VALIDATION AND CALIBRATION OF FINITE ELEMENT MODEL OF FORCES IN WINGWALLS

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16. Abstract

The abutment of Bridge HAM-74-1466, located on I-74 in Hamilton County, Ohio was instrumented with KM-100 and vibrating wire strain gages and temperature sensors to measure strains and compute stresses in the abutment. These stresses were compared to those computed by finite element models of the abutment created using SAP 2000 v. 19 and ABACUS CAE 2016. The predominant source of stress was environmental loads, but the measured stresses were well below AASHTO permissible design values. The complexity of bridge structures with wingwalls means that some three-dimensional finite element modelling is needed to complement an efficient design method; complexity is an even greater problem for skewed abutment bridges. Soil pressure from backfill is generally not a problem as it is accounted for in the design. Further monitoring is recommended, as is investigation into the interaction between the superstructure and substructure of bridges.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

Validation and Calibration of Finite Element Model of Forces in Wingwalls

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1 PROJECT BACKGROUND

1.1 STATEMENT OF THE PROBLEM

ODOT has been designing and installing bridges using abutments and wingwalls with turnbacks supported using drilled shafts placed in bedrock, as recommended in the 2007 ODOT Bridge Design Manual and 2012 AASHTO LRFD Specifications. This construction technique is economical and adapts well to some site conditions in Ohio. The design has been simulated using 3-dimensional finite element models [e.g. Wood, 2013 for ALL-75-0703 Bridge], but there is insufficient data to validate these models. The models indicate that the dominant force on the drilled shafts is uplift.

1.2 GOALS AND OBJECTIVES

To validate the finite element models and ensure the design concept is safe, sound, and economical, it was proposed that a new bridge in Ohio be instrumented to obtain the data. The instrumentation was designed to measure the amount of load and the stress (critical stress) transferred from the abutment to the wingwall at the interface and the forces in the drilled shafts, whether caused by live or dead loads or by environmental factors such as temperature changes or soil moisture.

2 RESEARCH CONTEXT

Metzger and Sargand [Metzger, 1995; Metzger and Sargand, 1997] instrumented a skewed, semi-integral abutment bridge over Route 180 and collected data to determine the effect temperature has on forces on the abutments. Parameters measured included temperature, strain, stress, and soil pressure. While the instrumentation was generally a success, it was noted that there was still uncertainty regarding the boundary conditions between the wingwall and the abutment that could be determined by installing load cells at the interface. It was also recommended to place instrumentation to monitor the approach slabs which are in contact with the bridge deck structure.

Steinberg, Sargand, and Bettinger [2001, 2004] instrumented two skewed, semi-integral abutment bridges in Tuscarawas and Athens Counties in Ohio to determine the forces on wingwalls resulting from changes in temperature. In both bridges, a stainless steel box fitted with load cells was placed between the wingwall and the diaphragm at the acute corner of the abutments. Thermocouples and Demec points in conjunction with a Whitmore gauge were also utilized for temperature and deflection readings respectively. Data were collected regularly and then modeled using the finite element analysis software SAP2000. The bridges were modeled with varying skews, backfill stiffness, and span lengths in order to get the most comprehensive results. The results from the Tuscarawas bridge showed the forces in the wingwall were significant, however, a relationship between air temperature and force could not be found. The maximum forces found in the bridges was 35.7 kips (159 kN) in the Tuscarawas bridge and 30.1 kips (134 kN) in the Athens bridge. In the Athens bridge a nonlinear relationship was found, showing that increased wingwall forces occurred with a decrease in bridge movement. Steinberg, Sargand, and Bettinger recommend more research should be conducted with bridges of different spans and skews, as well as more investigation into backfill stiffness behind the diaphragm and abutment.

Steinberg and Sargand [2010] continued their prior research [Steinberg, Sargand, and Bettinger, 2004] and instrumented semi-integral bridges in two more Ohio locations, this time choosing bridges with greater skew angles. The first was a 4-span, 440 ft (134 m), prestressed concrete I-beam bridge located near Defiance, Ohio and had a skew angle of 45°. The second bridge was two nearly identical steel plate girder bridges in Muskingum County, also with a skew angle of 45°. Vibrating wire strain gauges were used inside the wingwall to measure both the strain and temperature while Digimatic indicator targets were used to observe the movement of the diaphragm and wingwall joint. Wingwalls in the previous study [Steinberg, Sargand, and Bettinger, 2004] were parallel to the bridge diaphragm, however in many newer bridges the wingwalls are turned back and sometimes perpendicular to the diaphragm. Abutments with this turned-back design could be subject to an additional bending force due to temperature. From the Defiance bridge, it was concluded that as temperature increased, so did the average stress in the wingwall, however, the magnitude of the stress was not consistent with a specific temperature. The largest total change in the joint was over 2 in (50 mm) and the strain gauge readings varied but did not exceed 150 psi (1030 kPa). For the Muskingum County bridge, the largest total movement of the joint was 0.3 in (7.6 mm). Spalling of concrete was observed and could have been attributed to bearing failure of the concrete due to the small amount of cover. It was recommended that the bending from thermal expansion in the wingwall be considered when designing turned-back wingwalls in skewed, semi-integral abutment bridges. The researchers also suggested that a 100 psi (690 kPa) load be included at the wingwall/diaphragm interface for skewed, semi-integral abutment bridges with wingwalls that that run nearly parallel with the longitudinal axis.

Abendroth and Greiman [2005] conducted a research program to validate or alter current design procedures for integral abutment bridges subjected to thermal loading conditions. They monitored two integral abutment bridges in Iowa over a two-year period. Installed instrumentation measured displacement and rotation of the abutment, strain in the piles, temperature of concrete, and the fixity of piles and girders into the abutment. It was found that the longitudinal displacements of the abutments correlated well with changes in bridge temperatures. The researchers also determined that pile ductility may limit bridge length. To combat this, the upper portion of the pile should have a pre-bored hole that is then filled with a material having a low stiffness, as well as orienting the weak axis of the pile perpendicular to the longitudinal axis of the bridge. It was then recommended that laboratory studies regarding moment rotation relationships for the weak axis of HP piles be conducted in addition to further instrumentation and monitoring of integral abutment bridges.

Fennema, Laman, and Linzell [2005] examined several uncertainties of integral abutment bridge design and analysis. A Pennsylvania bridge was instrumented with 64 sensors to monitor pile strains, soil pressure behind abutments, abutment displacement/rotation, girder rotation, and girder strains. The bridge had three spans, four prestressed concrete I-shaped girders, and integral abutments supported by a single row of HP 12×74 piles. Numerical analysis was performed to evaluate and predict bridge behavior in the form of laterally loaded pile models, 2D single bent models, and 3D finite element models. The pile models confirmed that using multilinear soil springs derived from p-y curves is a valid approach for modeling soil-pile interaction in finite element software. The authors concluded that the primary mode of movement for the integral abutment was through rotation about its base and not longitudinal displacement as was previously assumed. They also found the girders experienced significant tensile strain due to temperature and this should be considered in their design.

Ooi, Lin, and Hamada [2010] observed the behavior of an integral abutment bridge supported on drilled shafts. The bridge was located in Kahuku, Hawaii, had a single span of roughly 80 ft (24 m) over a local stream, and wingwalls oriented parallel with the longitudinal axis of the bridge. The bridge was instrumented with 74 strain gauges throughout the structure. Inclinometers were placed in the abutment walls and drilled shafts and contact pressure cells mounted behind the abutment walls. The researchers monitored the movement of the drilled shafts and abutment due to seasonal changes. The abutments sat on highly plastic clay which caused the drilled shafts to bow toward the stream after being backfilled. Even though the shaft reinforcement extended all the way up the abutment wall, the shaft did not behave as fully fixed and it translated and rotated at the shaft-footing interface. This movement occurred before any superstructure was even in place. The loads observed at the top of the drilled shafts are significantly higher than the working loads. It was determined that this is most likely due to incorrect shaft axial stiffness, weight of the backfill, uneven load distribution among shafts, and creep of shaft concrete. The results showed that concrete creep and shrinkage may control motion relative to thermal movements for integral abutment bridges with low temperature swings. Ooi, Lin, and Hamada suggest that a staged construction analysis to get a predeflected profile of the structure may be important when building on highly plastic clays.

Arockiasamy, Butrieng, and Sivakumar [2004] conducted a parametric study regarding the effects of several variables on integral abutment bridges utilizing piles. The variables included the effects of a predrilled hole, the type of fill in the hole, elevation of water table, soil type, and pile orientation. The researchers highlight creep/shrinkage and thermal gradients, among others, as important factors when considering the design of integral abutment bridges. Lateral movement due to thermal expansion will reduce the vertical carrying capacity of the piles. It was found that piles in predrilled holes filled with sand saw a decrease in shear, moment, and stress. The location of the water table was observed at 8 ft (2.4 m) and again at 16 ft (4.8 m) below the top of the pile and was determined to have little to no effect on the values of displacement, moment, shear, and stress. Significant variations were found when the piles were driven into varying soil types. Moments are higher in stiff clay, very stiff clay, and dense sand while the axial force is lower in dense sand and high in very stiff clay. The orientation of the piles proved to be an important consideration for shear and horizontal displacement. A pile oriented along the weak axis showed higher stresses but is able to undergo larger horizontal displacement, which is necessary. Ultimately, Arockiasamy, Butrieng, and Sivakumar's study should aid in the selection and design of piles for integral abutment bridges.

A study into short-span, skewed, integral abutment bridges was conducted by Farhey, Zoghi, and Gawandi [2002] at the University of Dayton. The study was an investigation into the design methods of integral abutment bridges, which were often under-designed structures which then experienced cracking and deterioration. Their survey found the common design practice for such bridges were based on simplified two-dimensional rigid portal frames that neglect the effects of skew and laterally unsymmetrical vertical loadings. The researchers used a three-dimensional finite element modeling tool to determine the shortcomings of the two-dimensional method. It was found that positive and negative moment stresses are noticeably higher in the three-dimensional analysis and that the addition of a haunch was unable to compensate for this. Farhey, Zoghi, and Gawandi developed design modification factors that transform the moments from the two-dimensional frame analysis into values better representing the actual moments in the bridge, avoiding the use costly three-dimensional finite element software. However, more research into the developed factors is required before they are ready for actual design usage.

E.L. Robinson Engineering [Wood, 2013] conducted a finite element analysis for abutment design of Bridge ALL-75-0703 in Allen County, Ohio. The ALL-75-0703 Value-Engineering Change Proposal (VECP) involved redesigning the bridge from a three-span bridge to a single-span bridge. The original bridge design had a length of 213’-8” (65.1 m) while the VECP single-span bridge was reduced to a length of 123’-0” (37.5 m). The reduction in bridge length necessitated an increase in the height of the abutments. The new abutments were wall type abutments with turnback wingwalls. Additional counterforts were added at the stage construction locations and at the middle of the abutment. These counterforts are used for soil retention during stage construction along with providing support to the abutments. The abutments, wingwalls, and counterforts were supported on 3’-0” (0.91 m) diameter drilled shafts. The following describes the analysis and design methods used to design the abutments for the ALL-75-0703 VECP. The VECP abutments for ALL-75-0703 were modeled in the 3D finite element analysis (FEA) program STAAD.Pro. The overall STAAD.Pro model can be seen in Figure 1. The analysis and design recommendations were based on the requirements of the 2007 ODOT Bridge Design Manual and the 2012 AASHTO LRFD Specifications.

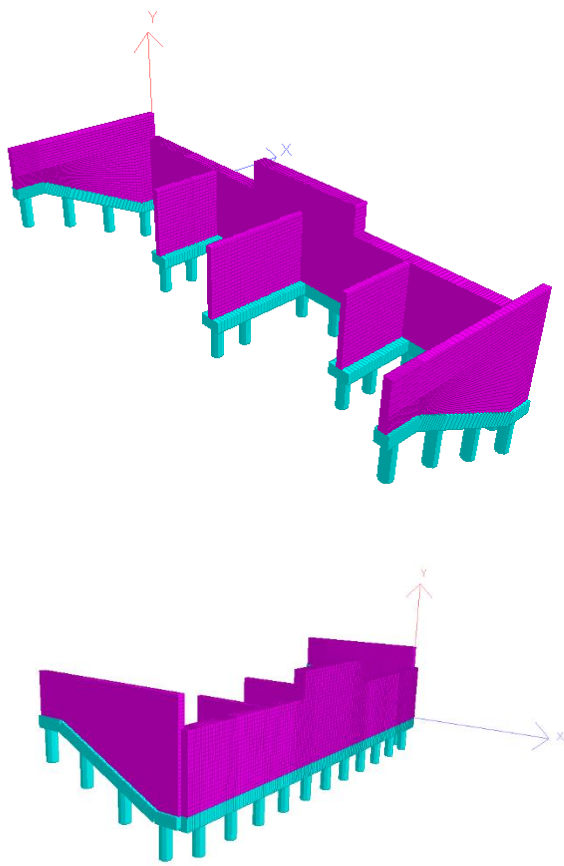

Figure 1. STAAD.Pro finite element model of abutments for Bridge ALL-75-0703.

Stage 1 and Stage 2 construction were investigated with separate models in STAAD.Pro. The model for final condition was the same as Stage 2, with modified load combinations. The walls were modeled as quadrilateral plate elements. Plate mesh size was approximately 1 ft × 1 ft (0.3 m × 0.3 m) with some variation due to local geometries. To better capture transverse shear results, the bottom 3'-8" (1.11 m) of the abutment wall was modeled as a beam element. The drilled shafts and wall footings were modeled as beam elements. The drilled shafts were modeled using an equivalent depth to fixity based on geotechnical conditions and using the program L-Pile. Beam end offsets were used to capture the distances between the bottom of wall and middle of the footings and the top of the drilled shafts. Due to soil capacities, the torsional restraint was released at the base support of the drilled shafts (equivalent depth to fixity). It was assumed that the drilled shafts were fully fixed at the connection into the footing.

All loads required by the 2007 ODOT Bridge Design Manual and the 2012 AASHTO LRFD Specifications where applied to the finite element model (FEM). The horizontal earth load was modeled using an active pressure applied to the back face of the walls. The vertical earth load was modeled as a uniform force applied to the length of the footings. Superstructure loads were applied as concentrated nodal loads.

The FEM results showed two way bending within the abutment wall and wingwall/counterfort walls. The reinforcing for the abutment walls, footings and drilled shafts were all designed based on the FEA results. Additional reinforcing steel was added at all corners between the abutment wall and either the wingwalls or counterforts. Also, a chamfer was added to reduce stress concentrations in these transitions. The bottom of the abutment wall was reinforced in a manner similar to a beam section. This will resist the localized forces due to the connection of drilled shafts to the abutment wall. Additional vertical reinforcing steel was added at the drilled shafts to distribute the forces from the drilled shafts to the entire wall.

Globally, the overturning forces are resisted by a combination of axial compression in the drilled shafts along the abutment face and uplift in the drilled shafts located in the wingwalls and counterfort walls. Locally, between the counterfort walls, the drilled shafts resist horizontal earth moments through the moment capacities of the shafts. Sliding is resisted by the shear capacities of the drilled shafts.

The governing factor in the layout of the drilled shafts was controlling the uplift forces in the counterfort wall drilled shafts. The counterfort walls were extended to a distance behind the abutments that exceeded what was needed for staged construction to reduce the uplift to a manageable level. Results from the FEA model were used to calculate required reinforcing steel in the abutment and drilled shafts.

3 RESEARCH APPROACH

The bridge selected for this project was HAM-74-1466, located on I-74 in Hamilton County, Ohio. The outline of the research process was as follows: 1. conduct a preliminary finite element analysis of the bridge with material properties inputs from the literature and the geometry from the bridge design. Use the FEM to estimate the location of critical stresses and conduct a parametric study to determine the sensitivity of the FEM to changes in inputs. 2. Develop an instrumentation plan that will place strain gauges and other appropriate sensors to monitor the critical stresses, measure load response, environmental conditions, and load transfer between bridge abutment components. 3. Once the instrumentation plan was approved by ODOT, the sensors were installed during construction, then connected to data acquisition systems to collect the strain and temperature measurements. 4. Concrete cylinders were collected before each stage of construction for testing in the laboratory to determine the actual compressive strength of the abutment concrete. Final as-built dimensions were also measured or taken from construction records. The inputs for the original FEM were updated to include these laboratory and field measurements. 5. The FEM was calibrated for the new data, and a new parametric analysis conducted. The finite element analysis was repeated and the results compared to instrumentation readings.

3.1 FIELD INSTRUMENTATION AND MONITORING

Based on the results of the finite element analysis, appropriate sensors were selected and their locations determined to monitor the critical stresses. These sensors were used to measure load response and environmental conditions, as well as load transfer between members. The final instrumentation plan included three different types of sensors installed in the drilled shafts, the footings, the wingwall, and the abutment. KM-100 strain gauges and Geokon vibrating wire strain gauges were used to measure the long-term strain, while thermocouples were used to measure the temperature in the concrete. Excerpts from the construction plans marked with details of the instrumentation are given in Appendix A. The timeline for construction and gage installation is given in Table 1, and drawings of the drill shafts, abutment, and wingwalls showing the locations of each gage are in Figure 2 through Figure 9. The elevations above sea level of the sensors are presented in Table 2. Some photographs of the sensor installation are in Figure 10 through Figure 12.

The instrumentation included TML KM100-B strain transducers [Tokyo Sokki Kenkyujo Co. Ltd., 2017]. These are designed to measure the strain in concrete, and allow measurement of strain due to applied load and environmental effects. They are impervious to water and have excellent long term stability. They feature a self-temperature compensated transducer with a linear thermal coefficient of thermal expansion similar to that of concrete. Adjacent to each of the KM-100 gages, a T-Type thermocouple was installed to measure the in-situ temperature.

Geokon Model 4200 vibrating wire strain gages are designed to be embedded directly into the concrete [Geokon, 2017a]. These gages use the vibrating wire principle to measure the strain. In addition, a thermistor is installed in the gage to allow the measurement of in-situ temperatures. These gages allow for long-term stability, water resistance, and the use of long lead wires.

Rebar strain meters, Geokon Model 4911, are designed to be embedded in the concrete to measure concrete strains due to load and temperature variation [Geokon, 2017b]. This rebar strain meter is designed to be welded into a rebar cage and becomes an integral part of this installation. Built-in thermistors allow the measurements of temperature. These sensors are fully waterproof.

Installation dates and gage factors for specific gages are given in Appendix B, followed by Geokon's calibration reports for their strain gages.

The following equation was used to calculate the strain with the data collected from the KM-100 gages:

$$\mathcal{E} = \text{Real Strain} - \text{Thermal Expansion} = C_{\varepsilon} * \mathcal{E}_i + (C_{\beta} - \Upsilon) * \Delta_t$$

Where:

$\mathcal{E}$ = Strain (*10^{-6}, i.e. in units $\mu\varepsilon$)

C_{ε} = Calibration coefficient ($\mu\varepsilon/\mu\varepsilon$)

$\mathcal{E}_i$ = Change of measured value from the initial value (at K = 2.00) ($\mu\varepsilon$)

C_{β} = Compensation coefficient ($\mu\varepsilon$/C°)

Υ = Thermal coefficient of linear expansion of specimen ($\mu\varepsilon$/C°)

Δ_t = Temperature change (C°)

The following equation was used to calculate the strain in the concrete with the data collected from the vibrating wire gages:

$$\mu\varepsilon \text{ load} = \mu\varepsilon \text{ actual} - \mu\varepsilon \text{ thermal} = (R_1 - R_0)\, B + (T_1 - T_0) * (CF_1 - CF_2)$$

Where:

R_1 = Subsequent reading
R_0 = Initial reading
B = gage factor
T_1 = subsequent temperature (°C)
T_0 = initial temperature (°C)
CF_1 = steel coefficient of expansion
CF_2 = concrete coefficient of expansion

Stresses were then computed by multiplying the strains by the modulus of elasticity of the concrete the strain gage was embedded in.

Table 1. Timeline of construction and sensor installation on HAM-74-1466.

Date	**Event**
11/21/2016	Installation of gages on rebar cages in Drilled Shafts 27, 29, 31, 35, and 37
11/23/2016	Concrete placed in Drilled Shafts 27, 29, 31, and 35
11/29/2016	Concrete placed in Drilled Shaft 37
12/5/2016	Installation of gages and placement of footer concrete in Drilled Shafts 27, 29, 31, and 35
12/13/2016	Installation of wall gages above Drilled Shafts 27, 29, and 31
12/15/2016	Concrete placed in wall above Drilled Shafts 27, 29, and 31
1/17/2017	Installation of gages in footer above Drilled Shaft 37
1/18/2017	Concrete placed in footer above Drilled Shaft 37
1/19/2017	Gages installed in wingwall above Drilled Shafts 35 and 37
1/24/2017	Concrete placed in wingwall up to elevation 934.82 ft (284.93 m)
1/30/2017	Bridge beam placement
1/30/2017	Backfill to top of abutments
1/30/2017	Backfill to top of first wingwall concrete pour
1/31/2017	Gages wired to multiplexers
2/1/2017	Data loggers began reading
3/7/2017	Remaining concrete pour in wingwalls
3/30/2017	Bridge deck pour
4/3/2017	Remaining backfill placed behind wingwalls

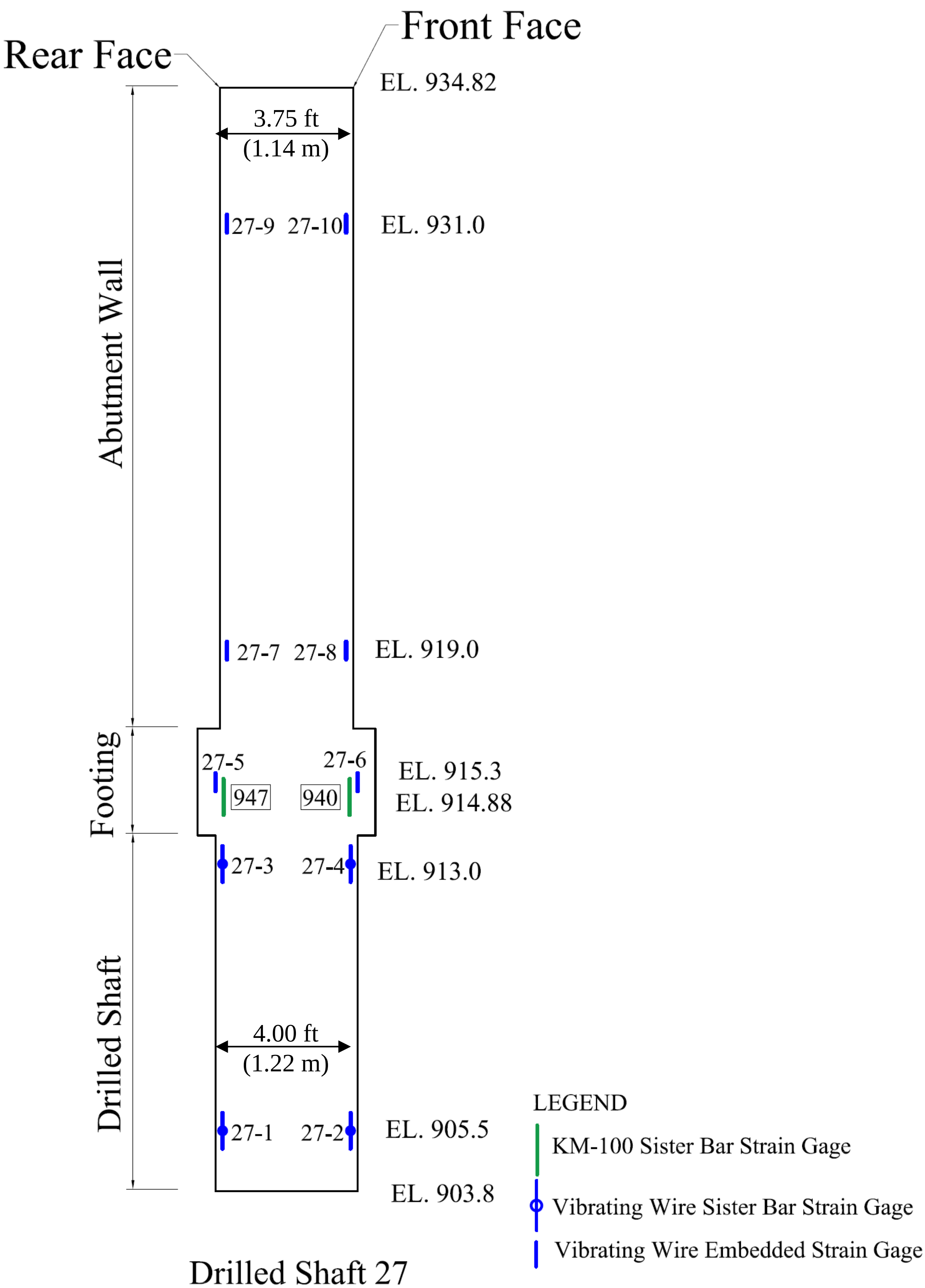

Figure 2. Gage locations in Drilled Shaft 27, footing, and abutment wall (EL in ft: 1 ft = 0.305 m).

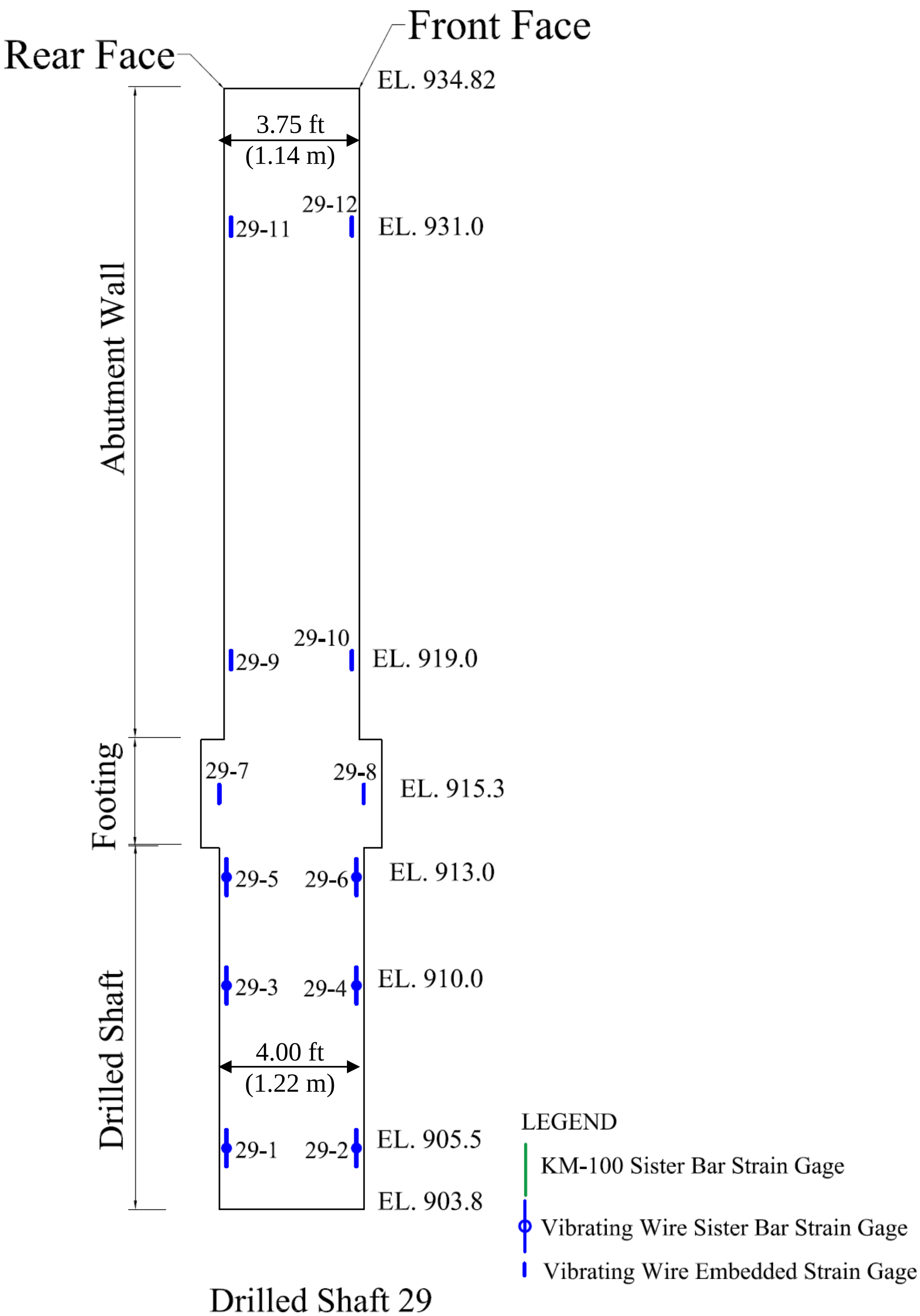

Figure 3. Gage locations in Drilled Shaft 29, footing, and abutment wall (EL in ft: 1 ft = 0.305 m).

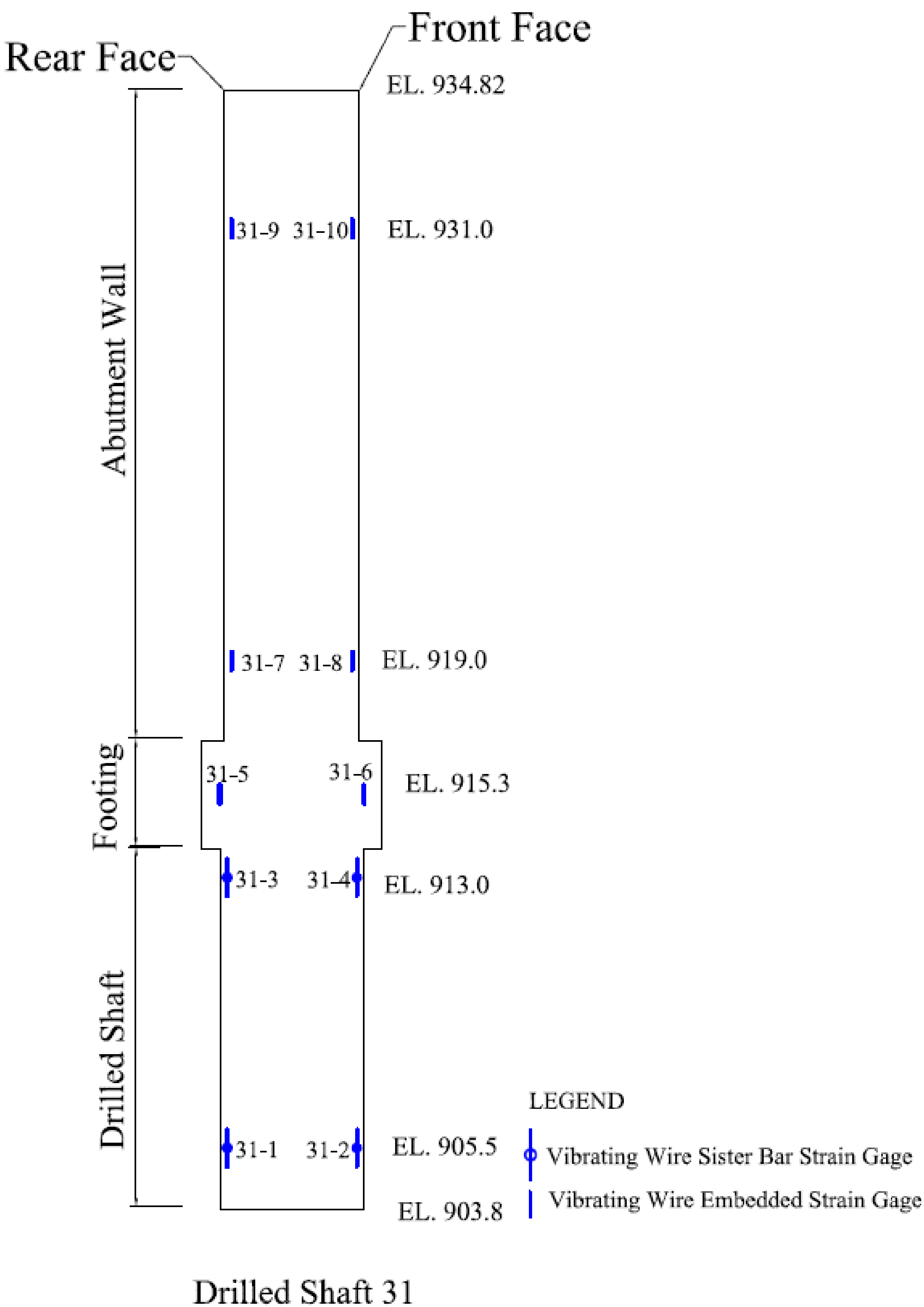

Figure 4. Gage locations in Drilled Shaft 31, footing, and abutment wall (EL in ft: 1 ft = 0.305 m).

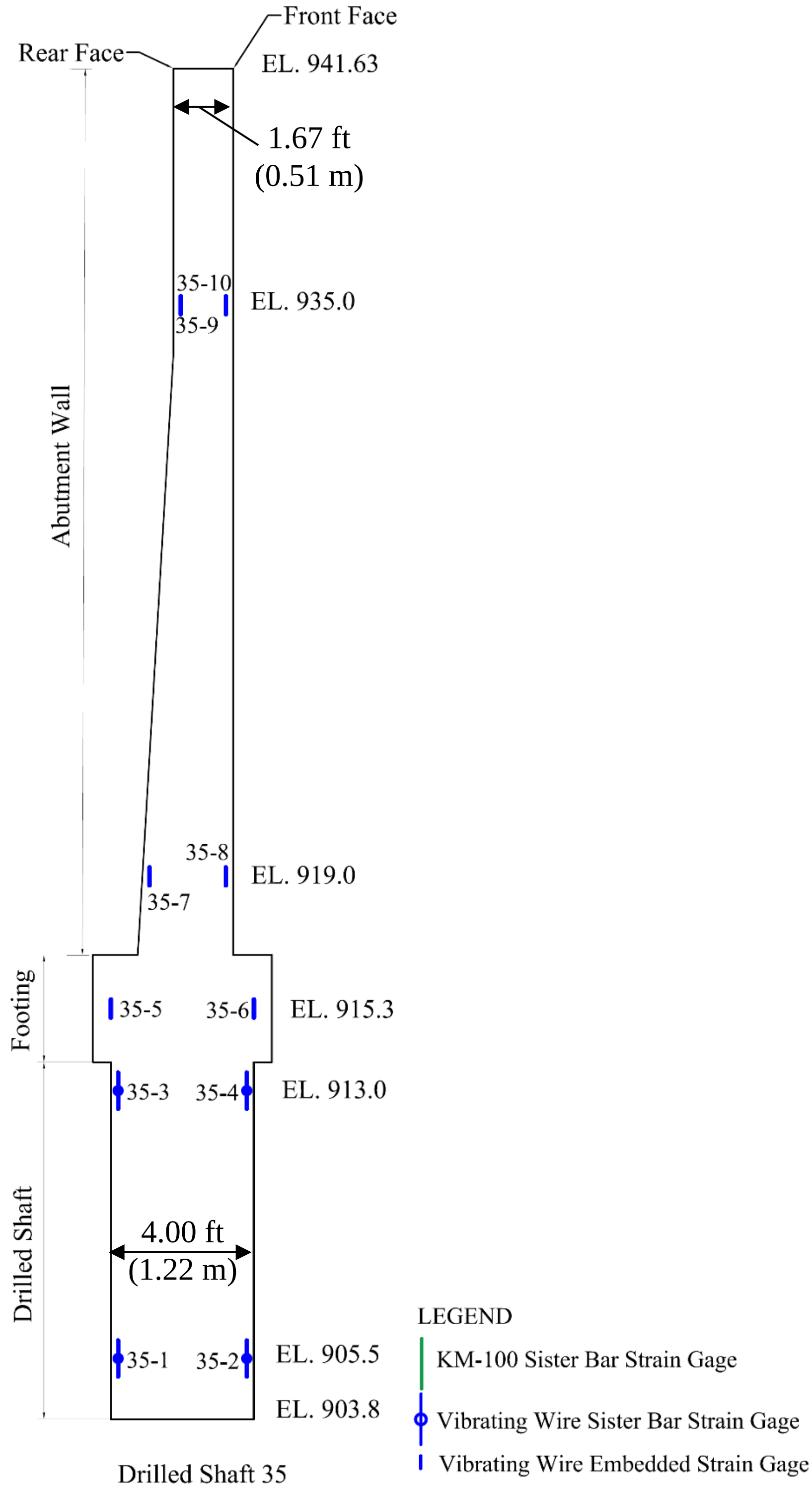

Figure 5. Gage locations in Drilled Shaft 35, footing, and abutment wall (EL in ft: 1 ft = 0.305 m).

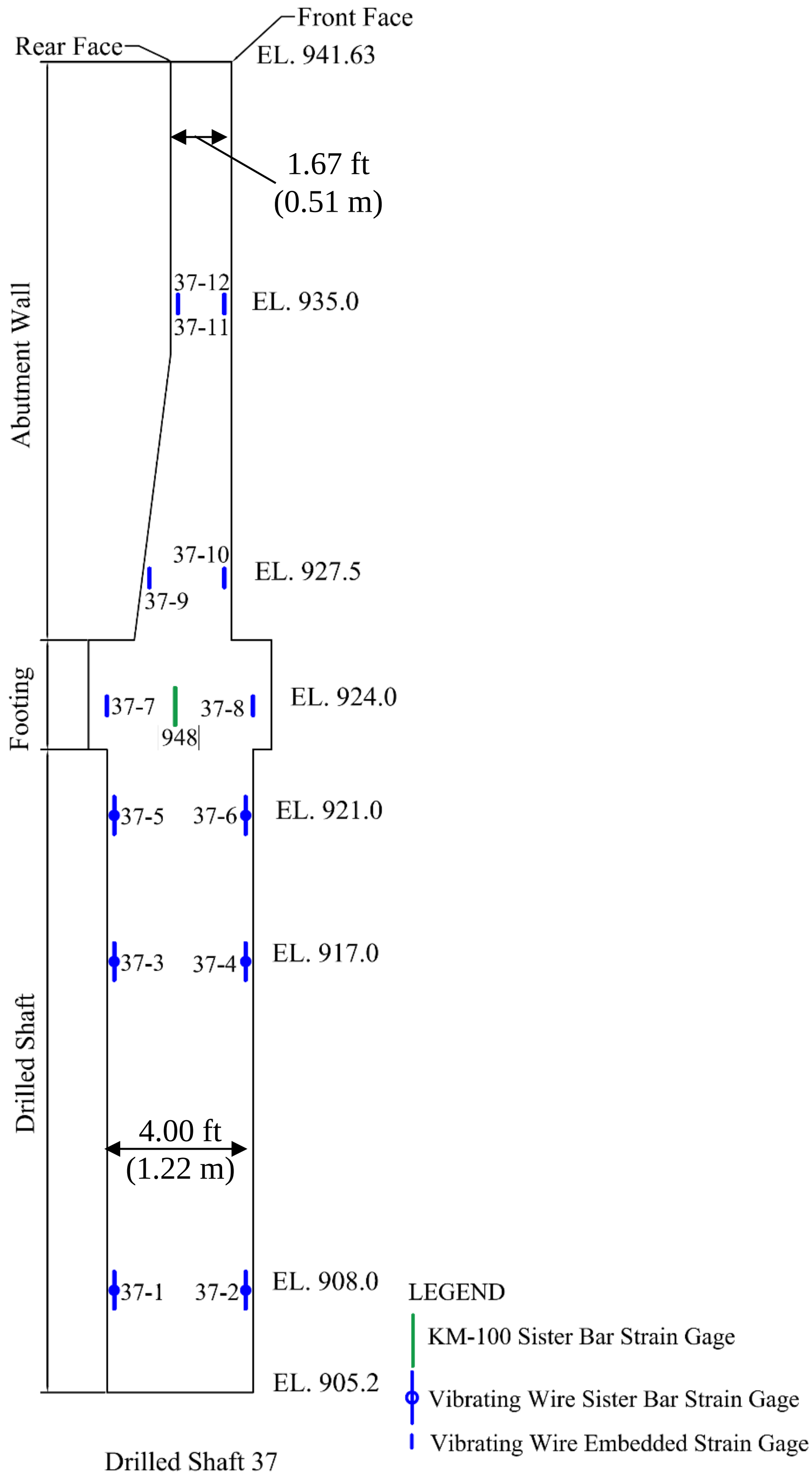

Figure 6. Gage locations in Drilled Shaft 37, footing, and abutment wall (EL in ft: 1 ft = 0.305 m).

