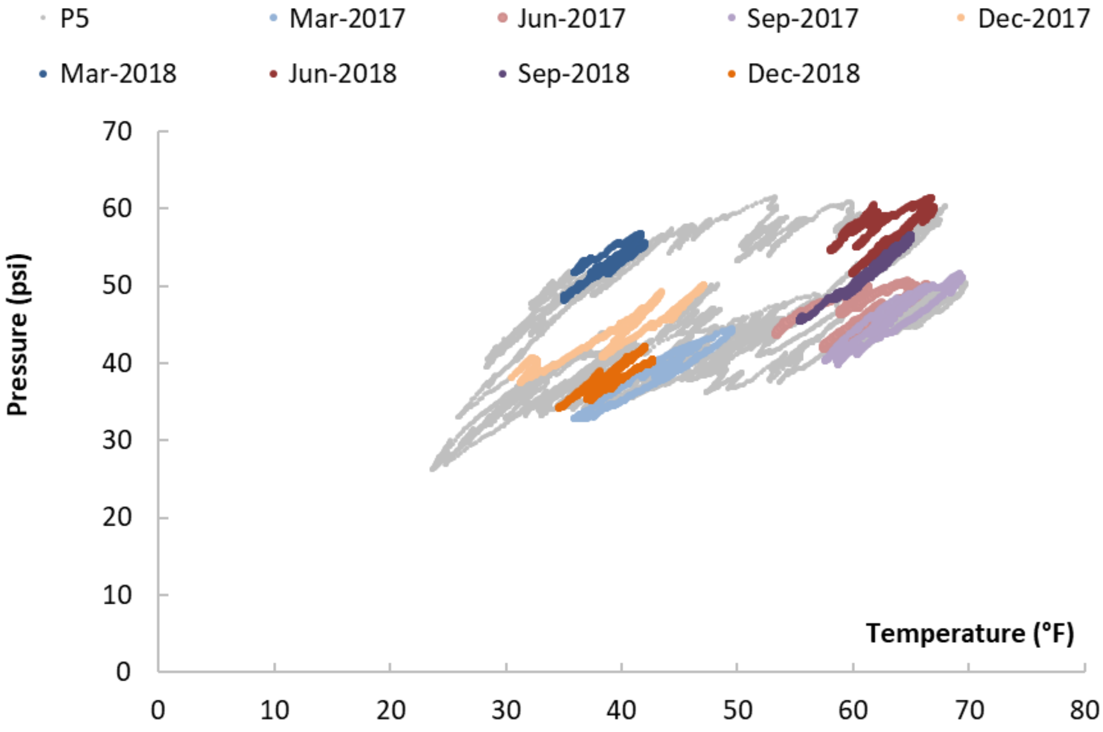
b) P2


P3
Mar-2017
Jun-2017
Sep-2017
Dec-2017
Mar-2018
Jun-2018
Sep-2018
Dec-2018
Pressure (psi)
Temperature (°F)
0
10
20
30
40
50
60
70
80

c) P3



d) P4



e) P5

Figure 23. Ida County pressure vs. temperature data (pressure data zeroed on July 28, 2016)

With the same scale on each plot, it is obvious that a greater slope exists in the data captured by P3, the pressure cell that measured the vertical pressure. In each plot, the data from four months of each year (March, June, September, and December) were highlighted. The results indicated that the pressure in the second year was greater than the pressure in the first year during the same month with a similar temperature range.

In general, the lateral earth pressure of P1 was greater than that of P2, and, similarly, P5 was greater than that of P4. This result satisfied the basic principle that the pressure is greater at deeper locations. Figure 24 plots the lateral pressure distribution throughout the height of the culvert.

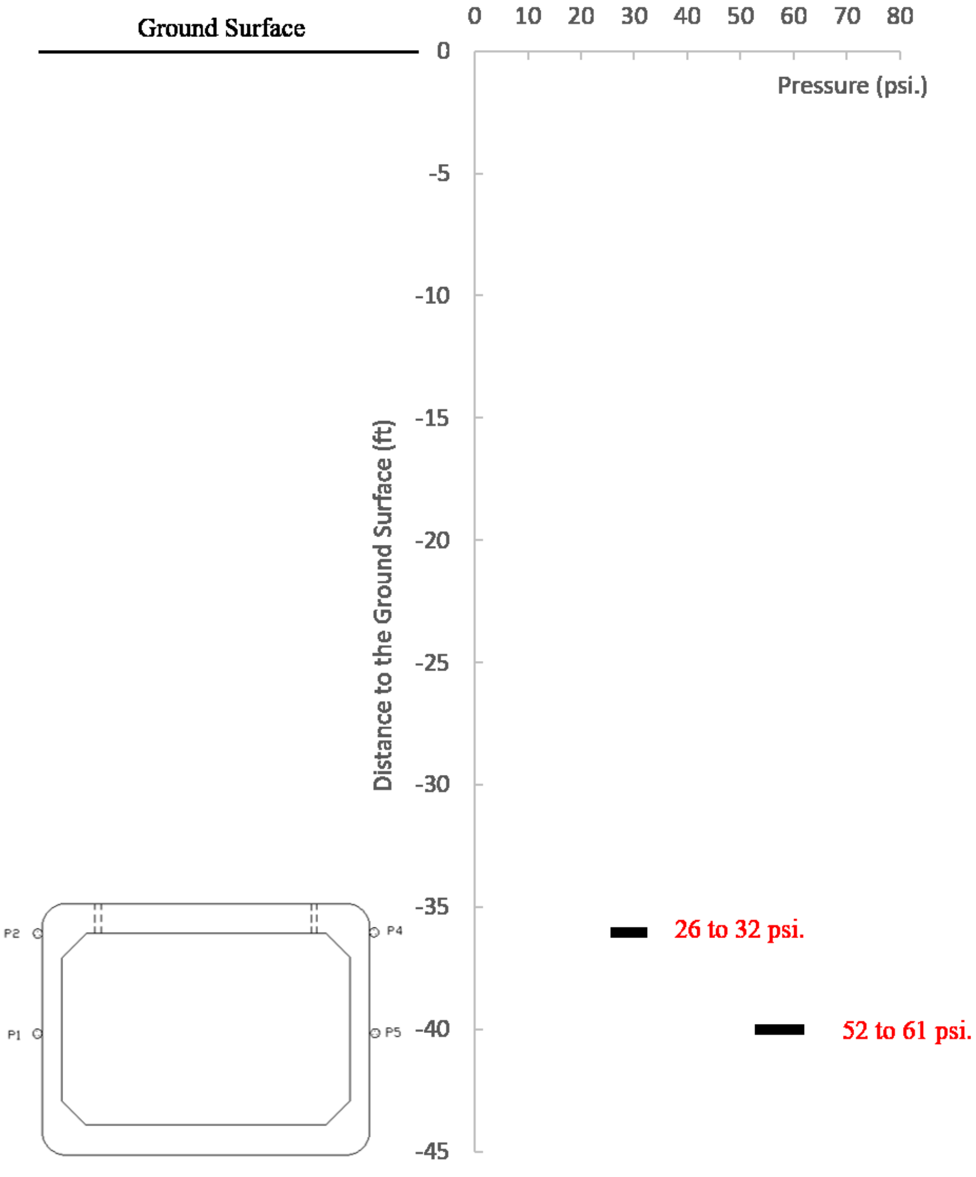


Figure 24. Ida County lateral pressure distribution (data on July 19, 2018 2:00 a.m.)

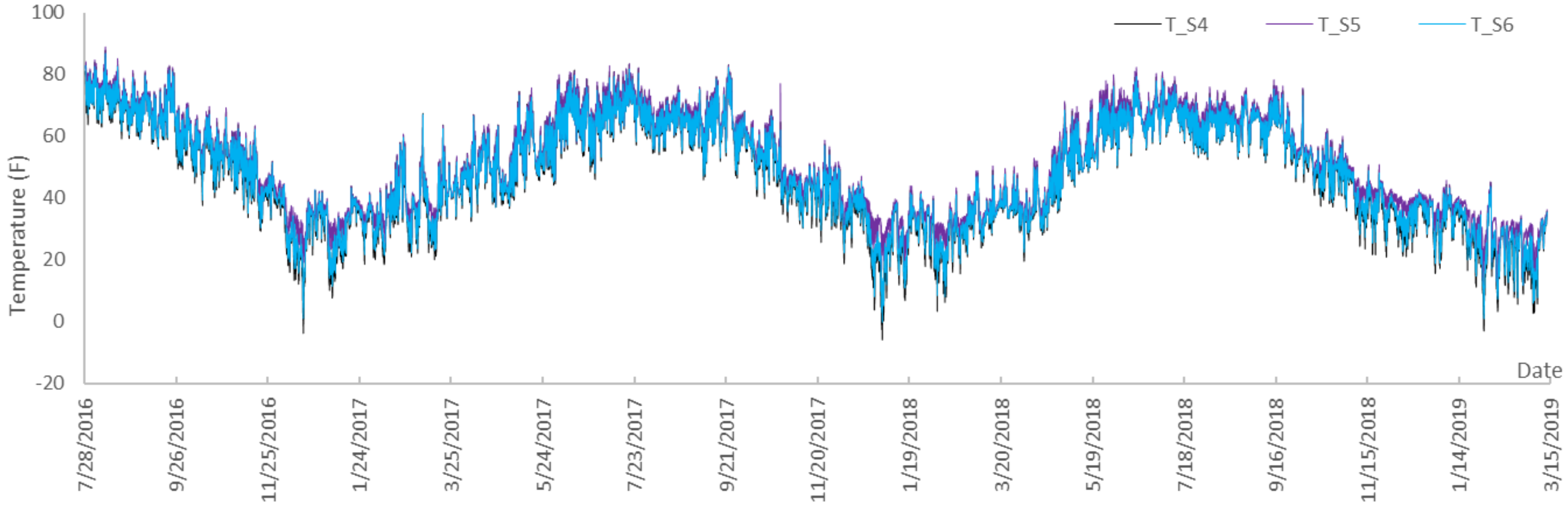
The data were captured on July 19, 2018 at 2:00 a.m. The lateral pressure at the mid-height of the culvert was much greater than the pressure data collected near the top of it. This was because the pressure data consisted of two resources: one was the “active pressure” form the soil lateral pressure and the other was the “passive pressure” coming from the culvert deformation due to the vertical pressure. The “passive pressure” was generated when the vertical pressure compressed the wall of the culvert and resulted in the mid-height of the wall tending to move outward.

The pressure data from November 4, 2016 to November 7, 2016 in Figure 24 also indicated that the “passive pressure” existed. During this period, with the same backfill soil height, all the lateral pressure cells should have experienced the same pressure behavior. However, the data indicated that P1 and P5 at the lower level experienced an increment of 8 to 10 psi while P2 and P4 showed a 2 to 5 psi increment.

4.5 Strain Result and Culvert Cracks

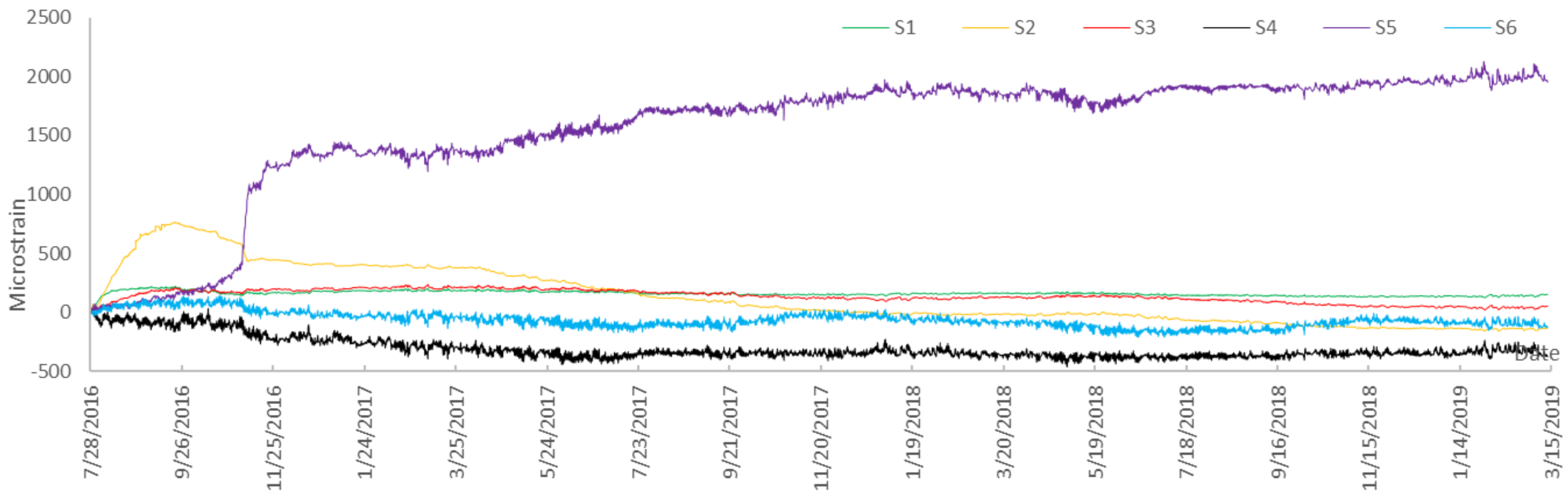
The temperature and strain data captured by the six VWSGs are shown in Figure 25 and Figure 26.