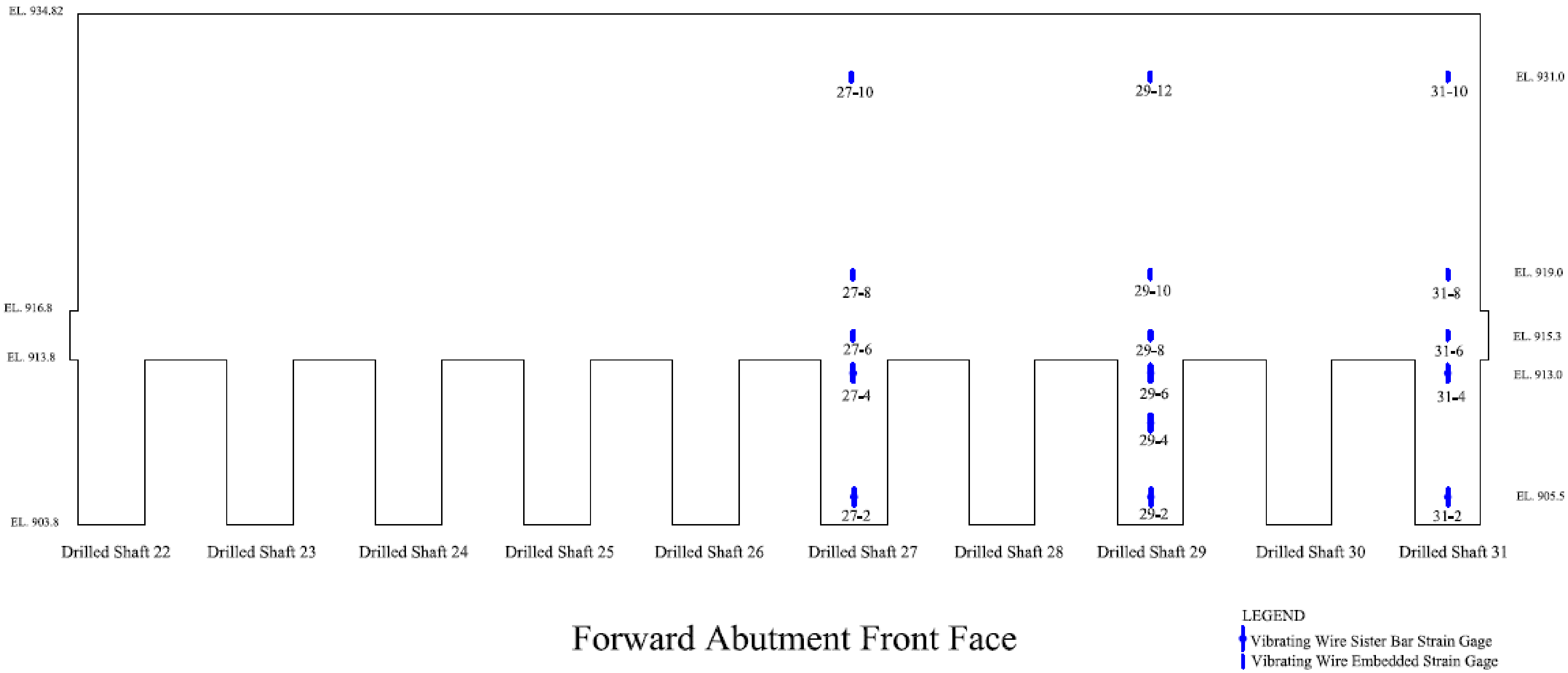

Figure 7. Gage locations in front face of forward abutment. (EL in ft: 1 ft = 0.305 m)

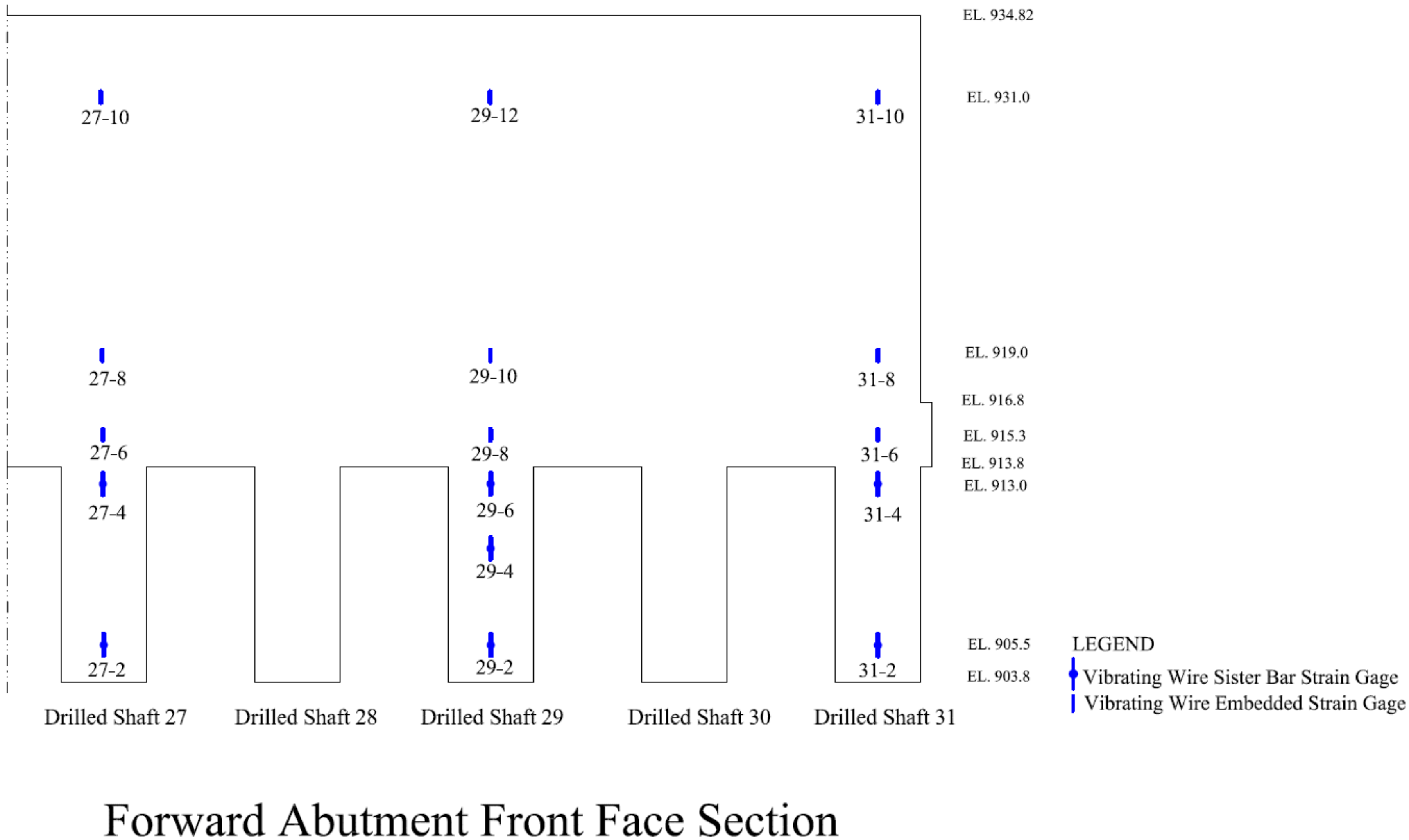

Figure 8. Detail of front face of forward abutment showing locations of gages. (EL in ft: 1 ft = 0.305 m)

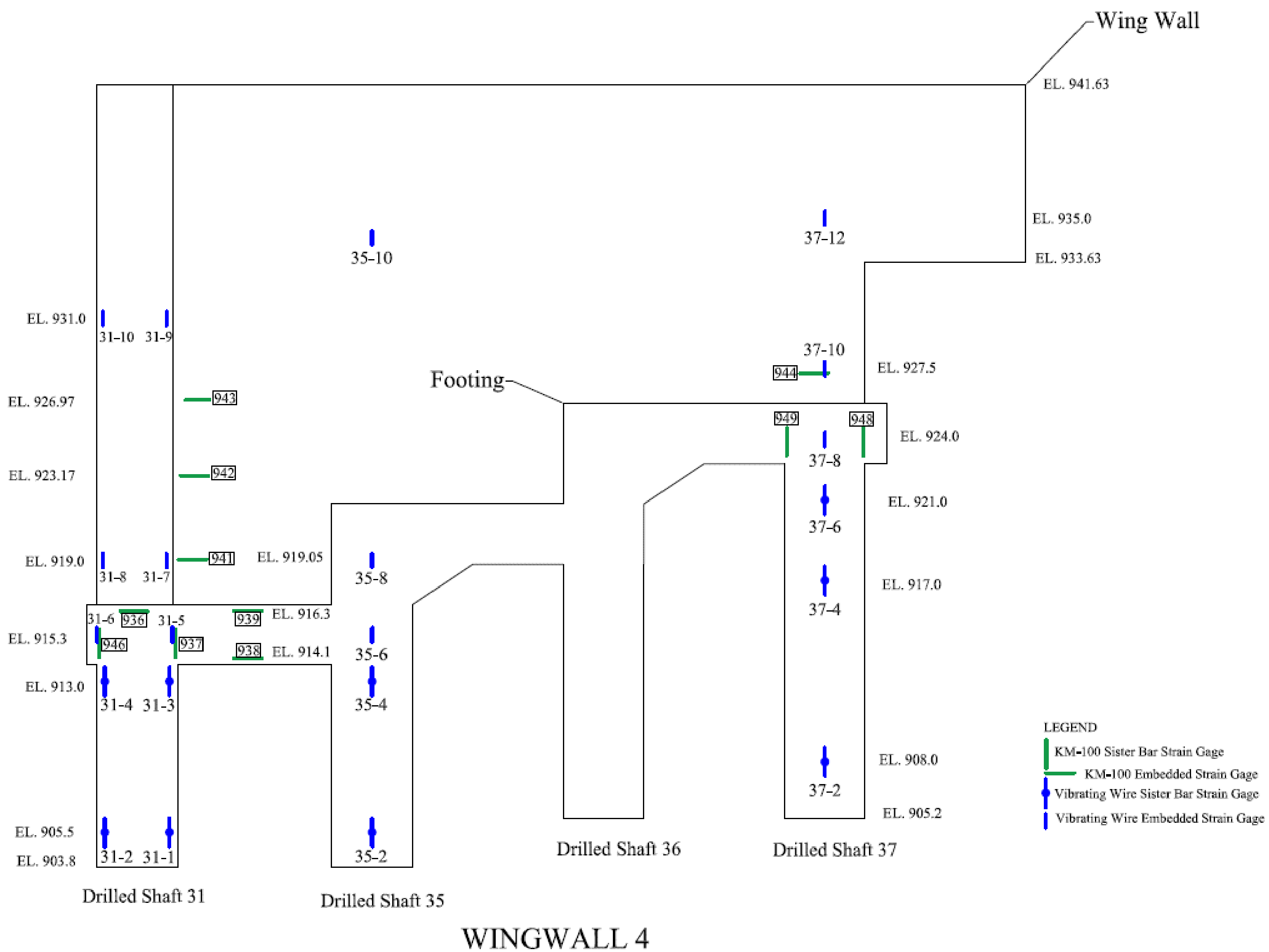

Figure 9. Gage locations in footing and Wingwall 4 (EL in ft: 1 ft = 0.305 m).

Table 2. Strain gage types, elevation, and dates of installation and concrete pours.

	Sensor ID	Strain gage type	Elevation of sensors (ft)	Elevation of sensors (m)	Date of Installation	Date of Concrete pour	Date of Initial data	Date of Final data
Drill Shaft 27	27-1 & 27-2	VW SB	905.5	276.00	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	27-3 & 27-4	VW SB	913.0	278.28	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	947 & 940	KM-100 SB	914.9	278.86	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	27-5 & 27-6	VW E	915.3	278.98	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	27-7 & 27-8	VW E	915.3	278.98	12/13/2016	12/15/2016	3/15/2017	11/2/2017
	27-9 & 27-10	VW E	931.0	283.77	12/13/2016	12/15/2016	3/15/2017	11/2/2017
Drill Shaft 29	29-1 & 29-2	VW SB	905.5	276.00	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	29-3 & 29-4	VW SB	910.0	277.37	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	29-5 & 29-6	VW SB	913.0	278.28	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	29-7 & 29-8	VW E	915.3	278.98	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	29-9 & 29-10	VW E	919.0	280.11	12/13/2016	12/15/2016	3/15/2017	11/2/2017
	29-11 & 29-12	VW E	931.0	283.77	12/13/2016	12/15/2016	3/15/2017	11/2/2017
Drill Shaft 31	31-1 & 31-2	VW SB	905.5	276.00	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	31-3 & 31-4	VW SB	913.0	278.28	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	938	KM-100 E	914.1	278.62	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	937 & 946	KM-100 SB	915.3	278.98	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	31-5 & 31-6	VW E	915.3	278.98	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	936 & 939	KM-100 E	916.3	279.29	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	31-7 & 31-8	VW E	919.0	280.11	12/13/2016	12/15/2016	3/15/2017	11/2/2017
	1-9 & 31-10	VW E	931.0	283.77	12/13/2016	12/15/2016	3/15/2017	11/2/2017
Drill Shaft 35	35-1 & 35-2	VW SB	905.5	276.00	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	35-3 & 35-4	VW SB	913.0	278.28	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	35-5 & 35-6	VW E	915.3	278.98	12/5/2016	12/5/2016	3/5/2017	11/2/2017
	35-7 & 35-8	VW E	922.3	281.12	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	941	KM-100 SB	919.0	280.11	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	942	KM-100 SB	923.2	281.38	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	943	KM-100 SB	931.0	283.77	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	35-9 & 35-10	VW E	935.0	284.99	1/19/2017	3/7/2017	6/5/2017	11/2/2017
Drill Shaft 37	37-1 & 37-2	VW SB	908.0	276.76	11/21/2016	11/29/2016	2/27/2017	11/2/2017
	37-3 & 37-4	VW SB	917.0	279.50	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	37-5 & 37-6	VW SB	921.0	280.72	11/21/2016	11/23/2016	2/21/2017	11/2/2017
	37-7 & 37-8	VW E	924.0	281.64	1/17/2017	1/18/2017	4/18/2017	11/2/2017
	948 & 949	KM-100 SB	924.0	281.64	1/17/2017	1/18/2017	4/18/2017	11/2/2017
	944	KM-100 E	927.5	282.70	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	37-9 & 37-10	VW E	927.5	282.70	1/19/2017	1/24/2017	4/24/2017	11/2/2017
	37-11 & 37-12	VW E	935.0	284.99	1/19/2017	3/7/2017	6/5/2017	11/2/2017

Key to strain gage abbreviations: VW = Vibrating Wire, E = embedded, SB = Sister Bar

Figure 10. Installing strain gages in the drilled shafts.

Figure 11. Installing strain gages in the footing.

Figure 12. Installing strain gages in the wingwall.

All the installed gages were connected to multiplexers and dataloggers and began reading on February 1, 2017 as shown in Figure 13.

Figure 13. View of multiplexers and datalogger in use collecting data.

3.2 LABORATORY TESTING OF MATERIALS

Measurement of concrete properties on test cylinders was performed in the laboratory by subcontractor Thelen Associates following ASTM Standard Test Methods C31, C39, C138, C143, C231, C1064, and C1231. Table 3 (Table 4) and Table 5 (Table 6) summarize the laboratory results in English (metric) units for concrete specimens collected from Phase 1 and Phase 2 construction, respectively.

Table 3. Laboratory test results for Drilled Shafts and Phase 1 Construction (English units).

Drilled Shafts 6, 7, 8, 9, and 10					
Slump, ASTM C143 (in)	6	Yield, ASTM C138 (ft^3)			26.4
Air content, ASTM C231 (%)	5.5	Weather (°F)			78° Sunny
Unit weight, ASTM C138 (pcf)	145.1	Temp. of concrete, ASTM C1064 (°F)			88°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	4350	Test date	6/7/2016	Cylinder test age (day)	4
Forward Abutment Drilled Shafts 22-26 and Wingwall Drilled Shafts 32-34					
Slump, ASTM C143 (in)	7	Yield, ASTM C138 (ft^3)			26.7
Air content, ASTM C231 (%)	5.4	Weather (°F)			74° Sunny
Unit weight, ASTM C138 (pcf)	143.7	Temp. of concrete, ASTM C1064 (°F)			82°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	3620	Test date	6/13/2016	Cylinder test age (day)	5
Pier Drilled Shafts 17, 18, and 19					
Slump, ASTM C143 (in)	7	Yield, ASTM C138 (ft^3)			27.1
Air content, ASTM C231 (%)	6.3	Weather (°F)			83° Cloudy
Unit weight, ASTM C138 (pcf)	142	Temp. of concrete, ASTM C1064 (°F)			84°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit, load (psi)	5880	Test date	7/12/2016	Cylinder test age (day)	28
Forward Abutment and Wingwall Footing, Lot 1, Sublot 2					
Slump, ASTM C143 (in)	7	Yield, ASTM C138 (ft^3)			26.9
Air content, ASTM C231 (%)	5.5	Weather (°F)			85° Cloudy
Unit weight, ASTM C138 (pcf)	144.2	Temp. of concrete, ASTM C1064 (°F)			82°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	6280	Test date	7/19/2016	Cylinder test age (day)	28
Forward Abutment and Wingwall Footing					
Slump, ASTM C143 (in)	7	Yield, ASTM C138 (ft^3)			26.9
Air content, ASTM C231 (%)	5.5	Weather (°F)			85° Cloudy
Unit weight, ASTM C138 (pcf)	144.2	Temp. of concrete, ASTM C1064 (°F)			82°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	4230	Test date	6/28/2016	Cylinder test age (day)	7

Table 4. Laboratory test results for Drilled Shafts and Phase 1 Construction (metric units).

<table>
<tr><td colspan="6">Drilled Shafts 6, 7, 8, 9, and 10</td></tr>
<tr><td colspan="2">Slump, ASTM C143 (mm)</td><td>152</td><td colspan="2">Yield, ASTM C138 (m^3)</td><td>0.748</td></tr>
<tr><td colspan="2">Air content, ASTM C231 (%)</td><td>5.5</td><td colspan="2">Weather (°C)</td><td>25.6° Sunny</td></tr>
<tr><td colspan="2">Unit weight, ASTM C138 (kg/m^3)</td><td>2324</td><td colspan="2">Temp. of concrete, ASTM C1064 (°C)</td><td>31.1°</td></tr>
<tr><td colspan="6">Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231</td></tr>
<tr><td>Unit load, (MPa)</td><td>29.99</td><td>Test date</td><td>6/7/2016</td><td>Cylinder test age (day)</td><td>4</td></tr>
<tr><td colspan="6">Forward Abutment Drilled Shafts 22-26 and Wingwall Drilled Shafts 32-34</td></tr>
<tr><td colspan="2">Slump, ASTM C143 (mm)</td><td>178</td><td colspan="2">Yield, ASTM C138 (m^3)</td><td>0.756</td></tr>
<tr><td colspan="2">Air content, ASTM C231 (%)</td><td>5.5</td><td colspan="2">Weather (°C)</td><td>23.3° Sunny</td></tr>
<tr><td colspan="2">Unit weight, ASTM C138 (kg/m^3)</td><td>2302</td><td colspan="2">Temp. of concrete, ASTM C1064 (°C)</td><td>27.8°</td></tr>
<tr><td colspan="6">Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231</td></tr>
<tr><td>Unit load, (MPa)</td><td>24.96</td><td>Test date</td><td>6/13/2016</td><td>Cylinder test age (day)</td><td>5</td></tr>
<tr><td colspan="6">Pier Drilled Shafts 17, 18, and 19</td></tr>
<tr><td colspan="2">Slump, ASTM C143 (mm)</td><td>178</td><td colspan="2">Yield, ASTM C138 (m^3)</td><td>0.767</td></tr>
<tr><td colspan="2">Air content, ASTM C231 (%)</td><td>5.5</td><td colspan="2">Weather (°C)</td><td>28.3° Cloudy</td></tr>
<tr><td colspan="2">Unit weight, ASTM C138 (kg/m^3)</td><td>2275</td><td colspan="2">Temp. of concrete, ASTM C1064 (°C)</td><td>28.9°</td></tr>
<tr><td colspan="6">Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231</td></tr>
<tr><td>Unit load, (MPa)</td><td>40.54</td><td>Test date</td><td>7/12/2016</td><td>Cylinder test age (day)</td><td>28</td></tr>
<tr><td colspan="6">Forward Abutment and Wingwall Footing, Lot 1, Sublot 2</td></tr>
<tr><td colspan="2">Slump, ASTM C143 (mm)</td><td>178</td><td colspan="2">Yield, ASTM C138 (m^3)</td><td>0.762</td></tr>
<tr><td colspan="2">Air content, ASTM C231 (%)</td><td>5.5</td><td colspan="2">Weather (°C)</td><td>29.4° Cloudy</td></tr>
<tr><td colspan="2">Unit weight, ASTM C138 (kg/m^3)</td><td>2310</td><td colspan="2">Temp. of concrete, ASTM C1064 (°C)</td><td>27.8°</td></tr>
<tr><td colspan="6">Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231</td></tr>
<tr><td>Unit load, (MPa)</td><td>43.30</td><td>Test date</td><td>7/19/2016</td><td>Cylinder test age (day)</td><td>28</td></tr>
<tr><td colspan="6">Forward Abutment and Wingwall Footing</td></tr>
<tr><td colspan="2">Slump, ASTM C143 (mm)</td><td>178</td><td colspan="2">Yield, ASTM C138 (m^3)</td><td>0.762</td></tr>
<tr><td colspan="2">Air content, ASTM C231 (%)</td><td>5.5</td><td colspan="2">Weather (°C)</td><td>29.4° Cloudy</td></tr>
<tr><td colspan="2">Unit weight, ASTM C138 (kg/m^3)</td><td>2310</td><td colspan="2">Temp. of concrete, ASTM C1064 (°C)</td><td>27.8°</td></tr>
<tr><td colspan="6">Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231</td></tr>
<tr><td>Unit load, (MPa)</td><td>29.16</td><td>Test date</td><td>6/28/2016</td><td>Cylinder test age (day)</td><td>7</td></tr>
</table>

Table 5. Laboratory test results for Phase 2 Construction (English units).

Forward Abutment Wall, Phase 2					
Slump, ASTM C143 (in)	5.25	Yield, ASTM C138 (ft^3)			27.2
Air content, ASTM C231 (%)	5.2	Weather (°F)			39° Clear
Unit weight, ASTM C138 (pcf)	142.5	Temp. of concrete, ASTM C1064 (°F)			64°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	8400	Test date	1/19/2017	Cylinder test age (day)	28
Phase 2, Pier Cap					
Slump, ASTM C143 (in)	5	Yield, ASTM C138 (ft^3)			26.6
Air content, ASTM C231 (%)	5.3	Weather (°F)			41° Clear
Unit weight, ASTM C138 (pcf)	145	Temp. of concrete, ASTM C1064 (°F)			65°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	8120	Test date	2/7/2017	Cylinder test age (day)	28
Phase 2, Pier Cap					
Slump, ASTM C143 (in)	5	Yield, ASTM C138 (ft^3)			26.6
Air content, ASTM C231 (%)	5.3	Weather (°F)			41° Clear
Unit weight, ASTM C138 (pcf)	145	Temp. of concrete, ASTM C1064 (°F)			65°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	3660	Test date	1/16/2017	Cylinder test age (day)	6
North Wingwall Footing, Phase 2					
Slump, ASTM C143 (in)	4.25	Yield, ASTM C138 (ft^3)			27
Air content, ASTM C231 (%)	6.1	Weather (°F)			35° Clear
Unit weight, ASTM C138 (pcf)	142.7	Temp. of concrete, ASTM C1064 (°F)			64°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	6800	Test date	2/10/2017	Cylinder test age (day)	28
North Wingwall Footing, Phase 2					
Slump, ASTM C143 (in)	4.25	Yield, ASTM C138 (ft^3)			27
Air content, ASTM C231 (%)	6.1	Weather (°F)			35° Clear
Unit weight, ASTM C138 (pcf)	142.7	Temp. of concrete, ASTM C1064 (°F)			64°
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (psi)	3830	Test date	1/20/2017	Cylinder test age (day)	7

Table 6. Laboratory test results for Phase 2 Construction (metric units).

Forward Abutment Wall, Phase 2					
Slump, ASTM C143 (mm)	133	Yield, ASTM C138 (m^3)		0.770	
Air content, ASTM C231 (%)	5.5	Weather (°C)		3.9° Clear	
Unit weight, ASTM C138 (kg/m^3)	2283	Temp. of concrete, ASTM C1064 (°C)		17.8°	
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (MPa)	57.92	Test date	1/19/2017	Cylinder test age (day)	28
Phase 2, Pier Cap					
Slump, ASTM C143 (mm)	127	Yield, ASTM C138 (m^3)		0.753	
Air content, ASTM C231 (%)	5.5	Weather (°C)		5.0° Clear	
Unit weight, ASTM C138 (kg/m^3)	2323	Temp. of concrete, ASTM C1064 (°C)		18.3°	
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (MPa)	55.99	Test date	2/7/2017	Cylinder test age (day)	28
Phase 2, Pier Cap					
Slump, ASTM C143 (mm)	127	Yield, ASTM C138 (m^3)		0.753	
Air content, ASTM C231 (%)	5.5	Weather (°C)		5.0° Clear	
Unit weight, ASTM C138 (kg/m^3)	2323	Temp. of concrete, ASTM C1064 (°C)		18.3°	
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (MPa)	25.23	Test date	1/16/2017	Cylinder test age (day)	6
North Wingwall Footing, Phase 2					
Slump, ASTM C143 (mm)	108	Yield, ASTM C138 (m^3)		0.765	
Air content, ASTM C231 (%)	5.5	Weather (°C)		1.7° Clear	
Unit weight, ASTM C138 (kg/m^3)	2286	Temp. of concrete, ASTM C1064 (°C)		17.8°	
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (MPa)	46.88	Test date	2/10/2017	Cylinder test age (day)	28
North Wingwall Footing, Phase 2					
Slump, ASTM C143 (mm)	108	Yield, ASTM C138 (m^3)		0.765	
Air content, ASTM C231 (%)	5.5	Weather (°C)		1.7° Clear	
Unit weight, ASTM C138 (kg/m^3)	2286	Temp. of concrete, ASTM C1064 (°C)		17.8°	
Laboratory Data from ASTM C31 and ASTM C39 and ASTM C1231					
Unit load, (MPa)	26.41	Test date	1/20/2017	Cylinder test age (day)	7

3.3 Data Analysis

Graphs showing time series data from strain gages installed in each drilled shaft are shown in Figure 14 through Figure 18. Appendix C has time series plots of the strains and temperatures from the 900 series gages (numbered 936 – 947). Examples of more detailed graphs comparing pairs of sensors are in Figure 19 and Figure 20; the full set of these graphs is given in Appendix D. Figure 20 shows an example of a sensor that stopped taking measurements before the end of the experiment in sensor 27-4. Initial data were collected 3 months after placement of the concrete at that location, while the final measurements were made on November 2, 2017, regardless of the age of the concrete.

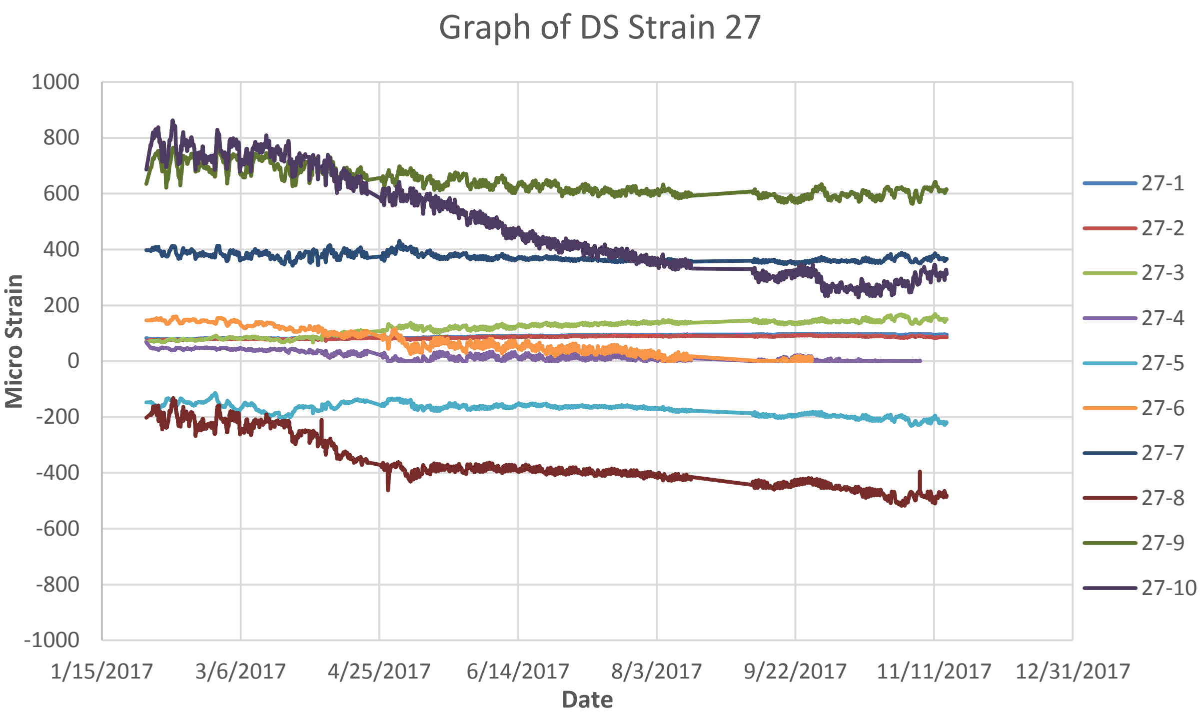

Figure 14. Time series graph of strains recorded by strain gages in Drill Shaft 27.

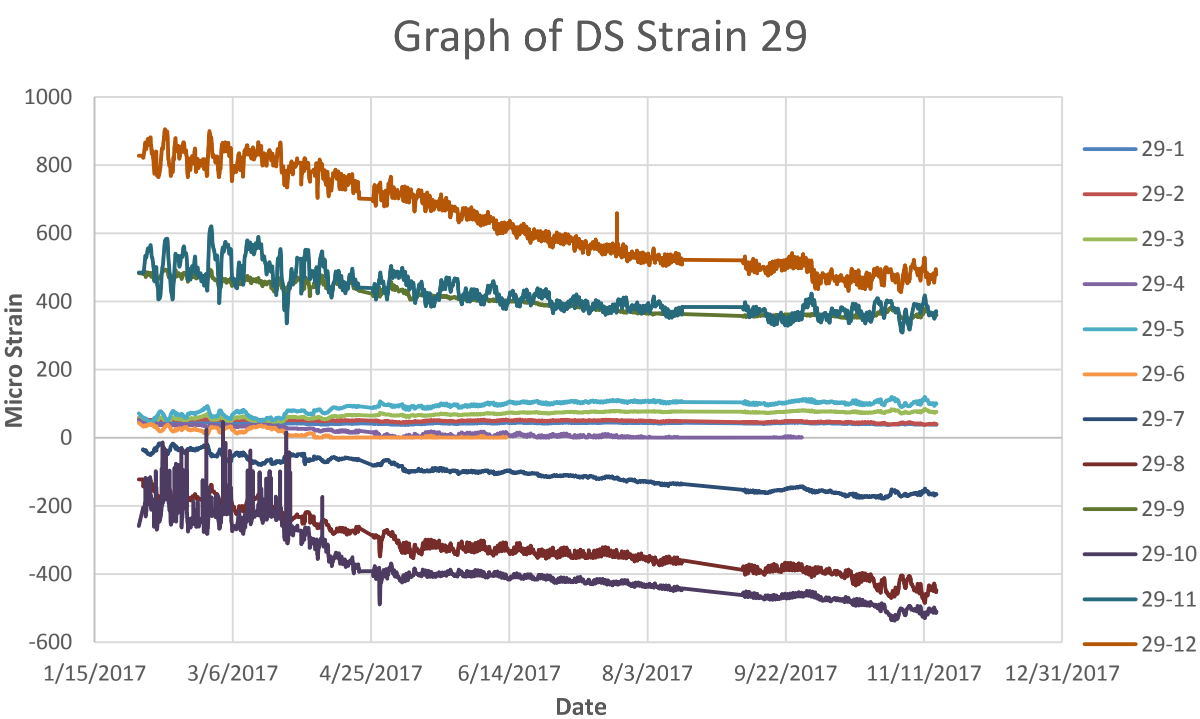

Figure 15. Time series graph of strains recorded by strain gages in Drill Shaft 29.

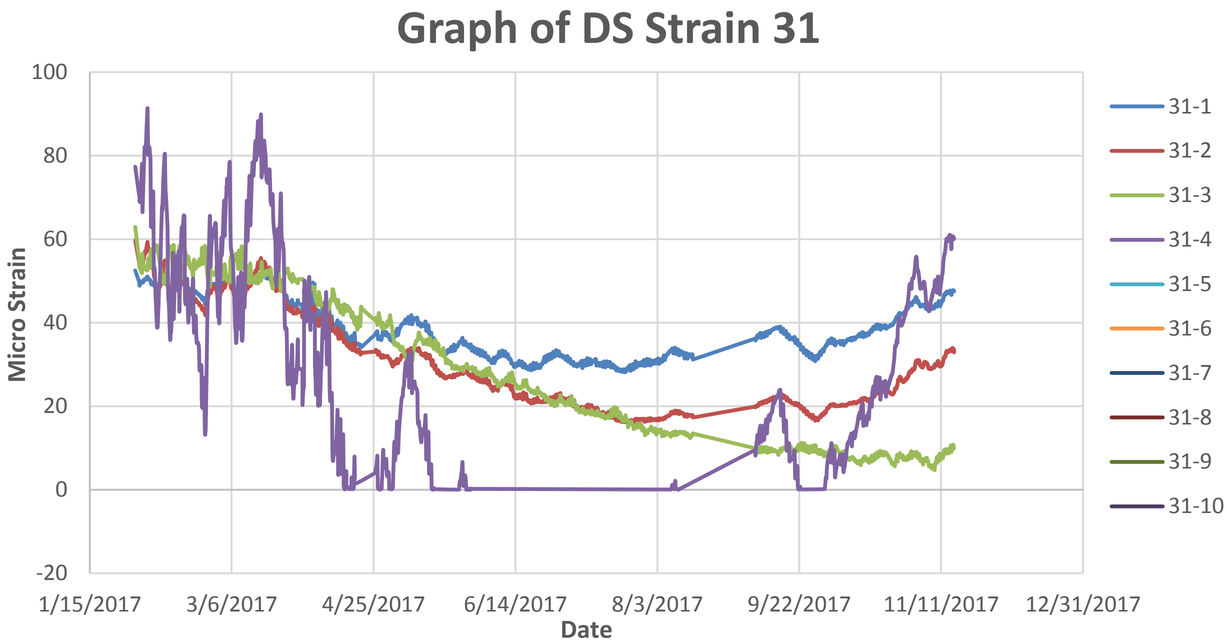

Figure 16. Time series graph of strains recorded by strain gages in Drill Shaft 31.

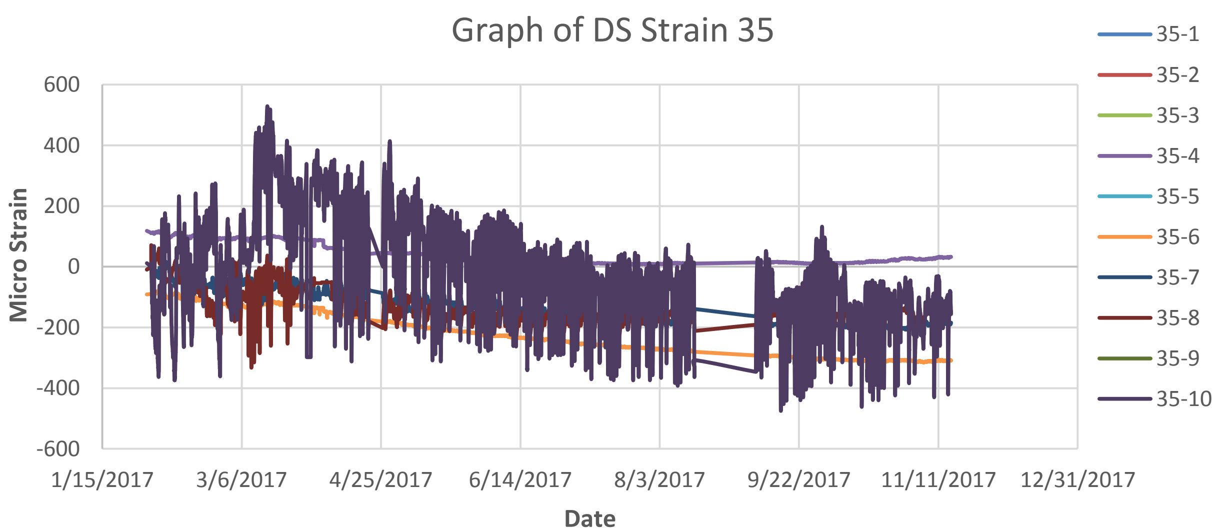

Figure 17. Time series graph of strains recorded by strain gages in Drill Shaft 35.

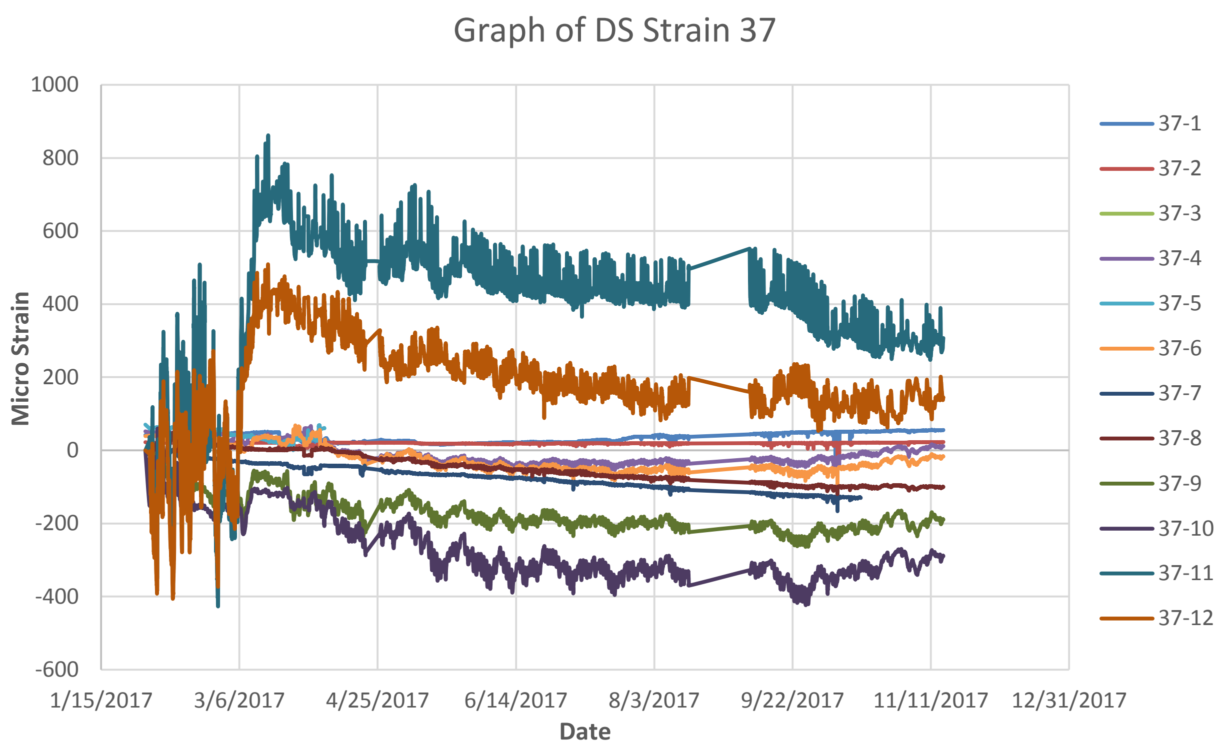

Figure 18. Time series graph of strains recorded by strain gages in Drill Shaft 37.

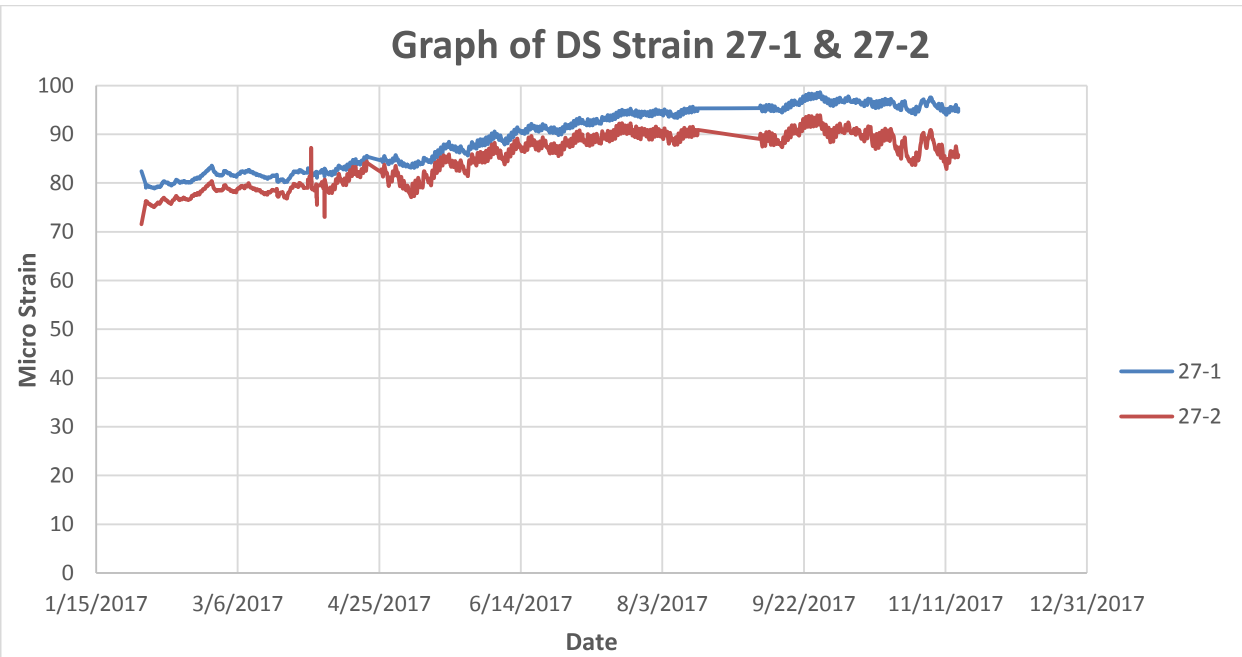

Figure 19. Time series graph of strains recorded by Strain Gages 27-1 and 27-1 in Drill Shaft 27.

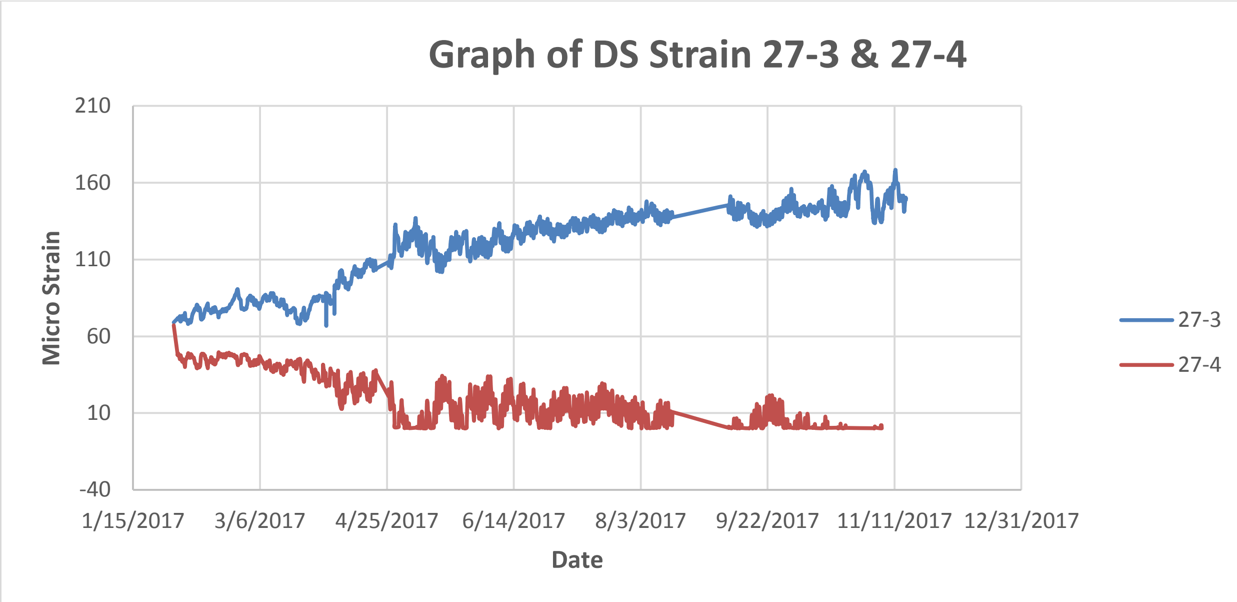

Figure 20. Time series graph of strains recorded by Strain Gages 27-3 and 27-4 in Drill Shaft 27.

3.4 Finite Element Model Calibration

3.4.1 SAP2000

The HAM-74-1466 bridge abutment was modeled using SAP2000 v. 19 software. The model was built in full three-dimensional (3D) fashion in which the abutment wall, wingwalls, and drilled shafts were all modeled in 3D Solid (Brick) elements. Each of the solid elements consists of eight nodes; each of the nodes has three translational degrees of freedom in x, y, and z directions. The advantage of using solid elements is the ability to model the exact geometry of the substructure.