a) Temperature data for S1, S2, and S3

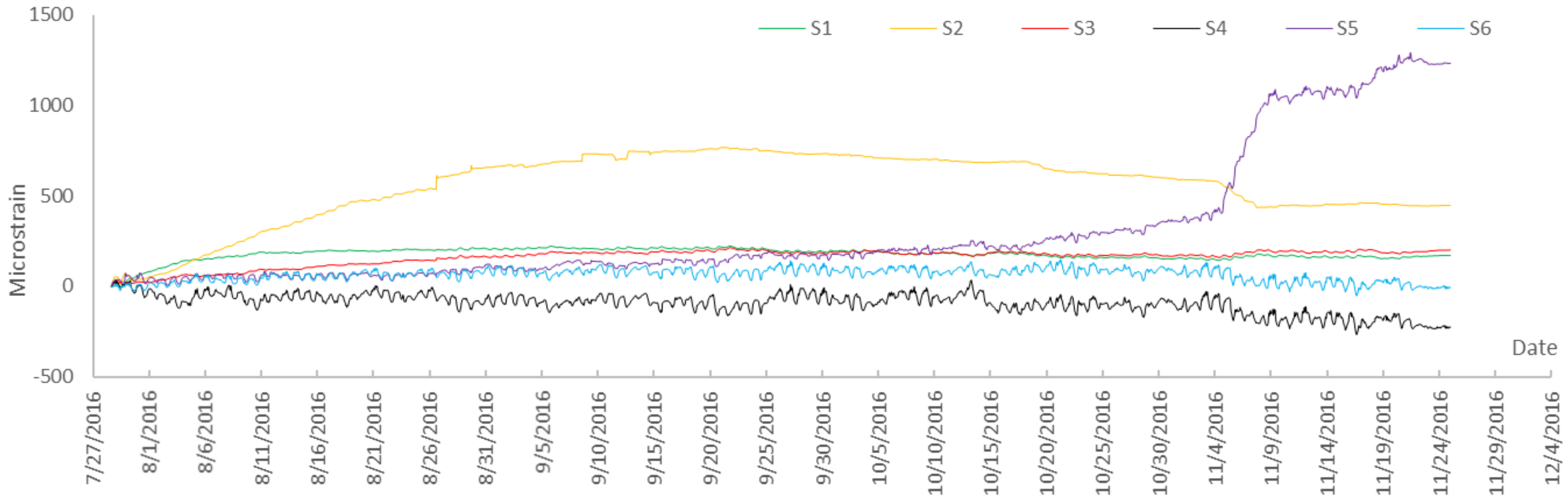


b) Temperature data for S4, S5, and S6

Figure 25. Ida County temperature data from VWSGs



a) Strain data during whole monitoring period



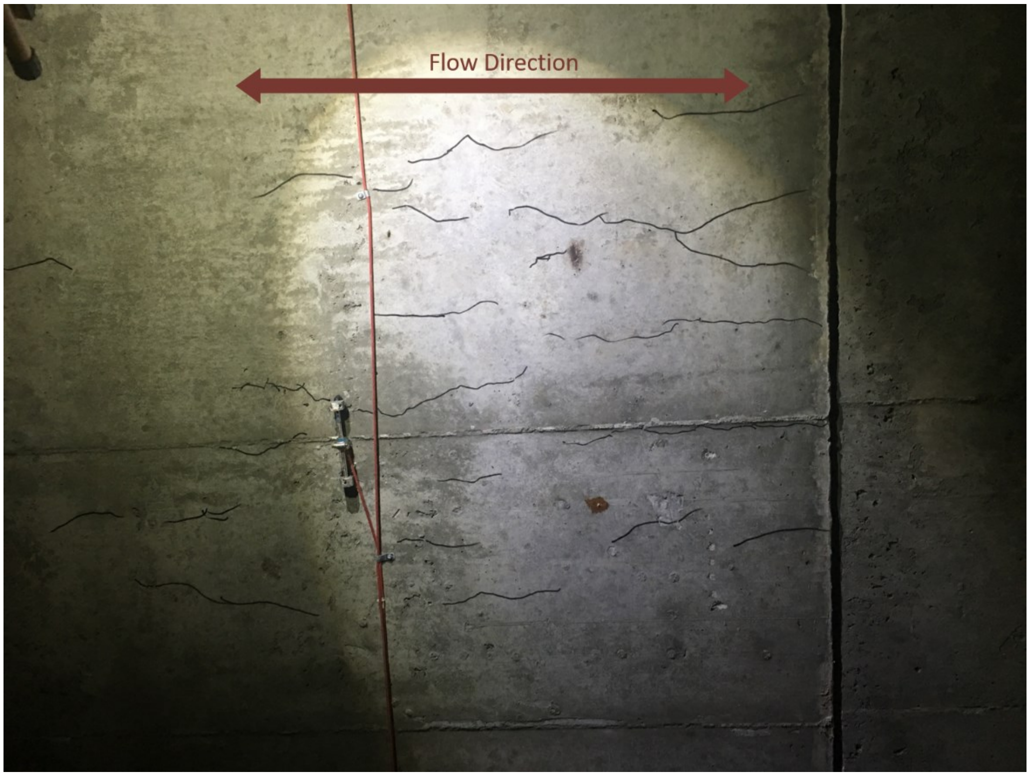
b) Strain data in first five months

Figure 26. Ida County strain data measured by VWSGs

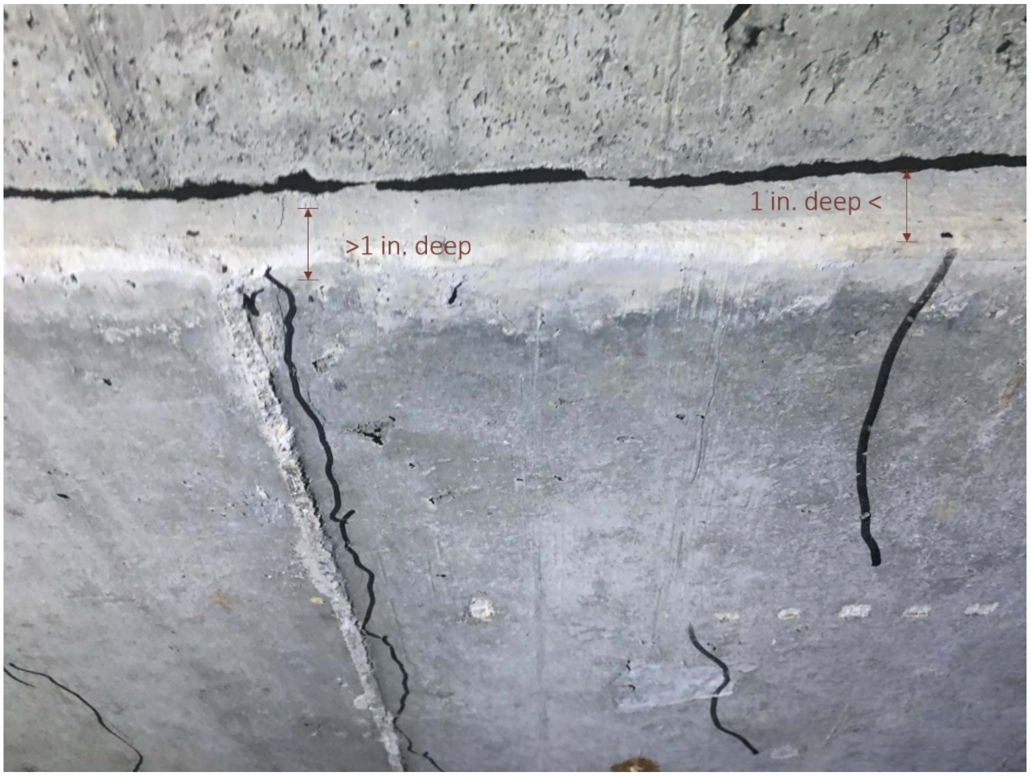
The strain data in Figure 26 have been thermally corrected, as previously discussed. Figure 26-a indicates that the strains of S2 and S5 were extremely large. Figure 26-b zooms in on the strain during the first five months. It indicates that, when the depth of the backfill was low, S2 was in tension, while S5 was in compression. The tension of S2 caused concrete cracking. As the fill depth increased, the tension side and compression side of top slab are reversed. When the fill depth increased to a certain level, the tension of S5 was great enough to cause the concrete cracking.

Although the strain readings after cracking may not be reliably correlated to the magnitude of external loading, the general trend was consistent with the monitored earth pressure. For example, the big earth pressure changes during November 5, 2017 and November 8, 2017 also led to significant strain changes in this period.

A field inspection was conducted on the instrumented box culvert to record any cracking. A significant number of cracks were found near the middle span of the top slab within the one-quarter span length on each side. The cracks were highlighted using black marker and are shown in Figure 27-a.



a) Longitudinal cracks on the bottom of the top slab

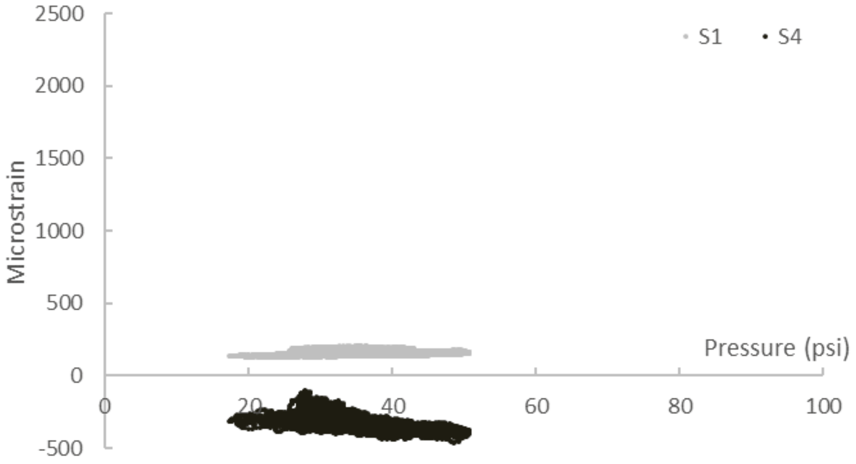


b) Crack depth at the end of instrumented culvert unit

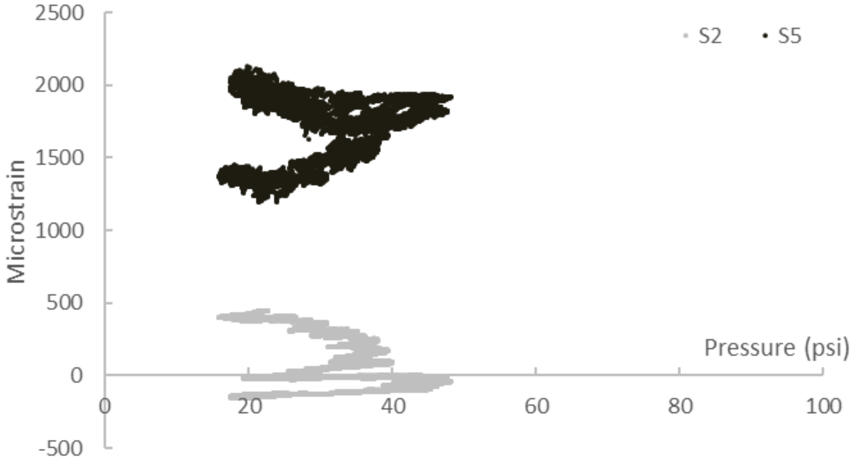
Figure 27. Ida County culvert crack situation

At the end of the culvert unit, it can be seen that some of the cracks propagated to more than 1 in. deep (see Figure 27-b). Since the cracking on the top slab increased the downward deflection at the mid-span of the top slab, part of the soil above the culvert tended to be carried by the surrounding soil due to the soil arching effect. This eventually reduced the pressure recorded by P3.

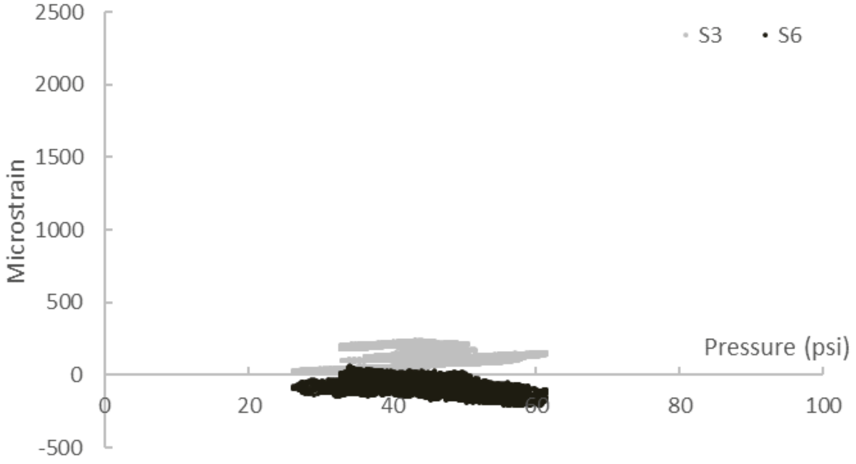
Figure 28 plots the strain data versus pressure data collected from the pressure cell.



a) S1, S4 vs. P1



b) S2, S5 vs. P3



c) S3, S6 vs. P5

Figure 28. Ida County strain vs. pressure data

As the pressure increased and the strain at the outside surface of the exterior wall increased, the strain at the interior surface decreased. This was because the bending caused by earth pressures led to tensile strain at the outside surface and compression at the inside surface.