The bearings were modeled as frame elements, the material assigned to the bearing element in the model was of elastomeric properties (shear modulus of the elastomer is 0.165 ksi (1140 kPa)). The frame element is a two-node element with one node at each end; each node has six degrees of freedom (three translational and three rotational). The bottom node of the bearing element was constrained with the surrounding adjacent solid element nodes to assure numerical stability of the bearing element. The model is shown in Figure 21.

Special importance was made to the interface of the circular-shaped drilled shaft elements and the rectangular-shaped abutment (and wingwalls) elements. Each of the drilled shaft element nodes was connected directly to nodes of abutment wall (or wingwall) elements, as shown in Figure 22, so both of the solid elements (on both sides of the interface) share some nodes. And this is true for elements at the face of the drilled shaft as well as the inside elements of the drilled shaft.

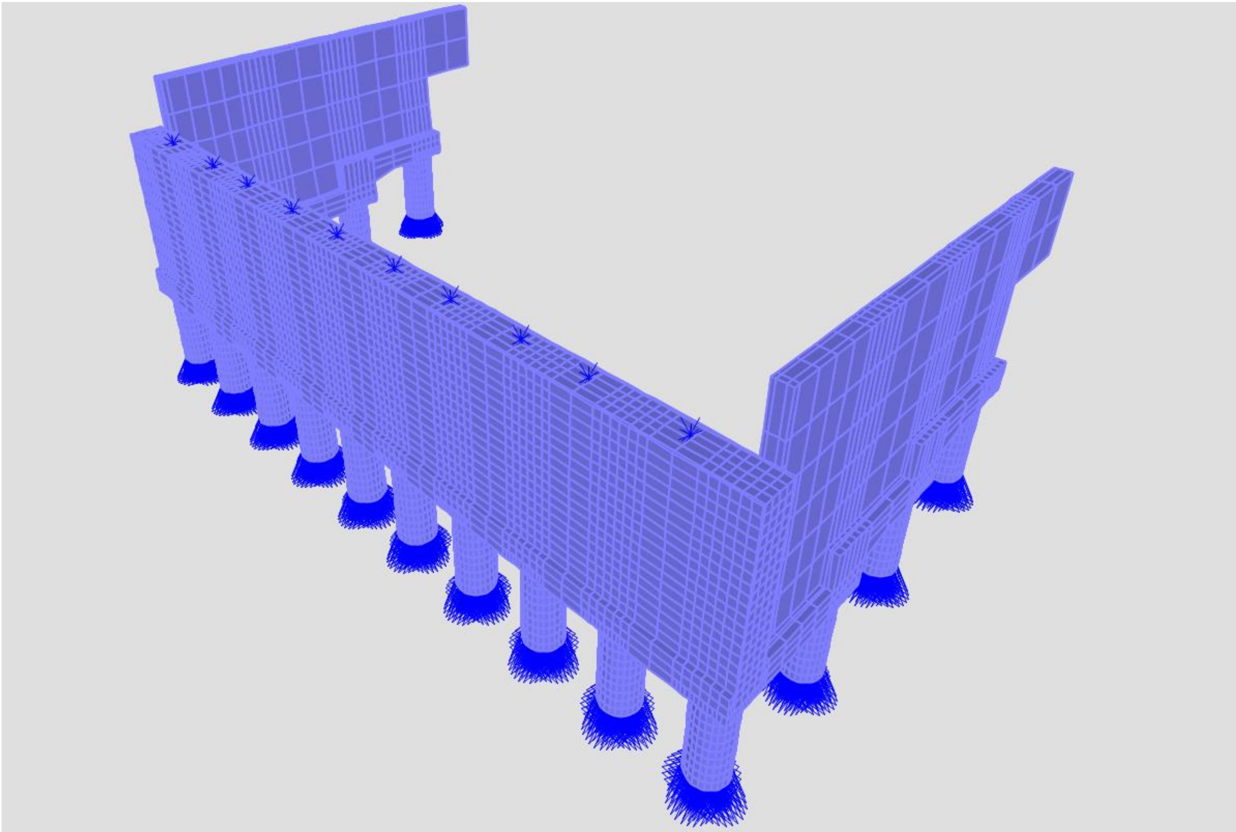

Figure 21. SAP2000 Finite Element Model of HAM-74-1466 bridge abutment.

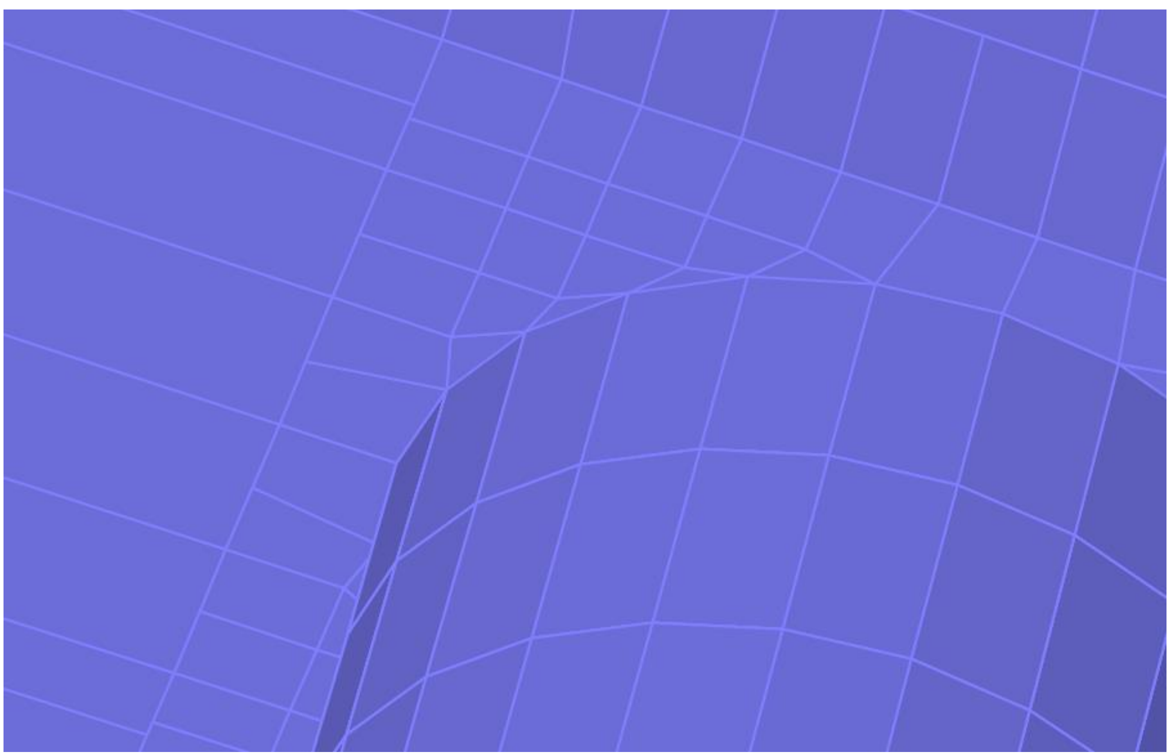

Figure 22. Drilled shaft – abutment wall element interface connection in SAP 2000.

The boundary conditions consist of drilled shaft surface-soil interaction and end bearing conditions. For the end bearing each node of the tip of the drilled shaft is assigned a pin connection. The drilled shaft surrounding rock was modeled by using linear springs at interface side of the solid elements nodes of the drilled shaft. Each linear spring constant was calculated based on Subgrade Modulus “k” value of 1000 pci (271 MN/m^3).

The applied loading involves the following:

1. Dead Load-Self weight – activated directly by the program
2. Dead Load from superstructure (DC) – applied as nodal load on the top of the bearing element
3. Live load from the superstructure (LL) – applied as nodal load on the top of the bearing element
4. Temperature load from superstructure (TU) – applied as deflection-controlled nodal displacement on the top of the bearing element
5. Lateral Earth Pressure (EH) – applied as triangular horizontal pressure on the back wall of the solid element
6. Surcharge (LS) – applied as rectangular horizontal pressure on the back wall of the solid element

The service load combination (DC, LL, TU, EH, and LS) was applied according to AASHTO 7th edition with 2015 interims. A linear elastic analysis was run to obtain computed stresses. The initial results determined the location of critical stresses in the drilled shafts which were used to determine the installation location of sensors. Figure 23 through Figure 32 show the computed stresses in the model. The maximum stresses in the forward abutment and the wingwalls are in Table 7. Figure 33 shows a drawing of the forward abutment plan with the drilled shafts numbered.

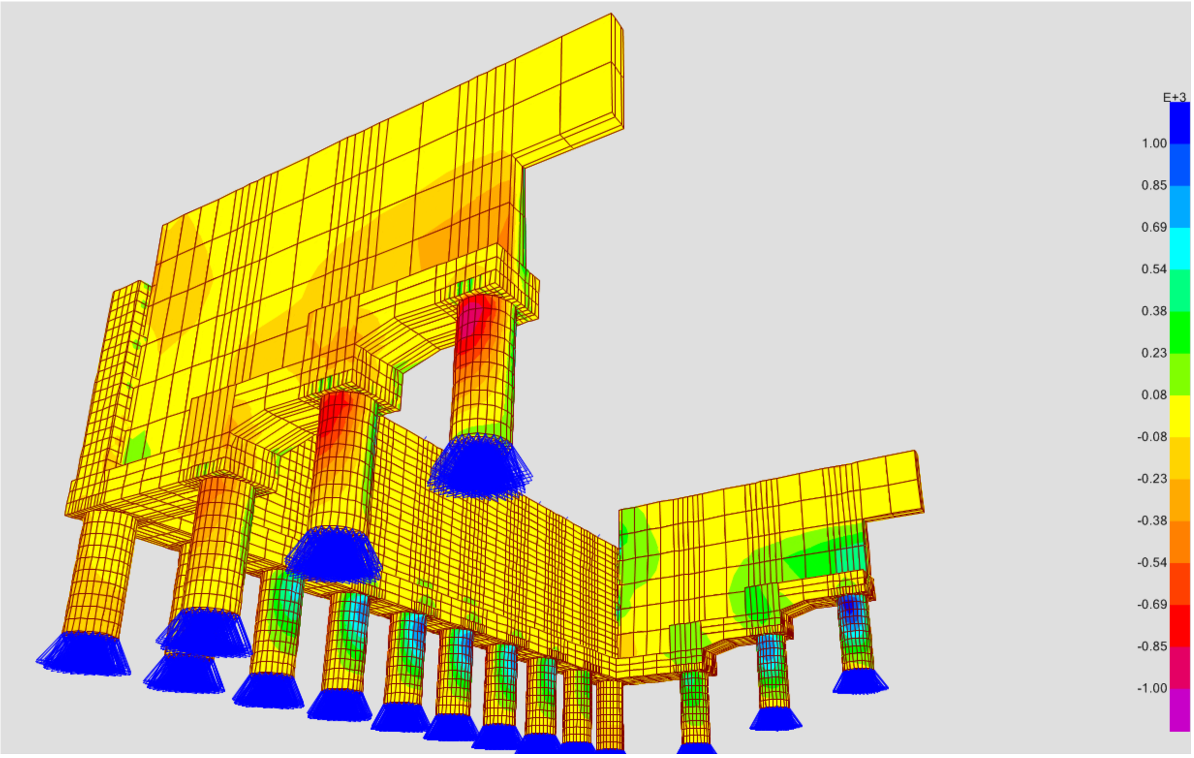

Figure 23. Service Load (DC, LL, TU, EH and LS) Vertical Stress (psi) – All members. (1 psi = 6.89 kPa)

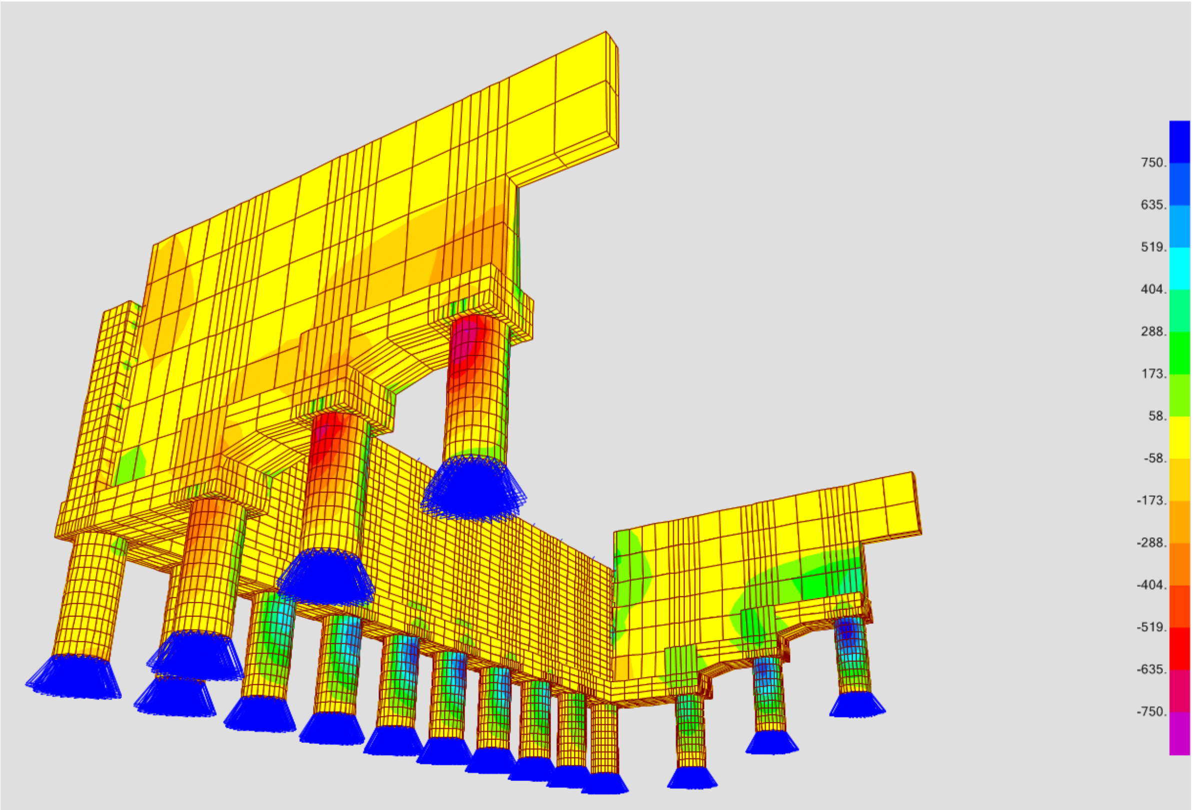

Figure 24. EH Vertical Stress (psi) – All members. (1 psi = 6.89 kPa)

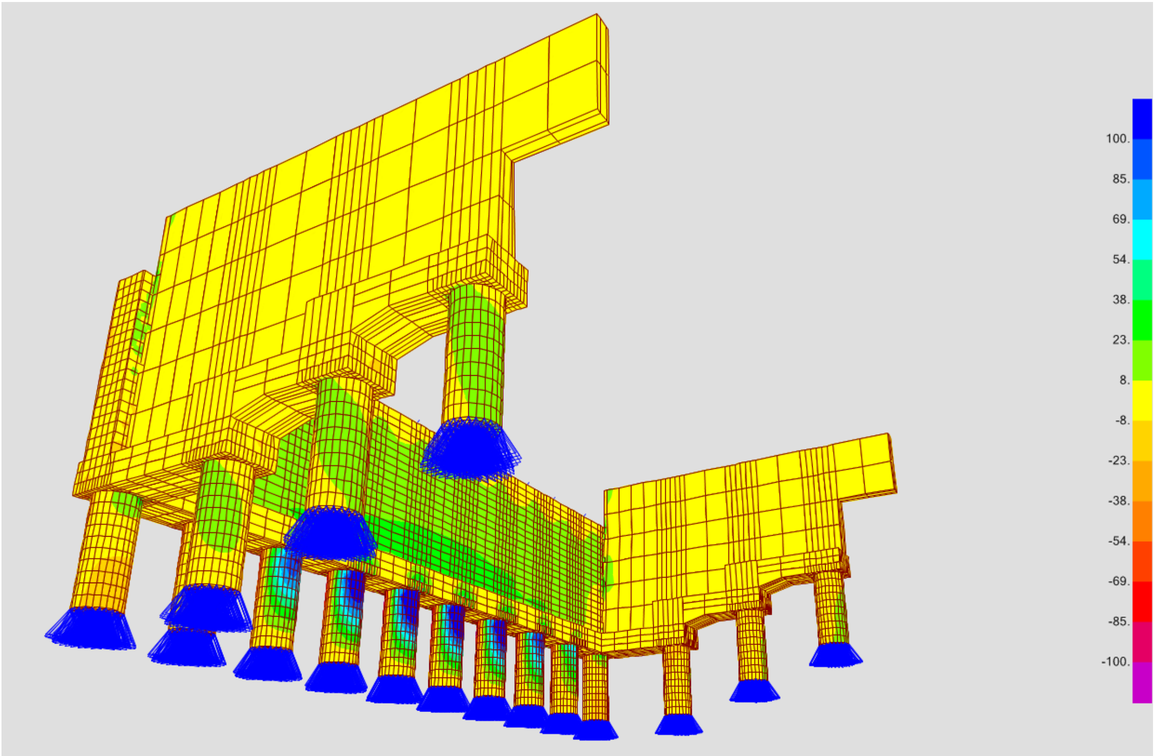

Figure 25. TU Vertical Stress (psi) – All members. (1 psi = 6.89 kPa)

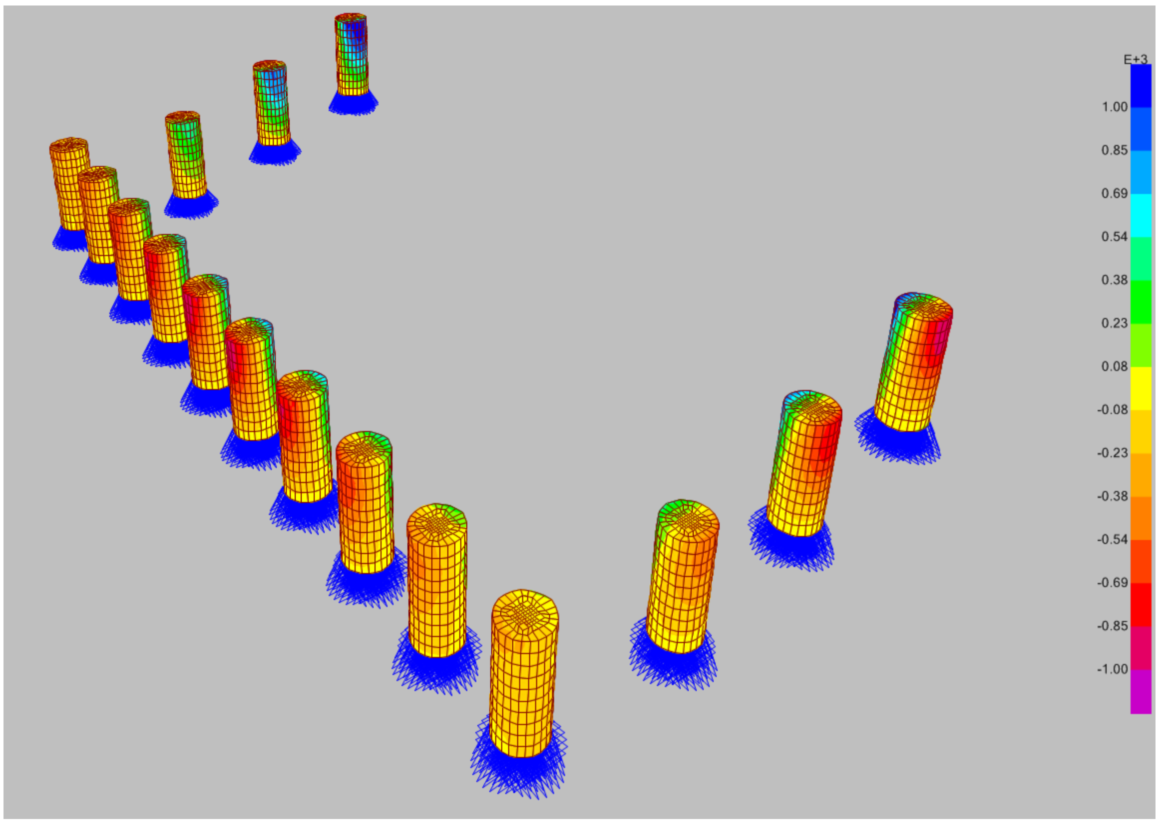

Figure 26. Service Load (DC, LL, TU, EH and LS) Vertical Stress (psi) – Drilled shafts. (1 psi = 6.89 kPa)

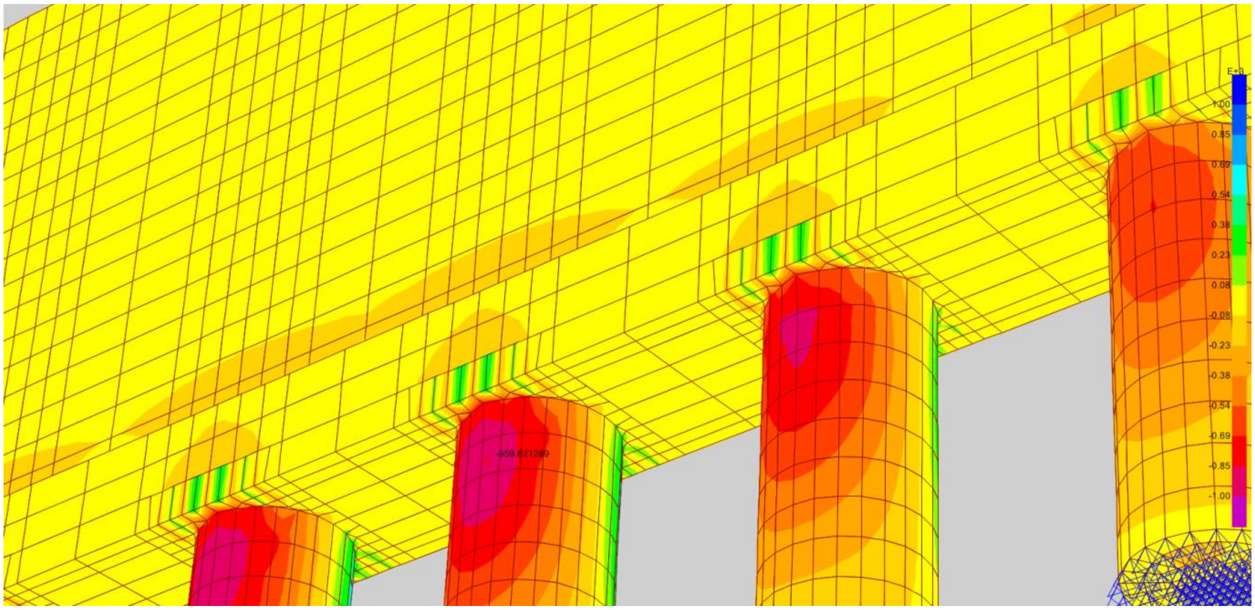

Figure 27. Service Load (DC, LL, TU, EH and LS) Vertical Stress (psi) – Abutment wall. (1 psi = 6.89 kPa)

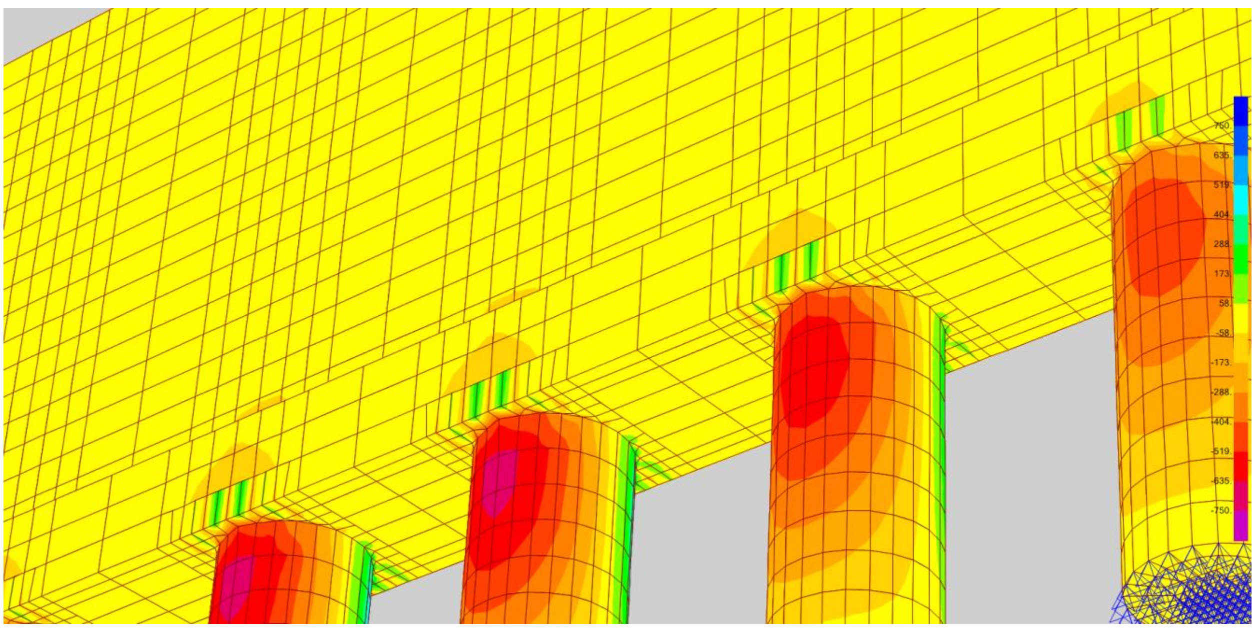

Figure 28. EH Vertical Stress (psi) – Abutment wall. (1 psi = 6.89 kPa)

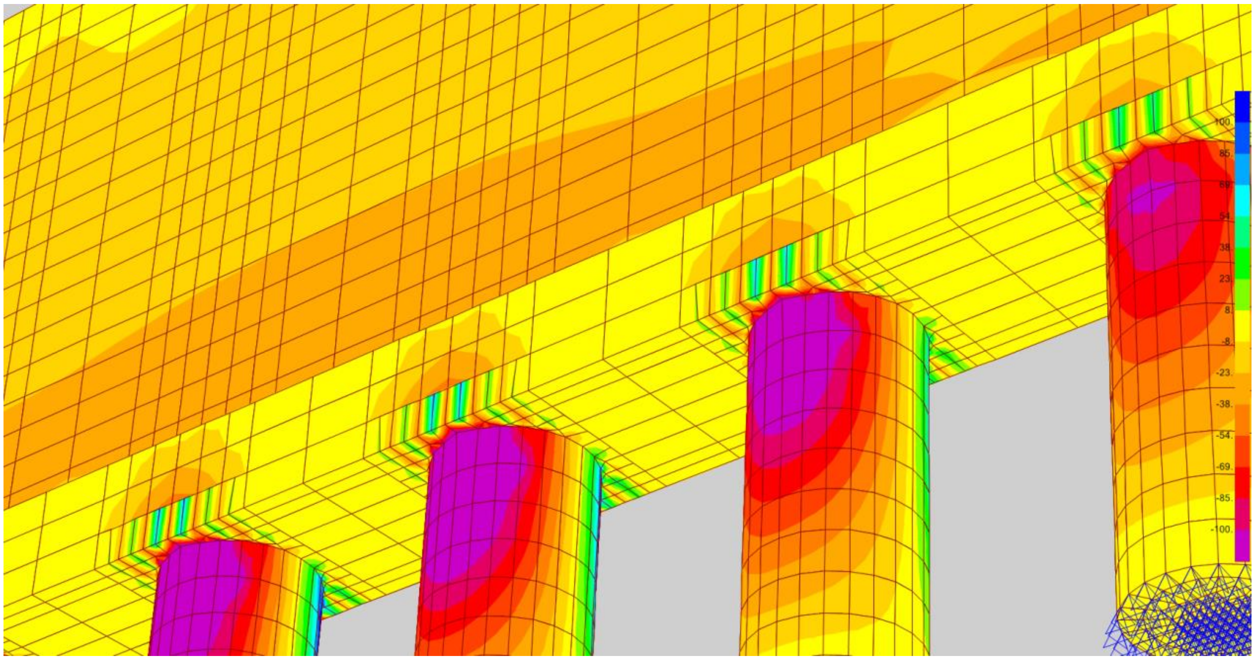

Figure 29. TU Vertical Stress (psi) – Abutment wall. (1 psi = 6.89 kPa)

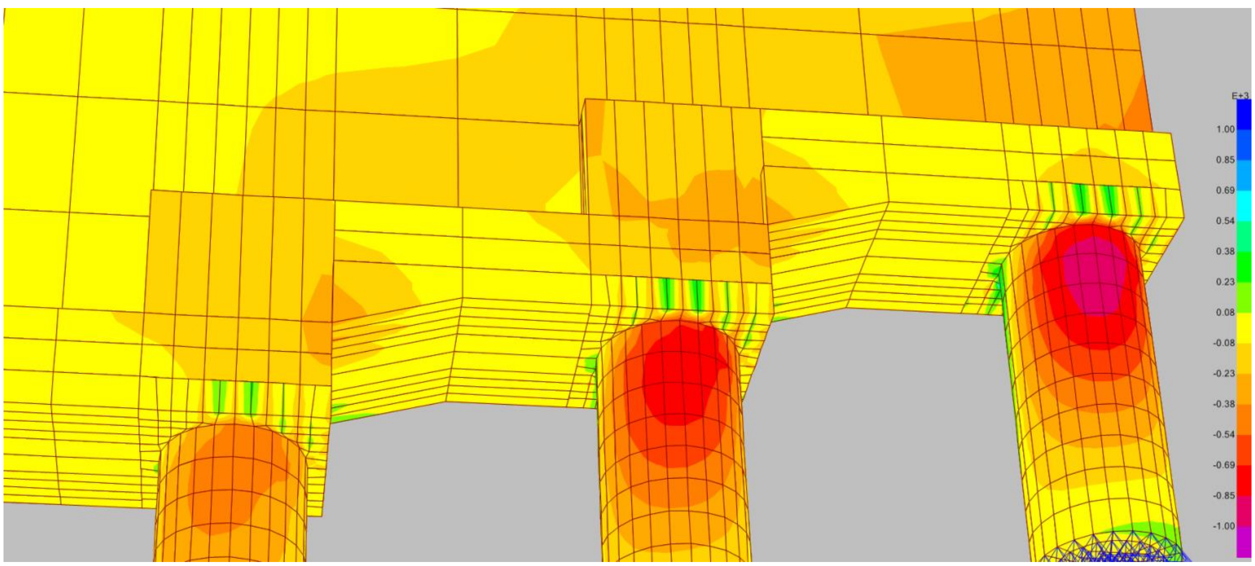

Figure 30. Service Load (DC, LL, TU, EH and LS) Vertical Stress (psi) – Wingwall. (1 psi = 6.89 kPa)

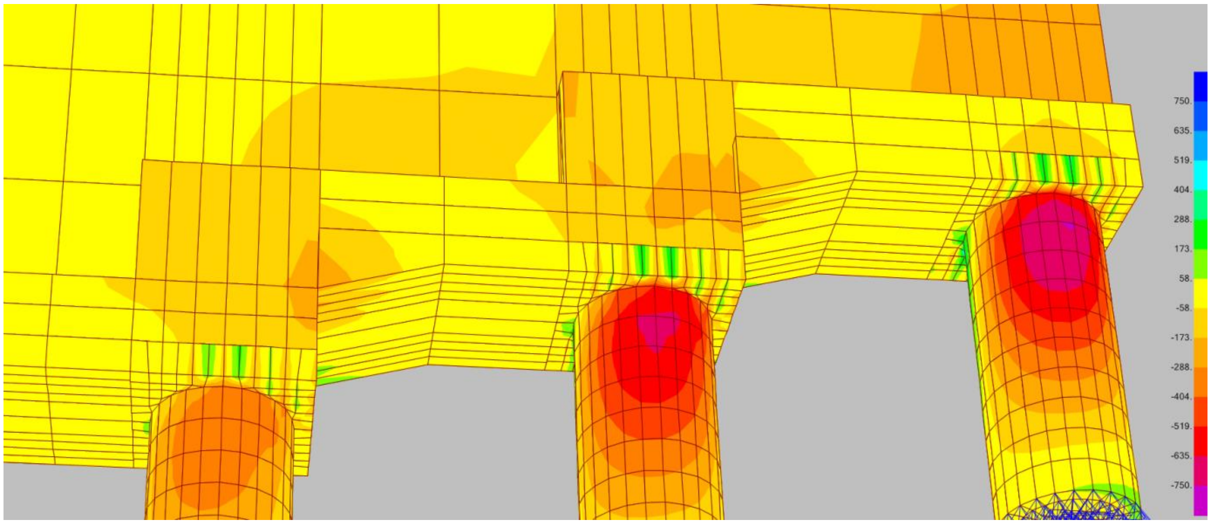

Figure 31. EH Vertical Stress (psi) – Wingwall. (1 psi = 6.89 kPa)

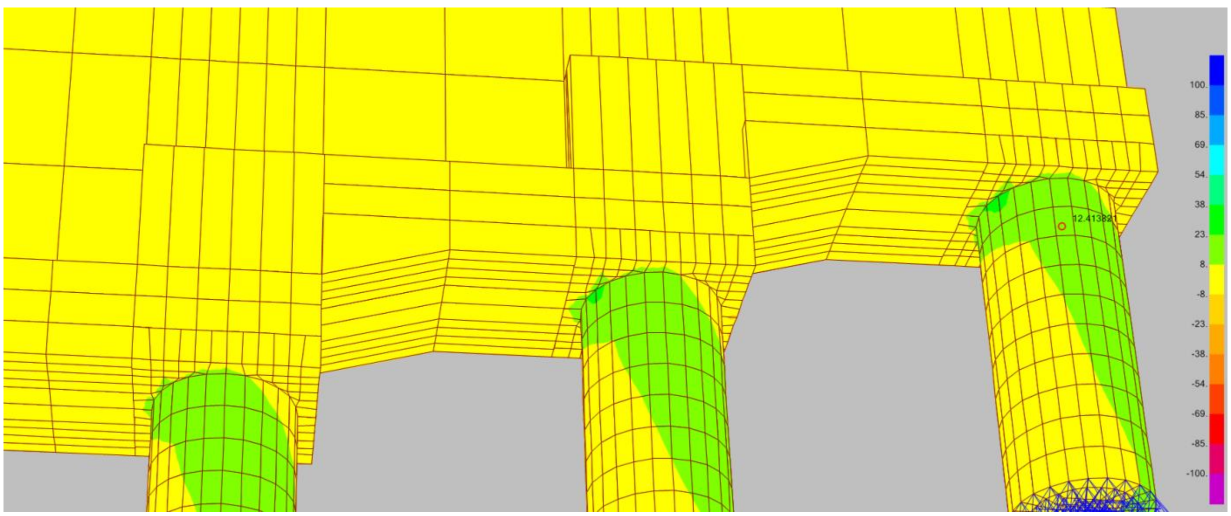

Figure 32. TU Vertical Stress (psi) – Abutment wall. (1 psi = 6.89 kPa)

Table 7. Maximum stresses as computed by SAP 2000 FEM.

Forward Abutment		
	Drilled Shaft	**Wall**
Maximum Stress	970 psi (6690 kPa) (compression)	220 psi (1520 kPa) (compression)
Location	1.5 ft (0.457 m) below bottom of drilled shaft cap front face for Drilled Shaft 27 and 28	1.0 ft (0.305 m) above bottom of drilled shaft cap front face above centerline of Drilled Shafts 27 and 28

Wingwall 3 and 4		
	Drilled Shaft	**Wall**
Maximum Stress	957 psi (6600 kPa) (compression)	392 (2700 kPa) (compression)
Location	1.5 ft (0.457 m) below bottom of drilled shaft cap front face for Drilled Shaft 34 and 37	3.5 ft (1.07 m) above bottom of drilled shaft cap front face above centerline of Drilled Shaft 34 and 37

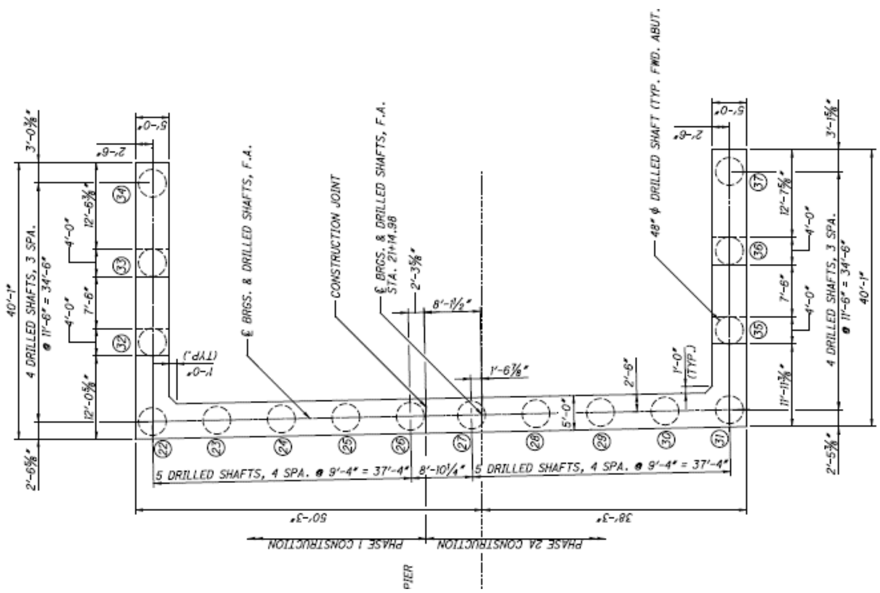

Figure 33. Forward abutment plan.

3.4.2 ABAQUS CAE

ABAQUS CAE 2016 software was also used to model the abutment. Three dimensional transit analysis were performed to evaluate the behavior of the deflection, stain, and stress in the abutments, wingwall, and drilled shafts. Eight-node block elements were used for the FEM mesh with 0.5 feet element size. The drilled shaft was subjected to two boundary conditions. First, the end bearing was assigned a pin connection at the tip of each node of the bottom of the drilled shaft. Second, the surface-soil interaction (rock surrounding the drilled shaft) was modeled as linear springs at the drilled shaft interface side of the solid element nodes. A subgrade modulus “k” value of 1000 pci (271 MN/m^3) was used to calculate each linear spring constant. The following loads were applied on the model, just as for the SAP 2000 FEM:

1. Dead Load-Self weight – activated directly by the program
2. Dead Load from superstructure (DC) – applied as nodal load on the top of the bearing element
3. Live load from the superstructure (LL) – applied as nodal load on the top of the bearing element
4. Temperature load from superstructure (TU) – applied as deflection-controlled nodal displacement on the top of the bearing element
5. Lateral Earth Pressure (EH) – applied as triangular horizontal pressure on the back wall of the solid element
6. Surcharge (LS) – applied as rectangular horizontal pressure on the back wall of the solid element

Figure 34 shows the FEM of the HAM-74-1466 bridge abutment. The boundary conditions are shown below: Figure 35 shows how the soil-surface interface was modeled with linear springs, while Figure 36 shows the pin connections applied to the base of the drilled shafts. The applied loads are shown in Figure 37, and the FEM mesh in Figure 38. Figure 39 through Figure 43 show the computed vertical stresses due to the service load (DC, LL, TU, EH, and LS), which is defined in the same way as for the SAP 2000 FEM.

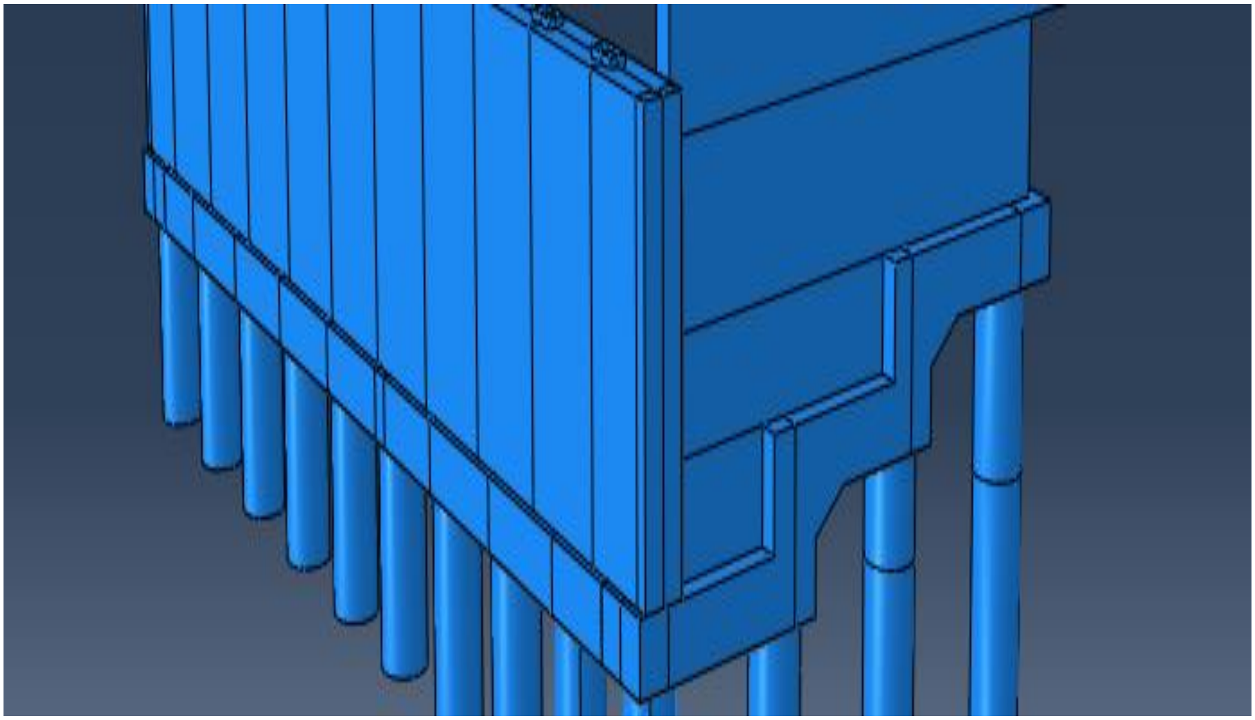

Figure 34. ABAQUS Finite Element Model of HAM-74-1466 bridge abutment.

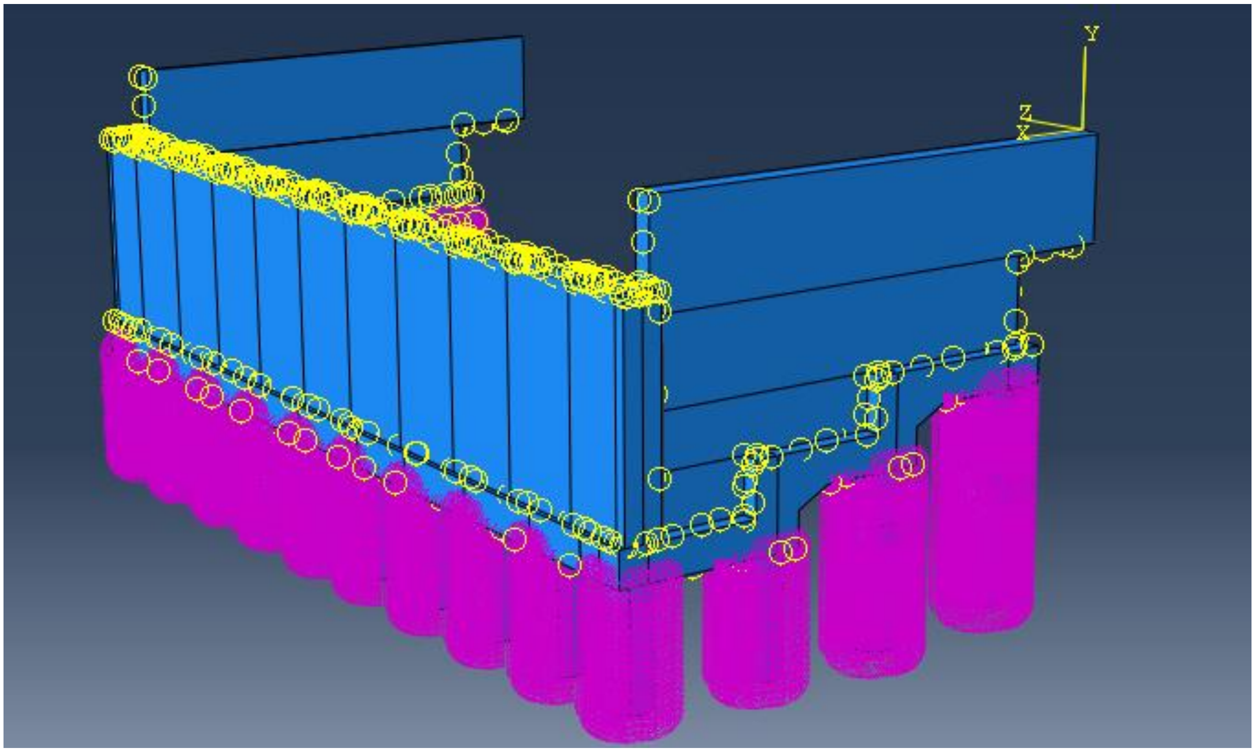

Figure 35. Linear springs (yellow and pink) surrounding the drilled shaft and tie connection between the abutment, wingwall, footing and drilled shafts.

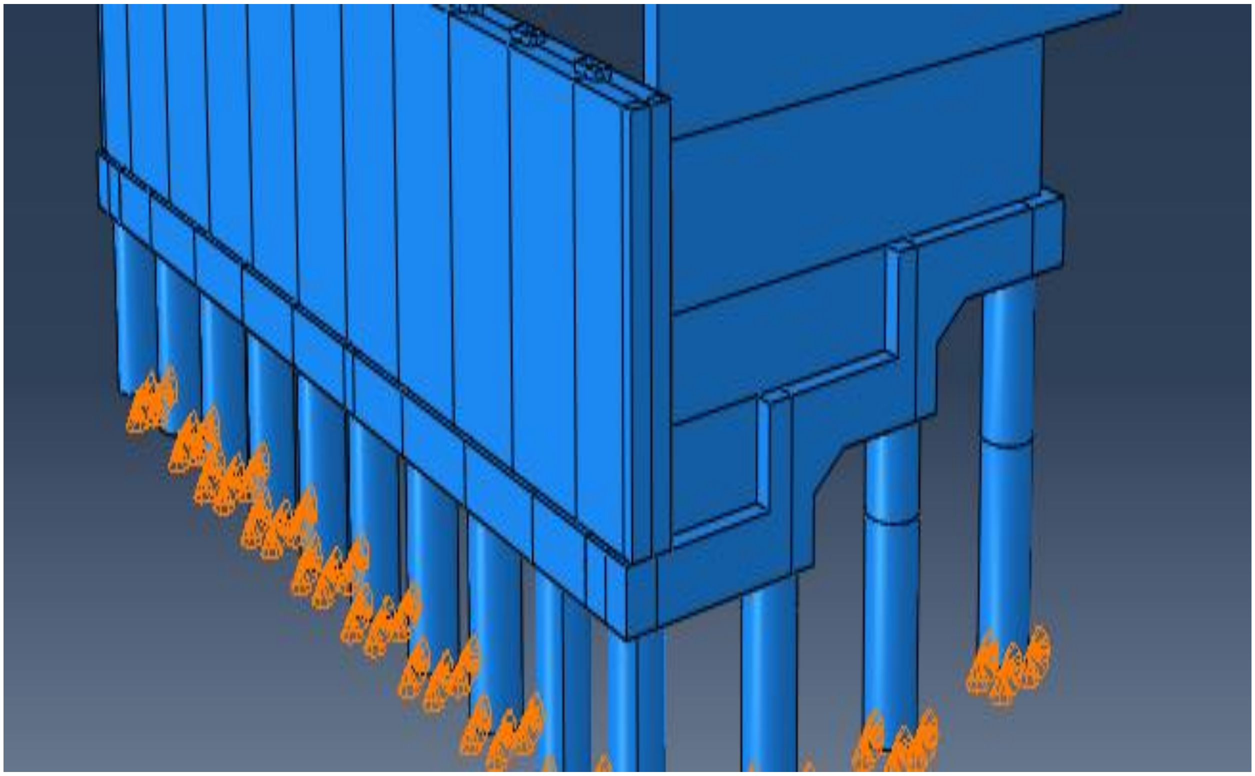

Figure 36. The pin connections (orange) at the bottom of the drilled shafts.

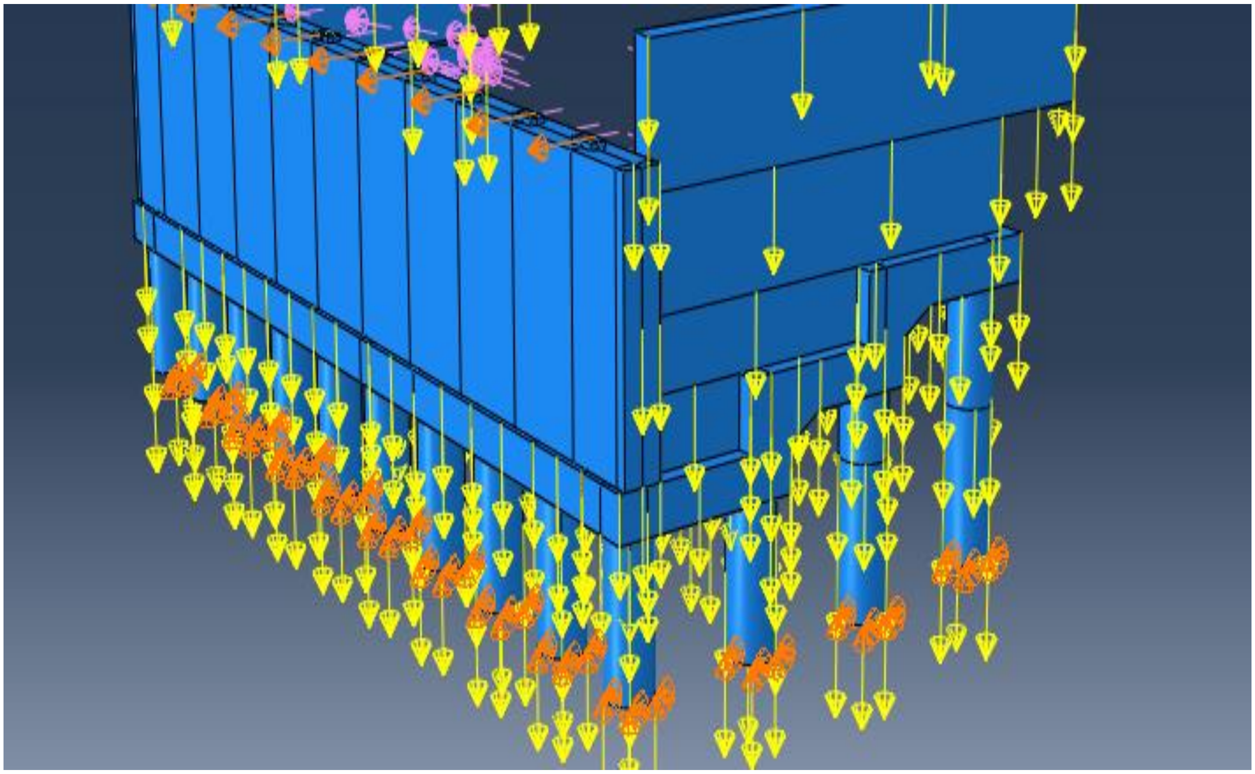

Figure 37. The applied loads on the ABAQUS model.

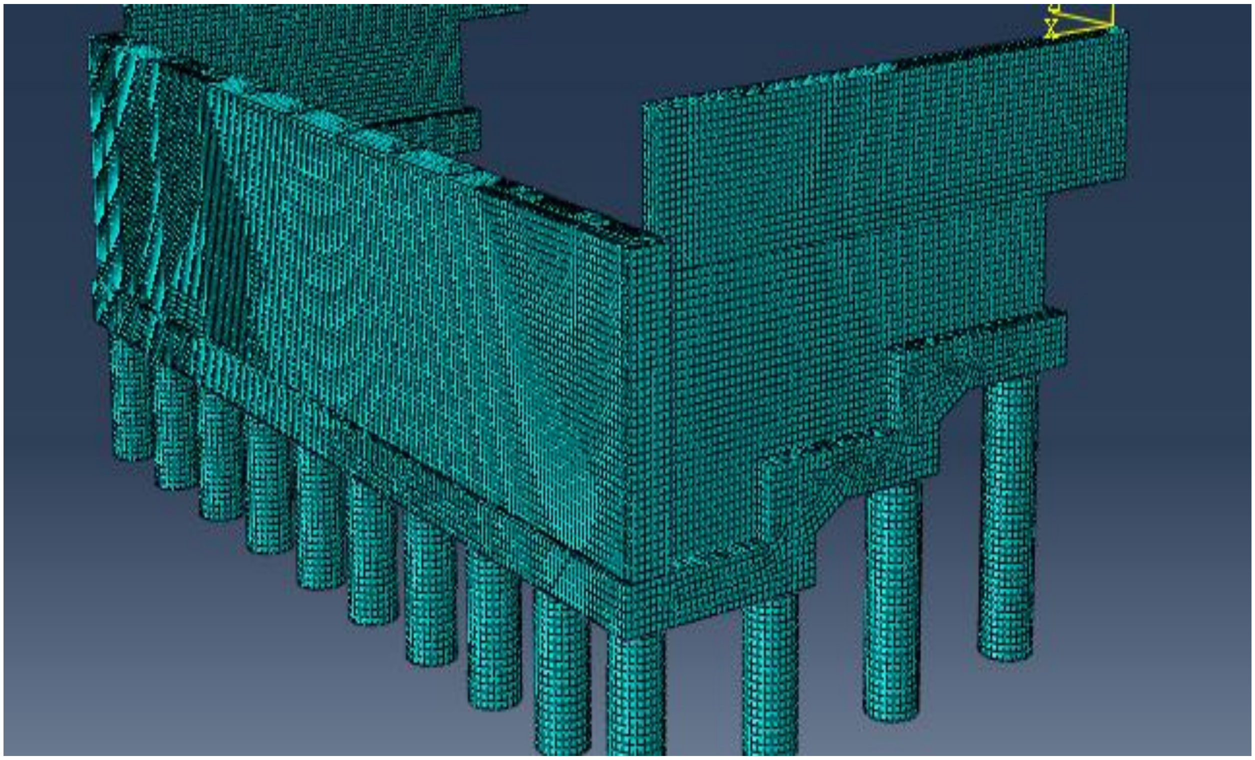

Figure 38. The FEM mesh with 0.5 ft element size.

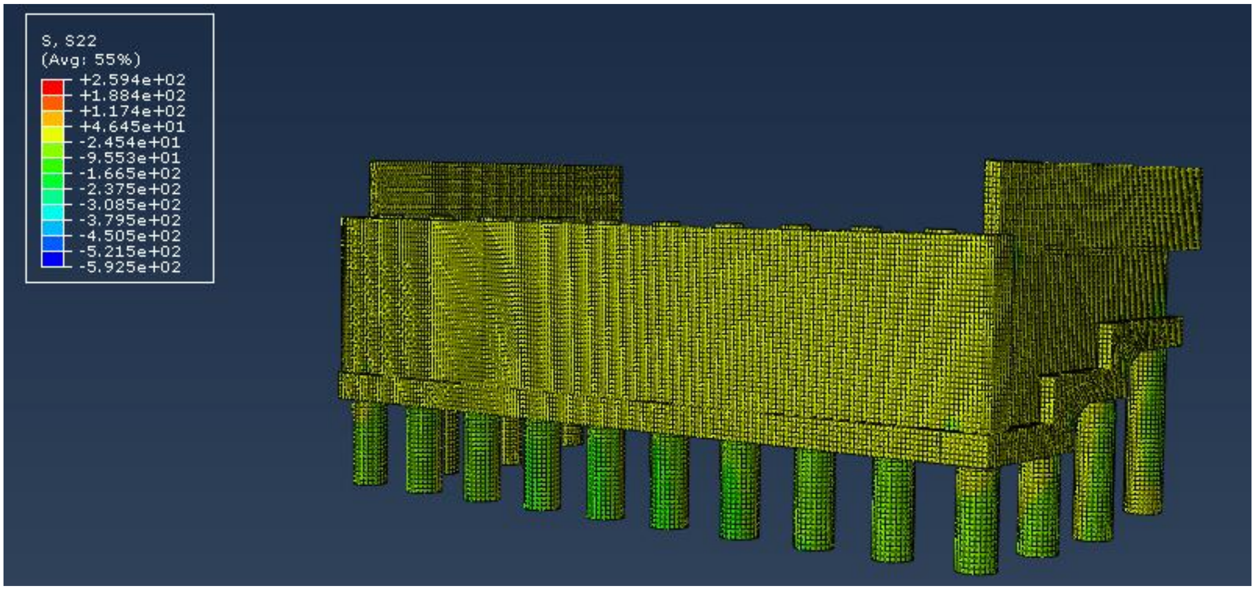

Figure 39. Vertical stress in ksf from service load (DC, LL, TU, EH, and LS) from ABAQUS. (1 ksf = 47.9 kPa)

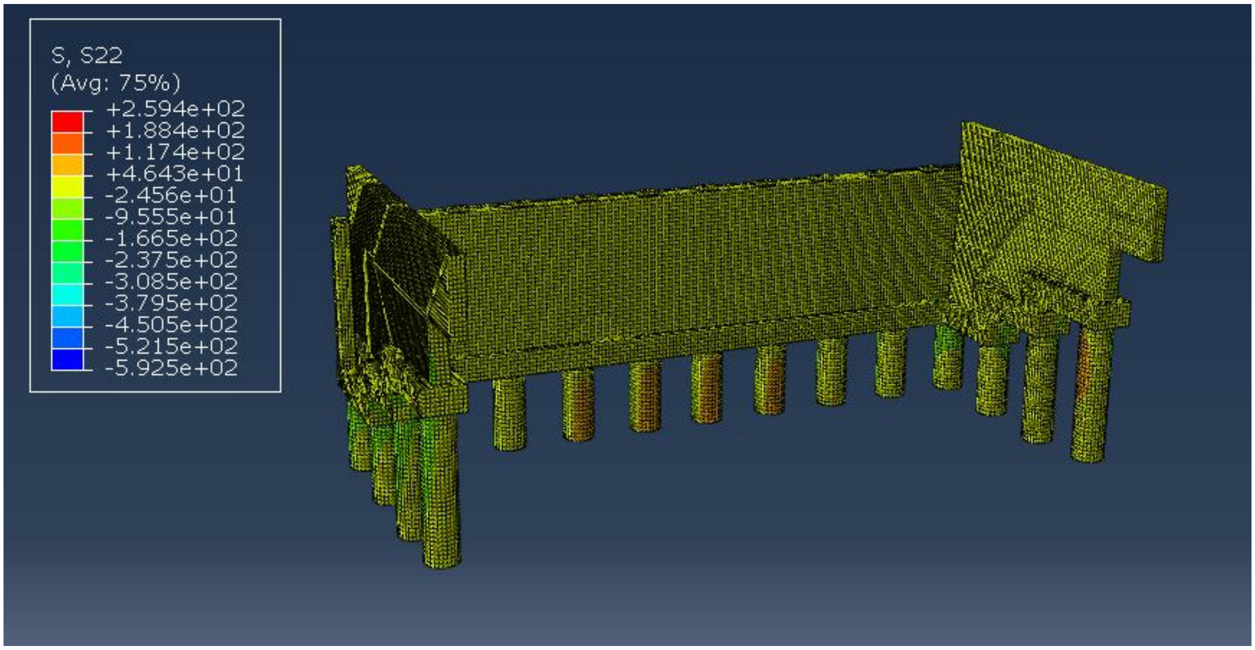

Figure 40. Vertical stress in ksf from service load (DC, LL, TU, EH, and LS) from ABAQUS. (1 ksf = 47.9 kPa)

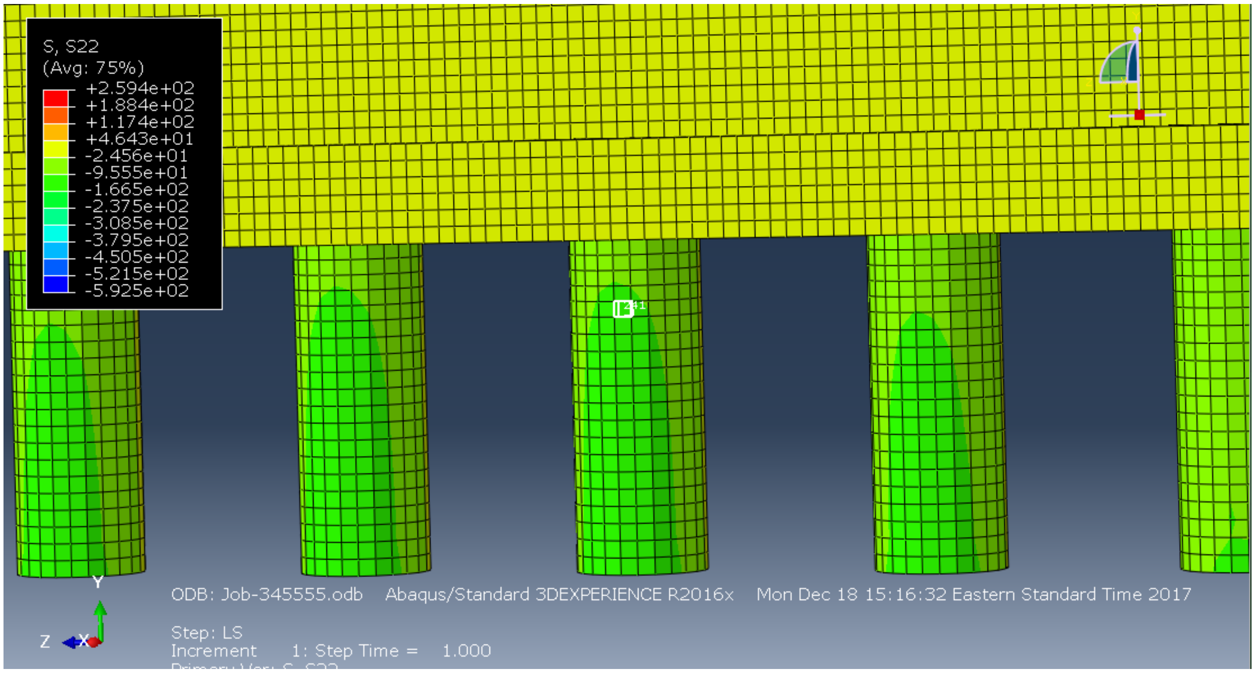

Figure 41. Vertical stress in ksf from service load (DC, LL, TU, EH, and LS) from ABAQUS. (1 ksf = 47.9 kPa)

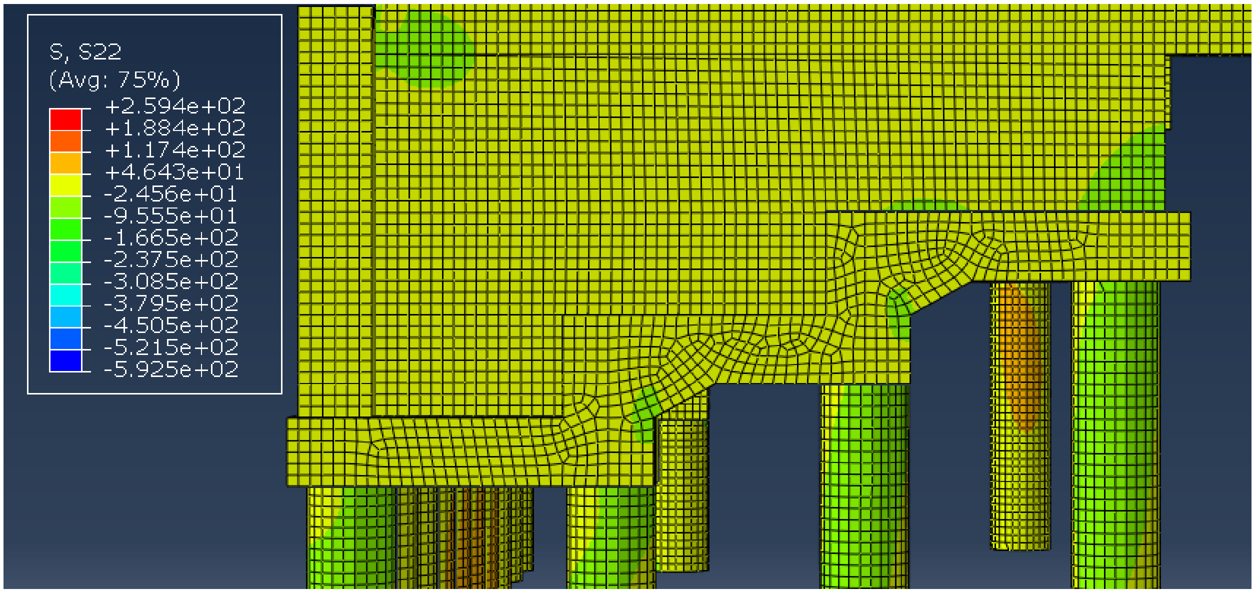

Figure 42. Vertical stress in ksf from service load (DC, LL, TU, EH, and LS) from ABAQUS in the wingwall. (1 ksf = 47.9 kPa)

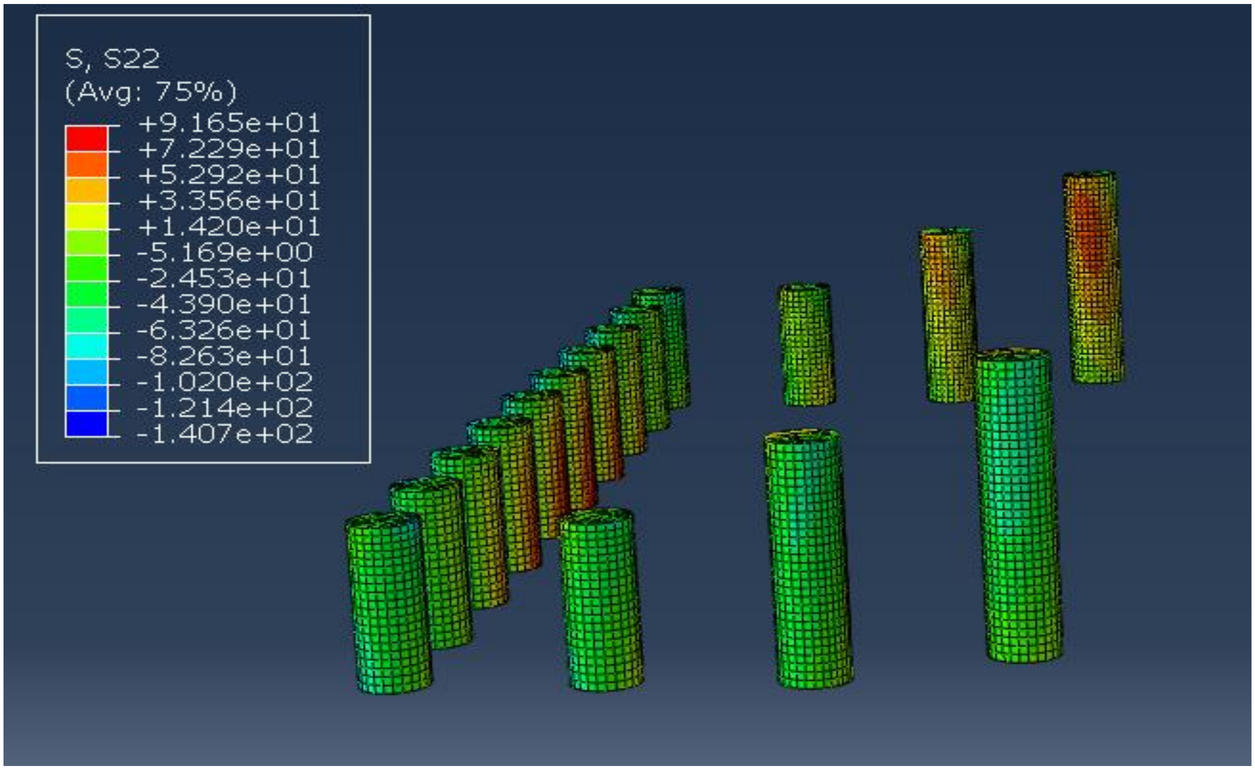

Figure 43. Vertical stress in ksf from service load (DC, LL, TU, EH, and LS) from ABAQUS in the drilled shafts. (1 ksf = 47.9 kPa)

3.5 COMPARISON BETWEEN FEM RESULTS AND EXPERIMENTAL MEASUREMENTS

A comparison of field results (strain measurements and stresses calculated from the strain measurements) with FEM computed stresses from SAP 2000 and ABAQUS is given in the figures and tables below. ABAQUS computed results in ksf (1 kip/ft^2 = 0.0479 MPa), which were converted to psi (1 psi = 6.89 kPa) to facilitate comparison with the other values. The types of loads included in the models are abbreviated as follows:

- DC: Dead Load from superstructure – applied as nodal load on the top of the bearing element
- LL: Live load from the superstructure – applied as nodal load on the top of the bearing element
- TU: Temperature load from superstructure – applied as deflection-controlled nodal displacement on the top of the bearing element
- EH: Lateral Earth Pressure – applied as horizontal pressure proportional to depth on the back wall of the solid element
- LS: Surcharge – applied as constant horizontal pressure on the back wall of the solid element
- Service Load – all of the above loads combined

Figure 44 and Figure 45 show the final vertical stresses calculated from the strain measurements in the field and computed for the service load by the two FEM models for selected gage locations overlaid on the instrumentation plans for the front and rear faces of the wingwall, respectively. Figure 46 and Figure 47 show the same stresses for the strain gages in Drilled Shaft 27 and Drilled Shaft 29, respectively. Table 8 through Table 13 and Figure 48 through Figure 61 below compare the stresses calculated from the strains measured at each strain gage and the corresponding initial and final FEM results for service loads. N/A in the experimental strain column indicates a sensor that did not provide readings. More detailed SAP2000 results are in Appendix E.

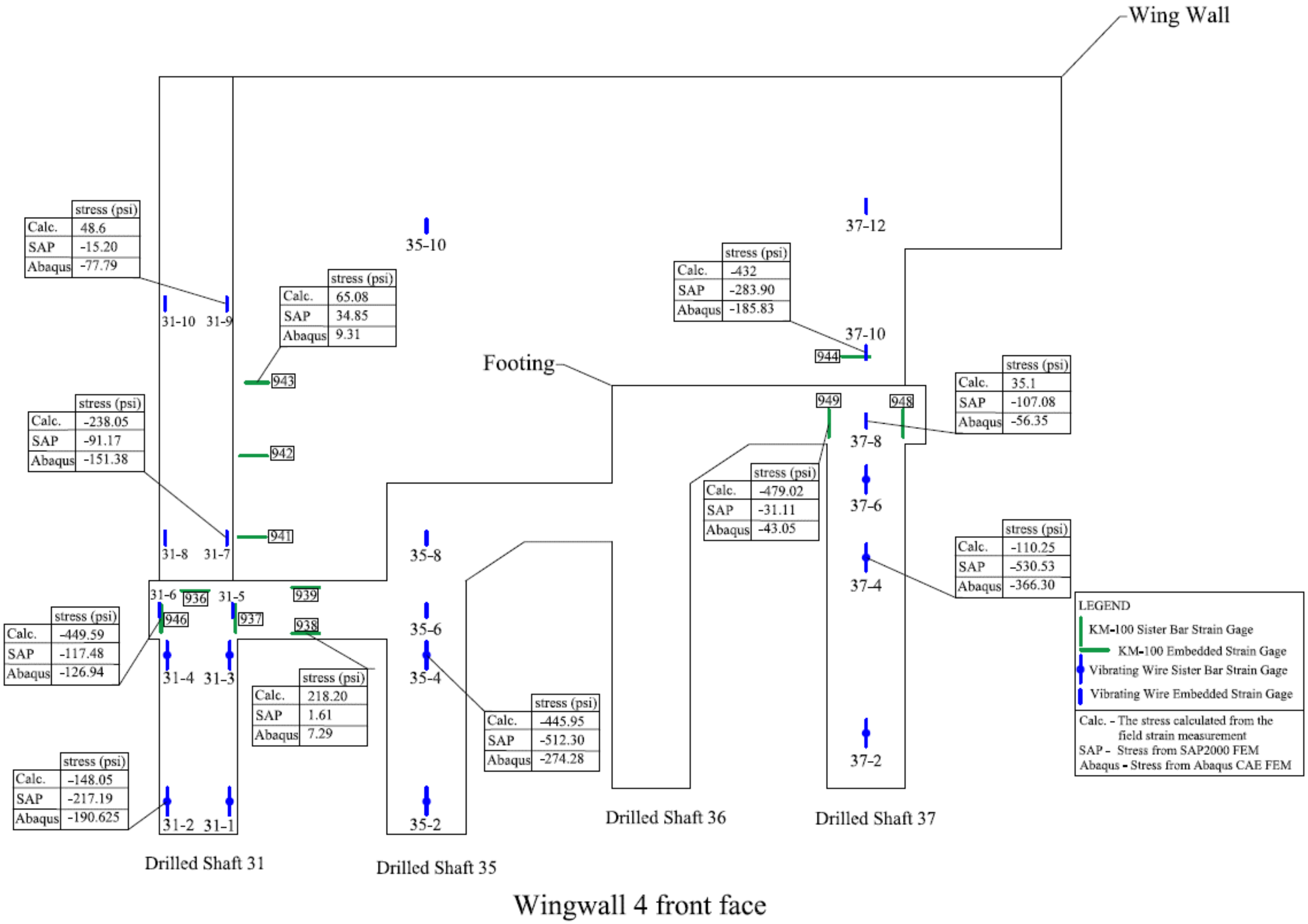

Figure 44. Final vertical stress in psi as calculated from strain gage measurements in the field and computed for service load in SAP and ABAQUS for selected gage locations on the front face of the HAM-74-1466 wingwall. (1 psi =6.89 kPa)

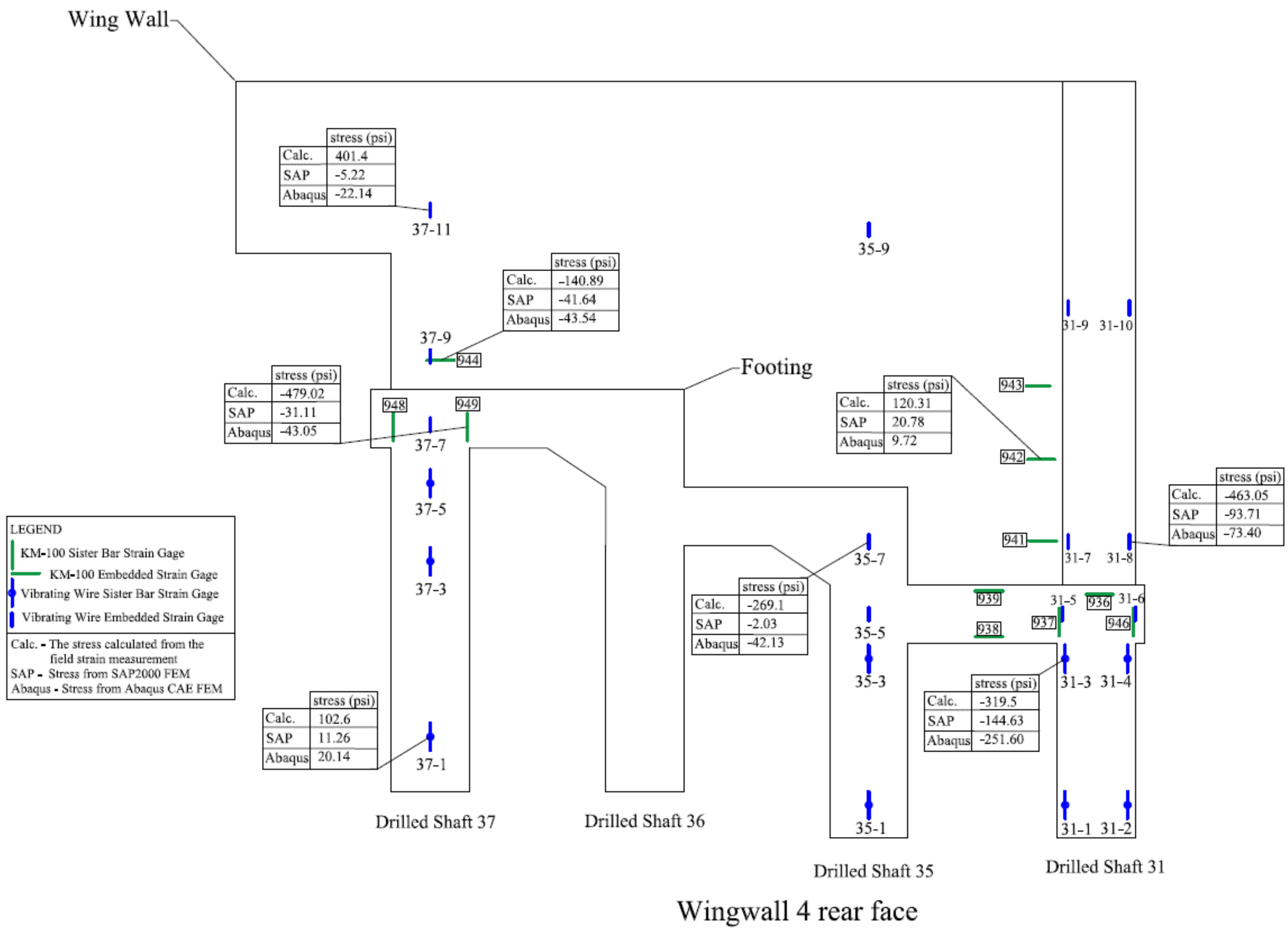

Figure 45. Final vertical stress in psi as calculated from strain gage measurements in the field and computed for service load in SAP and ABAQUS for selected gage locations on the rear face of the HAM-74-1466 wingwall. (1 psi =6.89 kPa)

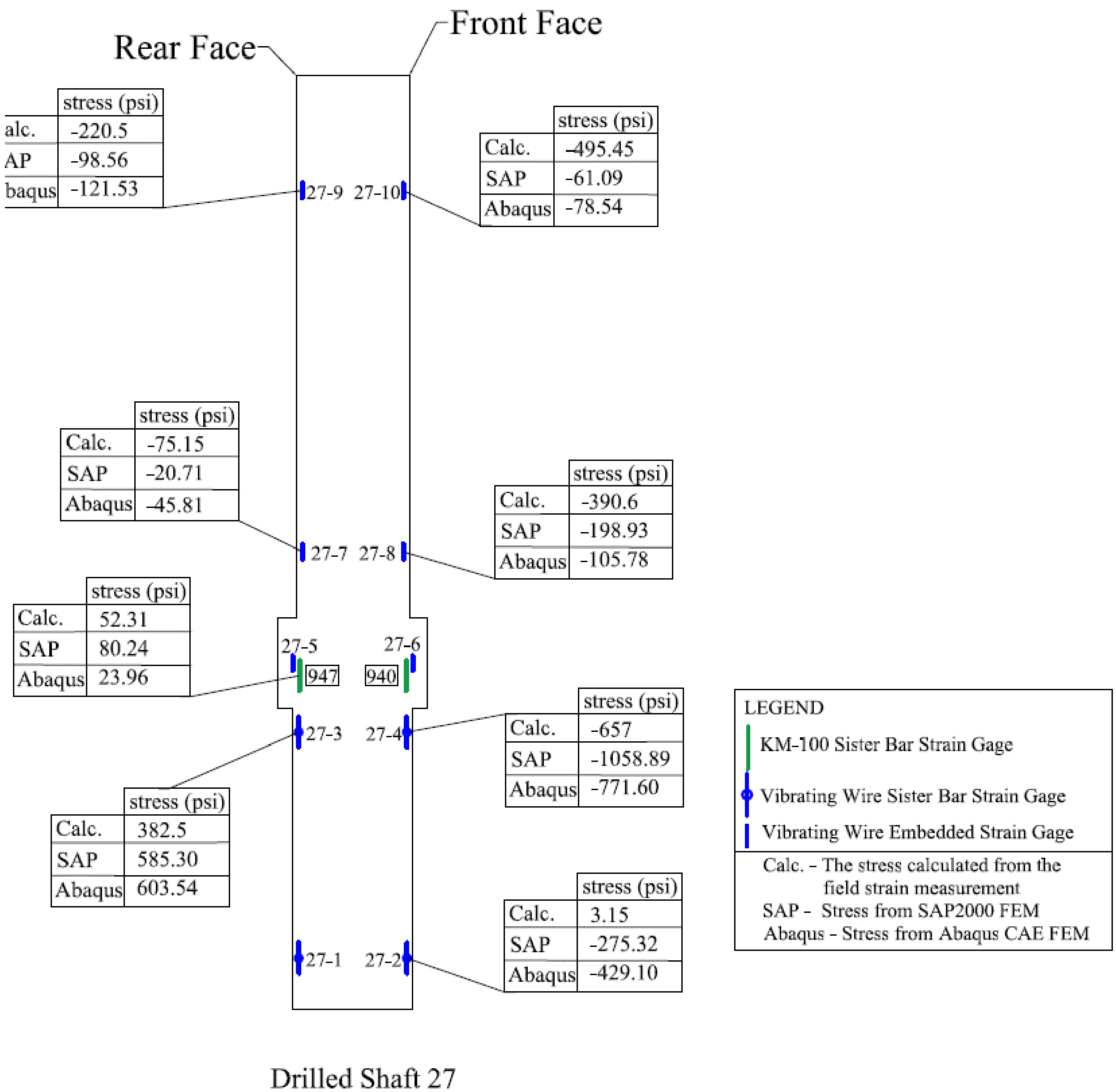

Figure 46. Final vertical stress in psi as calculated from strain gage measurements in the field and computed for service load in SAP and ABAQUS for selected gage locations in Drilled Shaft 27 of HAM-74-1466. (1 psi =6.89 kPa)

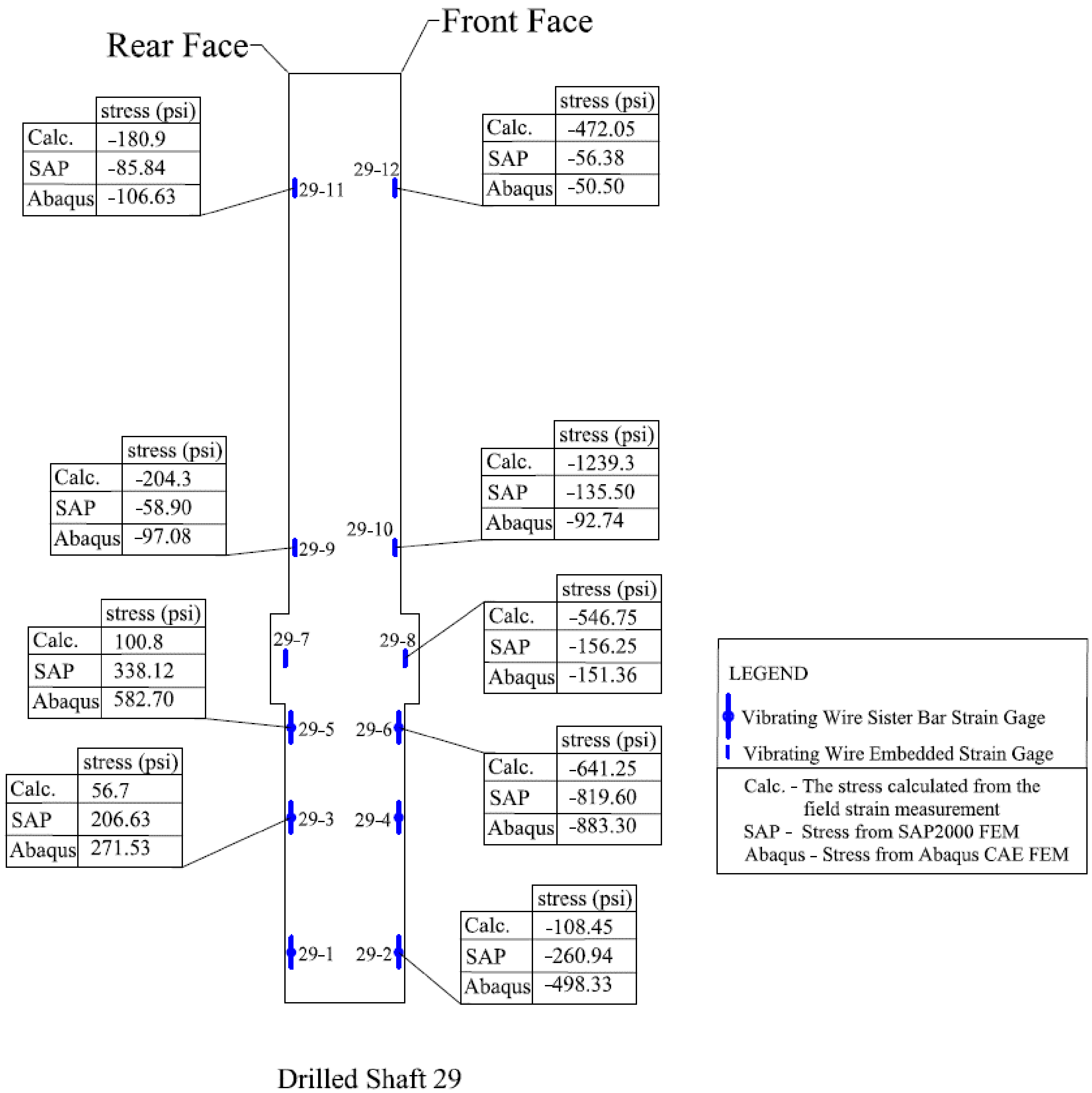

Figure 47. Final vertical stress in psi as calculated from strain gage measurements in the field and computed for service load in SAP and ABAQUS for selected gage locations in Drilled Shaft 29 of HAM-74-1466. (1 psi =6.89 kPa)