4.6 Comparison with Design Loading

In this section, the field-collected pressure data are compared with the design values. The design load was calculated following the AASHTO LRFD and ASD/LFD specifications. Table 2 presents the maximum and minimum monitored vertical and lateral earth pressures and corresponding codified earth pressures.

Table 2. Ida County comparison between the monitored and codified earth pressures

	Vertical Pressure	Lateral Pressure							
	P3	P1		P2		P4		P5	
	Max	Max	Min	Max	Min	Max	Min	Max	Min
Distance from the ground surface (ft)	35	40		36		36		40	
Monitored (psi)	47	52	18	32	14	26	10	61	26
Codified LRFD (psi)	33*	17	8.5	15	7.5	15	7.5	17	8.5
Codified LFD/ASD (psi)	29**	10	5	9	4.5	9	4.5	10	5

*Soil-structure interaction coefficient of 1.15 is included
**Although was not adopted by the Iowa DOT, AASHTO ASD specifications allow for a reduction in vertical earth pressure

The codified vertical pressure values were calculated assuming a soil weight of 120 lb/ft^3. The codified lateral pressure was calculated based on an earth pressure of 36/18 lb/ft^3 for LFD and ASD and 60/30 lb/ft^3 for LRFD. As can be seen, the monitored earth pressures were 2 to 4 times that of the design values with the LRFD and LFD/ASD methods. Compared to the LFD/ASD specifications, LRFD lateral earth pressure was closer to the monitoring data. However, the monitored data were still 2 to 3 times that of the design values with the LRFD method. This could be the reason that the instrumented culvert experienced cracking during the backfill work and before the road on top of the culvert was in service. It should be noted that the box culvert was not designed to be “crack-free.”

Although the top slab cracking and the arching effect may have reduced the pressure experienced at the P3 gauge, the maximum-recorded value (47 psi) was still higher than the codified earth pressure (33 or 29 psi). While the pressure values for P1 and P5 may have included the passive pressure due to culvert deformation, only the data from P2 and P4 were good representatives of the actual lateral earth pressure. However, both the maximum and minimum lateral pressures measured by P2 and P4 were still 2 to 4 times that of the corresponding design pressures.

4.7 Conclusions

Based on the analysis of the data collected from the Ida County culvert, a few conclusions were drawn, as follows:

- The maximum measured vertical earth pressure 35 ft below the ground was 47 psi. The maximum and minimum measured lateral pressure was about 32/10 psi at 36 ft deep and 61/18 at 40 ft.
- Compared to LFD/ASD specifications, LRFD lateral earth pressures were closer to the monitoring data. However, the monitored data were still 2 to 4 times that of the design values from the LRFD and LFD/ASD methods.
- As temperature increased, all the pressures tended to increase. This was because the culvert tended to expand when the temperature increased and, hence, increased the pressure between the soil and the culvert exterior surface.
- A significant number of cracks were found near the middle span of the top slab within the one-quarter span length on each side.

CHAPTER 5. CRAWFORD COUNTY FIELD MONITORING

Because of the surprising results from the Ida County culvert monitoring work that had extensive longitudinal cracking within the first year after construction, another precast reinforced concrete box culvert was selected, in Crawford County, for a second monitoring effort. The culvert transports the water of a stream under the embankment of US 59 into Coon Creek, as shown in Figure 29.

Imagery ©2021 Maxar Technologies, USDA Farm Service Agency, Map data ©2021 from Google

Figure 29. Crawford County culvert location

This specific culvert was ideal for this project with its large earth fills and the length of the structure. The instrumentation objective was to gather quality data to compare results to design specifications.

Based on the results from the previous project in Ida County, the level of instrumentation was increased using additional strain gauges and pressure cells. Moreover, two additional instrumented sections were added. Three types of data were recorded: pressure, strain, and temperature. Then, the data were analyzed and corrected based on the initial readings and the thermal equations previously described in Chapter 3. The corrected data were then compared to the design specifications and field inspections.

This chapter includes the details on the culvert, instrumentation design, pressure results, strain results, inspections, and design specification comparisons.

5.1 Culvert Information

The 8 ft×9 ft×277 ft culvert was constructed during the summer of 2020. The culvert was designed based on the Iowa DOT Standard Plan PRCB 8-13 with HL-93 & 25k Tandem live loads and earth fills of 21 to 25 ft. Figure 30 shows the typical cross-section view of the culvert.

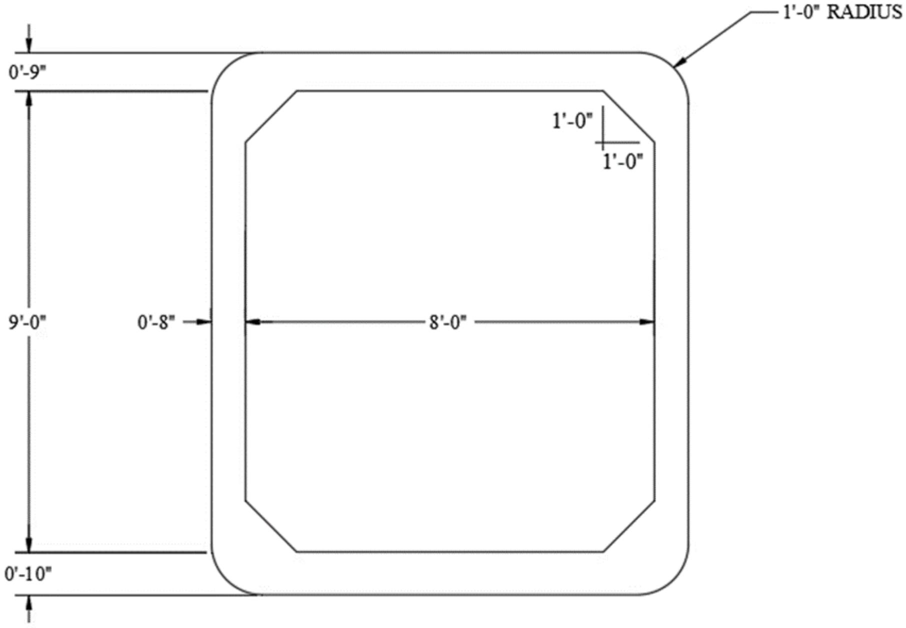


Figure 30. Crawford County box culvert cross-section view

The design included 61 five to six ft long precast reinforced concrete box segments (Figure 31).

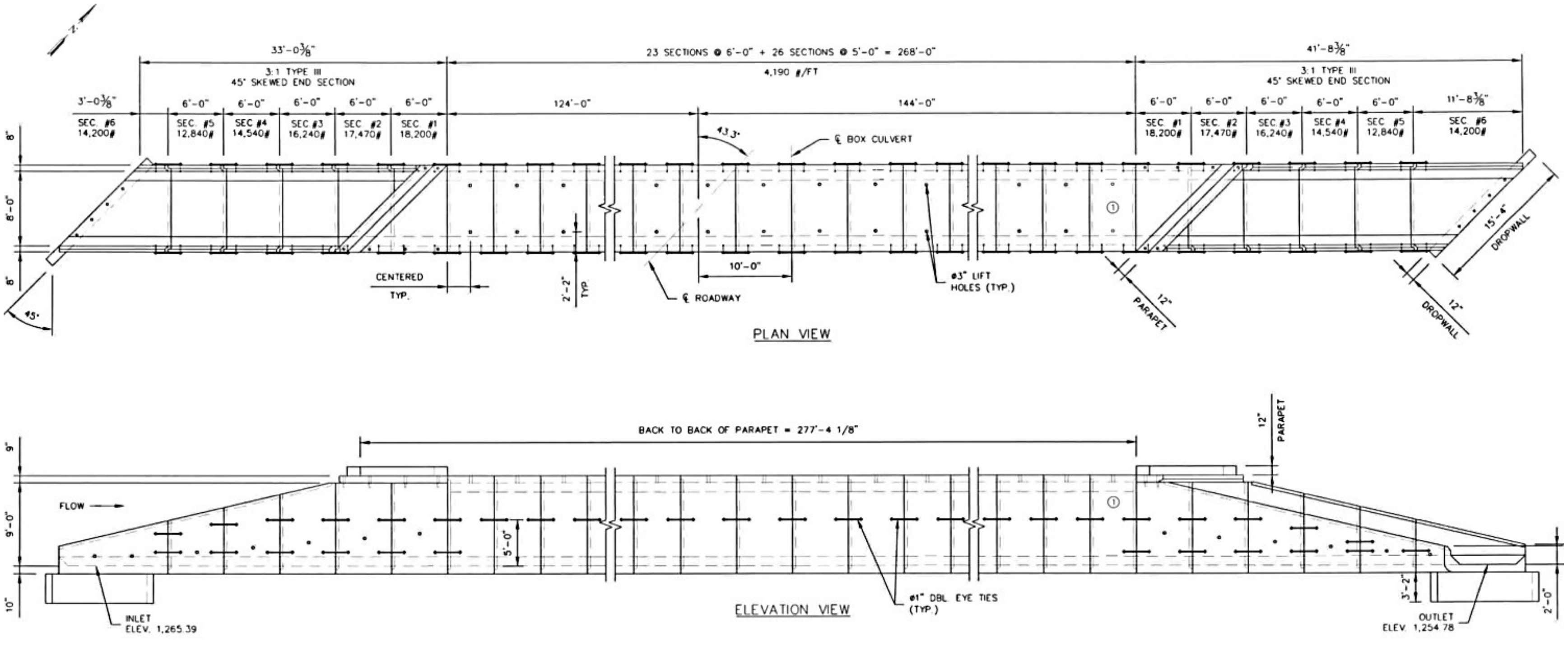
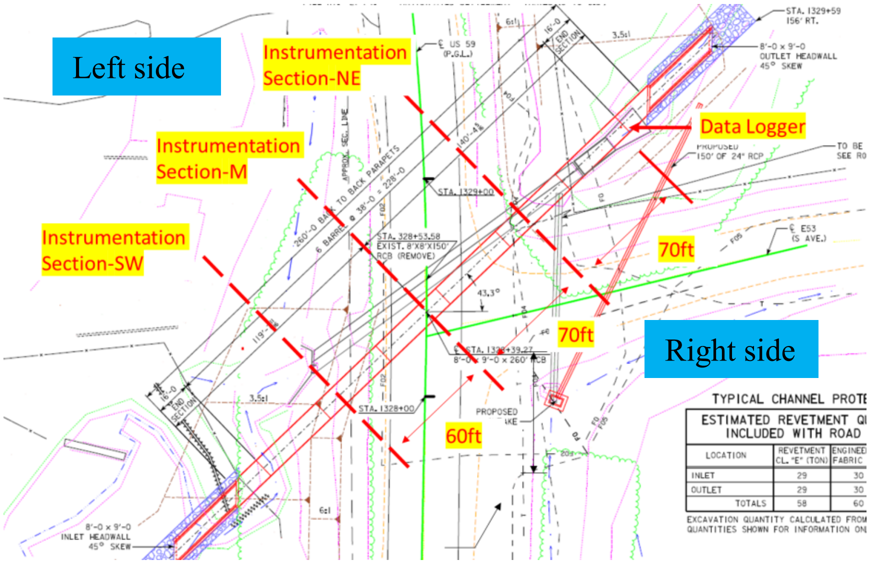


Figure 31. Crawford County culvert plan view and elevation view

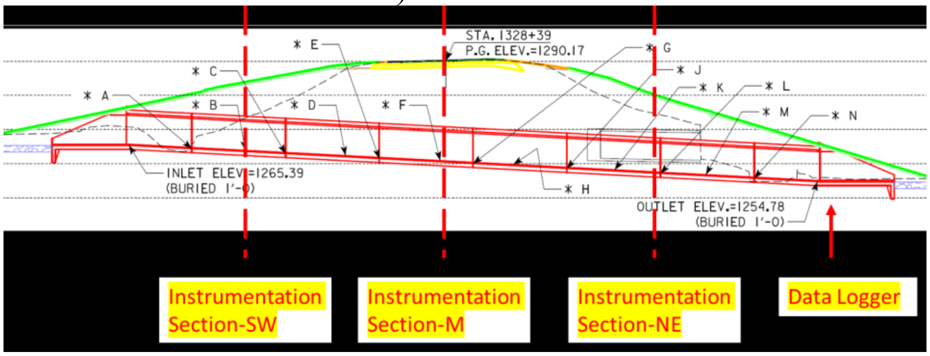
According to the culvert design book, the design soil weight was 120 lb/ft^3. The lateral pressure coefficients for the culvert were 0.5 for the maximum and 0.25 for the minimum.

5.2 Instrumentation Plan

The culvert was instrumented in three different locations, each with different fill heights. These instrumented sections are referred to as the northeast (NE) section, middle (M) section, and southwest (SW) section. The plan view and elevation view of the instrumentation locations are shown in Figure 32.



a) Plan View



b) Elevation View

Figure 32. Crawford County locations for instrumentation

From the northeast end, the data logger was located at the beginning of the barrel with the NE section at 70 ft, the M section at 140 ft, and the SW section 200 ft along the box culvert. According to the design drawing, the fill heights for each section were as follows: NE at 16 ft, M at 20 ft, and SW at 12 ft.

At each section, 11 GEOKON Vibrating Wire Model 4810 pressure cells and 10 GEOKON Model 4000 VWSGs were installed. Figure 33 shows the locations of the pressure cells and strain gauges.

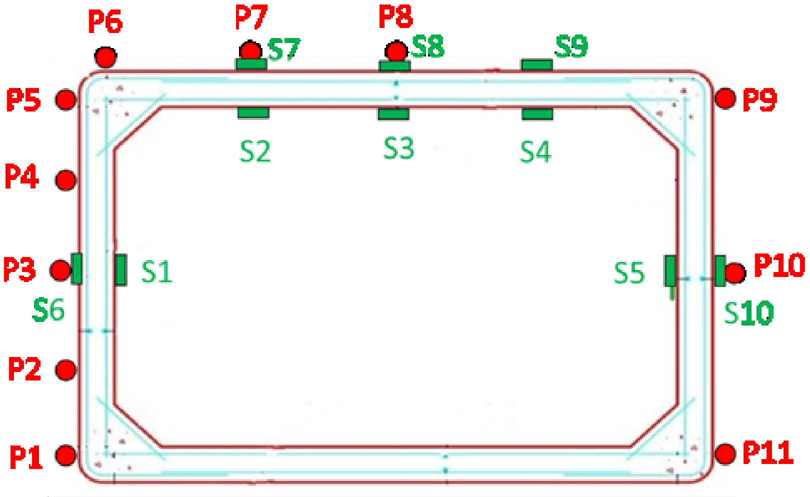


Figure 33. Crawford County locations for pressure cells and strain gauges

The left side of the culvert had five pressure cells to obtain a more accurate distribution of the pressure. The instrumentation of the top of the culvert utilized fewer gauges, placed to capture one full portion of data and relying on symmetry to extrapolate the other values if needed. Each strain gauge was located in an area where the most compression and tension were predicted.

Using mastic grout and concrete screws, the pressure cells were attached to the outside of the culvert. Then, the pressure cells were covered by rubber (see Figure 34).

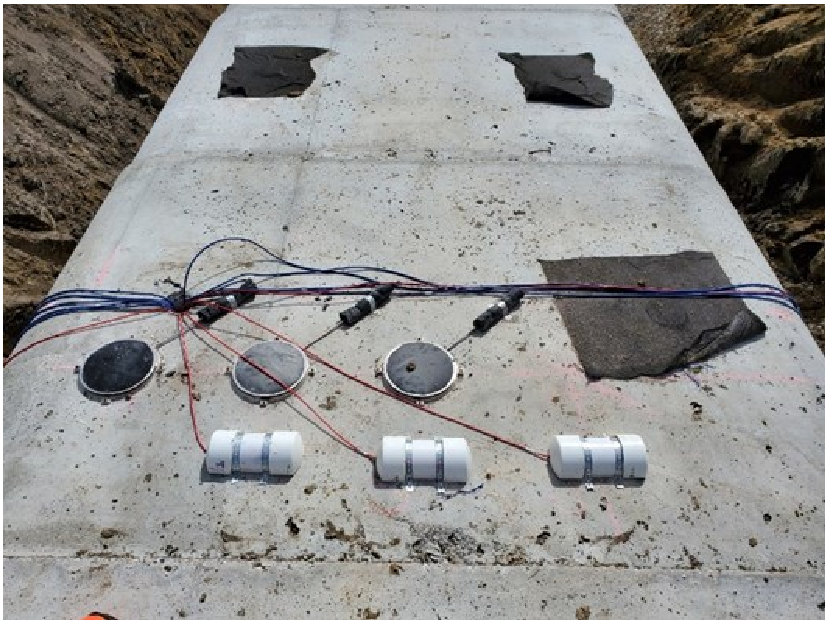


Figure 34. Crawford County pressure cells and strain gauges

The strain gauges were installed using the method outlined in the instruction manual (GEOKON 2017). The outside gauges were protected by PVC pipe and the inside gauges were left uncovered. All of the strain and pressure gauges were connected to a Campbell CR-1000 data logger, which was charged by a battery and a solar panel. The data logger collected measurements from the pressure cells and strain gauges every hour.

5.3 Field Condition and Construction

Construction was observed from August 4, 2020 through August 26, 2020. The backfill methods and the date on which each instrument was backfilled was noted. Table 3 shows when each of the pressure cells and strain gauges were covered with soil (see previous Figure 33 for instrumentation plan).

Table 3. Crawford County August 2020 backfill timeline

Date	NE Section	M Section	SW Section
8/3	No sensor covered	No sensor covered	No sensor covered
8/4	P11	P1, P11	No sensor covered
8/5	P1, P11	P1, P11	No sensor covered
8/6	P1–P5, P10–P11, S6, S10	P1–P3, P10–P11, S6, S10	P11
8/7	P1–P5, P10–P11, S6, S10	P1-P5, P10–P11, S6, S10	P1–P4, P10–P11, S6, S10
8/10	P1–P5, P9–P11, S6, S10	P1–P5, P9–P11, S6, S10	P1–P5, P9–P11, S6, S10
8/11	Culvert covered	Culvert covered	Culvert covered
8/12	Culvert covered	Culvert covered	Culvert covered

The backfill started with a 6 in. layer of Macadam Stone and special backfill, as shown in Figure 35.

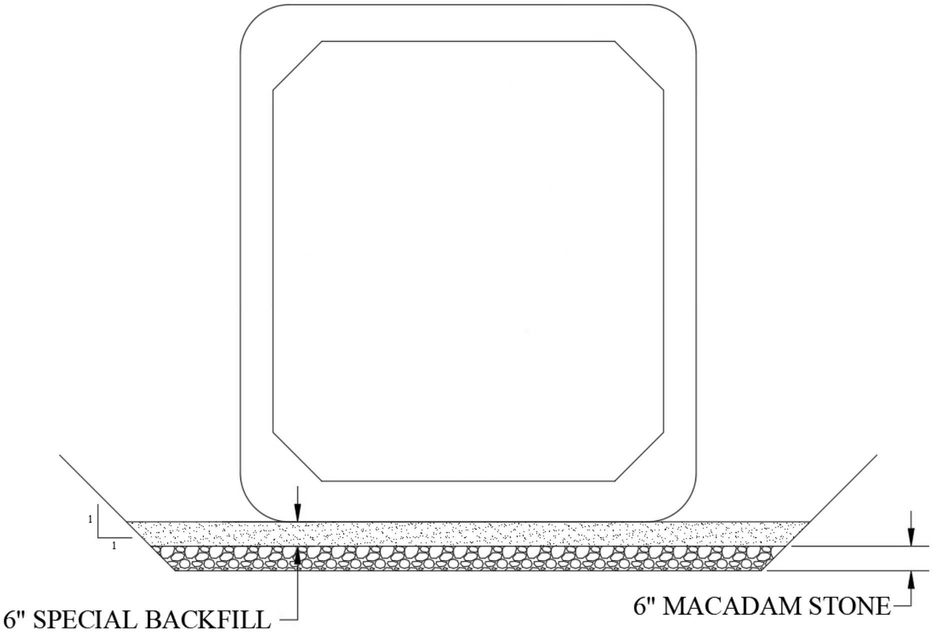


Figure 35. Crawford County backfill plan

Then, the contractor installed the culvert segments, and the instruments were installed. Following the placement of the culvert, the sides were compacted and filled every 8 to 12 in.

During construction observation, several images were captured to demonstrate the earthwork progress. Figure 36 shows the backfill progress and the completed project.

Northeast End (August 4, 2020)

Southwest End (August 4, 2020)

Northeast End (August 13, 2020) Southwest End (August 13, 2020)

Northeast End (August 24, 2020) Southwest End (August 24, 2020)

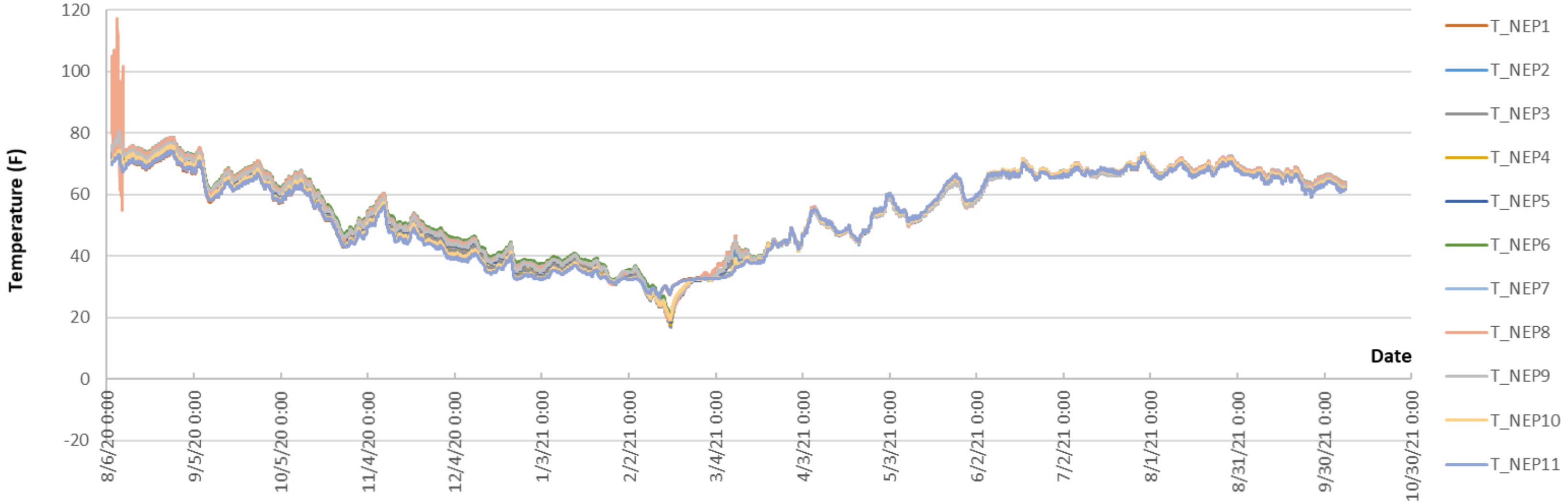
Northeast End (September 30, 2020) Road Above Culvert (September 30, 2020)

Figure 36. Crawford County earthwork progress

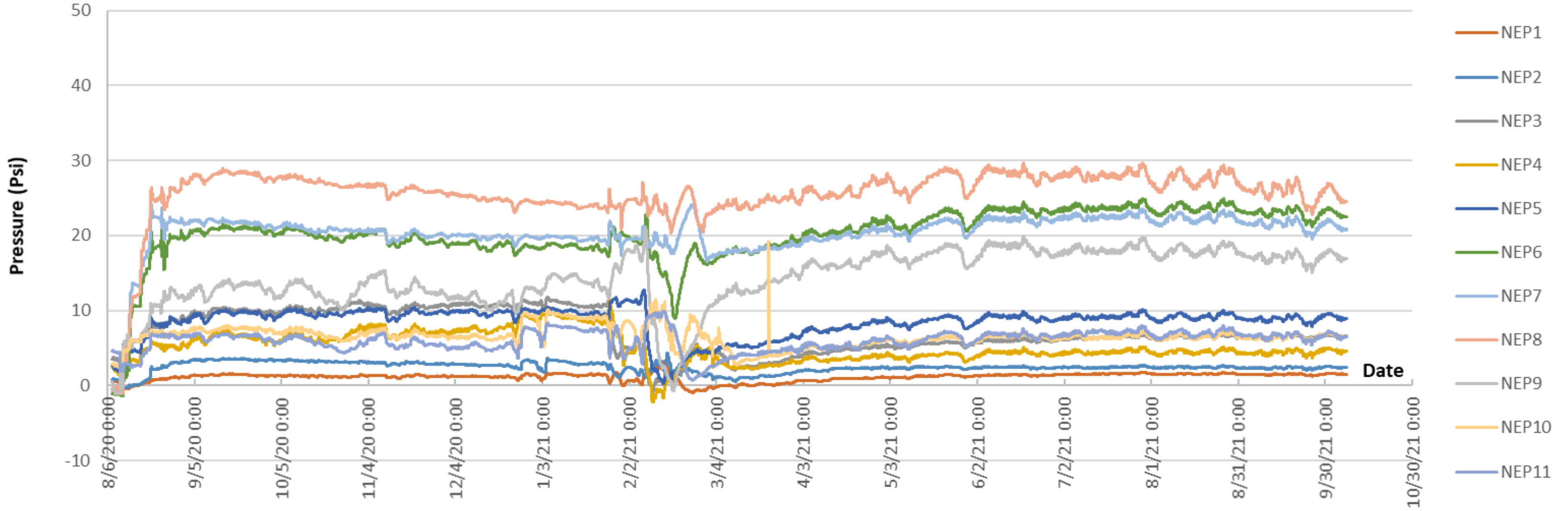
5.4 Pressure Results

The data collection started on August 3, 2020 and ended on October 7, 2021. This period covers the culvert construction from August 3, 2020 through September 30, 2020 and a full year cycle from October 1, 2020 through October 7, 2021. During this period, the culvert experienced construction loads, soil loads, and traffic loads. The pressure readings from the pressure cells were thermally corrected implementing the previous Equation 1 with the thermal factors provided on the gauge data sheet.