Table 8. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for Drilled Shaft 27.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
27-1	10.5	47.3	325.8	-209.6	-1445.1	-184.6	-1273.0	341.6	2355.2
27-2	0.7	3.2	21.7	-277.0	-1909.6	-275.3	-1898.3	-429.1	-2958.5
27-3	85.0	382.5	2637.2	597.0	4116.2	585.3	4035.5	603.5	4161.3
27-4	-146.0	-657.0	-4529.9	-1095.4	-7552.2	-1058.9	-7300.8	-771.6	-5320.0
27-5	-35.0	-157.5	-1085.9	53.1	365.8	50.8	350.3	41.6	286.8
27-6	-83.3	-374.9	-2584.5	-172.4	-1188.5	-176.0	-1213.3	-214.7	-1480.0
27-7	-16.7	-75.2	-518.1	-30.6	-210.6	-20.7	-142.8	-45.8	-315.8
27-8	-86.8	-390.6	-2693.1	-199.8	-1377.8	-198.9	-1371.6	-105.8	-729.3
27-9	-49.0	-220.5	-1520.3	-98.0	-675.7	-98.6	-679.5	-121.5	-837.9
27-10	-110.1	-495.5	-3416.0	-63.6	-438.8	-61.1	-421.2	-78.5	-541.5
947	11.624	52.308	360.7	94.5	651.7	80.2	553.2	24.0	165.2
940	78.744	354.35	2443.1	-93.4	-643.7	-96.2	-663.1	-165.0	-1137.6

Table 9. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for Drilled Shaft 29.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
29-1	-13.3	-59.9	-412.7	-179.3	-1236.5	-196.4	-1354.3	-56.1	-386.8
29-2	-24.1	-108.5	-747.7	-279.0	-1923.9	-260.9	-1799.1	-498.3	-3435.9
29-3	12.6	56.7	390.9	295.9	2040.0	206.6	1424.7	271.5	1872.1
29-4	-104.7	-471.2	-3248.5	-634.7	-4375.8	-630.9	-4349.6	-529.4	-3649.9
29-5	22.4	100.8	695.0	302.8	2088.0	338.1	2331.3	582.7	4017.6
29-6	-142.5	-641.3	-4421.3	-815.8	-5624.6	-819.6	-5650.9	-883.3	-6090.1
29-7	-52.9	-238.1	-1641.3	20.7	143.0	20.3	140.1	21.0	144.9
29-8	-121.5	-546.8	-3769.7	-137.4	-947.1	-156.3	-1077.3	-151.4	-1043.6
29-9	-45.4	-204.3	-1408.6	-59.5	-410.5	-58.9	-406.1	-97.1	-669.3
29-10	-275.4	-1239.3	-8544.7	-54.7	-377.0	-135.5	-934.2	-92.7	-639.4
29-11	-40.2	-180.9	-1247.3	-85.9	-592.1	-85.8	-591.8	-106.6	-735.2
29-12	-104.9	-472.1	-3254.7	-59.9	-412.9	-56.4	-388.7	-50.5	-348.2

Table 10. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for Drilled Shaft 31.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
31-1	-10.5	-47.3	-325.8	-240.2	-1656.4	-239.3	-1649.6	-284.0	-1958.3
31-2	-32.9	-148.1	-1020.8	-219.0	-1509.7	-217.2	-1497.5	-190.6	-1314.3
31-3	-71.0	-319.5	-2202.9	-104.4	-719.8	-144.6	-997.2	-251.6	-1734.7
31-4	-34.0	-153.0	-1054.9	-289.9	-1998.4	-305.8	-2108.5	-323.4	-2229.6
31-5	68.6	308.7	2128.4	-28.7	-197.9	-38.3	-263.9	-35.6	-245.6
31-6	-90.1	-405.5	-2795.5	-102.9	-709.3	-108.7	-749.3	-201.5	-1389.3
31-7	-52.9	-238.1	-1641.3	-91.0	-627.6	-91.2	-628.6	-151.4	-1043.7
31-8	-102.9	-463.1	-3192.6	-91.8	-633.1	-93.7	-646.1	-73.4	-506.1
31-9	10.8	48.6	335.1	-72.5	-500.1	-15.2	-104.8	-77.8	-536.3
31-10	61.7	277.7	1914.3	-70.8	-488.4	-67.4	-464.6	-52.6	-362.9
946	-99.909	-449.59	-3099.8	-100.3	-691.8	-117.5	-810.0	-126.9	-875.2
937	216.55	974.48	6718.8	-32.2	-222.0	-40.8	-281.6	-35.1	-242.3
936	8.239	37.077	255.6	8.0	55.4	7.9	54.5	24.3	167.5

Table 11. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for Drilled Shaft 35.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
35-1	N/A	-	-	-113.2	-780.6	-111.4	-768.0	-154.4	-1064.6
35-2	N/A	-	-	-124.5	-858.1	-119.9	-826.7	-180.2	-1242.5
35-3	N/A	-	-	244.0	1682.0	237.2	1635.6	209.7	1445.5
35-4	-99.10	-446.0	-3074.7	-505.5	-3485.0	-512.3	-3532.2	-274.3	-1891.1
35-5	N/A	-	-	84.2	580.7	95.0	655.1	79.1	545.3
35-6	-70.6	-317.7	-2190.5	-175.3	-1208.6	-187.0	-1289.5	-161.5	-1113.2
35-7	-59.8	-269.1	-1855.4	-2.6	-18.1	-2.0	-14.0	-42.1	-290.5
35-8	-48.0	-216.0	-1489.3	-74.9	-516.7	-79.0	-544.8	-62.8	-432.8
35-9	N/A	-	-	-11.2	-77.5	-9.6	-66.1	-7.6	-52.4
35-10	-49.0	-220.5	-1520.3	-16.5	-113.9	-14.2	-97.8	-43.0	-296.1

Table 12. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for Drilled Shaft 37.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
37-1	22.8	102.6	707.4	29.2	201.1	11.3	77.6	20.1	138.9
37-2	8.8	39.6	273.0	-30.2	-208.1	-35.0	-241.4	-44.3	-305.5
37-3	N/A	-	-	577.7	3983.3	580.6	4003.3	-402.2	-2772.9
37-4	-24.5	-110.3	-760.1	-571.5	-3940.2	-530.5	-3657.9	-366.3	-2525.5
37-5	N/A	-	-	799.2	5510.2	795.3	5483.7	425.6	2934.3
37-6	-47.7	-214.7	-1480.0	-786.0	-5419.6	-755.1	-5206.4	-511.0	-3523.5
37-7	-148.0	-666.0	-4591.9	83.8	578.1	88.9	612.7	45.6	314.4
37-8	7.8	35.1	242.0	-105.2	-725.2	-107.1	-738.3	-56.4	-388.5
37-9	-65.6	-295.2	-2035.3	282.2	1945.7	285.2	1966.4	169.0	1164.9
37-10	-96.0	-432.0	-2978.5	-281.0	-1937.3	-283.9	-1957.4	-185.8	-1281.3
37-11	89.2	401.4	2767.6	-12.4	-85.4	-5.2	-36.0	-22.1	-152.6
37-12	39.2	176.4	1216.2	-18.4	-126.7	-24.6	-169.7	-61.4	-423.5
949	-106.449	-479.02	-3302.7	-30.8	-212.5	-31.1	-214.5	-43.1	-296.8
948	40.447	182.01	1254.9	-14.1	-97.2	-29.5	-203.3	-35.8	-247.0
944	-31.309	-140.89	-971.4	-50.2	-346.3	-41.6	-287.1	-43.5	-300.2

Table 13. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for additional numbered KM-100 gages in wingwall and cap between Drilled Shafts 31 and 35.

Strain gage	Measured strain	Calculated stress		SAP 2000 initial stress		SAP 2000 final stress		ABAQUS final stress	
	(με)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
938	48.489	218.20	1504.4	-2.37	-16.34	-1.61	-11.10	7.29	50.26
939	118.276	532.24	3669.7	-0.64	-4.41	-0.58	-4.00	3.65	25.13
941	-24.864	-111.89	-771.4	38.57	265.93	52.60	362.66	44.18	304.61
942	26.736	120.31	829.5	16.16	111.42	20.78	143.27	9.72	67.02
943	14.462	65.08	448.7	31.14	214.70	34.85	240.28	9.31	64.16

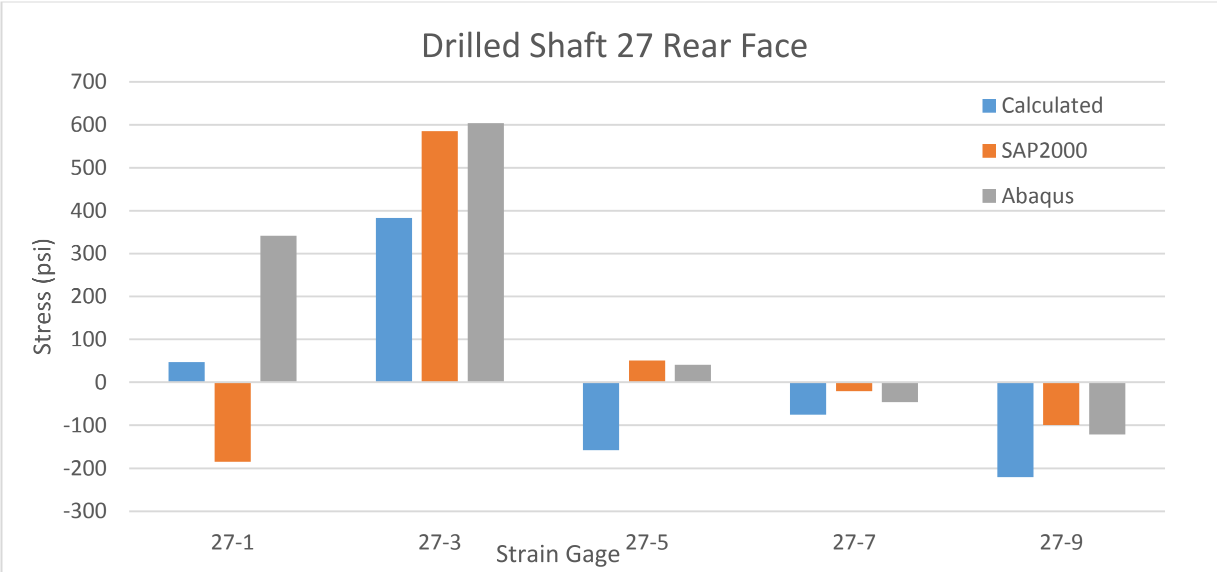

Figure 48. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for rear face of Drilled Shaft 27. (1 psi = 6.89 kPa)

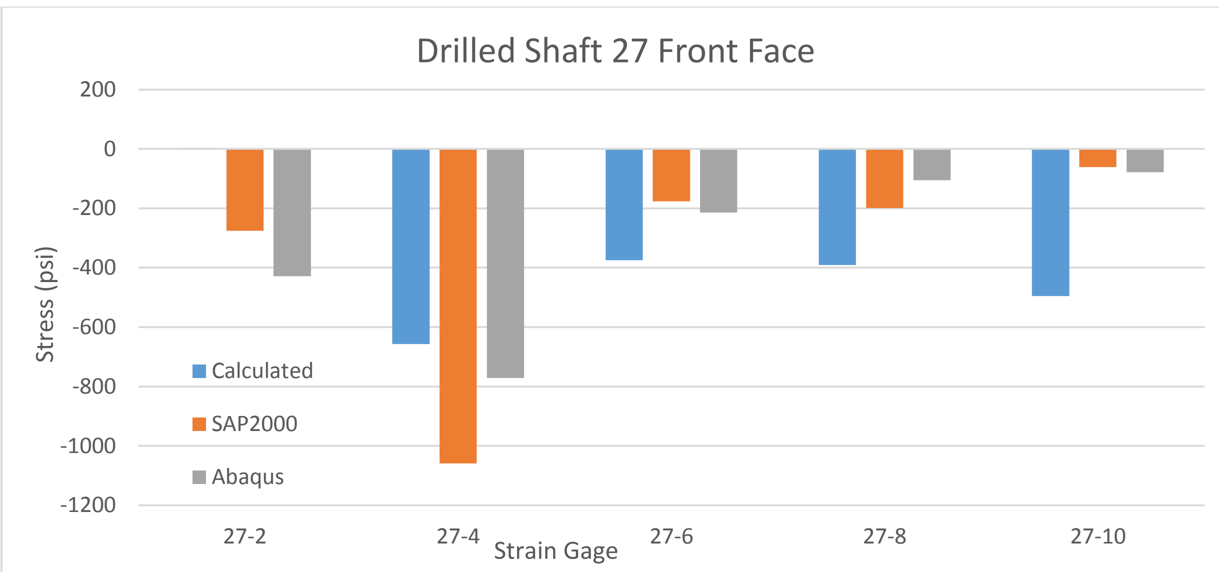

Figure 49. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for front face of Drilled Shaft 27. (1 psi = 6.89 kPa)

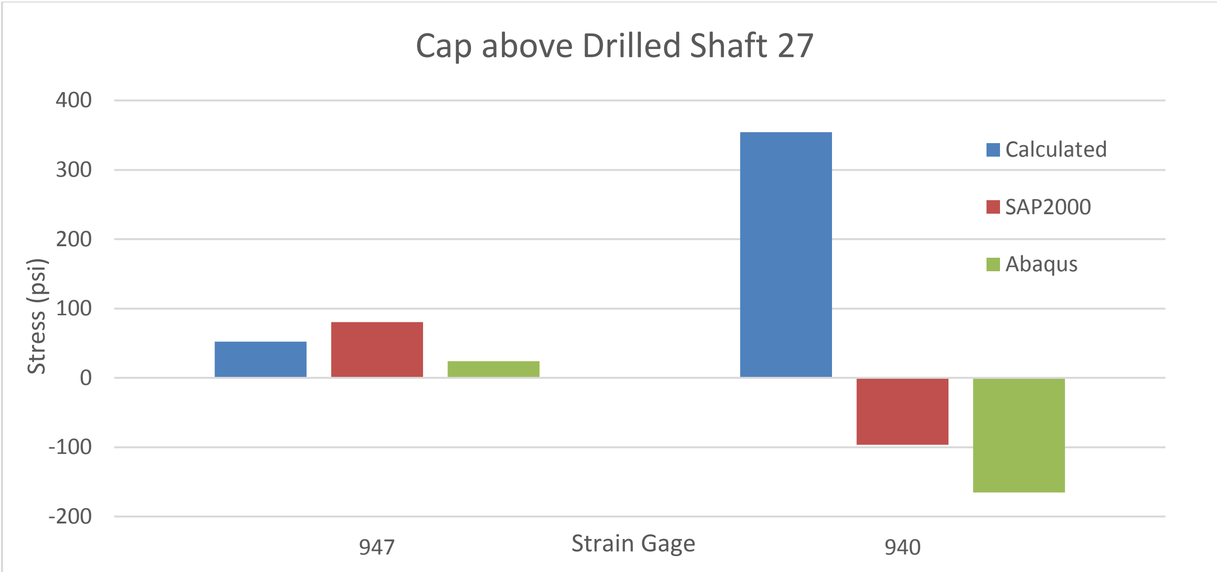

Figure 50. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for cap above Drilled Shaft 27. (1 psi = 6.89 kPa)

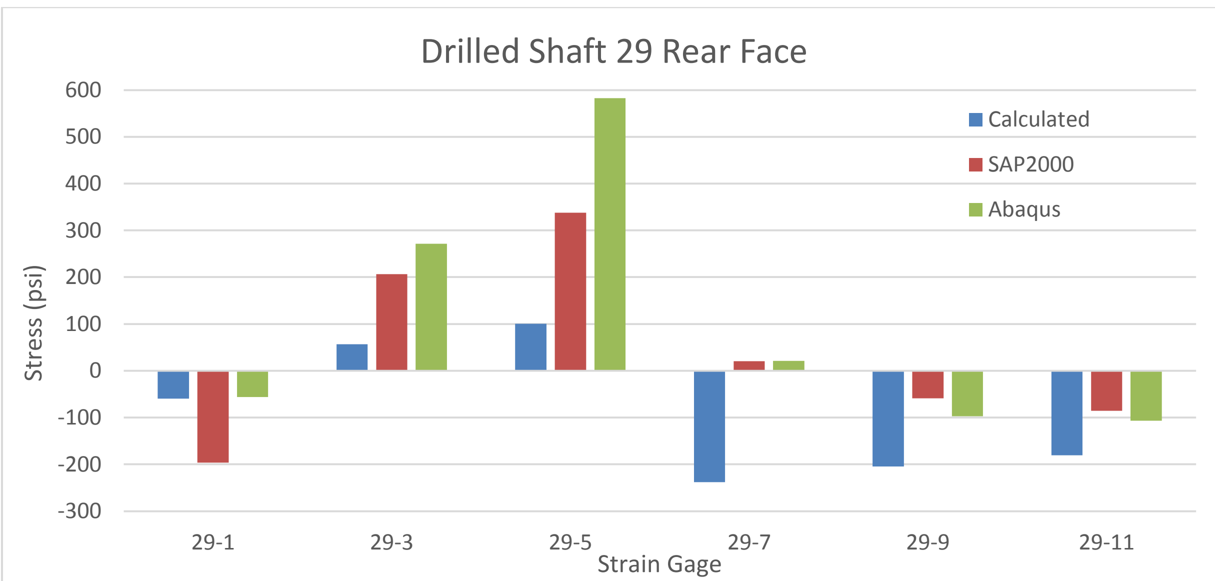

Figure 51. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for rear face of Drilled Shaft 29. (1 psi = 6.89 kPa)

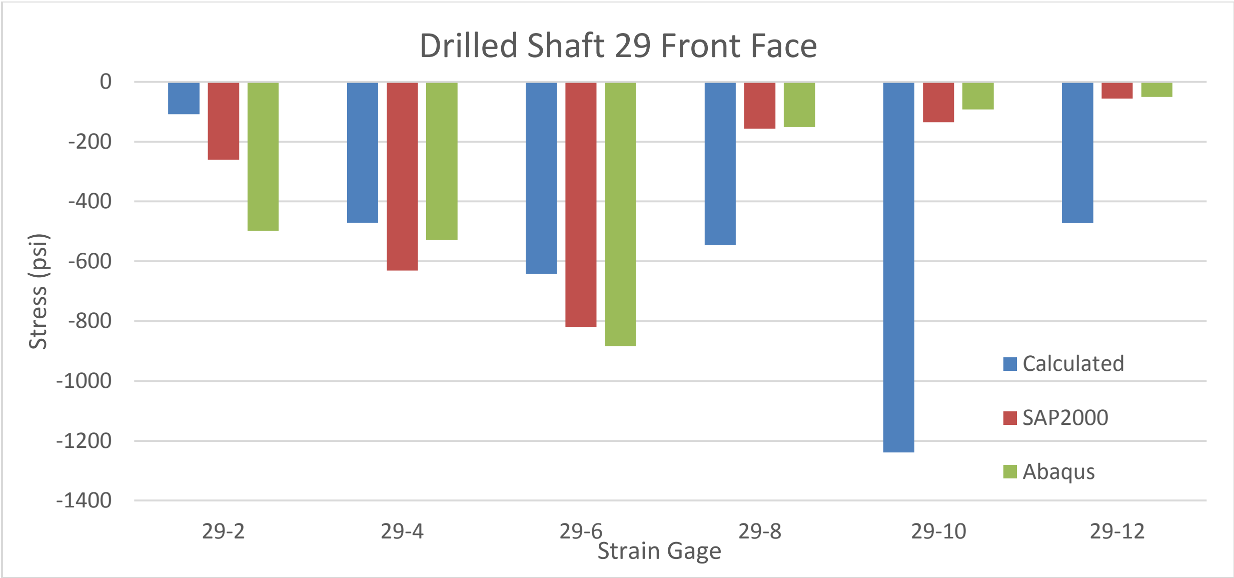

Figure 52. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for front face of Drilled Shaft 29. (1 psi = 6.89 kPa)

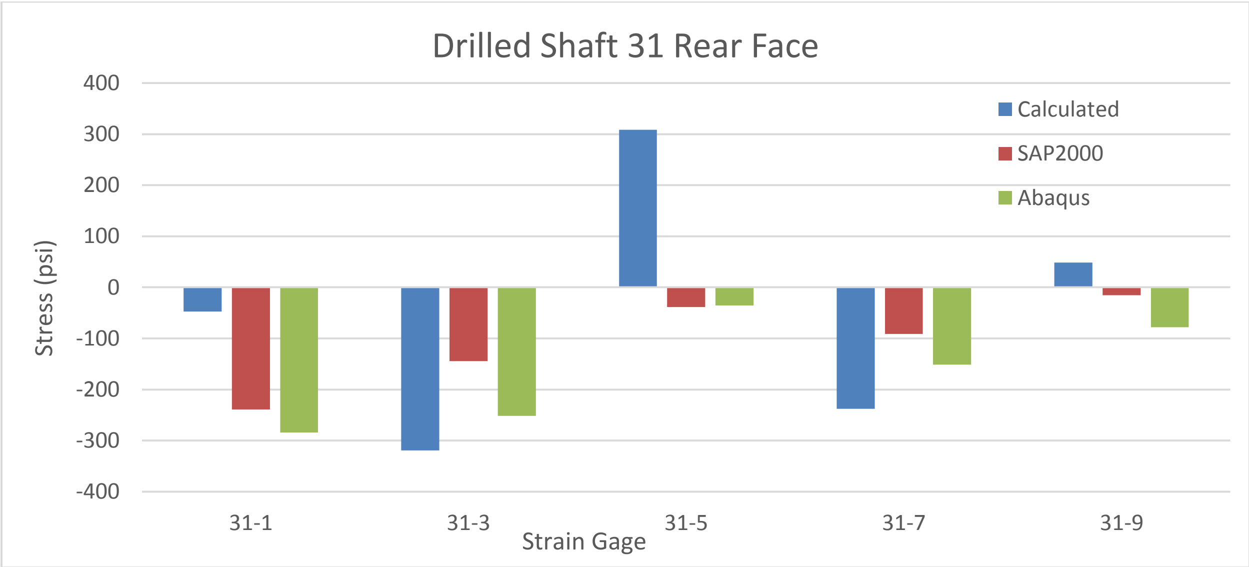

Figure 53. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for rear face of Drilled Shaft 31. (1 psi = 6.89 kPa)

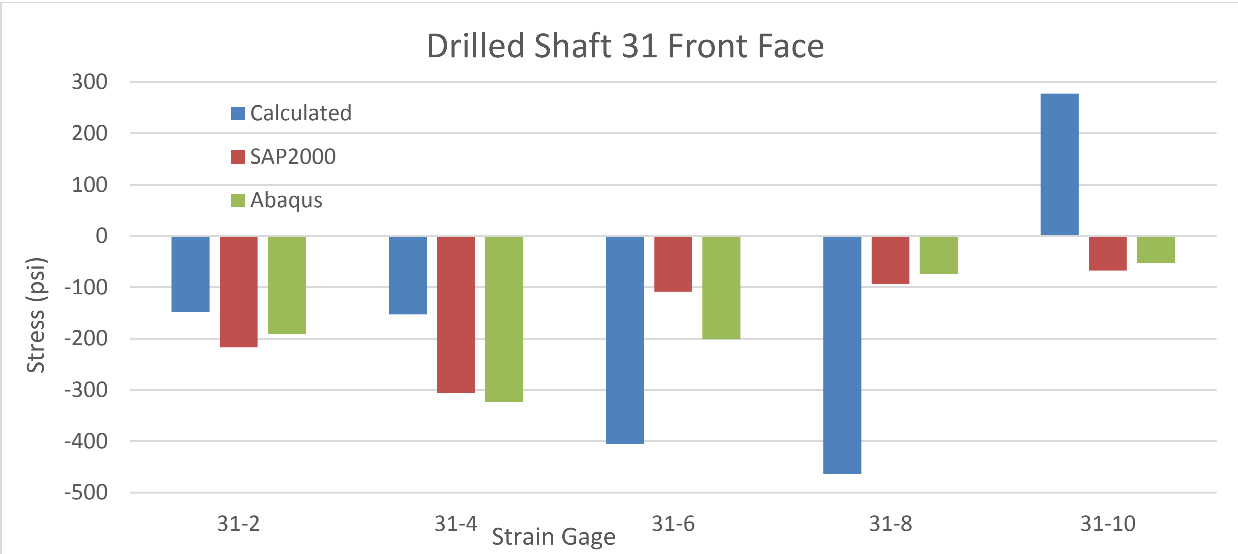

Figure 54. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for front face of Drilled Shaft 31. (1 psi = 6.89 kPa)

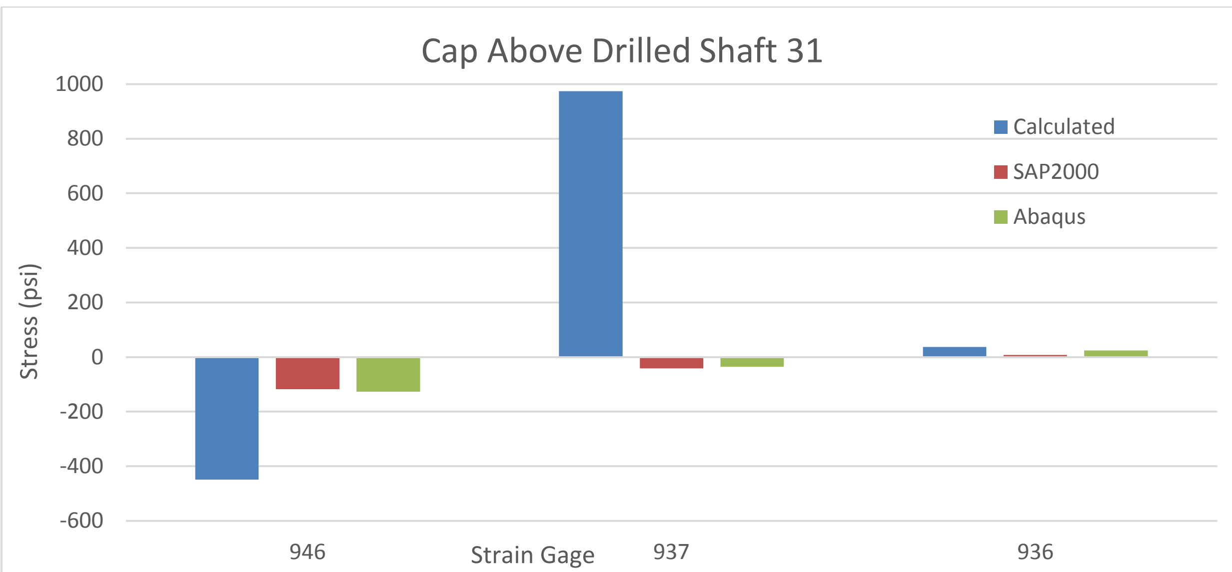

Figure 55. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for cap above Drilled Shaft 31. (1 psi = 6.89 kPa)

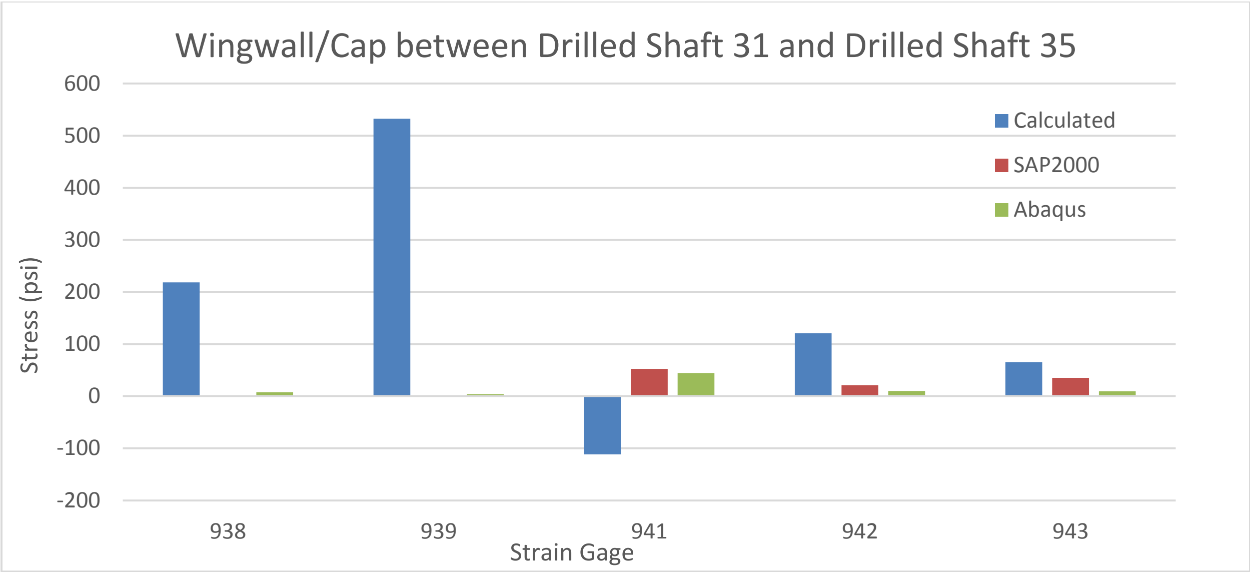

Figure 56. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for wingwall and cap between Drilled Shaft 31and Drilled Shaft 35. (1 psi = 6.89 kPa)

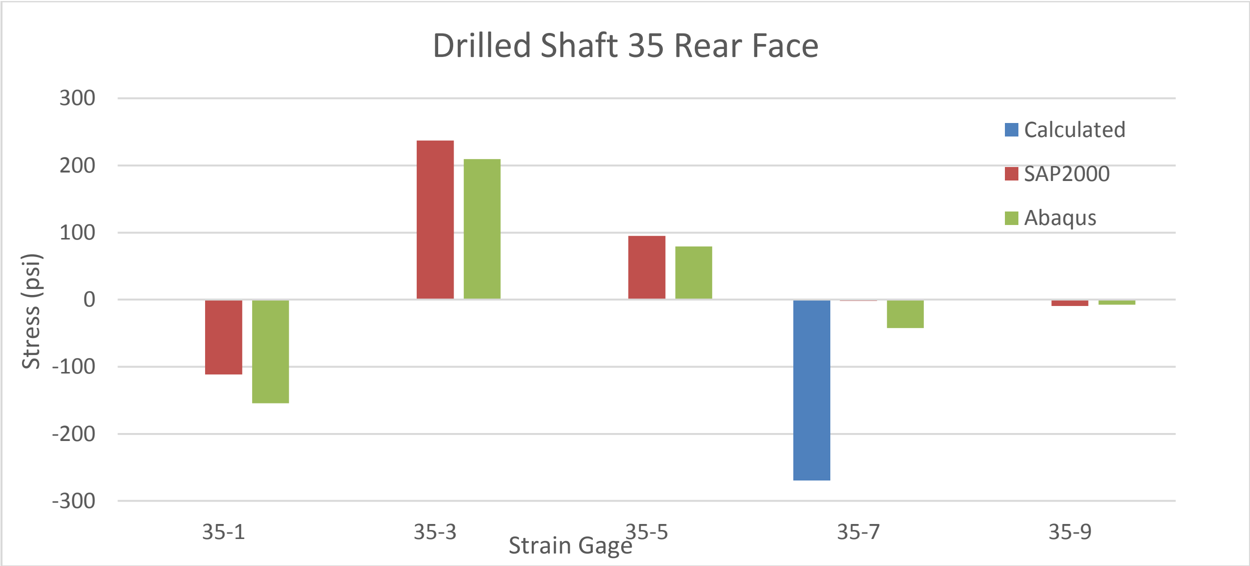

Figure 57. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for rear face of Drilled Shaft 35. (1 psi = 6.89 kPa)

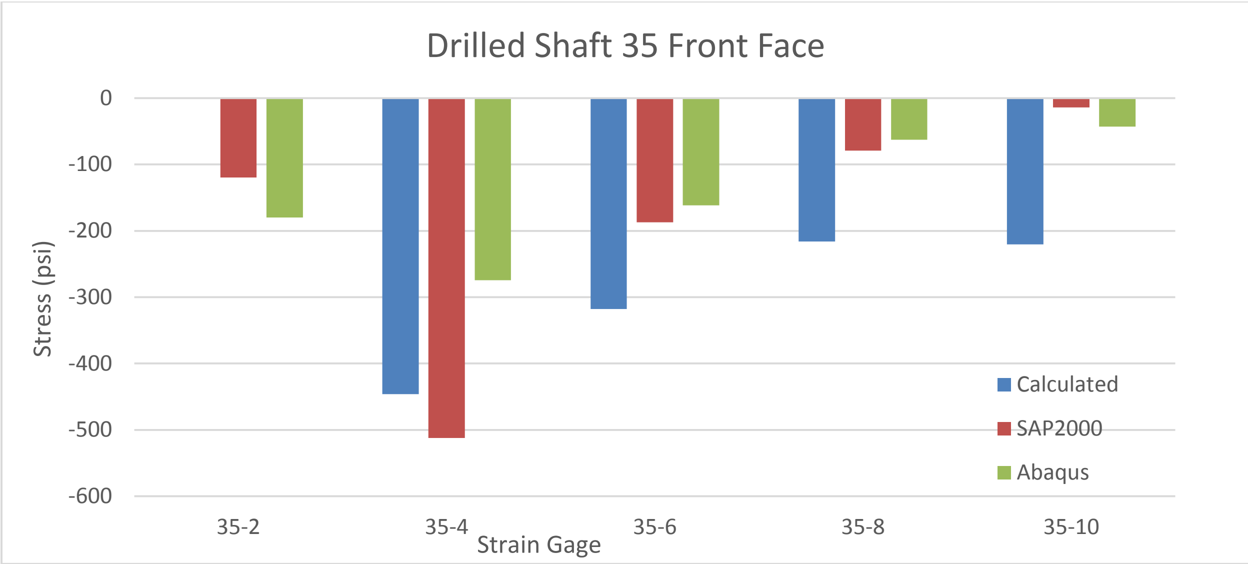

Figure 58. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for front face of Drilled Shaft 35. (1 psi = 6.89 kPa)

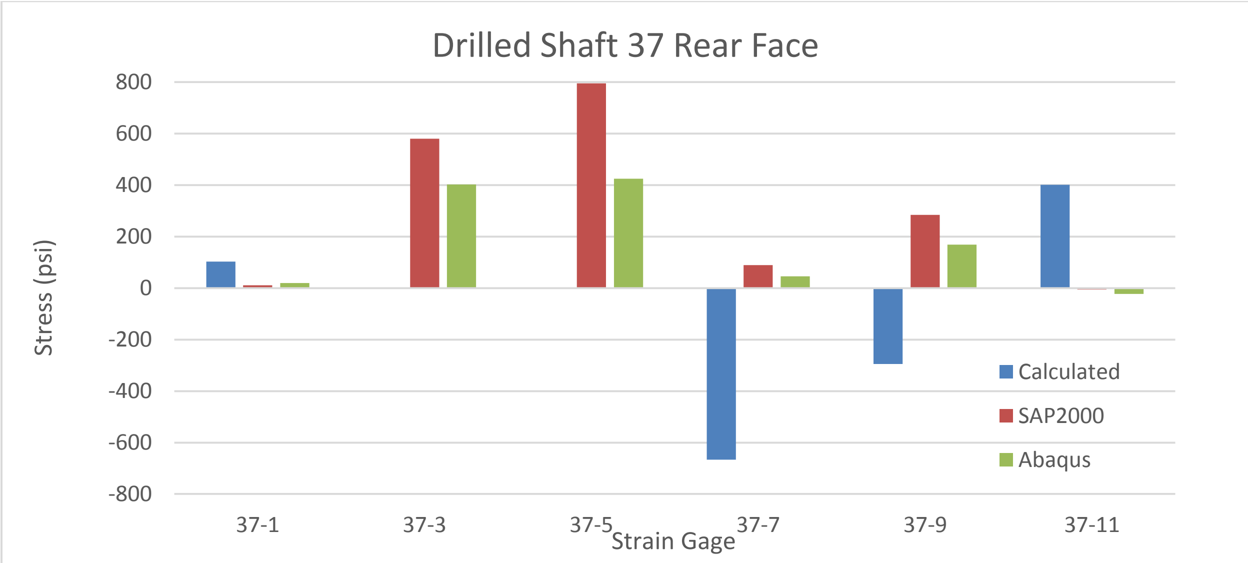

Figure 59. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for rear face of Drilled Shaft 37. (1 psi = 6.89 kPa)

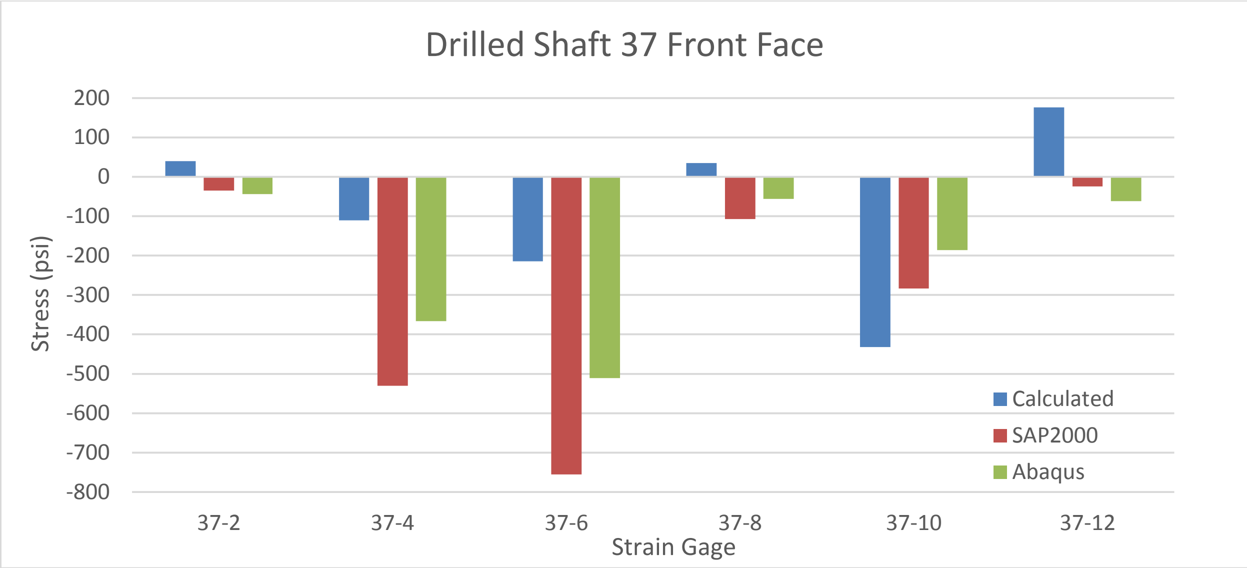

Figure 60. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for front face of Drilled Shaft 37. (1 psi = 6.89 kPa)

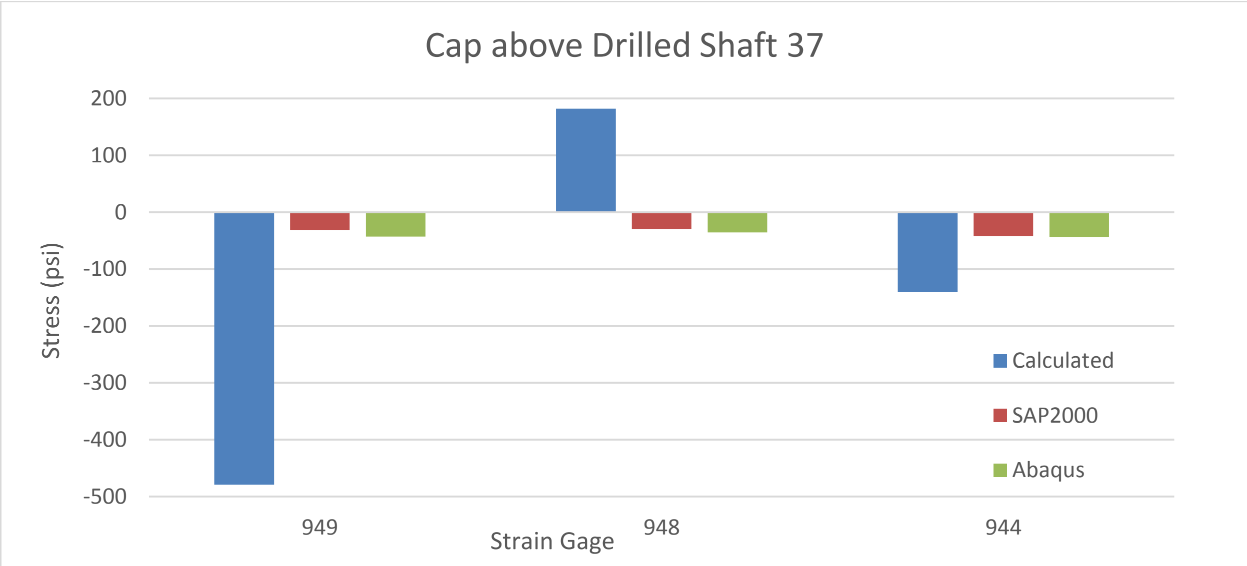

Figure 61. Stresses calculated from field measured strains compared to service load FEM stresses computed using SAP 2000 and ABAQUS for cap above Drilled Shaft 37. (1 psi = 6.89 kPa)

4 RESEARCH FINDINGS AND CONCLUSIONS

- The stresses due to environmental loads (changes in temperature) greatly exceed those from other loads. The measured stresses are still below the AASHTO permissible design values.
- There is not sufficient information to realistically incorporate the impact of temperature into the design process. Specifically lacking is a detailed understanding of how the abutment and wingwalls respond to these loads and also the magnitude of load from the superstructure. The stresses due to these factors may be lower in practice than what is computed in traditional design methods.
- The finite element modeling was conducted with two programs, SAP 2000 and ABAQUS. Both have good potential to verify designs. There are some differences in the results due to the different features and level of control over the models in each program, but both exhibit the same general trends. SAP 2000 and ABAQUS handle boundary conditions differently. There are also differences in the algorithm and interface elements, of which those in ABAQUS appear to be better.
- The bridge structure of an abutment and wingwalls is very complicated. Some kind of three-dimensional modeling is needed to complement an efficient design method.
- Future research is needed to understand how load is transferred from the bridge superstructure to the abutments and foundation elements.
- The HAM-74-1466 bridge is a straight alignment bridge. Skewed abutment bridges will be even more complicated to accurately model, in part because the skew induces asymmetric horizontal loads.
- Soil pressure from the backfill on this type of structure is generally not a problem as it is accounted for in the design. The findings from this study support this fact.
- The measurements of strains in the drilled shafts indicate that the level of stress is below the acceptable level of design stresses. An optimized design with smaller size shafts and no footing would be sufficient.
- The instrumentation results confirm that the shafts under the end of the wingwalls are subjected to uplift tension force (Shaft #37 in this study).
- The maximum stress in the drilled shafts was noticed at the interface between the drilled shafts and the footing at the abutment face and the magnitude of bending stress is less at the corner. The measured stresses are a combination of axial and bending stresses.
- It was noticed from the collected data that the upper portion of the wingwall away from the corner is subjected to tension with tensile stresses in the range of 350 psi (2068 kPa) to 400 psi (2757.9 kPa).