Figure 37 through Figure 39 show the temperature and pressure data collected by the pressure cells in each instrumentation section.

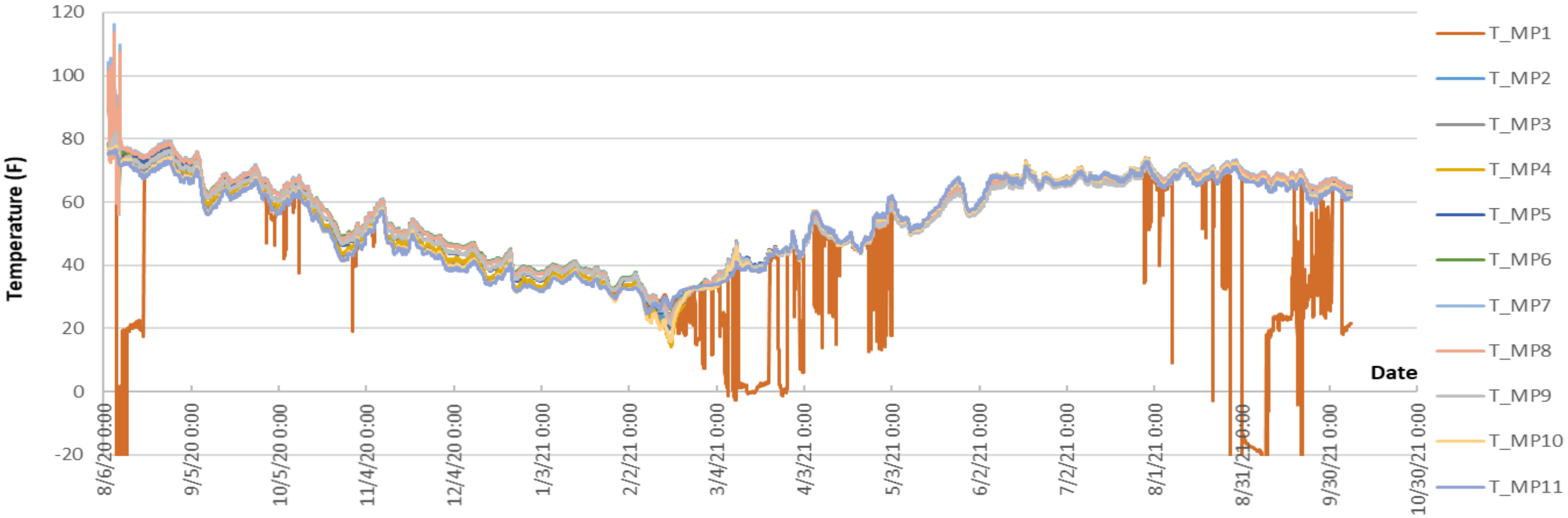


a) Temperature data

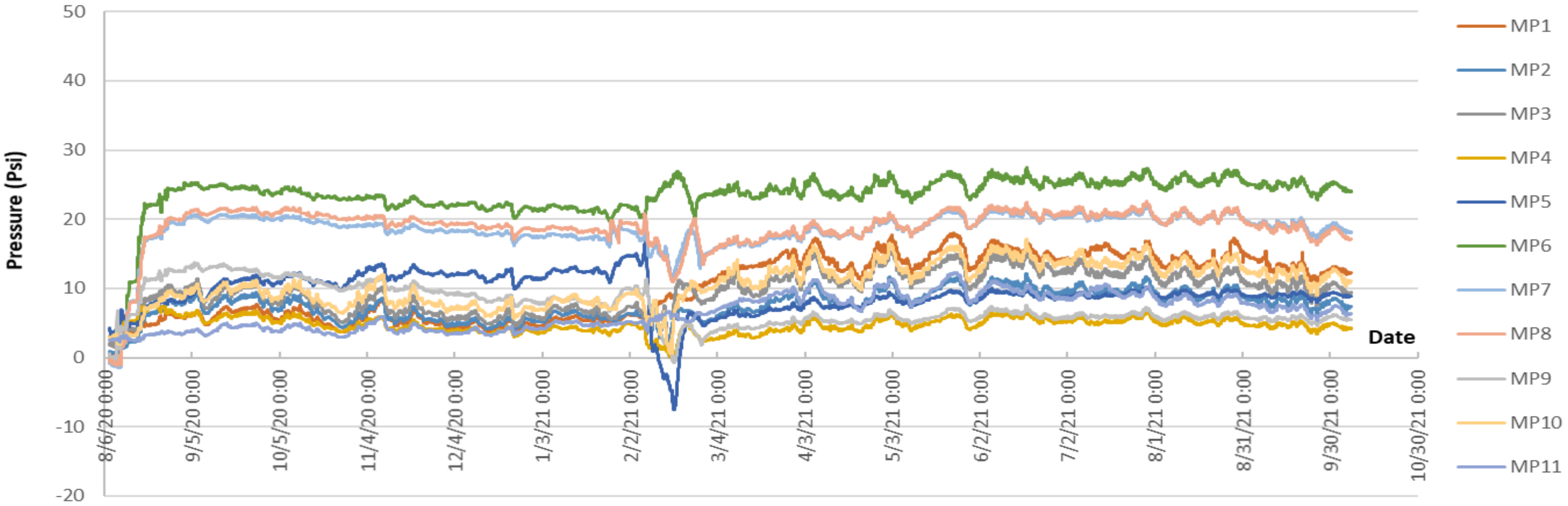


b) Pressure data

Figure 37. Crawford County NE section pressure cell readings

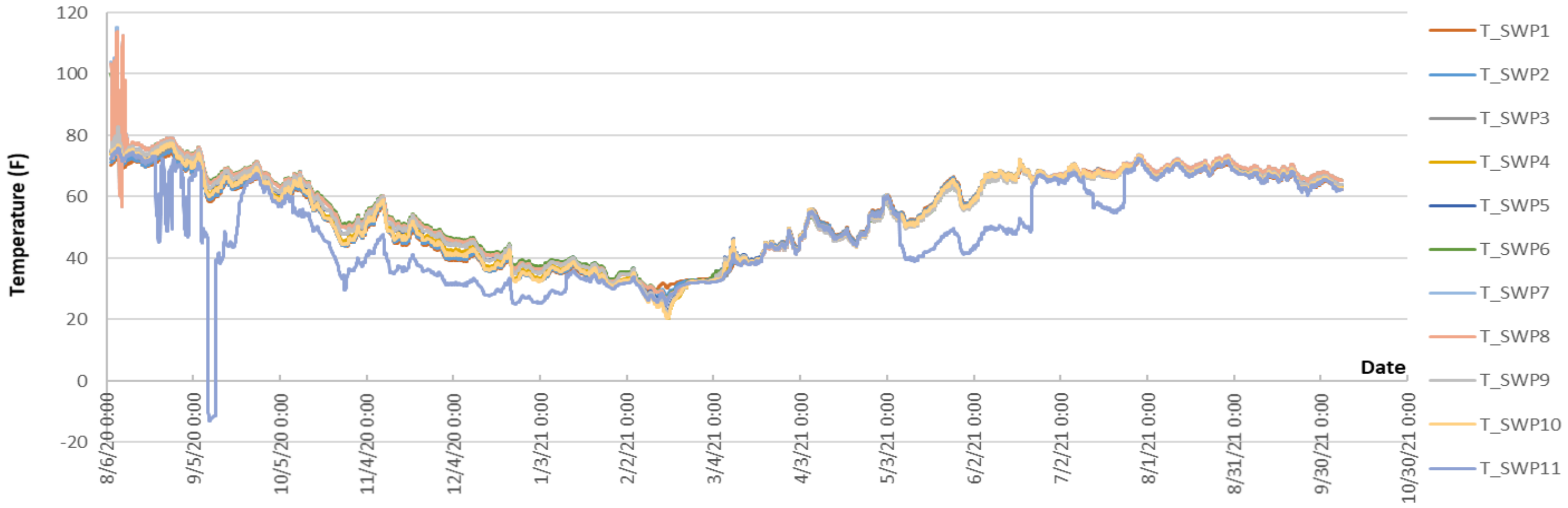


a) Temperature data

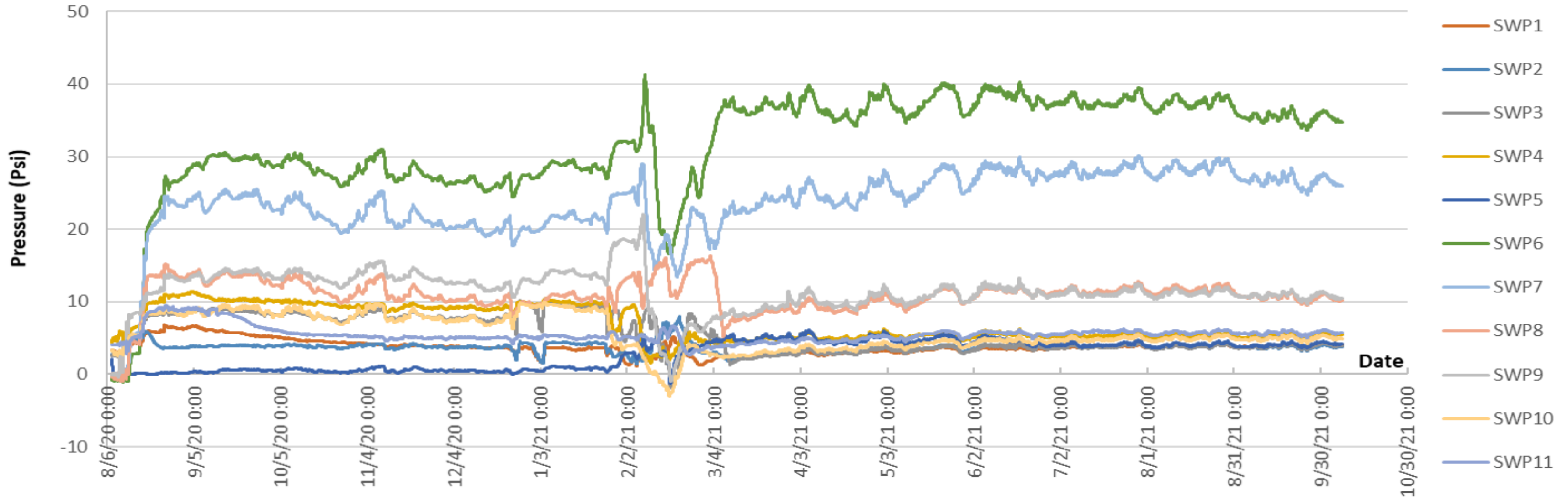


b) Pressure data

Figure 38. Crawford County M section pressure cell readings



a) Temperature data

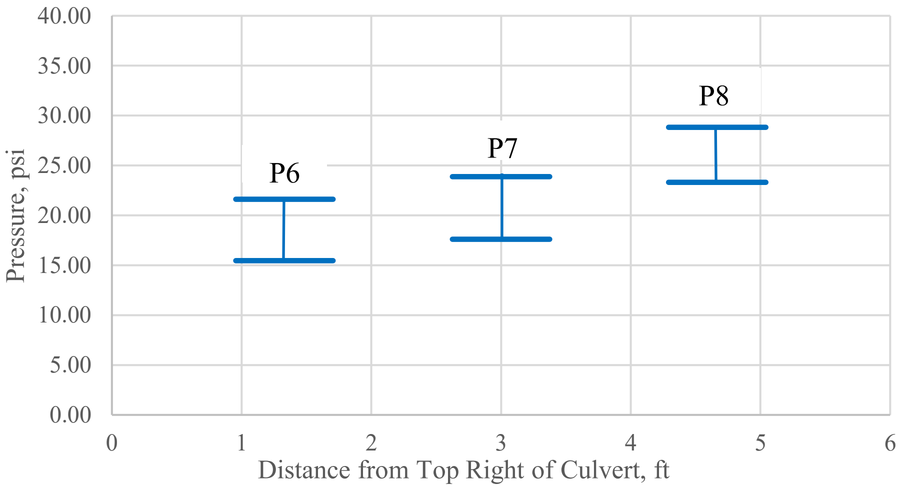


b) Pressure data

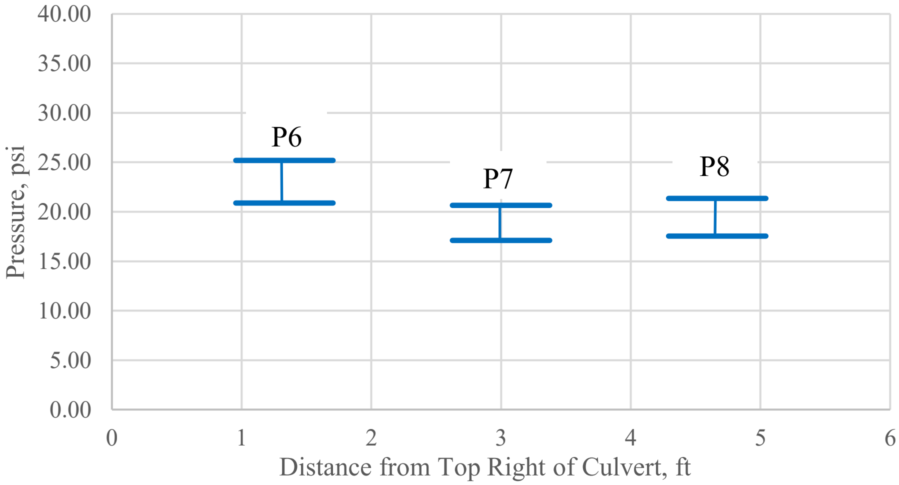
Figure 39. Crawford County SW section pressure cell readings

The data showed relationships regarding the soil pressure on the culvert, including the influence of temperature on the soil pressure and the pressure distribution on the culvert. The results indicated that the pressure increased during the time of construction. After construction was completed, the pressure had a slight decrease over time as the temperature decreased and vice versa. It was also found that, during the middle of February, when the temperature reached below freezing, a large variation occurred in the registered pressure data.