5 RECOMMENDATIONS

- It is necessary to gain a further understanding of the interaction between the superstructure and the substructure of bridges due to environmental factors such as temperature.
- It is recommended to continue the monitoring of the abutment for another year to have a complete cycle of weather change to better understand the effects of the environment on the abutment and to see if any buildup of stress is taking place. The duration of the monitoring was not adequate to fully capture the response.
    - Since all the installed sensors are functioning, ODOT will get a sizeable amount of information on the effects of environmental factors on these kinds of structures if monitoring is continued. It may be worth installing external sensors on the superstructure near the abutment to investigate the changes in horizontal forces on the abutment due to temperature and the interaction between the superstructure and the abutment.
- It is recommended to monitor a U-shape abutment supported on drilled shafts with no footing to understand the difference in behavior due to loading and environmental factors and optimize future designs. This can provide input into updating the design procedures by gaining more knowledge on the behavior of this type of foundation element.

6 REFERENCES

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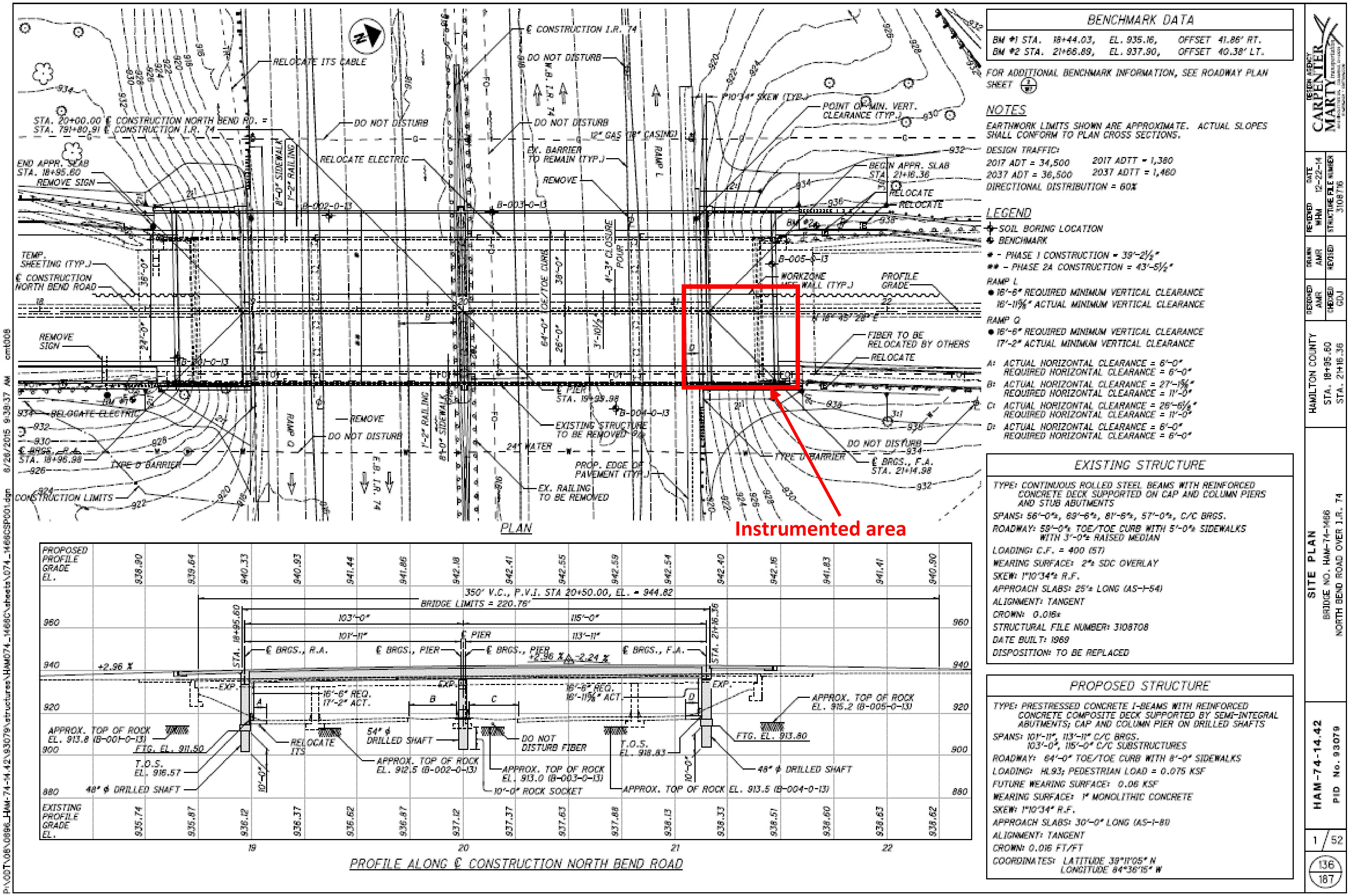
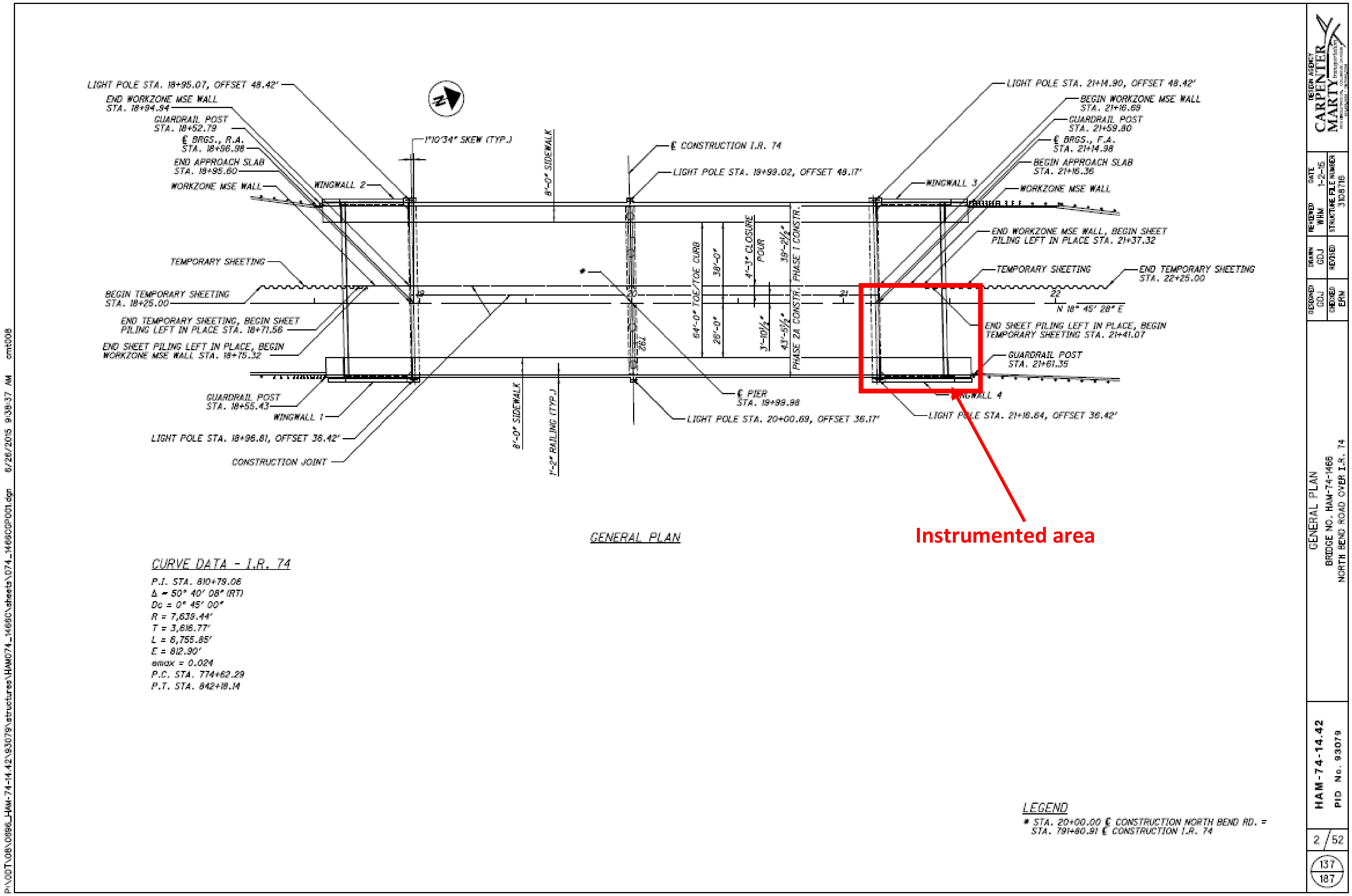
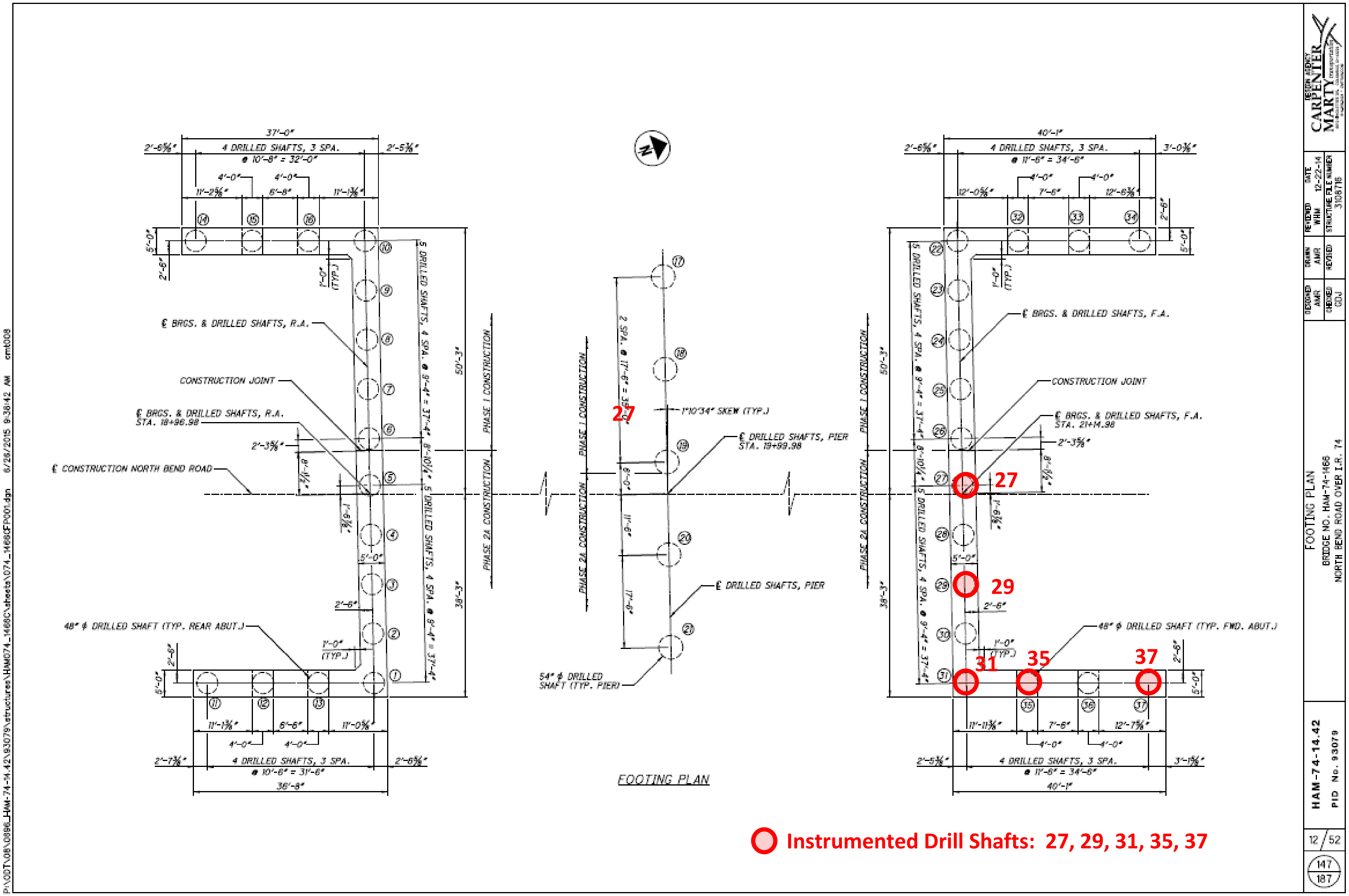
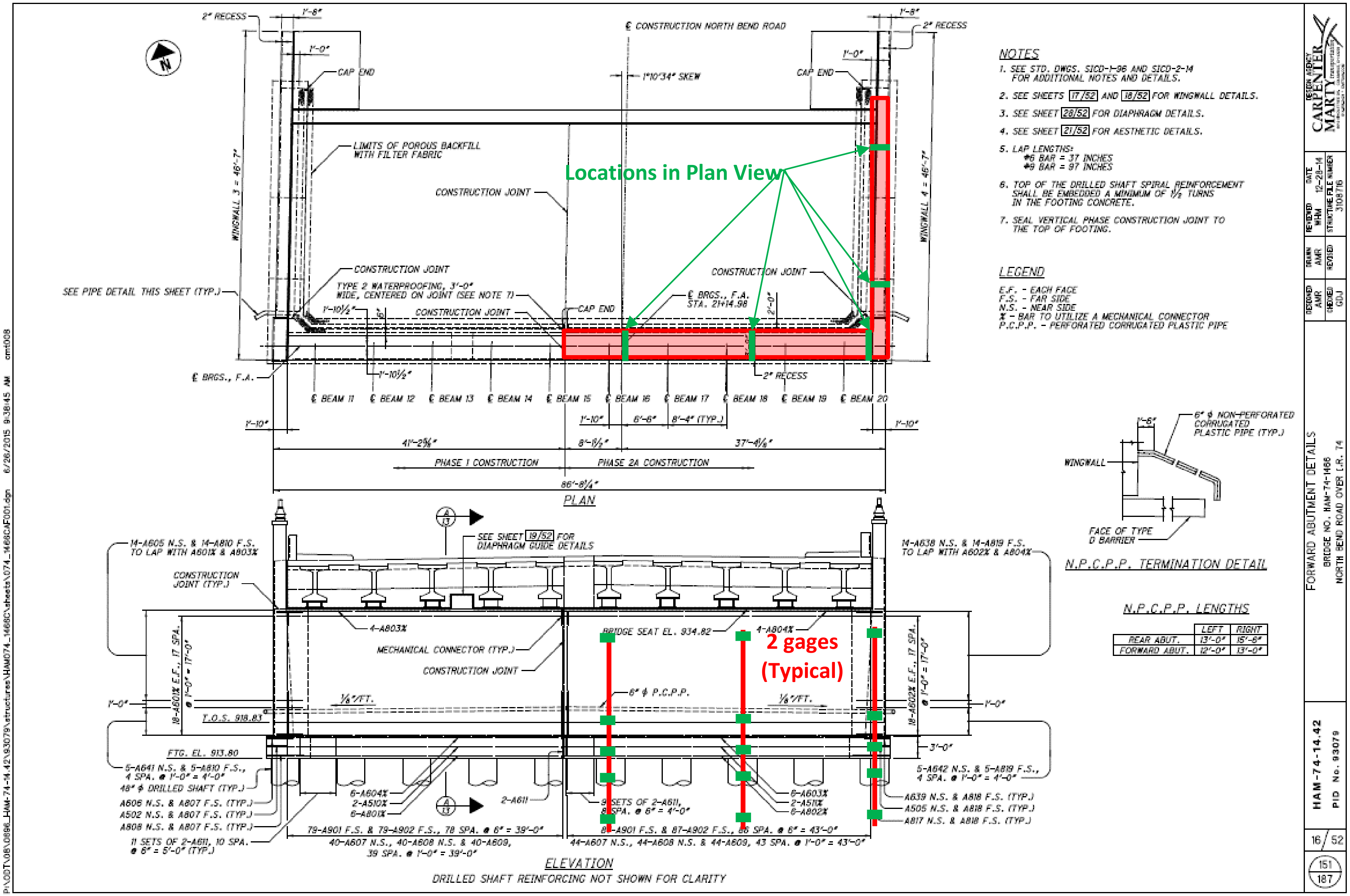
Appendix A. Instrumentation plans for bridge HAM-76-1466.


Instrumented area
PLAN
PROFILE ALONG ℄ CONSTRUCTION NORTH BEND ROAD
BENCHMARK DATA
BM #1 STA. 18+44.03, EL. 935.16, OFFSET 41.86' RT.
BM #2 STA. 21+66.89, EL. 937.90, OFFSET 40.38' LT.
FOR ADDITIONAL BENCHMARK INFORMATION, SEE ROADWAY PLAN SHEET
NOTES
EARTHWORK LIMITS SHOWN ARE APPROXIMATE. ACTUAL SLOPES SHALL CONFORM TO PLAN CROSS SECTIONS.
DESIGN TRAFFIC:
2017 ADT = 34,500 2017 ADTT = 1,380
2037 ADT = 36,500 2037 ADTT = 1,460
DIRECTIONAL DISTRIBUTION = 60%
LEGEND
SOIL BORING LOCATION
BENCHMARK
* - PHASE 1 CONSTRUCTION = 39'-2½"
** - PHASE 2A CONSTRUCTION = 43'-5½"
RAMP L
16'-6" REQUIRED MINIMUM VERTICAL CLEARANCE
16'-11⅝" ACTUAL MINIMUM VERTICAL CLEARANCE
RAMP Q
16'-6" REQUIRED MINIMUM VERTICAL CLEARANCE
17'-2" ACTUAL MINIMUM VERTICAL CLEARANCE
EXISTING STRUCTURE
TYPE: CONTINUOUS ROLLED STEEL BEAMS WITH REINFORCED CONCRETE DECK SUPPORTED ON CAP AND COLUMN PIERS AND STUB ABUTMENTS
SPANS: 56'-0"±, 69'-6"±, 81'-6"±, 57'-0"±, C/C BRGS.
LOADING: C.F. = 400 (57)
WEARING SURFACE: 2"± SDC OVERLAY
SKEW: 1°10'34"± R.F.
APPROACH SLABS: 25'± LONG (AS-1-54)
ALIGNMENT: TANGENT
CROWN: 0.016±
STRUCTURAL FILE NUMBER: 3108708
DATE BUILT: 1969
DISPOSITION: TO BE REPLACED
PROPOSED STRUCTURE
TYPE: PRESTRESSED CONCRETE I-BEAMS WITH REINFORCED CONCRETE COMPOSITE DECK SUPPORTED BY SEMI-INTEGRAL ABUTMENTS; CAP AND COLUMN PIER ON DRILLED SHAFTS
SPANS: 101'-11", 113'-11" C/C BRGS. 103'-0", 115'-0" C/C SUBSTRUCTURES
ROADWAY: 64'-0" TOE/TOE CURB WITH 8'-0" SIDEWALKS
LOADING: HL93; PEDESTRIAN LOAD = 0.075 KSF
FUTURE WEARING SURFACE: 0.06 KSF
WEARING SURFACE: 1" MONOLITHIC CONCRETE
SKEW: 1°10'34" R.F.
APPROACH SLABS: 30'-0" LONG (AS-1-81)
ALIGNMENT: TANGENT
CROWN: 0.016 FT/FT
COORDINATES: LATITUDE 39°11'05" N LONGITUDE 84°36'15" W
SITE PLAN
BRIDGE NO. HAM-74-1466
NORTH BEND ROAD OVER I.R. 74
HAMILTON COUNTY
HAM-74-14.42
PID No. 93079
1 / 52

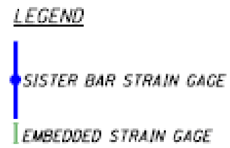

LIGHT POLE STA. 18+95.07, OFFSET 48.42'
END WORKZONE MSE WALL STA. 18+94.94
GUARDRAIL POST STA. 18+52.79
℄ BRGS., R.A. STA. 18+96.98
END APPROACH SLAB STA. 18+95.60
WORKZONE MSE WALL
WINGWALL 2
1°10'34" SKEW (TYP.)
8'-0" SIDEWALK
℄ CONSTRUCTION I.R. 74
LIGHT POLE STA. 19+99.02, OFFSET 48.17'
LIGHT POLE STA. 21+14.90, OFFSET 48.42'
BEGIN WORKZONE MSE WALL STA. 21+16.69
GUARDRAIL POST STA. 21+59.80
℄ BRGS., F.A. STA. 21+14.98
BEGIN APPROACH SLAB STA. 21+16.36
WINGWALL 3
WORKZONE MSE WALL
END WORKZONE MSE WALL, BEGIN SHEET PILING LEFT IN PLACE STA. 21+37.32
TEMPORARY SHEETING
END TEMPORARY SHEETING STA. 22+25.00
N 18° 45' 28" E
END SHEET PILING LEFT IN PLACE, BEGIN TEMPORARY SHEETING STA. 21+41.07
GUARDRAIL POST STA. 21+61.35
WINGWALL 4
LIGHT POLE STA. 21+16.64, OFFSET 36.42'
Instrumented area
TEMPORARY SHEETING
BEGIN TEMPORARY SHEETING STA. 18+25.00
END TEMPORARY SHEETING, BEGIN SHEET PILING LEFT IN PLACE STA. 18+71.56
END SHEET PILING LEFT IN PLACE, BEGIN WORKZONE MSE WALL STA. 18+75.32
GUARDRAIL POST STA. 18+55.43
WINGWALL 1
LIGHT POLE STA. 18+96.81, OFFSET 36.42'
CONSTRUCTION JOINT
8'-0" SIDEWALK
1'-2" RAILING (TYP.)
℄ PIER STA. 19+99.98
LIGHT POLE STA. 20+00.69, OFFSET 36.17'
64'-0" TOE/TOE CURB
38'-0"
26'-0"
4'-3" CLOSURE POUR
3'-10½"
39'-2½"
43'-5½"
PHASE 1 CONSTR.
PHASE 2A CONSTR.
GENERAL PLAN
CURVE DATA - I.R. 74
P.I. STA. 810+79.06
Δ = 50° 40' 08" (RT)
Dc = 0° 45' 00"
R = 7,639.44'
T = 3,616.77'
L = 6,755.85'
E = 812.90'
emax = 0.024
P.C. STA. 774+62.29
P.T. STA. 842+18.14
LEGEND
* STA. 20+00.00 ℄ CONSTRUCTION NORTH BEND RD. = STA. 791+80.91 ℄ CONSTRUCTION I.R. 74
CARPENTER MARTY
GENERAL PLAN
BRIDGE NO. HAM-74-1466
NORTH BEND ROAD OVER I.R. 74
HAM-74-14.42
PID No. 93079
2/52
137
187

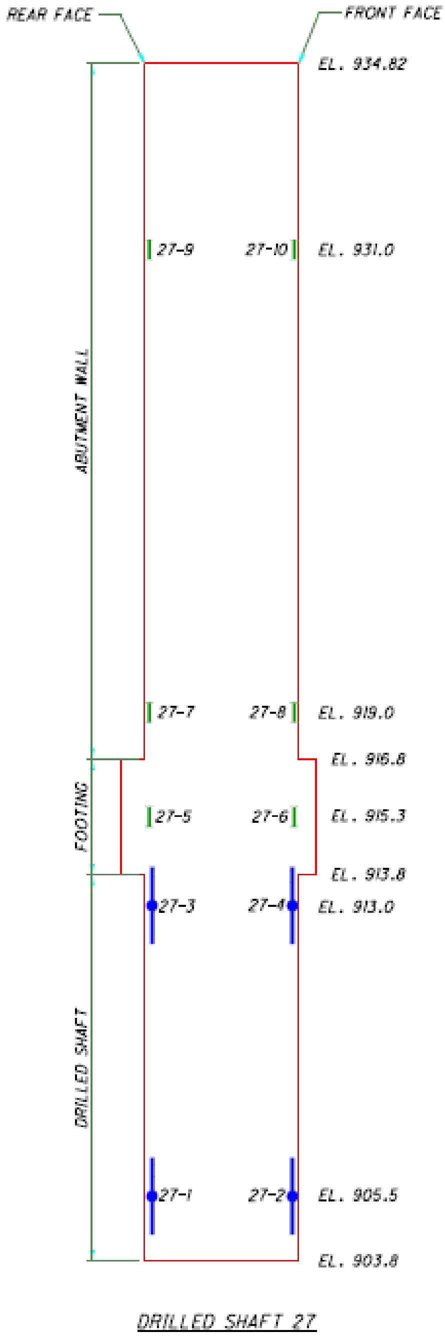


FOOTING PLAN
4 DRILLED SHAFTS, 3 SPA. @ 10'-8" = 32'-0"
37'-0"
¢ BRGS. & DRILLED SHAFTS, R.A.
CONSTRUCTION JOINT
¢ BRGS. & DRILLED SHAFTS, R.A. STA. 18+96.98
¢ CONSTRUCTION NORTH BEND ROAD
48" ϕ DRILLED SHAFT (TYP. REAR ABUT.)
4 DRILLED SHAFTS, 3 SPA. @ 10'-6" = 31'-6"
36'-8"
5 DRILLED SHAFTS, 4 SPA. @ 9'-4" = 37'-4"
PHASE I CONSTRUCTION
PHASE 2A CONSTRUCTION
1°10'34" SKEW (TYP.)
¢ DRILLED SHAFTS, PIER STA. 19+99.98
¢ DRILLED SHAFTS, PIER
54" ϕ DRILLED SHAFT (TYP. PIER)
4 DRILLED SHAFTS, 3 SPA. @ 11'-6" = 34'-6"
40'-1"
¢ BRGS. & DRILLED SHAFTS, F.A.
CONSTRUCTION JOINT
¢ BRGS. & DRILLED SHAFTS, F.A. STA. 21+14.98
48" ϕ DRILLED SHAFT (TYP. FWD. ABUT.)
27
29
31
35
37
Instrumented Drill Shafts: 27, 29, 31, 35, 37
FOOTING PLAN
BRIDGE NO. HAM-74-1466
NORTH BEND ROAD OVER I.R. 74
HAM-74-14.42
PID No. 93079
12/52
147/187


Locations in Plan View
2 gages (Typical)
PLAN
ELEVATION
DRILLED SHAFT REINFORCING NOT SHOWN FOR CLARITY
NOTES
1. SEE STD. DWGS. SICD-1-96 AND SICD-2-14 FOR ADDITIONAL NOTES AND DETAILS.
2. SEE SHEETS 17/52 AND 18/52 FOR WINGWALL DETAILS.
3. SEE SHEET 28/52 FOR DIAPHRAGM DETAILS.
4. SEE SHEET 21/52 FOR AESTHETIC DETAILS.
5. LAP LENGTHS: #6 BAR = 37 INCHES #9 BAR = 97 INCHES
6. TOP OF THE DRILLED SHAFT SPIRAL REINFORCEMENT SHALL BE EMBEDDED A MINIMUM OF 1½ TURNS IN THE FOOTING CONCRETE.
7. SEAL VERTICAL PHASE CONSTRUCTION JOINT TO THE TOP OF FOOTING.
LEGEND
E.F. - EACH FACE
F.S. - FAR SIDE
N.S. - NEAR SIDE
X - BAR TO UTILIZE A MECHANICAL CONNECTOR
P.C.P.P. - PERFORATED CORRUGATED PLASTIC PIPE
N.P.C.P.P. TERMINATION DETAIL
N.P.C.P.P. LENGTHS
FORWARD ABUTMENT DETAILS
BRIDGE NO. HAM-74-1466
NORTH BEND ROAD OVER I.R. 74
HAM-74-14.42
PID No. 93079
16/52

P:\99625\Design\Geotechnical\Sheets\16120_GT001.dgn Sheet 12/15/2016 4:31:29 PM gantonios





DRILLED SHAFT 27

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	27-1	1635589	0.350
11/21/2016	27-2	1635590	0.352
11/21/2016	27-3	1635591	0.348
11/21/2016	27-4	1635592	0.346
12/9/2016	27-5		
12/9/2016	27-6		
12/13/2016	27-7		
12/13/2016	27-8		
12/13/2016	27-9		
12/13/2016	27-10		

CALCULATED XXX
CHECKED XXX

E.L. ROBINSON ENGINEERING

INSTRUMENTATION DETAILS
SECTION AT DRILLED SHAFT 27

HAM-74-1466

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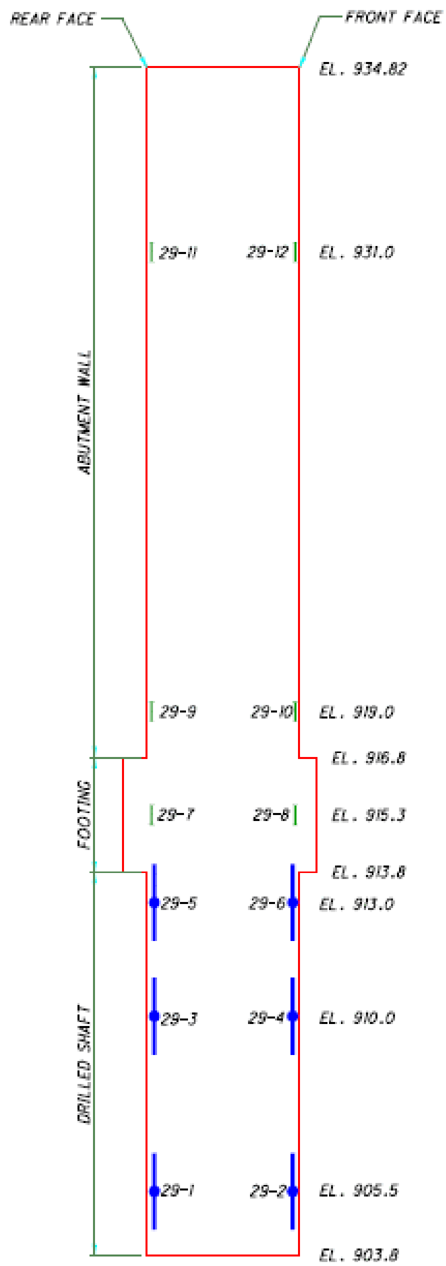
P:\99625\Design\Geotechnical\Sheets\16120_CT001.dgn Sheet 12/15/2016 4:31:30 PM gantonios

LEGEND

SISTER BAR STRAIN GAGE

EMBEDDED STRAIN GAGE



DRILLED SHAFT 29

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	29-1	1635593	0.352
11/21/2016	29-2	1635594	0.350
11/21/2016	29-3	1635595	0.345
11/21/2016	29-4	1635596	0.350
11/21/2016	29-5	1635597	0.352
11/21/2016	29-6	1635598	0.349
12/9/2016	29-7		
12/9/2016	29-8		
12/13/2016	29-9		
12/13/2016	29-10		
12/13/2016	29-11		
12/13/2016	29-12		

CALCULATED XXX
CHECKED XXX

E.L. ROBINSON ENGINEERING

INSTRUMENTATION DETAILS
SECTION AT DRILLED SHAFT 29

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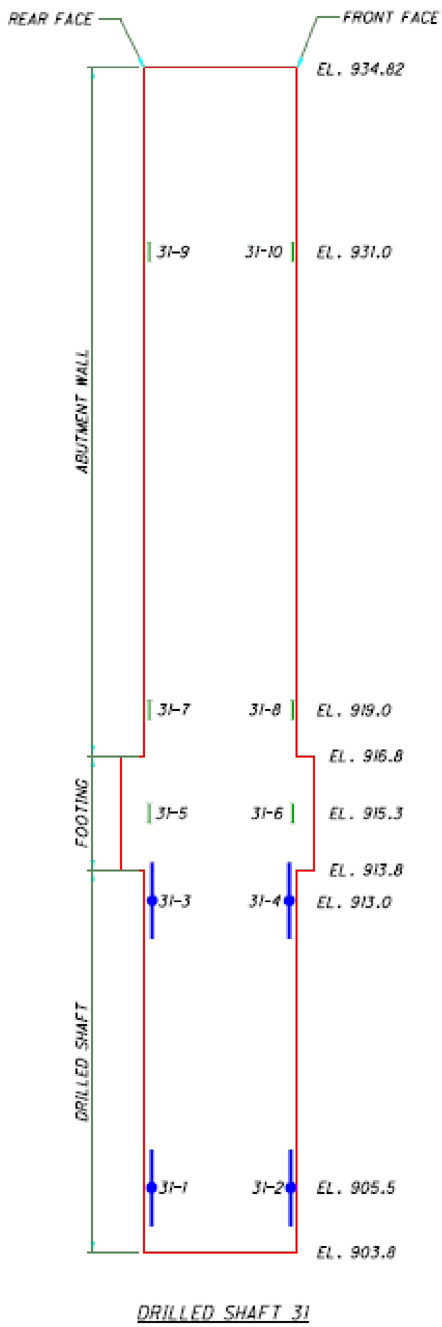
LEGEND

SISTER BAR STRAIN GAGE

EMBEDDED STRAIN GAGE



DRILLED SHAFT 31

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	31-1	1635599	0.351
11/21/2016	31-2	1635600	0.351
11/21/2016	31-3	1635603	0.344
11/21/2016	31-4	1635604	0.348
12/9/2016	31-5		
12/9/2016	31-6		
12/13/2016	31-7		
12/13/2016	31-8		
12/13/2016	31-9		
12/13/2016	31-10		

CALCULATED XXX
CHECKED XXX

E.L. ROBINSON ENGINEERING

INSTRUMENTATION DETAILS
SECTION AT DRILLED SHAFT 31

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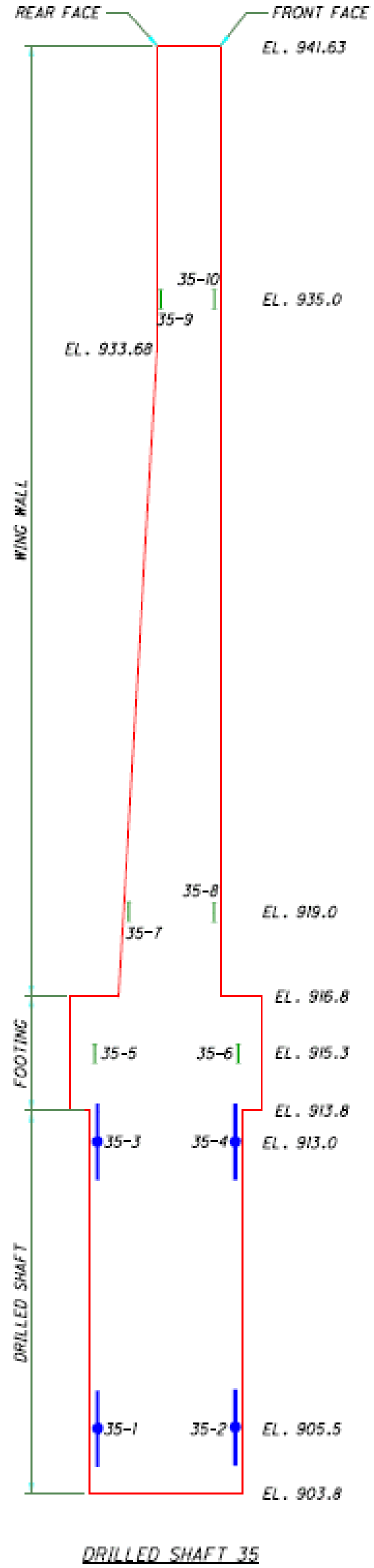
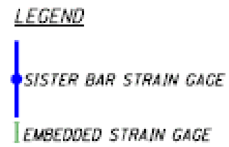
P:\99625\Design\Geotechnical\Sheets\16120_GT001.dgn Sheet 12/15/2016 4:31:30 PM gantonios



DRILLED SHAFT 35



INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	35-1	1635605	0.347
11/21/2016	35-2	1635606	0.349
11/21/2016	35-3	1635607	0.350
11/21/2016	35-4	1635608	0.350
12/9/2016	35-5		
12/9/2016	35-6		
	35-7		
	35-8		
	35-9		
	35-10		

CALCULATED XXX CHECKED XXX

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INSTRUMENTATION DETAILS
SECTION AT DRILLED SHAFT 35

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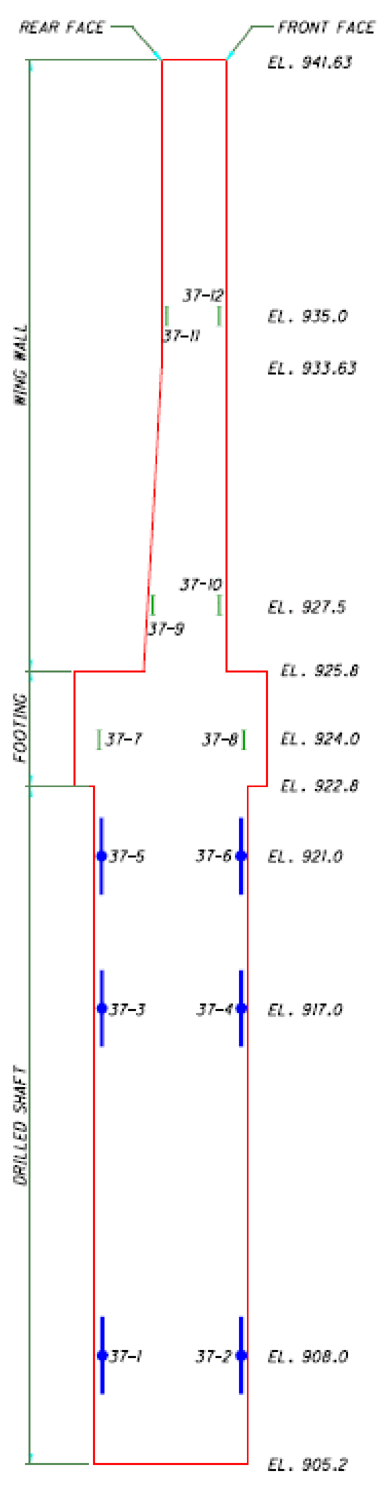

DRILLED SHAFT 37

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	37-1	1635601	0.350
11/21/2016	37-2	1635602	0.347
11/21/2016	37-3	1635609	0.352
11/21/2016	37-4	1635610	0.354
11/21/2016	37-5	1635611	0.345
11/21/2016	37-6	1635612	0.351
	37-7		
	37-8		
	37-9		
	37-10		
	37-11		
	37-12		

CALCULATED XXX
CHECKED XXX

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INSTRUMENTATION DETAILS
SECTION AT DRILLED SHAFT 37

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Appendix B. Strain gage installation dates, gage factors, and Geokon calibration reports.