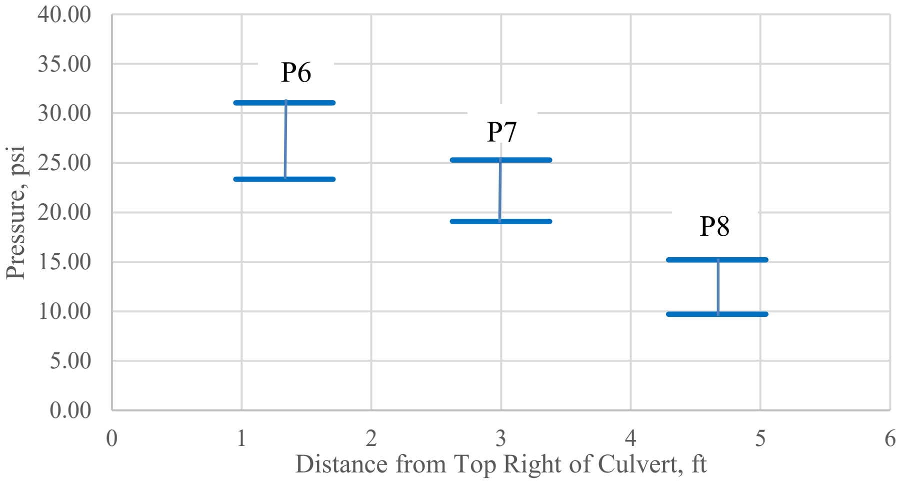
Figure 40, Figure 41, and Figure 42 show the pressure distribution on the top and both sides of the culvert.



a) NE section

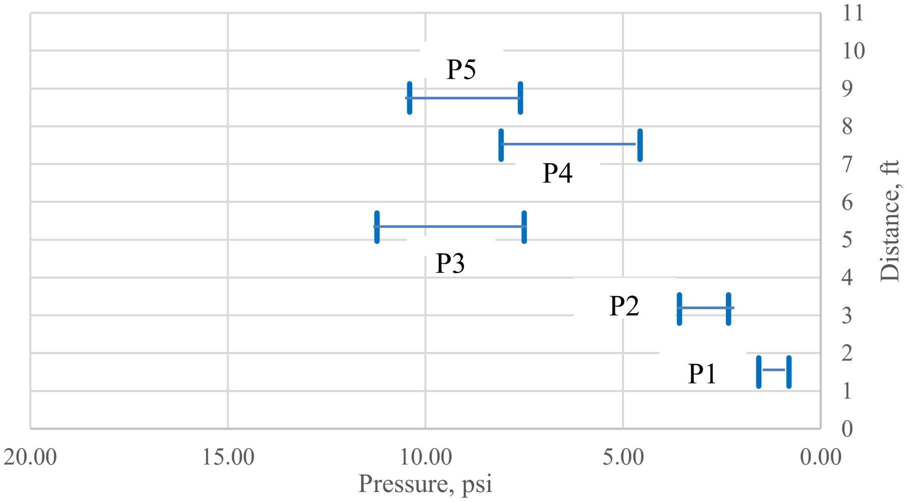


b) M section

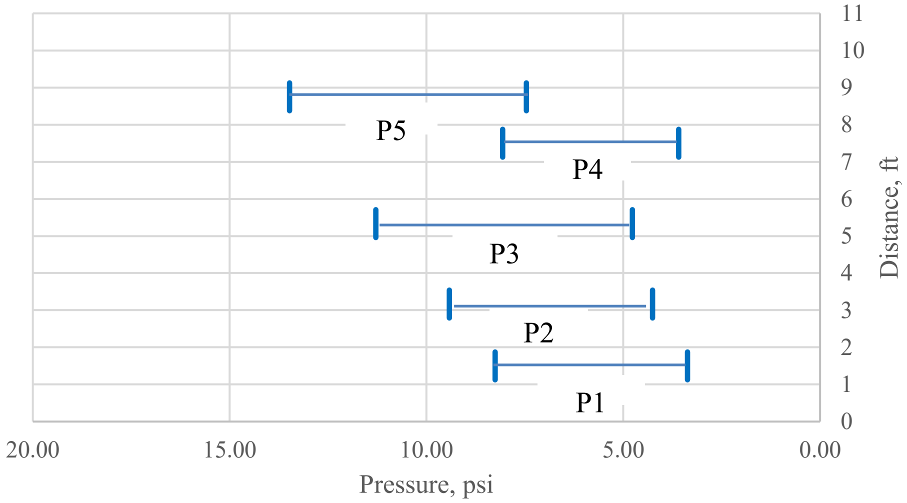


c) SW section

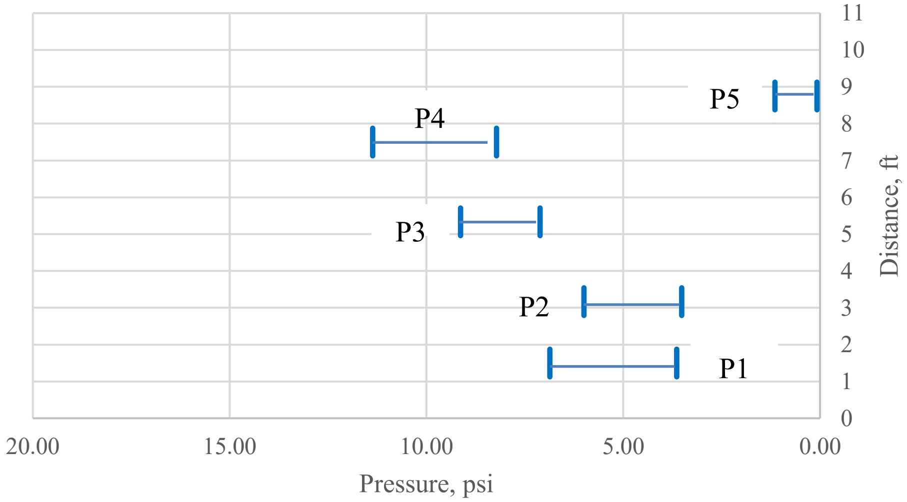
Figure 40. Crawford County pressure distribution on top of culvert



a) NE section

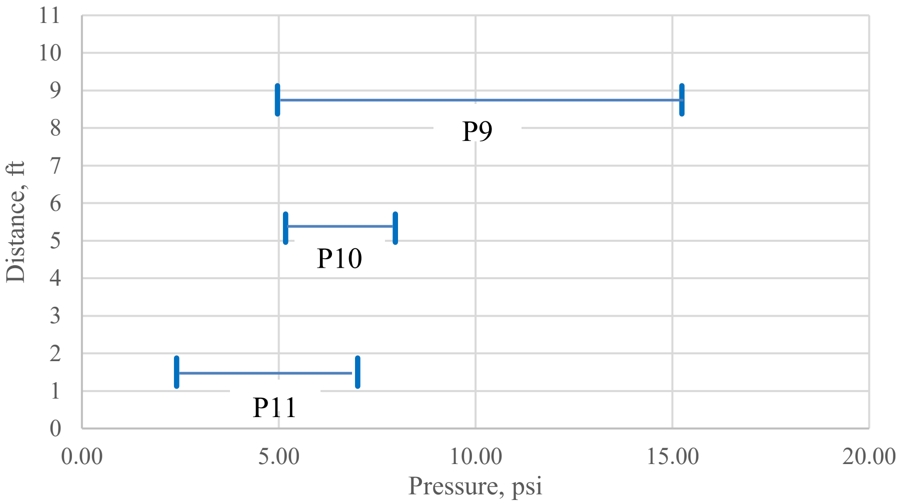


b) M section

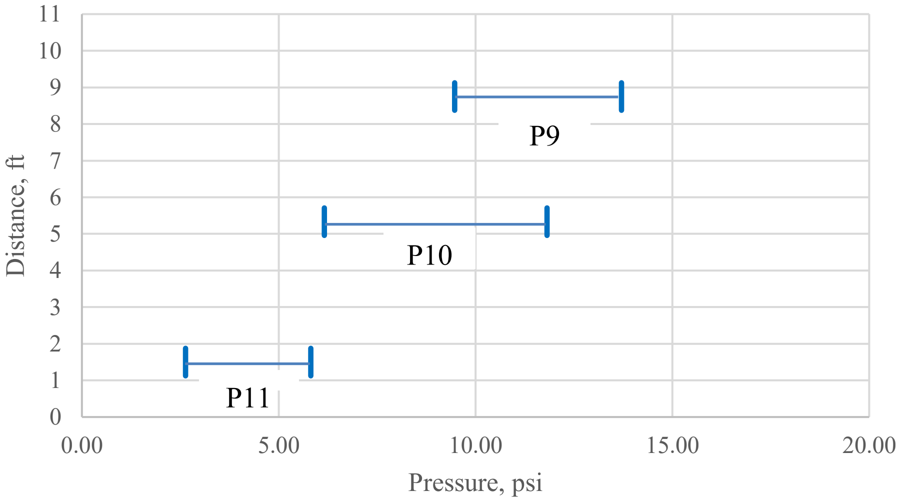


c) SW section

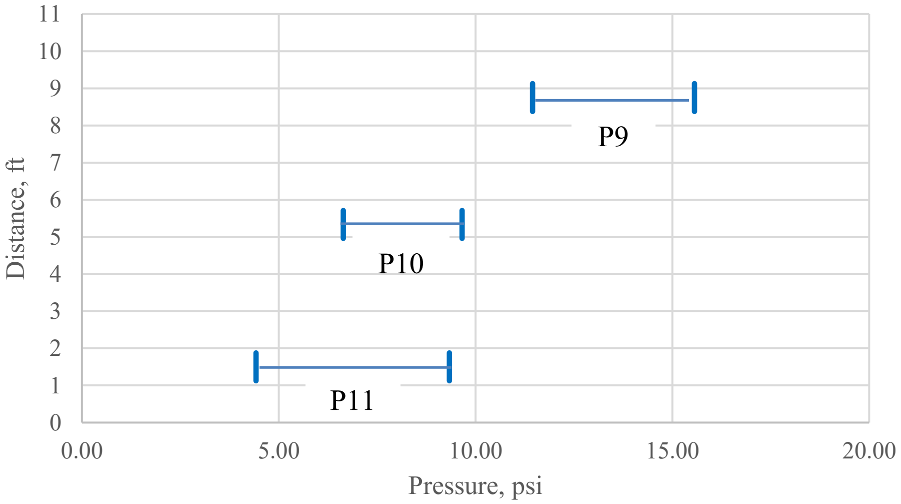
Figure 41. Crawford County pressure distribution on right side of culvert



a) NE section



b) M section



c) SW section

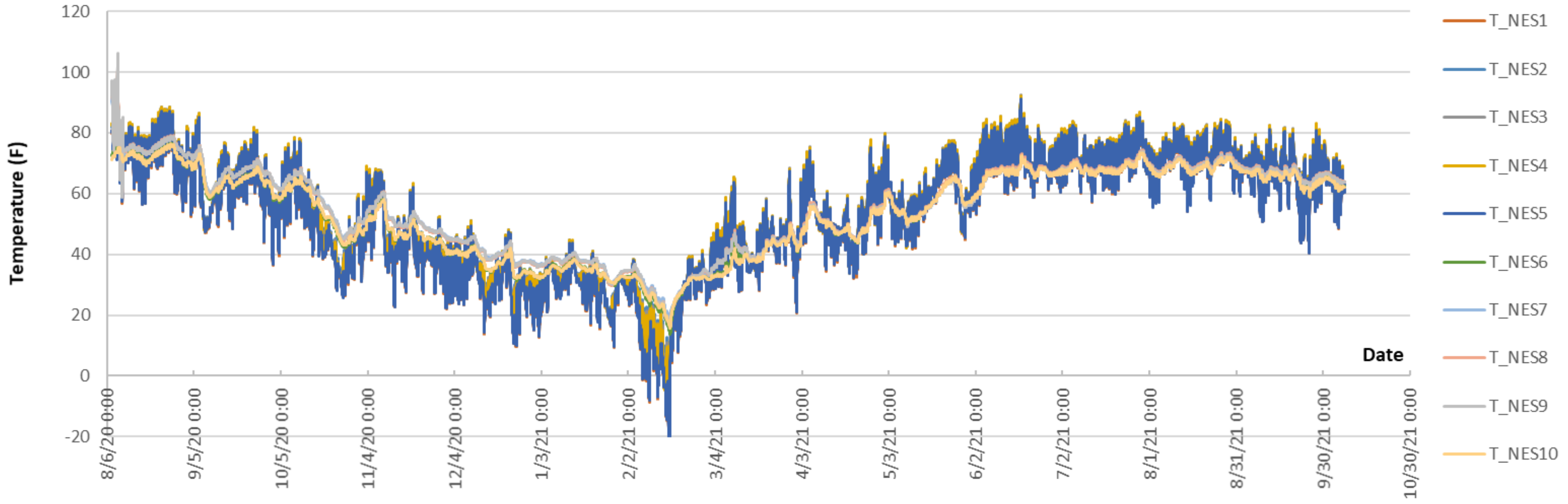
Figure 42. Crawford County pressure distribution on left side of culvert

The data used to plot these figures includes only those captured after construction. The vertical pressure distribution shown in the previous Figure 40 indicated that the top slab of the culvert measured greater pressure on the edges than at the middle. This distribution shows agreement with Dasgupta and Sengupta (1991) and Katona and Vittes (1982) in that the actual pressure distribution on the top slab of a culvert is parabolic instead of uniform.