Drilled Shaft 27

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	27-1	1635589	0.350
11/21/2016	27-2	1635590	0.352
11/21/2016	27-3	1635591	0.348
11/21/2016	27-4	1635592	0.346
12/9/2016	27-5		
12/9/2016	27-6		
12/13/2016	27-7		
12/13/2016	27-8		
12/13/2016	27-9		
12/13/2016	27-10		

Drilled Shaft 31

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	31-1	1635599	0.350
11/21/2016	31-2	1635600	0.352
11/21/2016	31-3	1635603	0.348
11/21/2016	31-4	1635604	0.346
12/9/2016	31-5		
12/9/2016	31-6		
12/13/2016	31-7		
12/13/2016	31-8		
12/13/2016	31-9		
12/13/2016	31-10		

Drilled Shaft 29

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	29-1	1635593	0.352
11/21/2016	29-2	1635594	0.350
11/21/2016	29-3	1635595	0.345
11/21/2016	29-4	1635596	0.350
11/21/2016	29-5	1635597	0.352
11/21/2016	29-6	1635598	0.349
12/9/2016	29-7		
12/9/2016	29-8		
12/13/2016	29-9		
12/13/2016	29-10		
12/13/2016	29-11		
12/13/2016	29-12		

Drilled Shaft 35

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	35-1	1635605	0.347
11/21/2016	35-2	1635606	0.349
11/21/2016	35-3	1635607	0.350
11/21/2016	35-4	1635608	0.350
12/9/2016	35-5		
12/9/2016	35-6		
	35-7		
	35-8		
	35-9		
	35-10		

Drilled Shaft 37

INSTALLATION DATE	STRAIN GAGE	SERIAL NUMBER	GAGE FACTOR
11/21/2016	37-1	1635601	0.350
11/21/2016	37-2	1635602	0.347
11/21/2016	37-3	1635609	0.352
11/21/2016	37-4	1635610	0.354
11/21/2016	37-5	1635611	0.345
11/21/2016	37-6	1635612	0.351
	37-7		
	37-8		
	37-9		
	37-10		
	37-11		
	37-12		

48 Spencer St. Lebanon, NH 03766 USA

<u>Sister Bar Calibration Report</u>

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635589

Cable Length: 100 feet

Prestress: 35,000 psi

Regression Zero: 7318

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7368	7372	7370		
1500	8038	8037	8038	568	-0.09
3000	8760	8759	8760	722	-0.10
4500	9487	9484	9486	726	0.04
6000	10207	10210	10209	723	0.06
100	7372	7372	7372		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

<u>Users are advised to establish their own zero conditions.</u>

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number:	4911-4	Date of Calibration:	November 01, 2016
			This calibration has been verified/validated as of 11/11/2016
Serial Number:	1635590	Cable Length:	100 feet
Prestress:	35,000 psi	Regression Zero:	7388
Temperature:	21.8 °C	Technician:	
Calibration Instruction:	CI-VW Rebar		

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7443	7443	7443		
1500	8097	8096	8097	654	-0.22
3000	8811	8809	8810	713	-0.26
4500	9532	9532	9532	722	-0.01
6000	10251	10251	10251	719	0.14
100	7443	7441	7442		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.352 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635591

Cable Length: 90 feet

Prestress: 35,000 psi

Regression Zero: 7135

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7188	7194	7191		
1500	7858	7852	7855	664	-0.21
3000	8581	8583	8582	727	-0.18
4500	9314	9317	9316	734	0.08
6000	10043	10042	10043	727	0.11
100	7194	7194	7194		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.348 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635592

Cable Length: 90 feet

Prestress: 35,000 psi

Regression Zero: 7231

Temperature: 21.8 °C

Technician: [signature]

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7293	7292	7293		
1500	7955	7954	7955	662	-0.33
3000	8688	8685	8687	732	-0.37
4500	9434	9435	9435	748	0.13
6000	10165	10173	10169	734	0.18
100	7292	7294	7293		

For conversion facıor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.346 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635593

Cable Length: 90 feet

Prestress: 35,000 psi

Regression Zero: 7486

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7540	7538	7539		
1500	8196	8195	8196	657	-0.17
3000	8910	8913	8912	716	-0.10
4500	9630	9634	9632	720	0.12
6000	10344	10344	10344	712	0.04
100	7539	7540	7540		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.352 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635594

Cable Length: 90 feet

Prestress: 35,000 psi

Regression Zero: 7349

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7401	7402	7402		
1500	8066	8066	8066	664	-0.15
3000	8789	8787	8788	722	-0.14
4500	9516	9512	9514	726	0.02
6000	10238	10235	10237	723	0.06
100	7403	7405	7404		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number:	4911-4	Date of Calibration:	November 01, 2016
			This calibration has been verified/validated as of 11/11/2016
Serial Number:	1635595	Cable Length:	90 feet
Prestress:	35,000 psi	Regression Zero:	7145
Temperature:	21.8 °C	Technician:	
Calibration Instruction:	CI-VW Rebar		

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7204	7196	7200		
1500	7873	7869	7871	671	-0.33
3000	8619	8618	8619	748	0.07
4500	9355	9353	9354	735	0.06
6000	10087	10089	10088	734	0.00
100	7198	7202	7200		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.345 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635596

Cable Length: 90 feet

Prestress: 35,000 psi

Regression Zero: 7104

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7160	7158	7159		
1500	7815	7815	7815	656	-0.39
3000	8553	8550	8552	737	0.11
4500	9271	9271	9271	719	0.01
6000	9992	9995	9994	723	0.02
100	7159	7162	7161		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635597

Cable Length: 80 feet

Prestress: 35,000 psi

Regression Zero: 7066

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7116	7121	7119		
1500	7779	7776	7778	659	-0.10
3000	8485	8482	8484	706	-0.39
4500	9217	9215	9216	732	0.24
6000	9923	9923	9923	707	-0.01
100	7122	7120	7121		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.352 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635598

Cable Length: 80 feet

Prestress: 35,000 psi

Regression Zero: 7317

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7374	7371	7373		
1500	8034	8036	8035	662	-0.23
3000	8764	8758	8761	726	-0.18
4500	9493	9492	9493	732	0.05
6000	10219	10218	10219	726	0.10
100	7371	7370	7371		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.349 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635599

Cable Length: 60 feet

Prestress: 35,000 psi

Regression Zero: 7110

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7166	7165	7166		
1500	7817	7820	7819	653	-0.34
3000	8543	8546	8545	726	-0.08
4500	9267	9268	9268	723	0.08
6000	9986	9983	9985	717	0.04
100	7166	7169	7168		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.351 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635600

Cable Length: 60 feet

Prestress: 35,000 psi

Regression Zero: 7064

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7127	7121	7124		
1500	7774	7771	7773	649	-0.31
3000	8488	8485	8487	714	-0.44
4500	9215	9216	9216	729	-0.04
6000	9945	9938	9942	726	0.26
100	7123	7121	7122		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.351 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635601

Cable Length: 60 feet

Prestress: 35,000 psi

Regression Zero: 6953

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7013	7013	7013		
1500	7662	7663	7663	650	-0.38
3000	8385	8385	8385	722	-0.30
4500	9118	9121	9120	735	0.19
6000	9841	9834	9838	718	0.11
100	7014	7014	7014		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635602

Cable Length: 60 feet

Prestress: 35,000 psi

Regression Zero: 6995

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7057	7055	7056		
1500	7716	7717	7717	661	-0.24
3000	8439	8441	8440	723	-0.42
4500	9181	9181	9181	741	0.01
6000	9919	9916	9918	737	0.28
100	7056	7057	7057		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.347 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635603

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7166

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7219	7222	7221		
1500	7894	7899	7897	676	-0.25
3000	8641	8644	8643	746	0.04
4500	9380	9384	9382	739	0.10
6000	10118	10116	10117	735	0.00
100	7223	7217	7220		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.344 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635604

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7049

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7109	7110	7110		
1500	7767	7768	7768	658	-0.32
3000	8494	8495	8495	727	-0.36
4500	9236	9237	9237	742	0.13
6000	9966	9965	9966	729	0.16
100	7111	7110	7111		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.348 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635605

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7199

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7256	7258	7257		
1500	7920	7920	7920	663	-0.27
3000	8649	8651	8650	730	-0.23
4500	9386	9386	9386	736	0.01
6000	10119	10120	10120	734	0.17
100	7258	7260	7259		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.347 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635606

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7009

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7066	7068	7067		
1500	7718	7722	7720	653	-0.42
3000	8451	8454	8453	733	-0.09
4500	9178	9182	9180	727	0.06
6000	9904	9903	9904	724	0.08
100	7068	7068	7068		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.349 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635607

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7064

Temperature: 21.8 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7119	7118	7119		
1500	7779	7778	7779	660	-0.24
3000	8502	8503	8503	724	-0.14
4500	9229	9231	9230	727	0.07
6000	9950	9952	9951	721	0.06
100	7117	7118	7118		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635608

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7400

Temperature: 22.6 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7460	7457	7459		
1500	8111	8109	8110	651	-0.33
3000	8829	8830	8830	720	-0.33
4500	9563	9560	9562	732	0.11
6000	10284	10279	10282	720	0.13
100	7457	7456	7457		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.350 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635609

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 7148

Temperature: 22.6 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7202	7202	7202		
1500	7856	7857	7857	655	-0.22
3000	8575	8574	8575	718	-0.10
4500	9295	9295	9295	720	0.10
6000	10010	10007	10009	714	0.05
100	7201	7201	7201		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.352 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635610

Cable Length: 50 feet

Prestress: 35,000 psi

Regression Zero: 6944

Temperature: 22.6 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	6997	6996	6997		
1500	7652	7651	7652	655	-0.12
3000	8363	8361	8362	710	-0.14
4500	9078	9076	9077	715	0.00
6000	9791	9791	9791	714	0.11
100	6996	6998	6997		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.354 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635611

Cable Length: 40 feet

Prestress: 35,000 psi

Regression Zero: 7021

Temperature: 22.6 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	7079	7080	7080		
1500	7749	7746	7748	668	-0.30
3000	8485	8483	8484	736	-0.26
4500	9229	9230	9230	746	0.09
6000	9968	9963	9966	736	0.11
100	7079	7079	7079		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.345 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

48 Spencer St. Lebanon, NH 03766 USA

Sister Bar Calibration Report

Model Number: 4911-4

Date of Calibration: November 01, 2016

This calibration has been verified/validated as of 11/11/2016

Serial Number: 1635612

Cable Length: 40 feet

Prestress: 35,000 psi

Regression Zero: 6876

Temperature: 22.6 °C

Technician:

Calibration Instruction: CI-VW Rebar

Applied Load (pounds)	Readings				Linearity % Max. Load
	Cycle #1	Cycle #2	Average	Change	
100	6930	6929	6930		
1500	7588	7586	7587	657	-0.23
3000	8309	8310	8310	723	-0.07
4500	9033	9031	9032	722	0.10
6000	9747	9748	9748	716	0.02
100	6929	6930	6930		

For conversion factor, load to strain, refer to table C-2 of the Installation Manual

Gage Factor: 0.351 microstrain/ digit (GK-401 Pos. "B")

Calculated Strain = Gage Factor(Current Reading - Zero Reading)

Note: The above calibration uses the linear regression method.

Users are advised to establish their own zero conditions.

Linearity: ((Calculated Load - Applied Load)/Max. Applied Load) X 100 percent

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.

GEOKON 48 Spencer St. Lebanon, N.H. 03766 USA

Vibrating Wire Strain Gage Batch Calibrations

Revision Date: June 29, 2016

Technician: *K.L. Bellavance*

Strain Gage Type	Nominal Batch Factor (B)
Model 4000	0.96
Model 4100 / 4150 / 4151 / 4202	0.93
Model 4200	0.98

Please Note: To calculate changes of strain use the formula $\Delta\mu = (R1\text{-}RO)G \times B$ where G is the gage factor for that particular model of strain gage.

This applies only to dataloggers

Where the strains are read using GK403 or GK404 readout boxes on the appropriate channels C, D or E, the displayed readings already include the gage factor ,G, so that with portable readout boxes the change of strain is simply (R1-RO) x B microstrain

Gage Model	G
4000	4.062
4100/4150/4202	0.391
4200	3.304

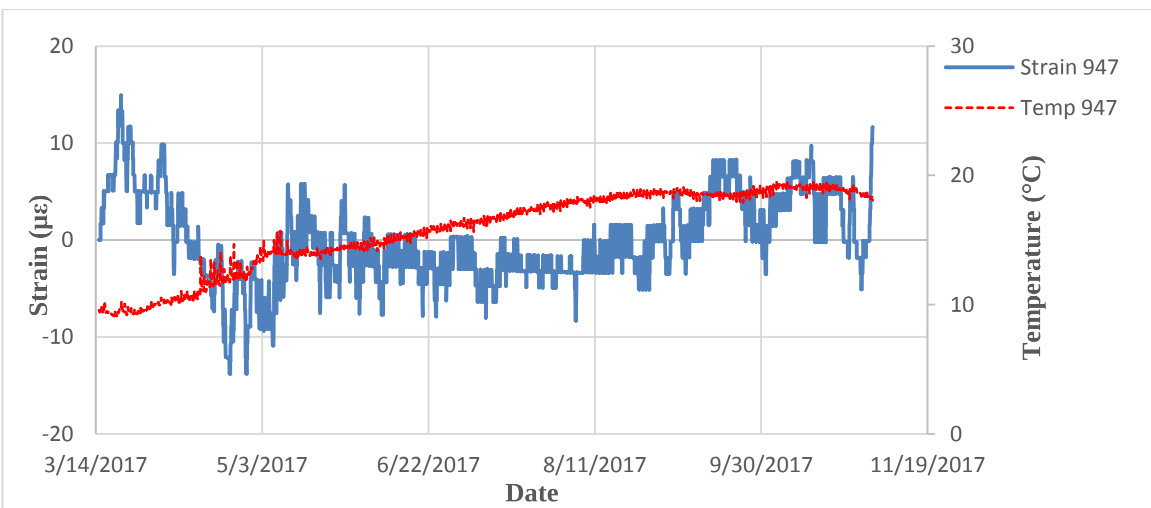
Model:	4200	4202	4204	4210	4212	4214
Gage Factor:	3.304	0.391	1.422	0.3568	0.3624	0.3665
Start Frequency (P28):	4(450 Hz)	14 (1400 Hz)	8 (800 Hz)	14 (1400 Hz)	14 (1400 Hz)	14 (1400 Hz)
End Freguency (P28):	12 (1200 Hz)	35 (3500 Hz)	16 (1600 Hz)	35 (3500 Hz)	35 (3500 Hz)	35 (3500 Hz)

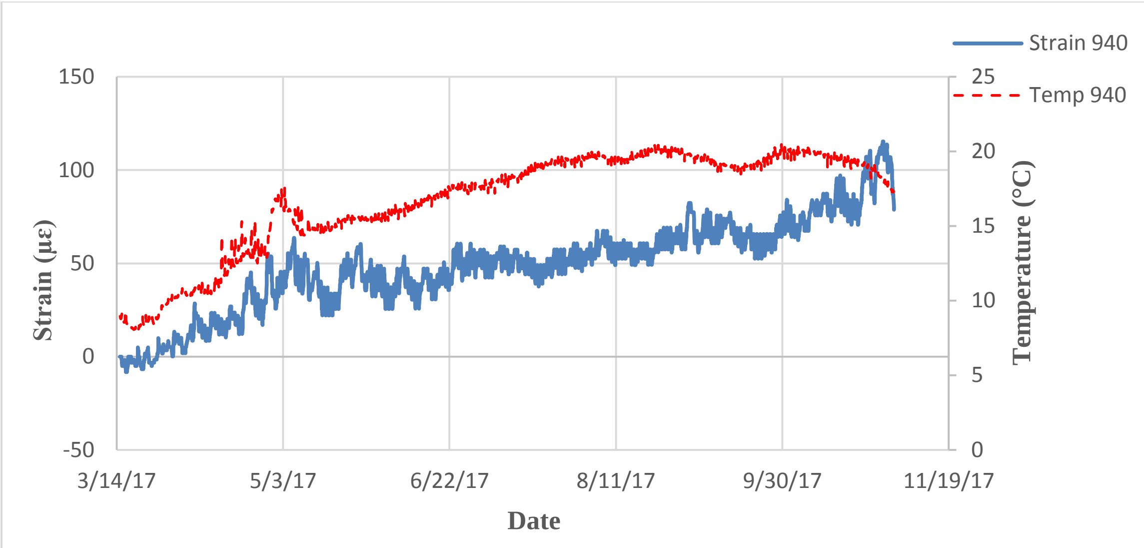
The above factor is derived by averaging the gage factors of controlled samples of all gages produced. The data from calibration of the above instrument samples was collected using standards traceable to the NIST and in compliance with ANSI/NCSL Z540-1.

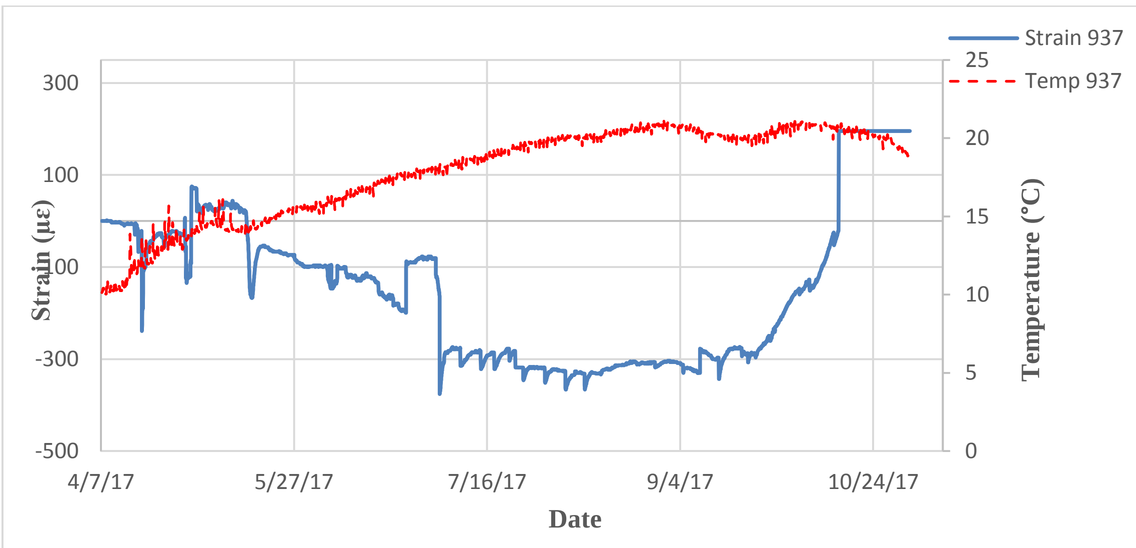
Appendix C. Time series graphs of strain and temperature data.

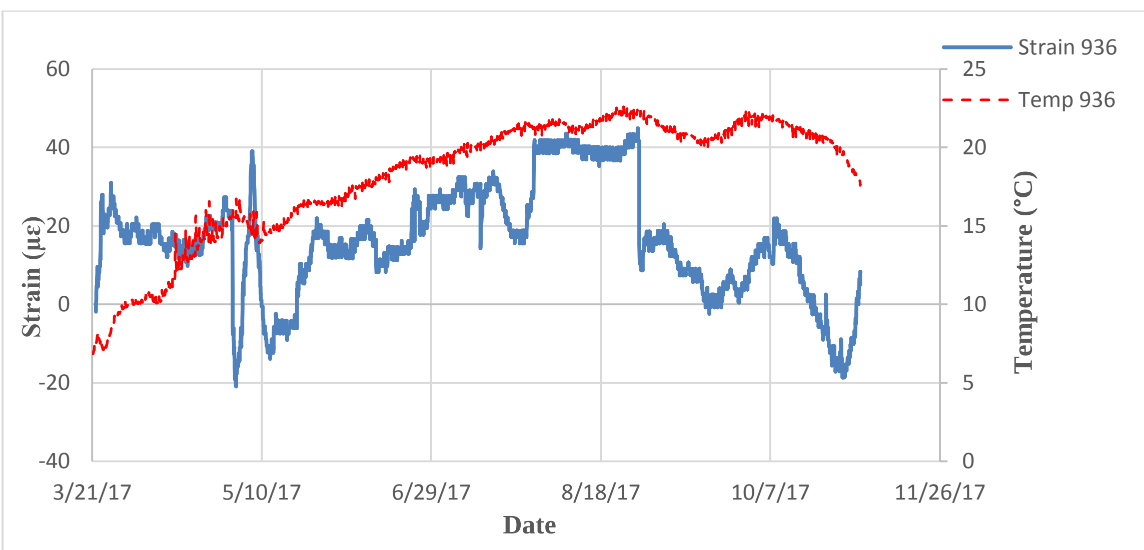
Key to strain gage numbers in following graphs

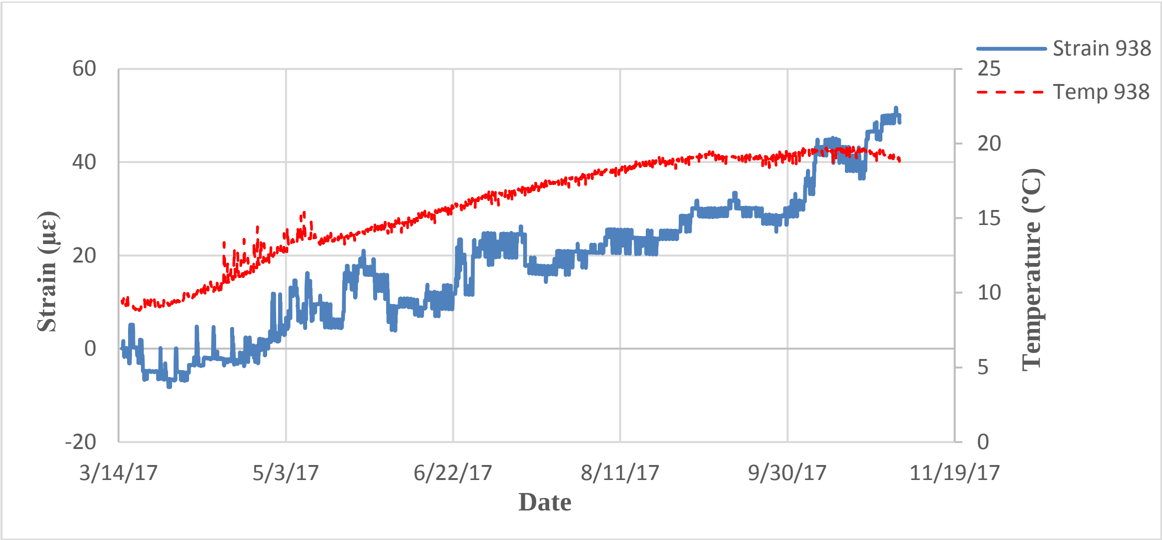
Location	Installation date	Strain gage no.	Direction	Pouring date
Cap over Drilled Shaft 27	12/5/2016	947	Sister bar	12/15/2016
Cap over Drilled Shaft 27	12/5/2016	940	Sister bar	12/15/2016
Cap over Drilled Shaft 31	12/5/2016	946	Sister bar	12/15/2016
Cap over Drilled Shaft 31	12/5/2016	937	Sister bar	12/15/2016
Cap over Drilled Shaft 31	12/5/2016	936	Embedded	12/15/2016
Cap between Drilled Shafts 31 & 35	12/5/2016	938	Embedded	12/15/2016
Cap between Drilled Shafts 31 & 35	12/5/2016	939	Embedded	12/15/2016
Cap over Drilled Shaft 37	1/17/2017	949	Sister bar	1/18/2017
Cap over Drilled Shaft 37	1/17/2017	948	Sister bar	1/18/2017
Wingwall 4 between Drilled Shafts 31 & 35	1/19/2017	941	Embedded	1/24/2017
Wingwall 4 between Drilled Shafts 31 & 35	1/19/2017	942	Embedded	1/24/2017
Wingwall 4 between Drilled Shafts 31 & 35	1/19/2017	943	Embedded	1/24/2017
Wingwall 4 between Drilled Shafts 31 & 35	1/19/2017	944	Embedded	1/24/2017

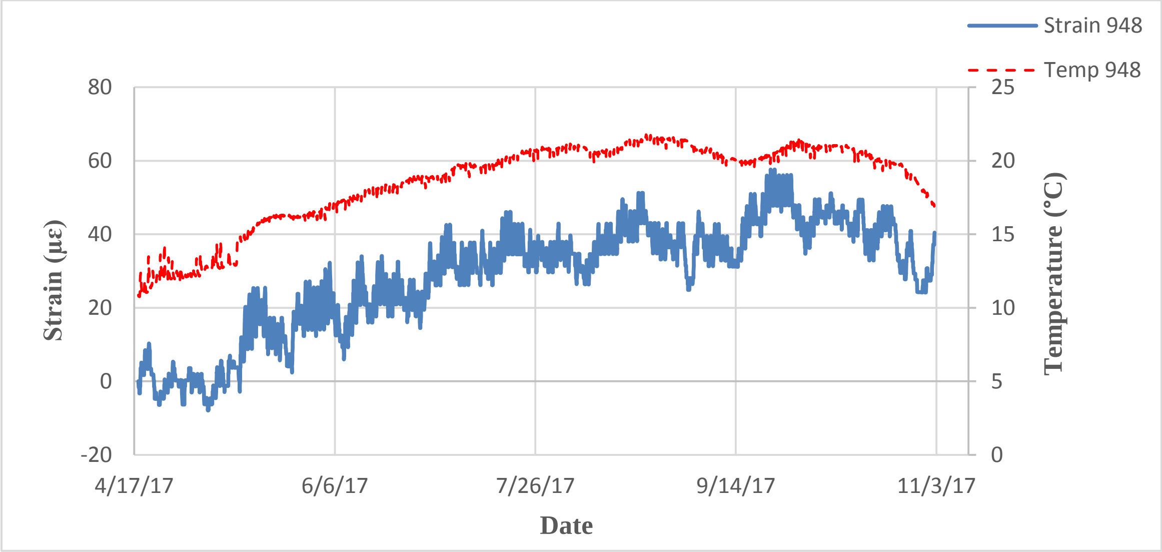


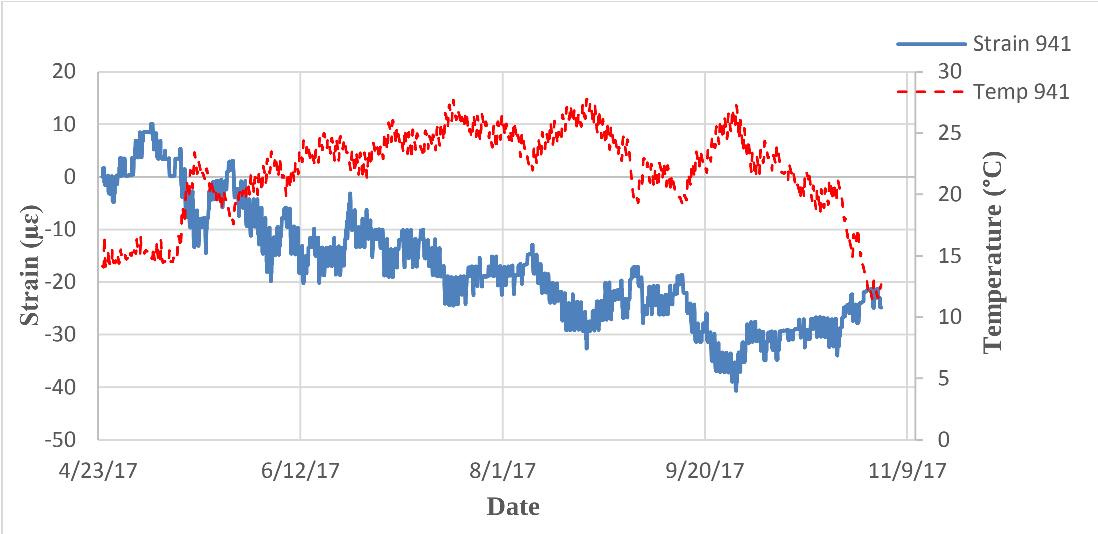

Strain 940
Temp 940
Strain (με)
Temperature (°C)
Date
150
100
50
0
-50
25
20
15
10
5
0
3/14/17
5/3/17
6/22/17
8/11/17
9/30/17
11/19/17

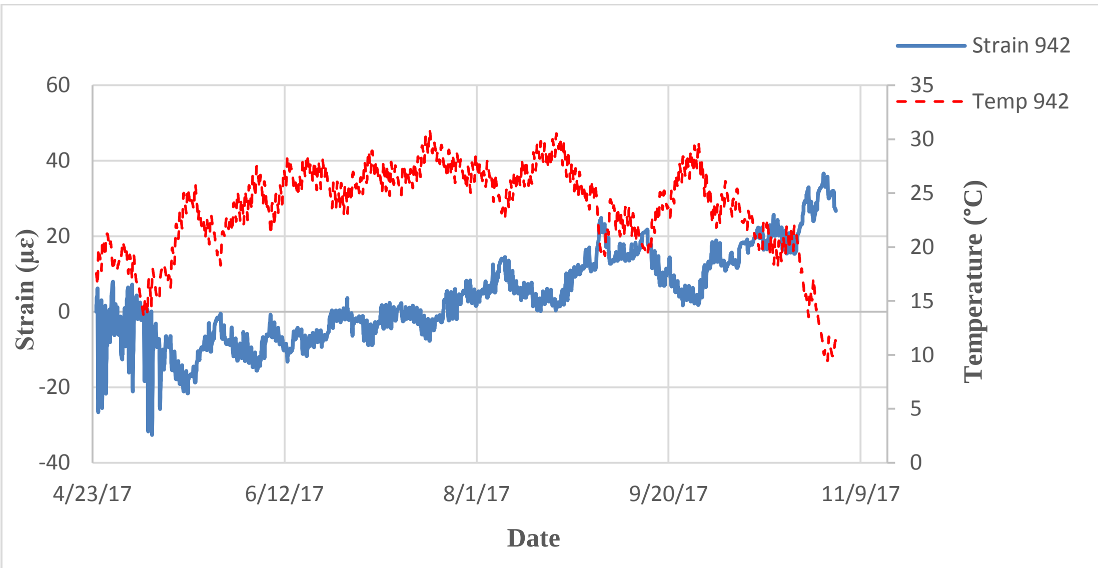

Strain 937
Temp 937
Strain (με)
Temperature (°C)
Date
300
100
-100
-300
-500
25
20
15
10
5
0
4/7/17
5/27/17
7/16/17
9/4/17
10/24/17

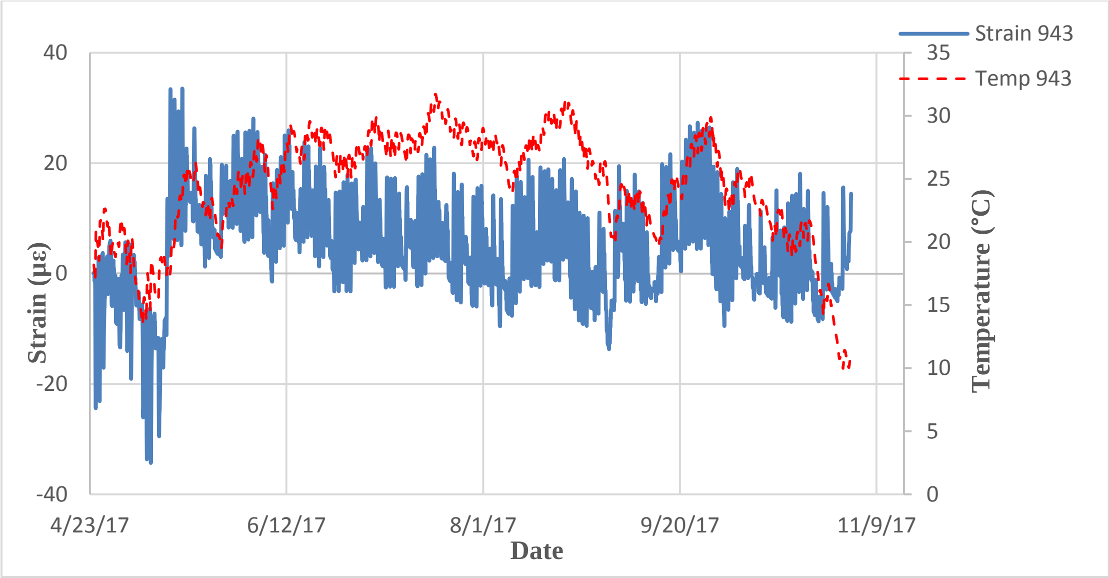

Strain 936
Temp 936
Strain (με)
Temperature (°C)
Date
60
40
20
0
-20
-40
25
20
15
10
5
0
3/21/17
5/10/17
6/29/17
8/18/17
10/7/17
11/26/17

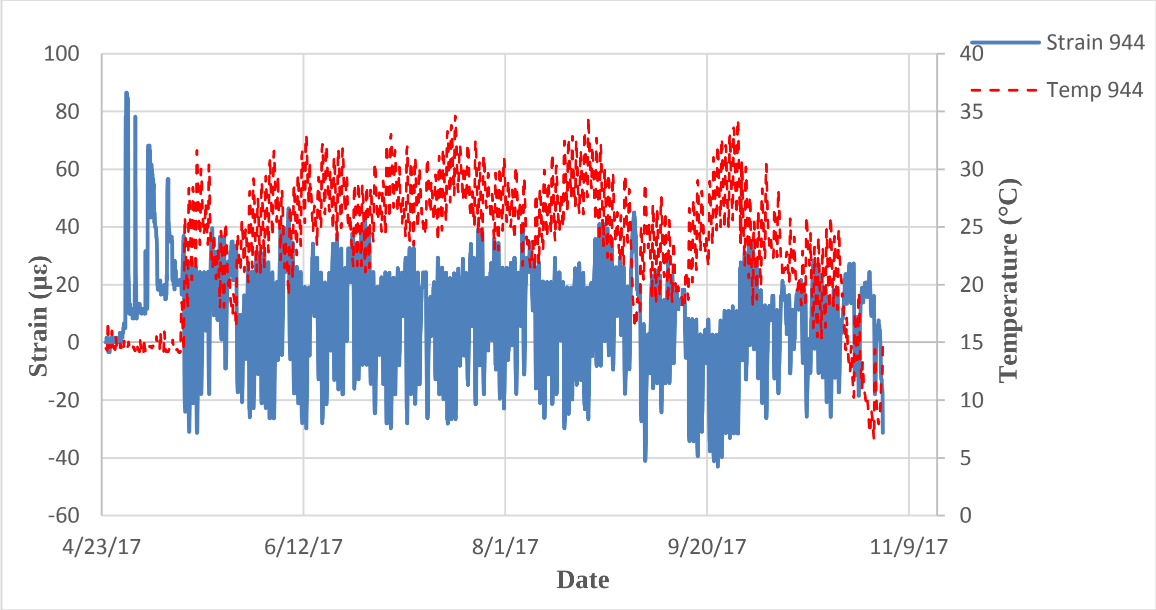

Strain 938
Temp 938
60
40
20
0
-20
25
20
15
10
5
0
Strain (με)
Temperature (°C)
3/14/17
5/3/17
6/22/17
8/11/17
9/30/17
11/19/17
Date


Strain 948
Temp 948
80
60
40
20
0
-20
25
20
15
10
5
0
Strain (με)
Temperature (°C)
4/17/17
6/6/17
7/26/17
9/14/17
11/3/17
Date


Strain 941
Temp 941
Strain (με)
Temperature (°C)
Date
20
10
0
-10
-20
-30
-40
-50
30
25
20
15
10
5
0
4/23/17
6/12/17
8/1/17
9/20/17
11/9/17

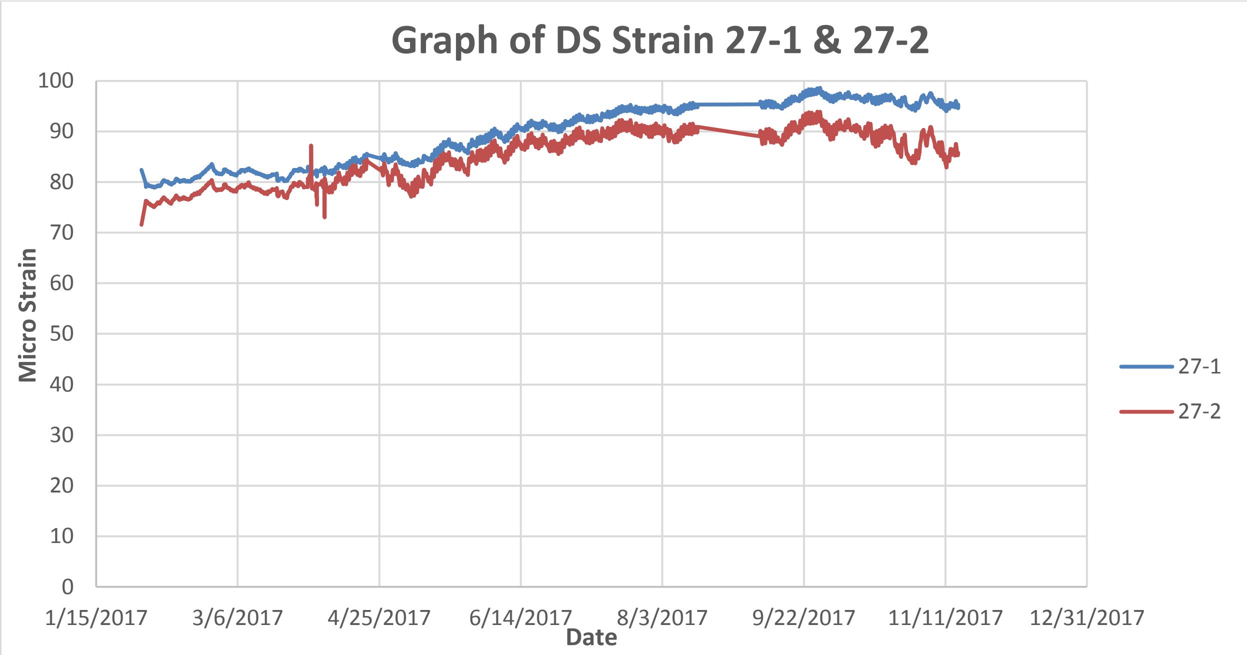

Strain 942
Temp 942
Strain (με)
Temperature (°C)
Date
60
40
20
0
-20
-40
35
30
25
20
15
10
5
0
4/23/17
6/12/17
8/1/17
9/20/17
11/9/17

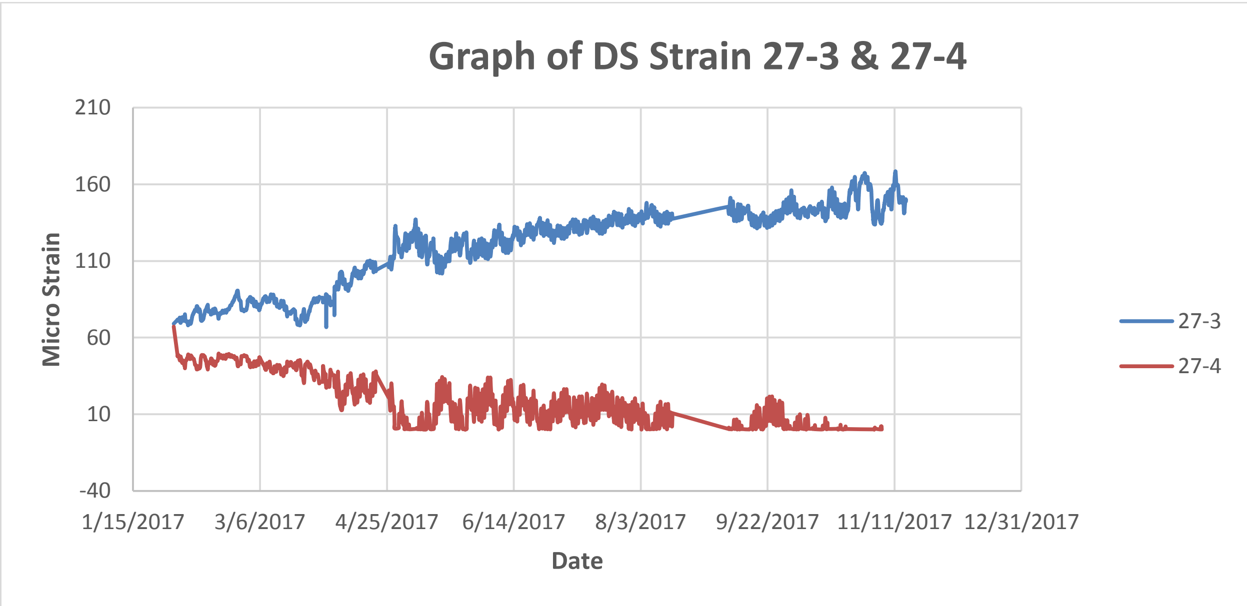

Strain 943
Temp 943
Strain (με)
Temperature (°C)
Date
40
20
0
-20
-40
35
30
25
20
15
10
5
0
4/23/17
6/12/17
8/1/17
9/20/17
11/9/17

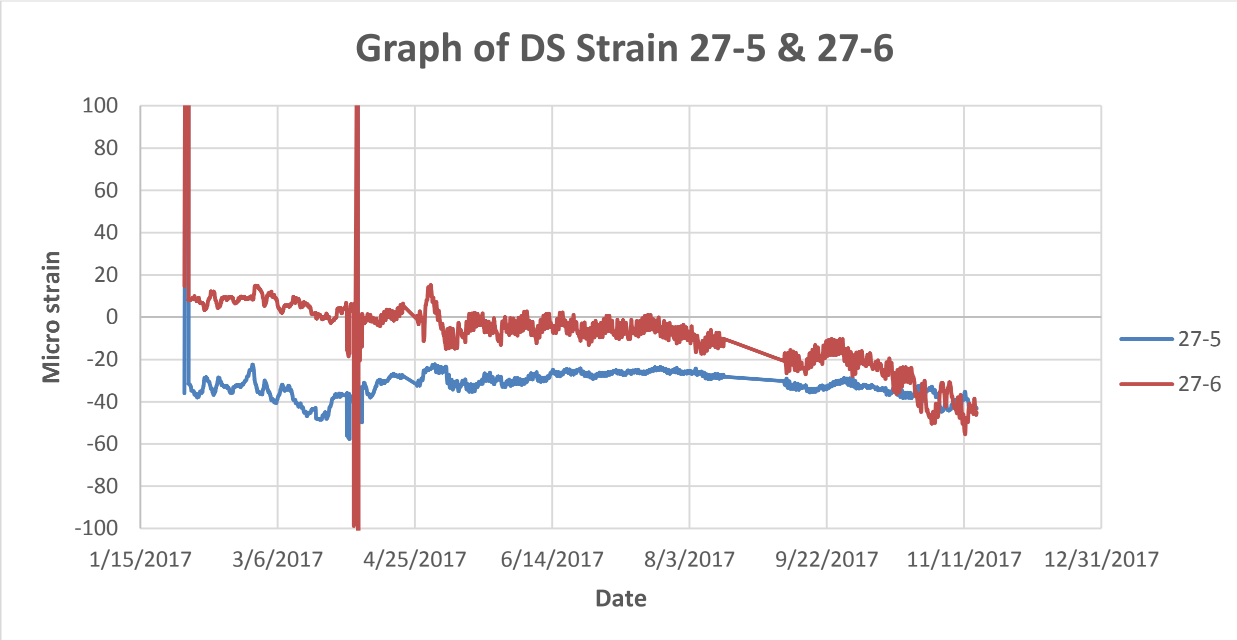

Strain 944
Temp 944
Strain (με)
Temperature (°C)
Date
100
80
60
40
20
0
-20
-40
-60
40
35
30
25
20
15
10
5
0
4/23/17
6/12/17
8/1/17
9/20/17
11/9/17

Appendix D. Time series graphs of strains from paired strain gages in drill shafts.