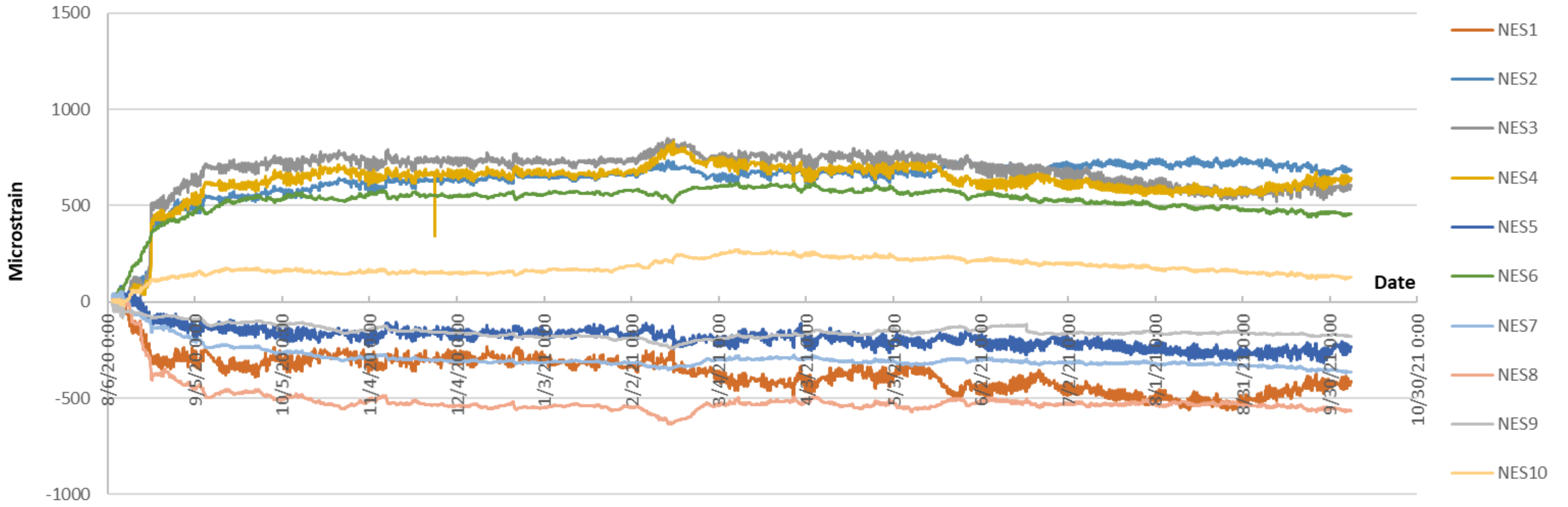
The lateral pressure distributions in Figure 41 and Figure 42 indicated that the upper portion of the culvert experienced greater lateral pressure than the lower portion of the culvert. This finding matches with the James et al. (1986) theory that the soil configuration of soft soil over stiff soil with a fixed boundary creates a shear plane that carries part of the soil weight and reduces the lateral pressure near the bottom of the culvert.

5.5 Strain Results

The strain data were monitored from August 3, 2020 through October 7, 2021, with the data logger collecting a reading every hour for more than one year. The temperature and strain data collected from VWSG are shown in Figure 43 through Figure 45.

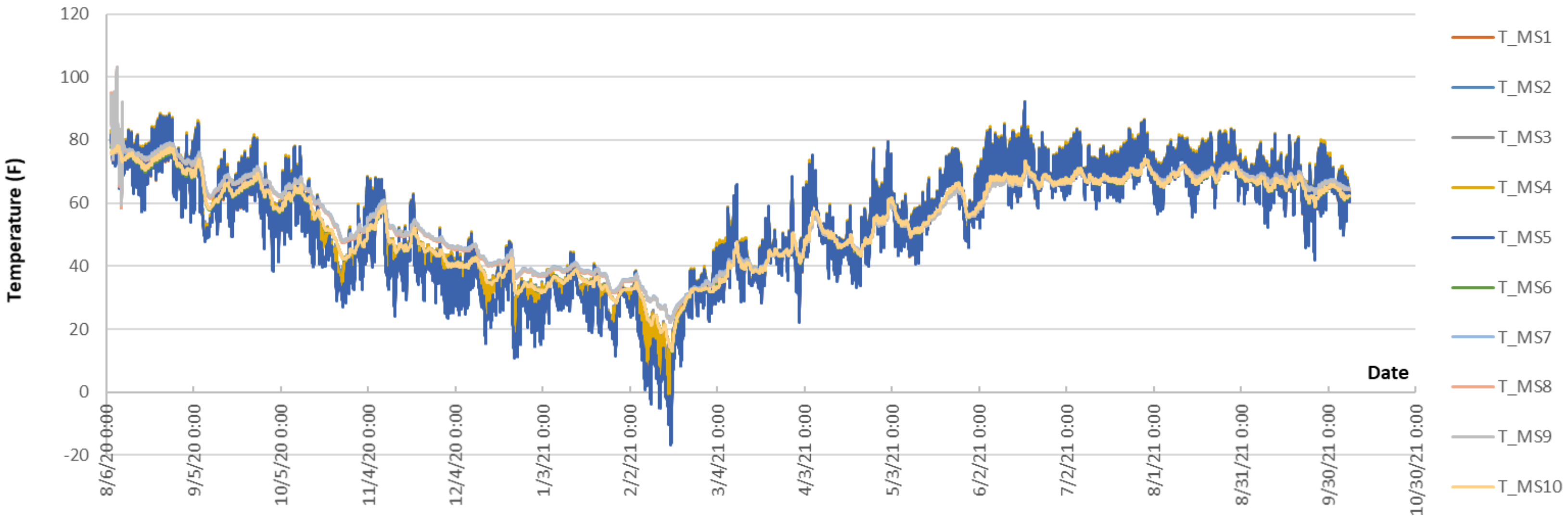


a) Temperature data

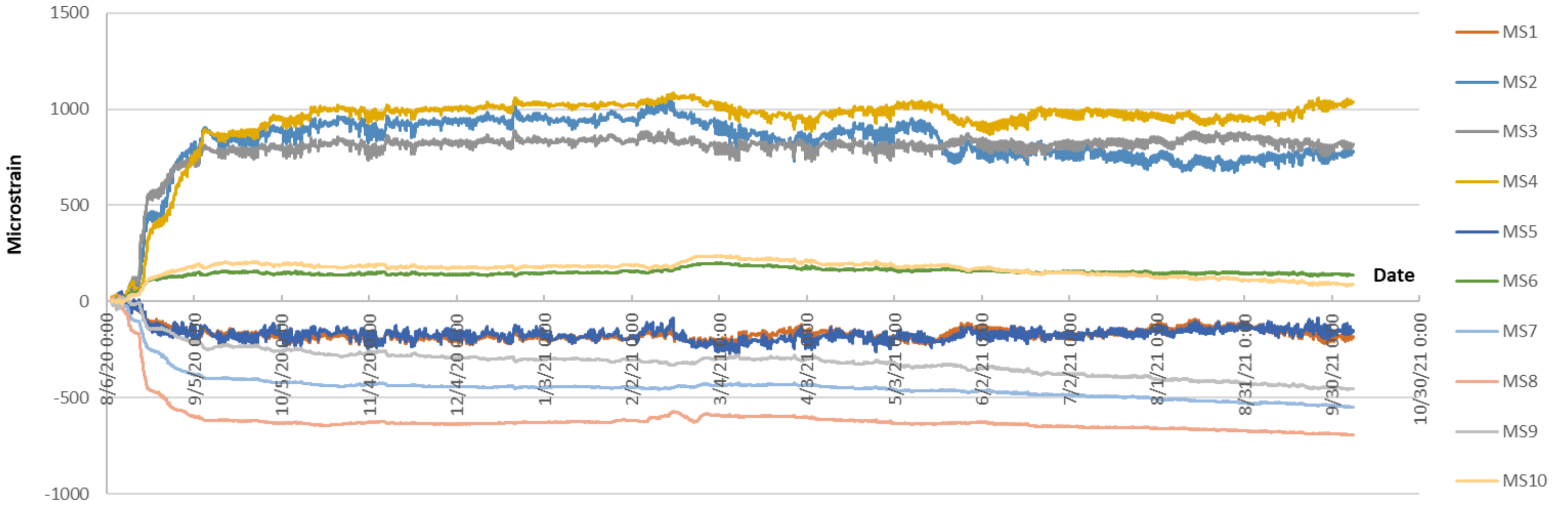


b) Strain data

Figure 43. Crawford County NE section strain gauge readings

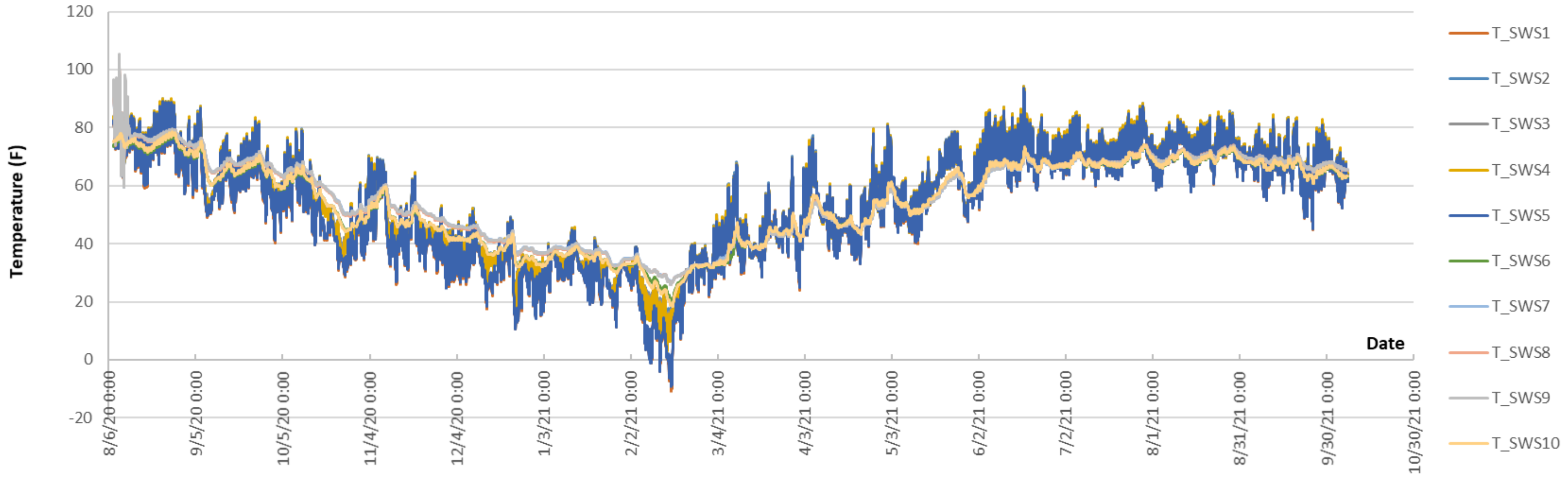


a) Temperature data

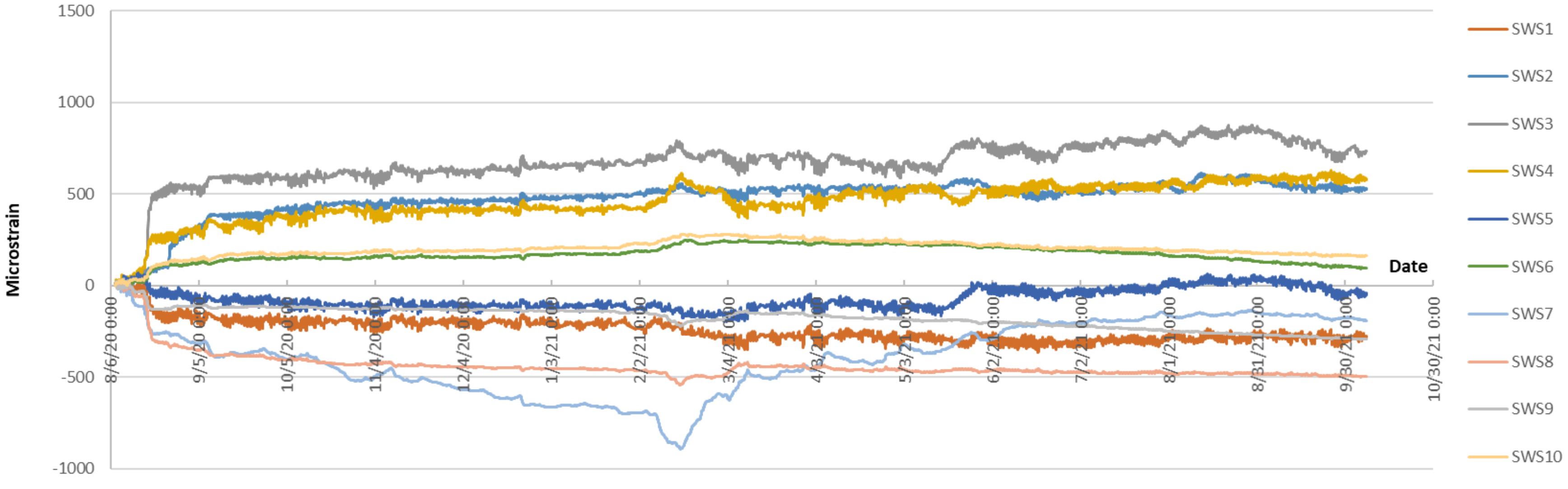


b) Strain data

Figure 44. Crawford County M section strain gauge readings



a) Temperature data



b) Strain data

Figure 45. Crawford County SW section strain gauge readings

The strain readings were thermally corrected using the previous Equation 2.

For all sections, gauges S1, S5, S7, S8, and S9 recorded negative strains while gauges S2, S3, S4, S6, and S10 recorded positive strains. The negative strains reflected areas under compression and the positive strains reflected areas under tension. Based on these results, a deformed shape of the culvert is shown in Figure 46.

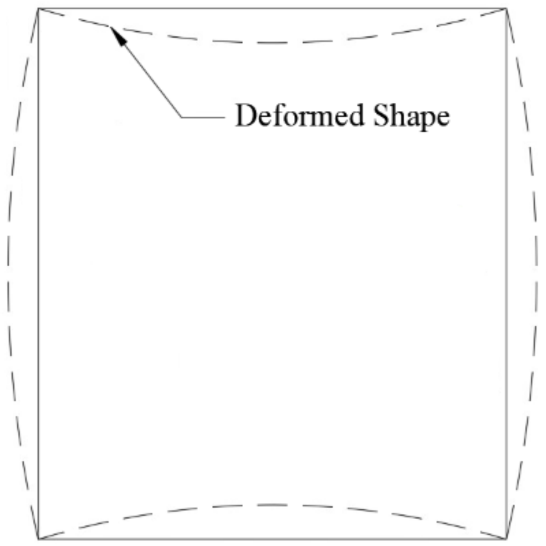


Figure 46. Crawford County deformed shape of culvert

It can be concluded that the vertical pressures dominated the deformed shape of the culvert.

The researchers found that, in all sections, the strain data measured from the gauges at the bottom surfaces of the top slabs indicated a high magnitude of 500 to 1,000 microstrain. This indicated that cracking was likely on the top slab.

5.6 Inspections

The culvert was inspected on March 10, 2021 to assess cracking and the condition of the culvert. Figure 47-a and -b show the cracking, marked using chalk on the bottom of the top slab in the NE section.

a. Top slab crack-1 b. Top slab cracking-2

c. Crack gauge d. Crack depth

Figure 47. Crawford County cracking inspection in NE section

A significant number of longitudinal cracks were found on the bottom surface of the top slab of the culvert for all three sections. Cracks were measured at each location using a crack gauge, as shown in Figure 47-c. The crack width varied from 0.015 to 0.02 in. AASHTO Bridge Element Inspection (2019) provides the crack width classification for reinforced concrete elements shown in Table 4.

Table 4. AASHTO crack width classification for reinforced concrete elements

Material	Insignificant cracking, defect not warranted	Moderate cracking	Wide cracking
Reinforced Concrete	Less than 0.012 in. wide	0.012 to 0.05 in. wide	Greater than 0.05 in. wide

AASHTO Bridge Element Inspection 2019

The cracking level for the Crawford County culvert was in the Moderate cracking range.

The cracks propagated more than 1 in. into the slab, as seen in Figure 47-d. In addition to the instrumented sections, cracks spanned the top slab, and there was periodical spalling in the culvert as well. The culvert did not have significant cracking on the side walls throughout the culvert.

5.7 Comparison with Design Loading

In this section, the field-collected pressure data are compared to the design values provided in the LRFD and LFD/ASD specifications. The soil weight used in the design and to calculate the codified vertical pressure was 120 lb/ft^3. The codified lateral pressure was calculated based on an earth pressure of 36/18 lb/ft^3 in LFD and ASD and 60/30 lb/ft^3 in LRFD. For the LRFD case, the soil-structure interaction coefficient of 1.15 was included for the vertical pressure loads. Table 5 through Table 7 compare the field results to the LRFD and LFD/ASD pressures for the NE, M, and W section, respectively.

Table 5. Crawford County NE section results compared with design

	Vertical Pressure			Lateral Pressure															
	P6	P7	P8	P1		P2		P3		P4		P5		P9		P10		P11	
	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Distance from the ground surface (ft)	16	16	16	25.08		23.41		21.25		19.08		17.83		17.83		25.08		16	
Monitored (psi)	22.84	23.88	28.82	3.16	0	4.15	0.44	11.67	0	11.15	0	12.8	0	20.99	0	11.49	2.76	9.93	0.71
Codified LRFD (psi)	15.33	15.33	15.33	10.45	5.23	9.75	4.88	8.85	4.43	7.95	3.98	7.43	3.71	7.43	3.71	8.85	4.43	10.45	5.23
Codified LFD/ASD (psi)	13.33	13.33	13.33	6.27	3.14	5.85	2.93	5.31	2.66	4.77	2.39	4.46	2.23	4.46	2.23	5.31	2.66	6.27	3.14

Table 6. Crawford County M section results compared with design

	Vertical Pressure			Lateral Pressure															
	P6	P7	P8	P1		P2		P3		P4		P5		P9		P10		P11	
	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Distance from the ground surface (ft)	20	20	20	29.08		27.41		25.25		23.08		21.83		21.83		25.25		29.08	
Monitored (psi)	26.69	20.65	21.35	12.48	3.37	9.42	0.97	11.94	0	8.06	0	17.12	0	13.71	0	13.37	0.14	7.76	2.63
Codified LRFD (psi)	19.17	19.17	19.17	12.12	6.06	11.42	5.71	10.52	5.26	9.62	4.81	9.1	4.55	9.1	4.55	10.52	5.26	12.12	6.06
Codified LFD/ASD (psi)	16.67	16.67	16.67	7.27	3.64	6.85	3.43	6.31	3.16	5.77	2.89	5.46	2.73	5.46	2.73	6.31	3.16	7.27	3.64

Table 7. Crawford County SW section results compared with design

	Vertical Pressure			Lateral Pressure															
	P6	P7	P8	P1		P2		P3		P4		P5		P9		P10		P11	
	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Distance from the ground surface (ft)	12	12	12	21.08		19.41		17.25		15.08		13.83		13.83		17.25		21.08	
Monitored (psi)	41.31	28.62	16.21	6.86	1.07	8.13	1.55	10.36	0	11.37	1.11	5.53	0	21.73	0	9.78	0	9.34	2.36
Codified LRFD (psi)	11.5	11.5	11.5	8.78	4.39	8.09	4.04	7.19	3.59	6.28	3.14	5.76	2.88	5.76	2.88	7.19	3.59	8.78	4.39
Codified LFD/ASD (psi)	10	10	10	5.27	2.64	4.85	2.43	4.31	2.16	3.77	1.89	3.46	1.73	3.46	1.73	4.31	2.16	5.27	2.64

The tables present the minimum and maximum values of the pressure recorded by the pressure cells after the completion of construction. Moreover, the fill height for each cell is shown.

In general, all the instrumented sections had higher recorded values than the codified values for the vertical pressure on the top slab. Most of the lateral pressure values exceeded the maximum or did not achieve the minimum specification values.

The maximum-recorded vertical pressure value was 41.31 psi, measured in the SW section, and the maximum pressure, according to the LRFD and LFD/ASD for this location, was 11.50 psi and 10 psi, respectively. This is more than 3 times the codified values. The average recorded value was 27.48 psi for this location, still 2 times the codified values.

The maximum lateral pressure was 21.73 psi, measured in the SW section, while the codified maximum lateral pressure at this location according to the LRFD and LFD/ASD was 5.76 psi and 3.46 psi, respectively. This indicates that the measured values were about 4 to 6 times of the codified values.

5.8 Conclusions

According to the pressure and strain results, the following can be concluded from the monitoring results from the second culvert:

- The pressures exceeded the codified design values of 120 lb/ft^3 for vertical pressure and 60/30 lb/ft^3 for lateral pressure. Similar to the results from the Ida County culvert monitoring, the monitored data measured from Crawford County were 3 to 6 times that of the design values with the LRFD and LFD/ASD methods.

- The inspection results indicated that extensive longitudinal cracking (parallel to the flow) occurred on the bottom of the top slab, induced by the high vertical soil pressure.

- The pressure results indicated greater pressure on the edges of the top slab. Moreover, the sides had greater pressure toward the top of the culvert.

- The data indicated that, when the temperature reached below freezing, a large variation occurred on the registered pressure data.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND FURTHER RESEARCH RECOMMENDATIONS

6.1 Summary and Conclusions

In this project, two concrete box culverts (one in Ida County and the other in Crawford County) were monitored for 2.5 years and 1 year, respectively, to identify the realistic design soil pressure for Iowa soil conditions. The captured pressure, strain, and temperature data were analyzed to find the relation between the temperature and earth pressure experienced by the culverts. The measured vertical and lateral pressures were compared with specified design pressure loading.

The first monitored box culvert was located on US 20 in Ida County. The complete underground structure was 533 ft long and consisted of 27 6 ft long precast culvert sections next to the precast drop inlet, two 12 ft long cast-in-place barrels, and another 46 6 ft long precast culvert sections next to the end sections. The exterior of the culvert was 10 ft high and 13.5 ft wide. The instrumented section was selected at about 189 ft from the end with a soil embankment of 35 ft.

The results indicated that the maximum measured vertical earth pressure 35 ft below the ground was 47 psi. The maximum and minimum lateral pressures measured were about 32/10 psi at 36 ft deep and 61/18 at 40 ft. Compared to the LRFD and LFD/ASD specifications, monitored data were still 2 to 4 times that of the design values.

The researchers found that, as temperature increased, all the pressures tended to increase. This was because the culvert tended to expand when the temperature increased and, hence, increased the pressure between the soil and the culvert exterior surface. A significant number of cracks were found near the middle span of the top slab within the one-quarter span length on each side.

The second monitored culvert was in Crawford County. The culvert was 8 ft×9 ft×277 ft and consisted of 61 five to six ft long precast reinforced concrete box segments. The culvert was instrumented in three different locations, each with different fill heights (12 ft, 16 ft, and 20 ft). At each section, 11 pressure cells and 10 VWSGs were installed.

The results indicated that the pressures exceeded the specified design values of 120 lb/ft^3 for vertical pressure and 60/30 lb/ft^3 for lateral pressure. The monitored data measured from Crawford County were 3 to 6 times that of the design values with the LRFD and LFD/ASD methods.

The researchers found that the vertical pressure increased 1 to 2 psi with every additional foot of fill on the top slab, while the lateral pressure increased 0.25 to 0.5 psi with every additional foot of fill. The inspection results indicated that extensive longitudinal cracking (parallel to the flow) occurred on the bottom of the top slab, as induced by the high vertical soil pressure. The data indicated that, when the temperature reached below freezing, a large variation occurred on the registered pressure data.

The monitoring results from both culverts led to the consistent conclusion that the pressure experienced by the culverts is much greater (2 to 6 times more) than the current design values using the LRFD or LFD/ASD method. Due to the pressures, extensive longitudinal cracking (parallel to the flow) was observed at the bottom surface of the top slab on both culverts.

6.2 Further Research Recommendations

According to the findings from this research, further research is recommended in the following areas:

- *Determination of a realistic design soil pressure and the relation between the soil weight and culvert vertical/lateral pressure for Iowa design specifications*

  The monitoring results from both culverts led to the consistent conclusion that the pressures experienced by the culverts are much greater (2 to 6 times more) than the current design values; however, it is still not clear what the relation is between the soil weight and the vertical/lateral pressure.

  Further research is recommended to determine a realistic soil pressure design and the relation between the soil weight and the culvert vertical/lateral pressures for Iowa. This would require the instrumentation of additional culverts.

  Although the previous monitoring work provided extensive data on the vertical/lateral pressures experienced by a culvert, both monitored culverts experienced extensive cracks during the early stages of construction, which significantly reduced the structure stiffness. This may induce an effect on the recorded pressure due to the soil arching effect. Further monitoring work is recommended to record the pressure on a concrete box culvert designed based on the increased earth pressure.

- *Design and construction of a new culvert with updated design for vertical/lateral pressure*

  Once the improved design soil pressure and the relation between the soil weight and the culvert vertical/lateral pressures are identified, a new culvert is recommended to be designed, constructed, and monitored following the updated design for vertical and lateral pressures.

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