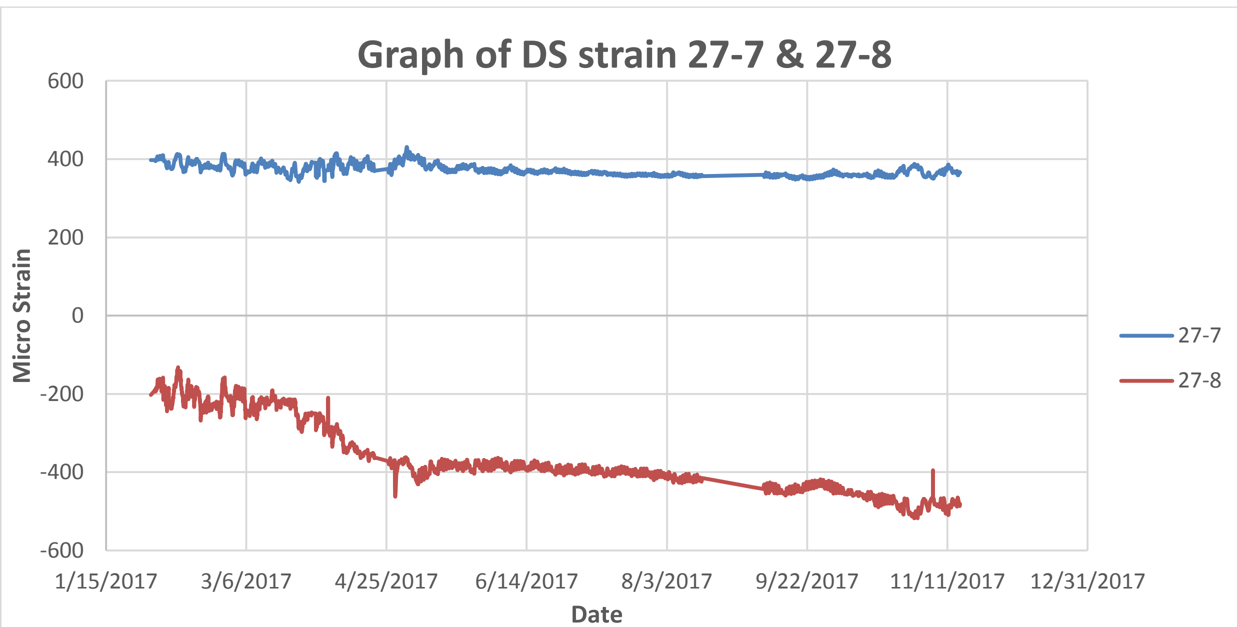
Drill Shaft 27



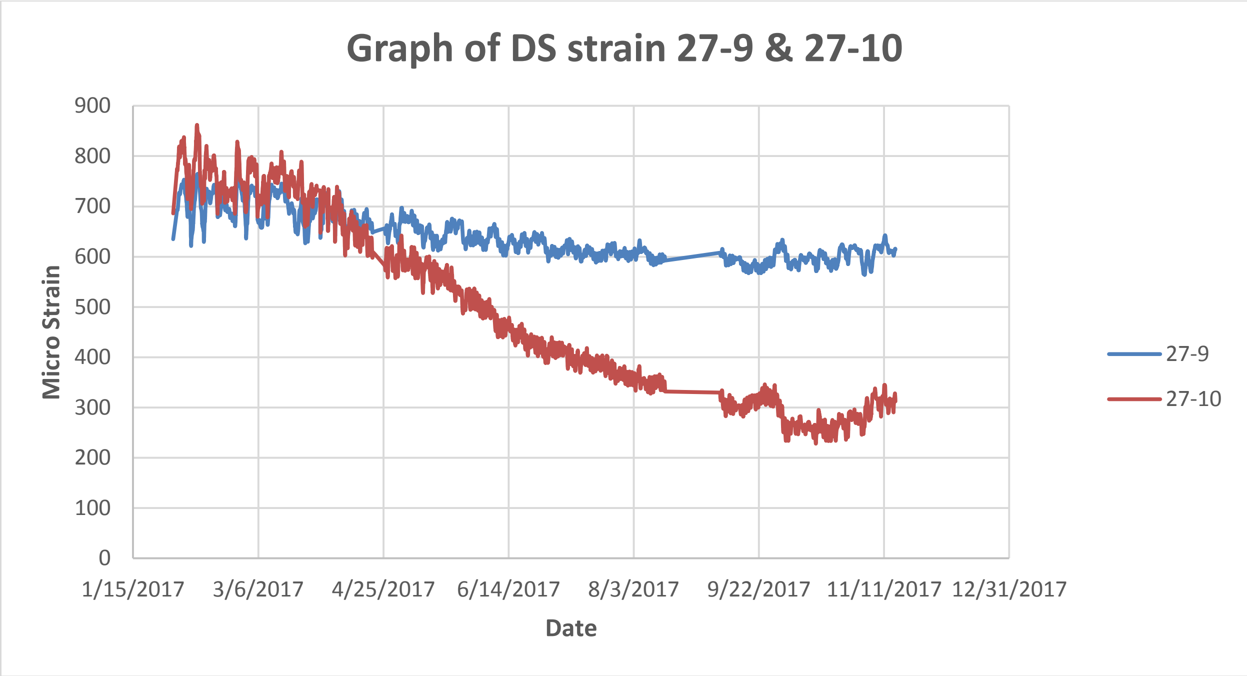




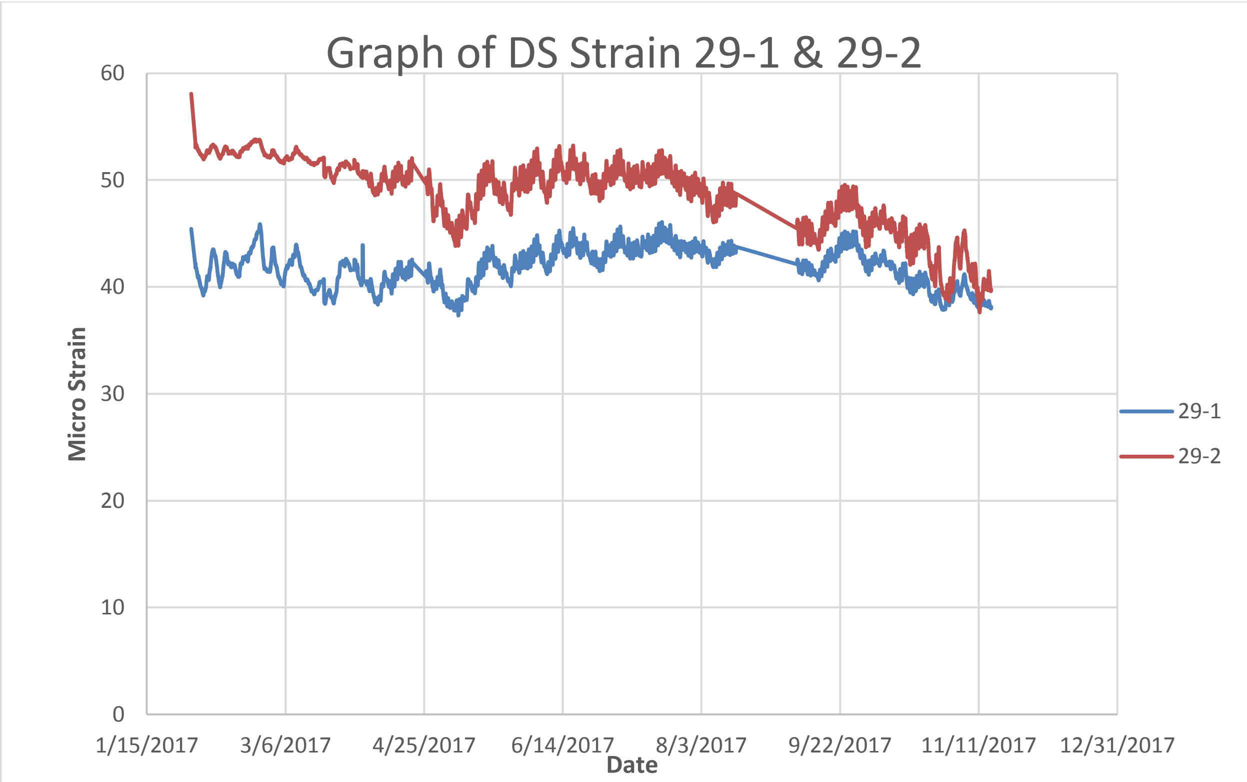
Graph of DS Strain 27-5 & 27-6
Micro strain
100
80
60
40
20
0
-20
-40
-60
-80
-100
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
27-5
27-6

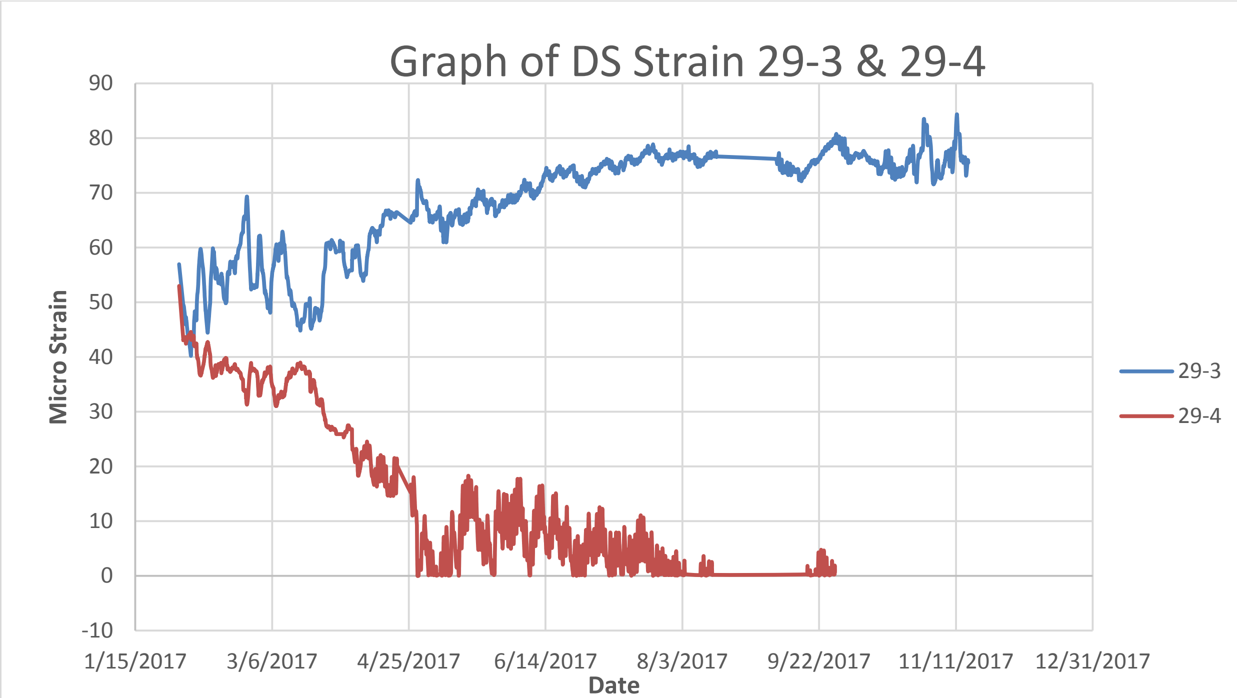


Graph of DS strain 27-7 & 27-8
Micro Strain
600
400
200
0
-200
-400
-600
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
27-7
27-8

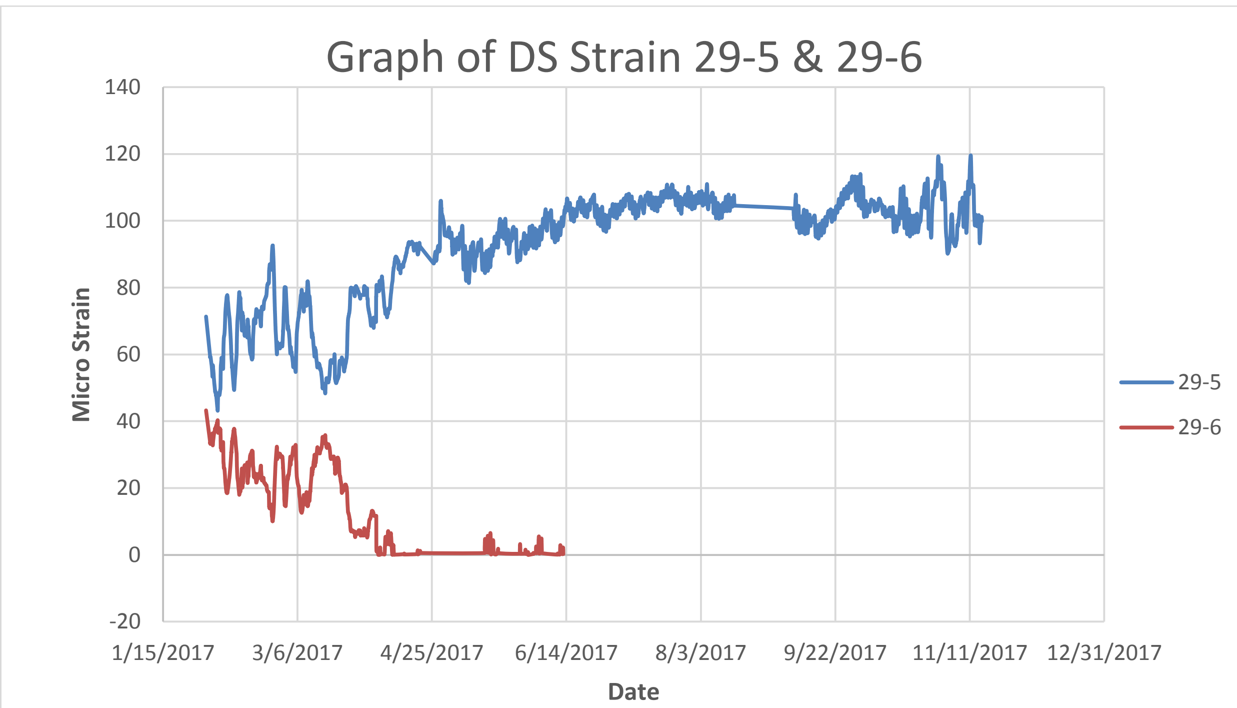


Drill Shaft 29

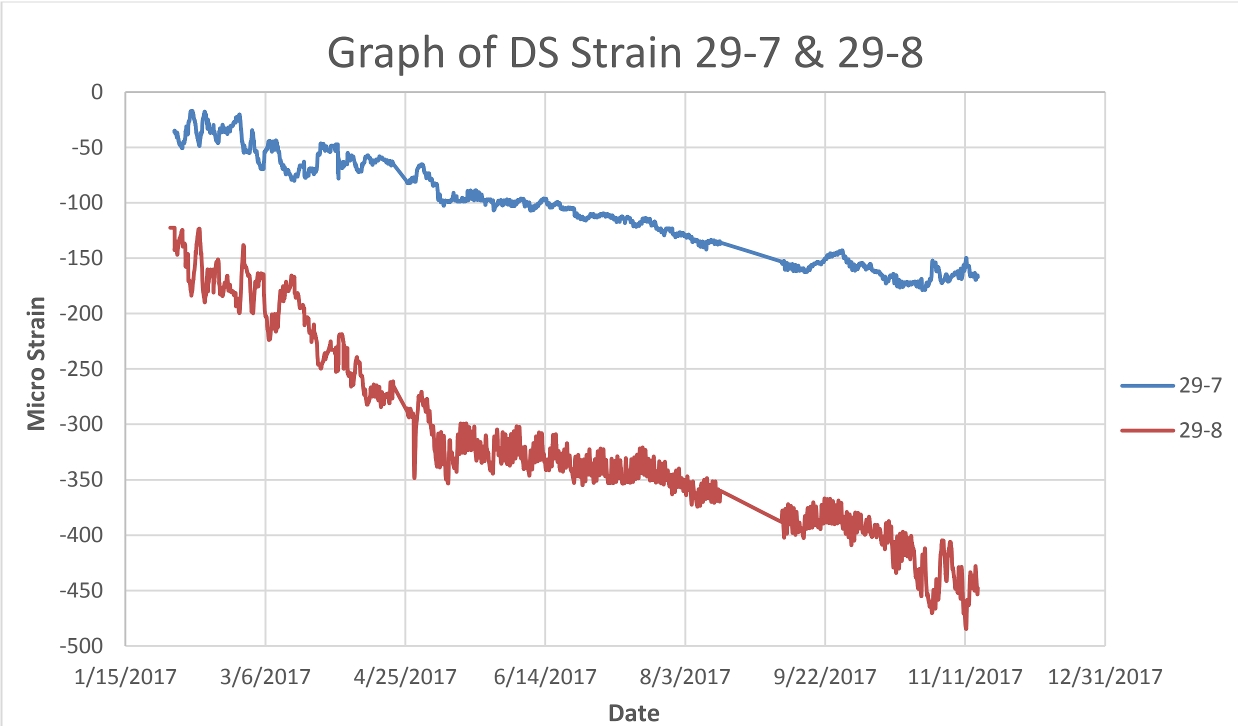




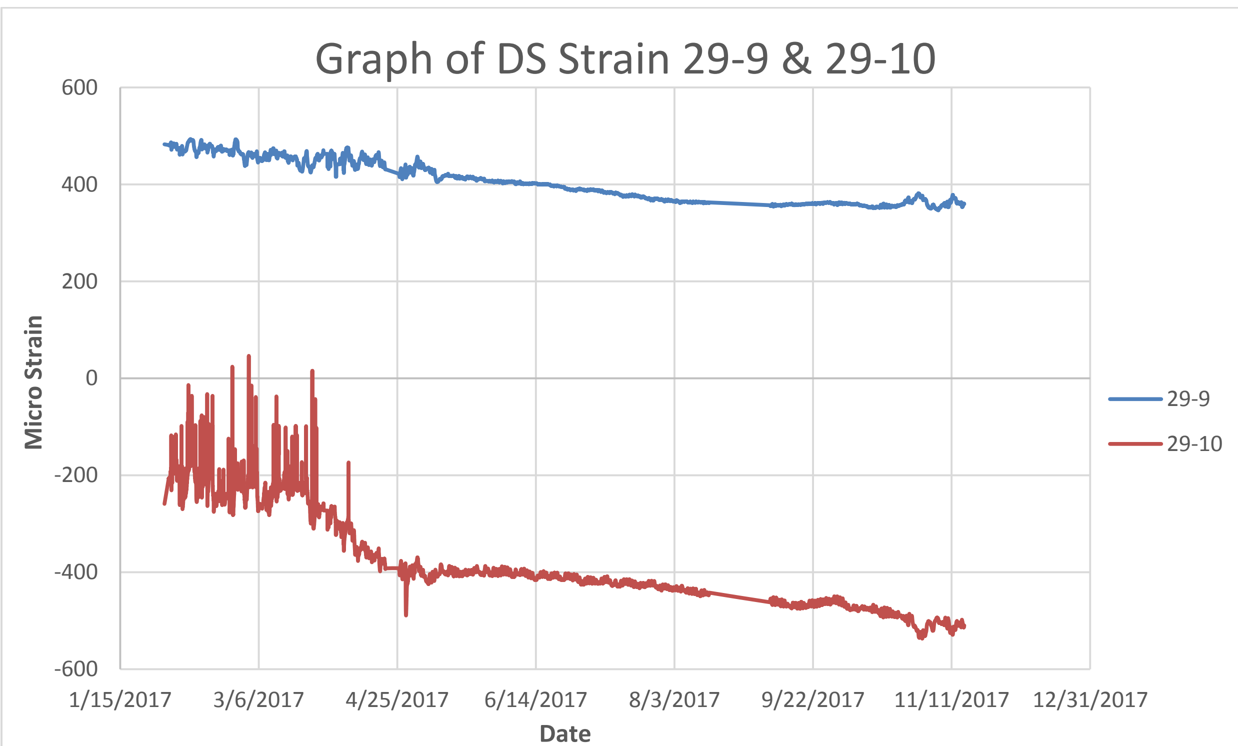
Graph of DS Strain 29-3 & 29-4
Micro Strain
90
80
70
60
50
40
30
20
10
0
-10
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
29-3
29-4



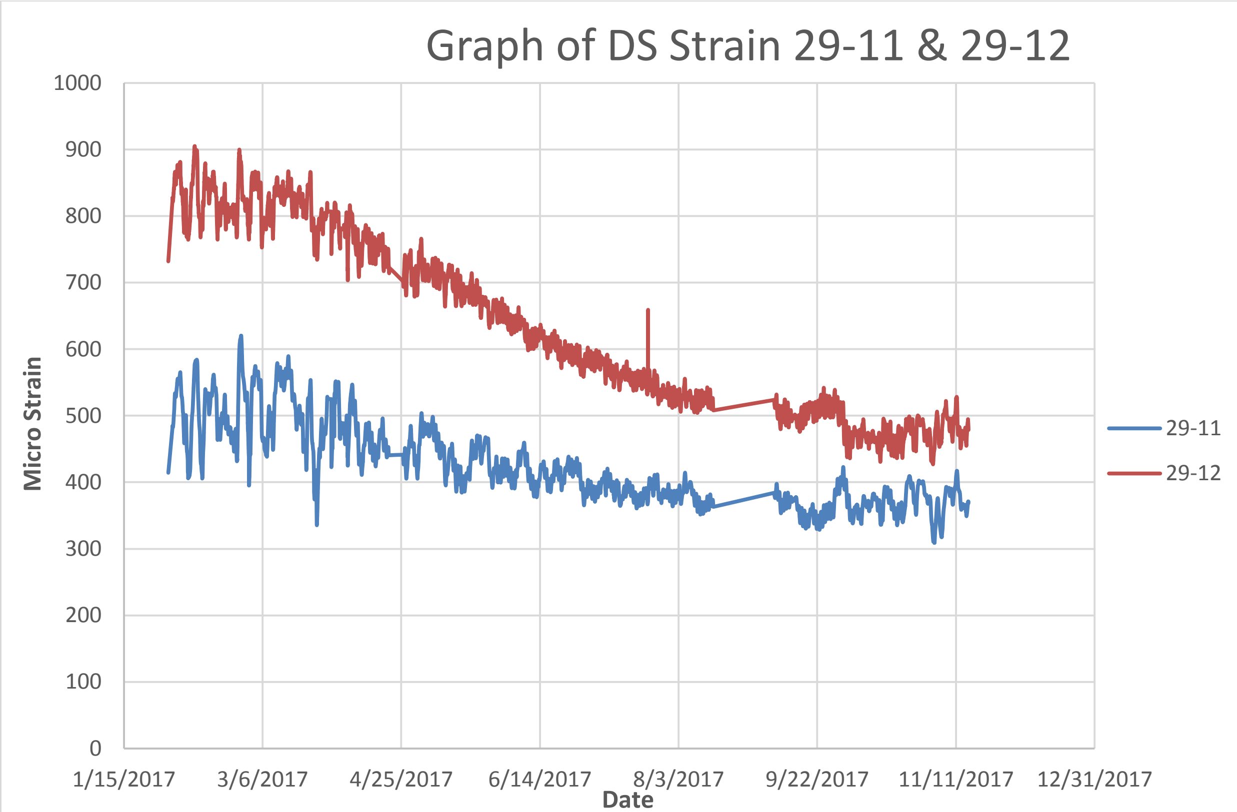
Graph of DS Strain 29-5 & 29-6
Micro Strain
140
120
100
80
60
40
20
0
-20
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
29-5
29-6



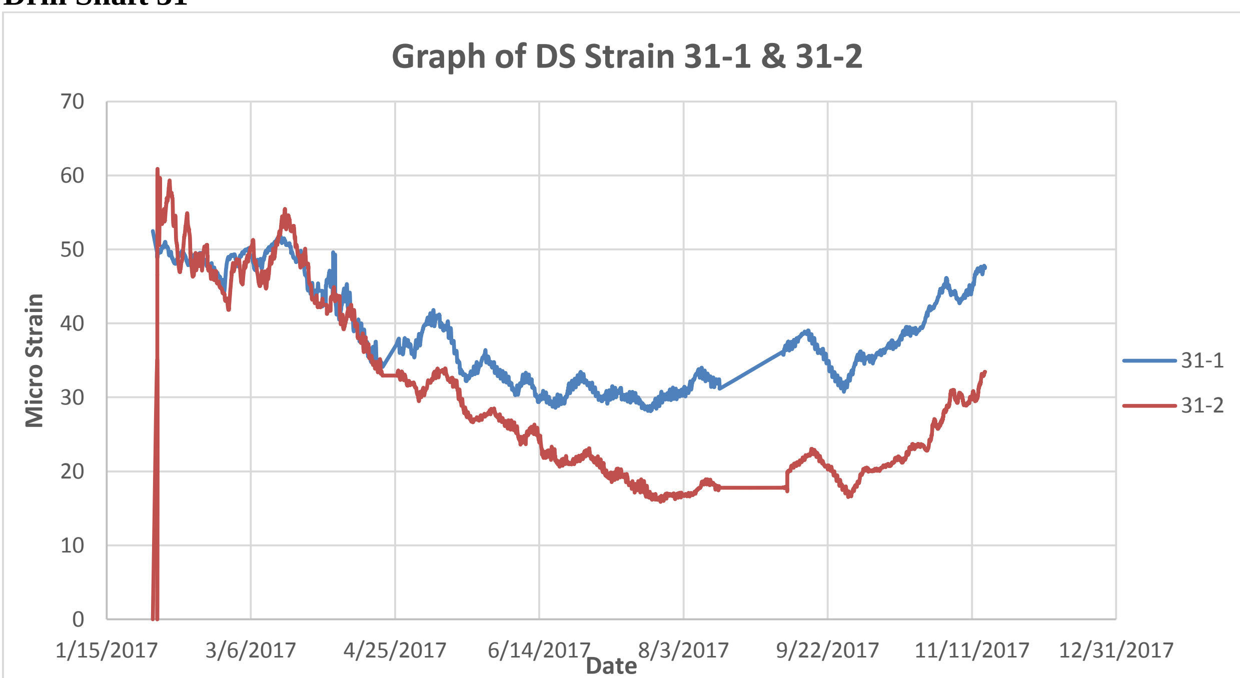
Graph of DS Strain 29-7 & 29-8
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
29-7
29-8

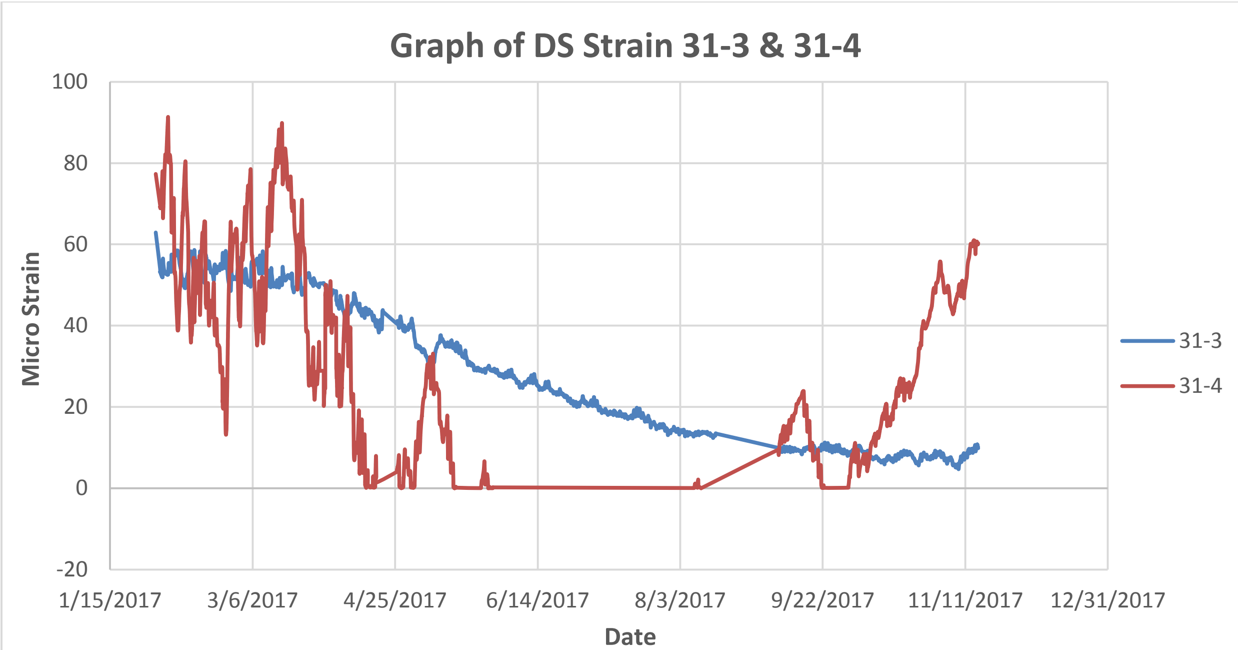


Graph of DS Strain 29-9 & 29-10
600
400
200
0
-200
-400
-600
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
29-9
29-10



Drill Shaft 31

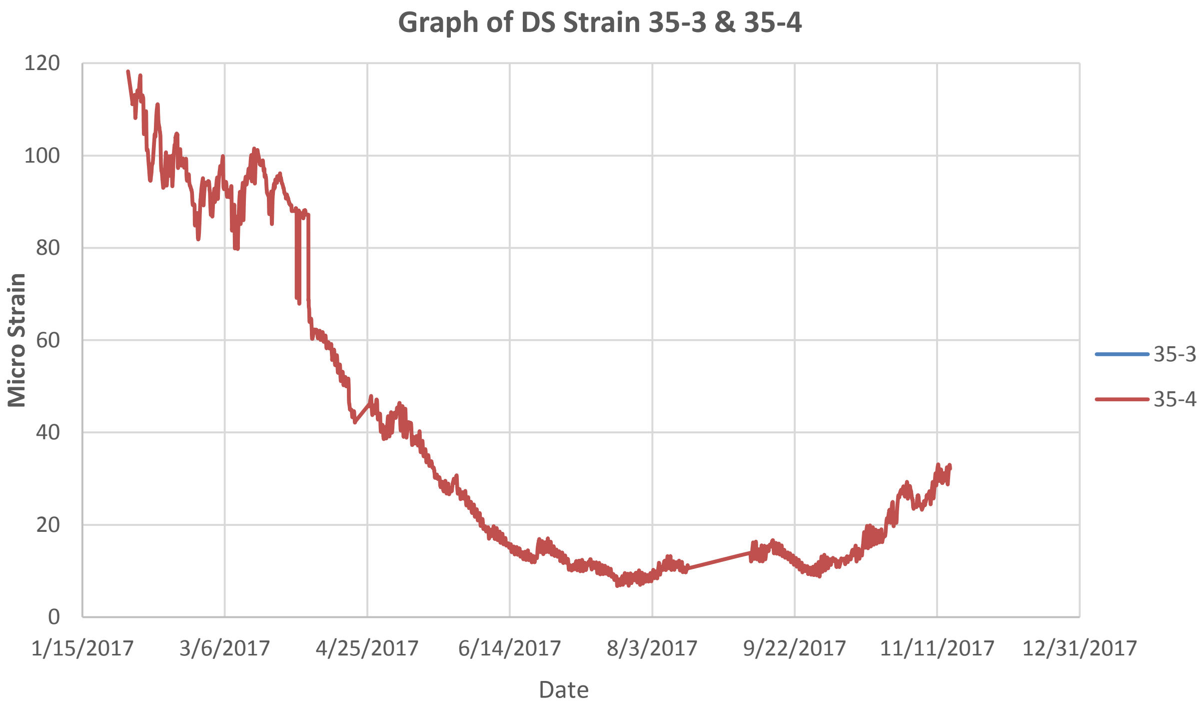


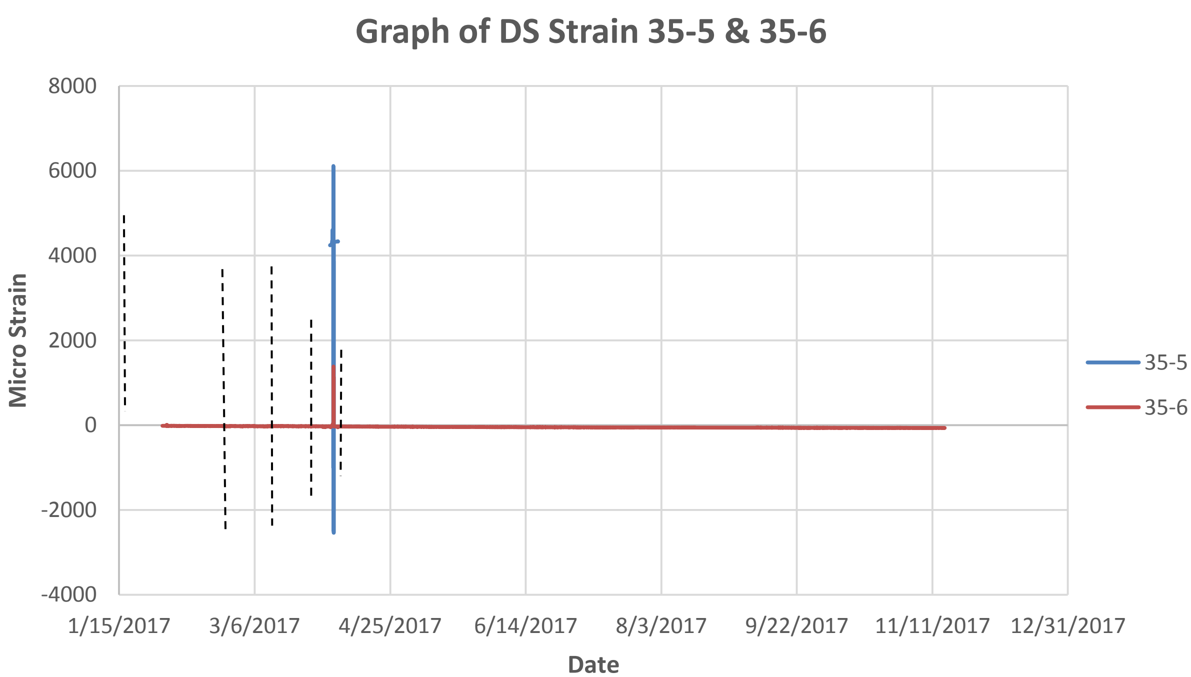


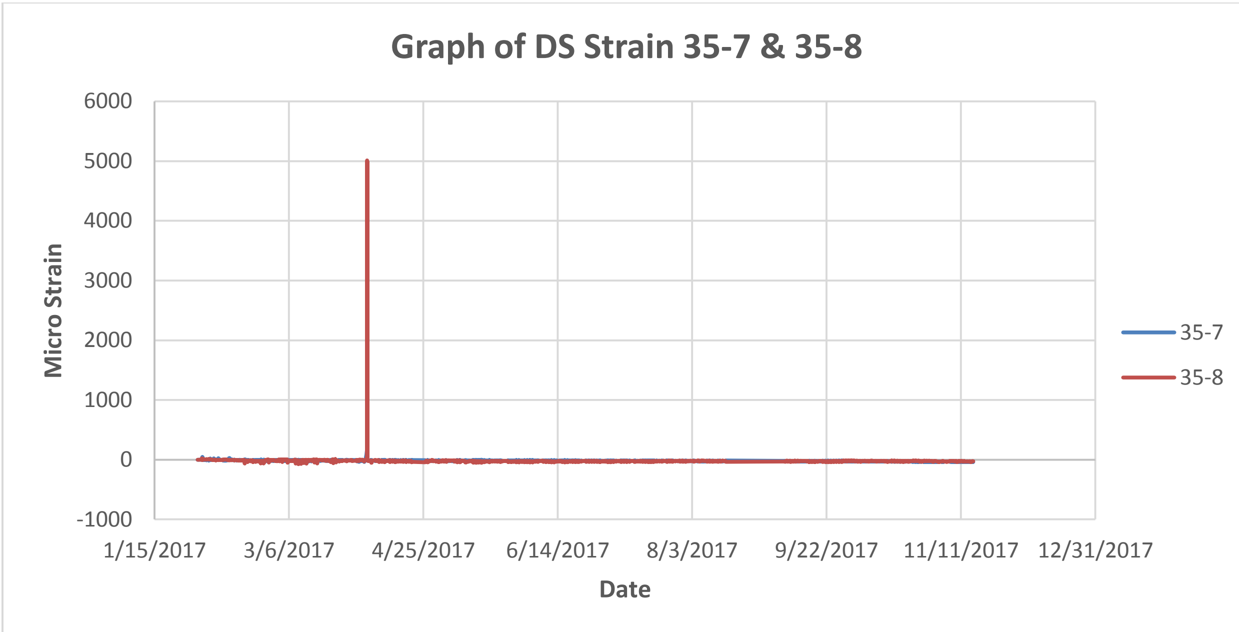
Note: Drill Shaft 31 Strain gages 31-5, 31-6, 31-7, 31-8, 31-9, and 31-10 were damaged during construction and did not report data.

Drill Shaft 35

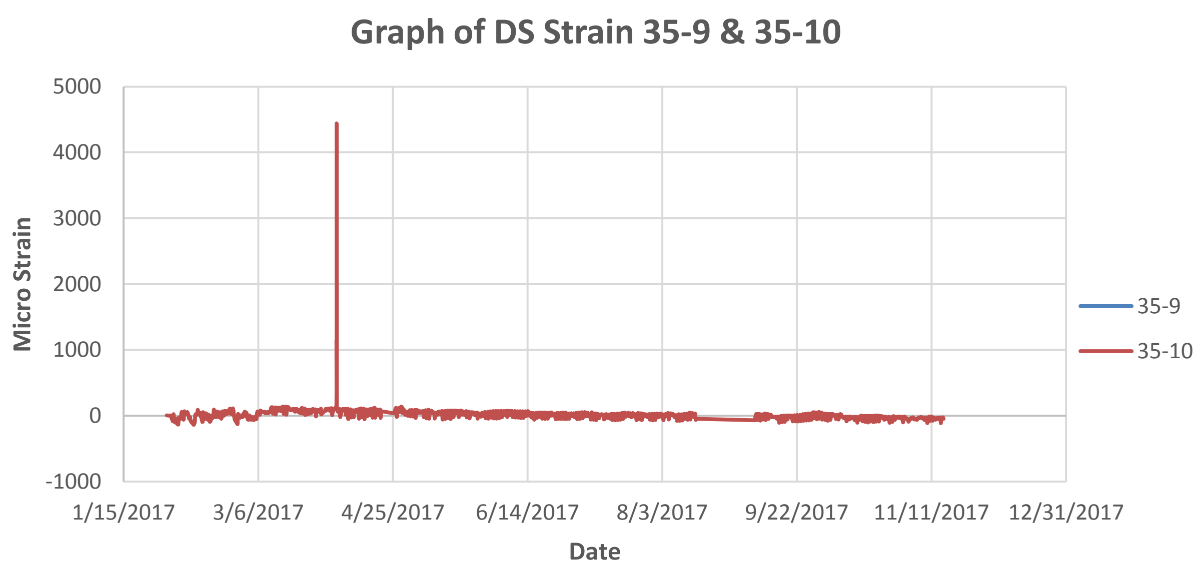
Note: Drill Shaft 35 Strain gages 35-1, 35-2, 35-3, 35-5, and 35-9 were damaged during construction and did not report data.


Graph of DS Strain 35-3 & 35-4
Micro Strain
120
100
80
60
40
20
0
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
35-3
35-4


Graph of DS Strain 35-5 & 35-6
Micro Strain
8000
6000
4000
2000
0
-2000
-4000
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
35-5
35-6



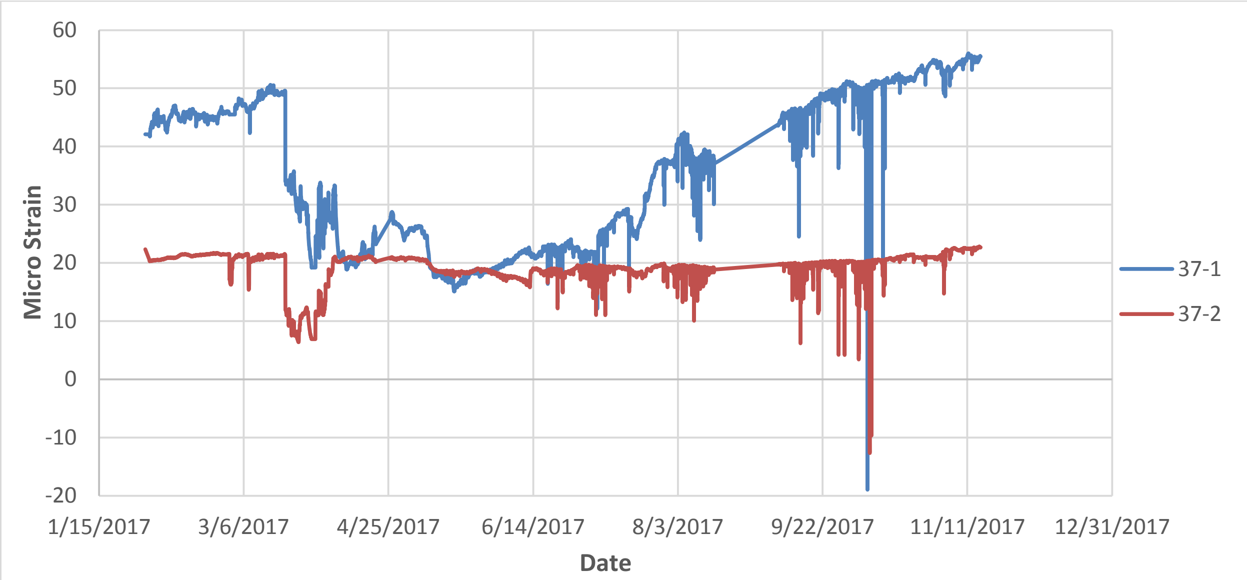
Graph of DS Strain 35-7 & 35-8
Micro Strain
6000
5000
4000
3000
2000
1000
0
-1000
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
35-7
35-8

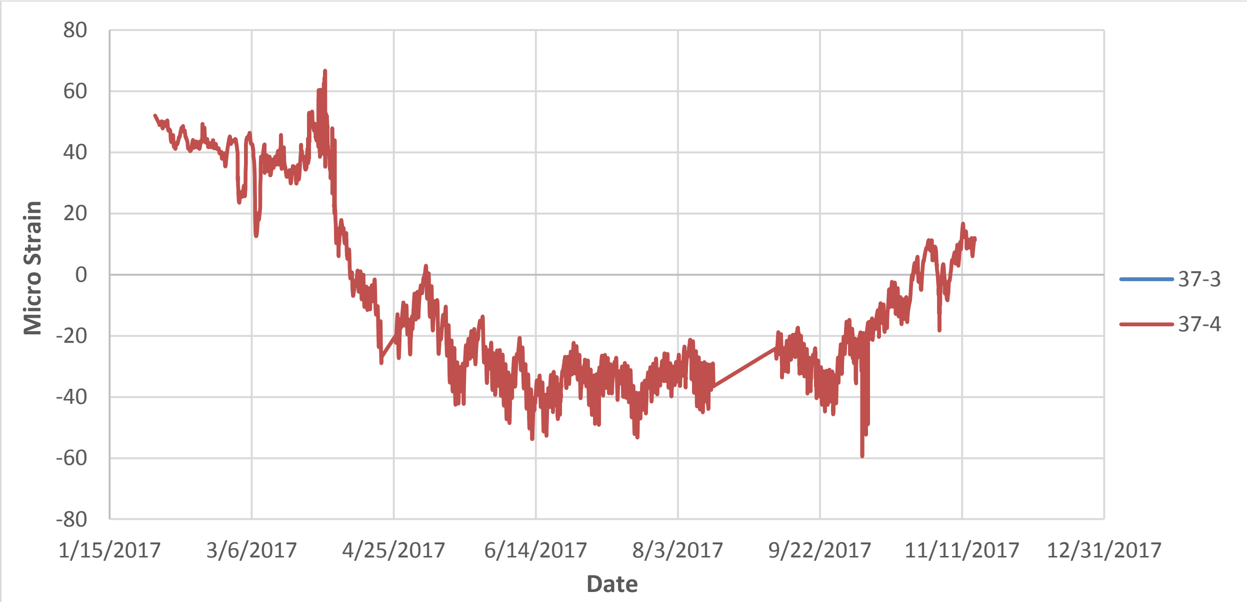


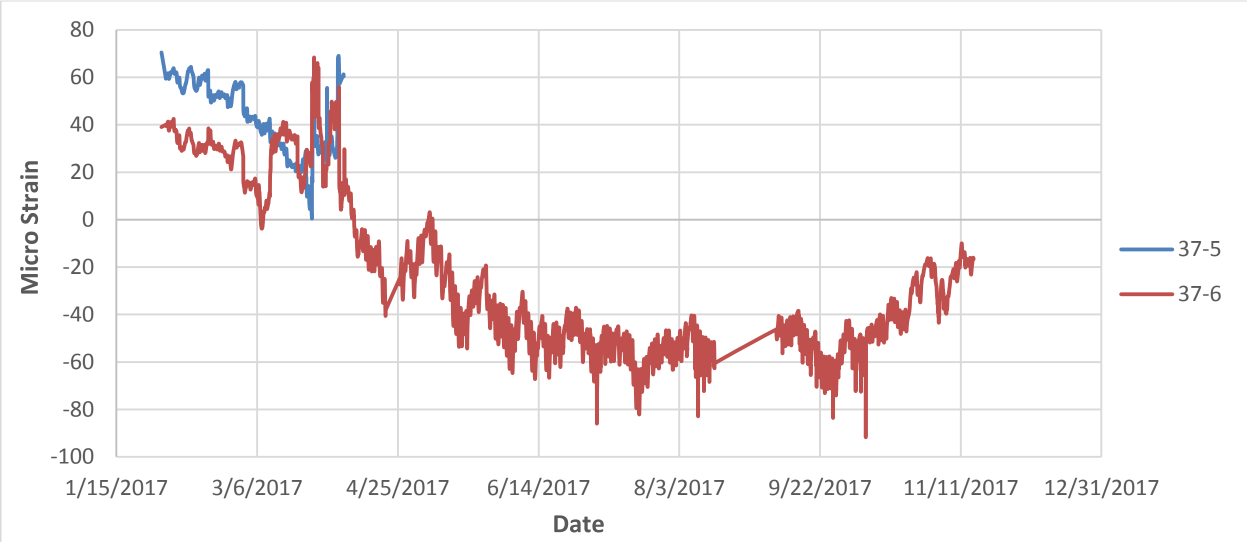
Graph of DS Strain 35-9 & 35-10
Micro Strain
5000
4000
3000
2000
1000
0
-1000
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
35-9
35-10

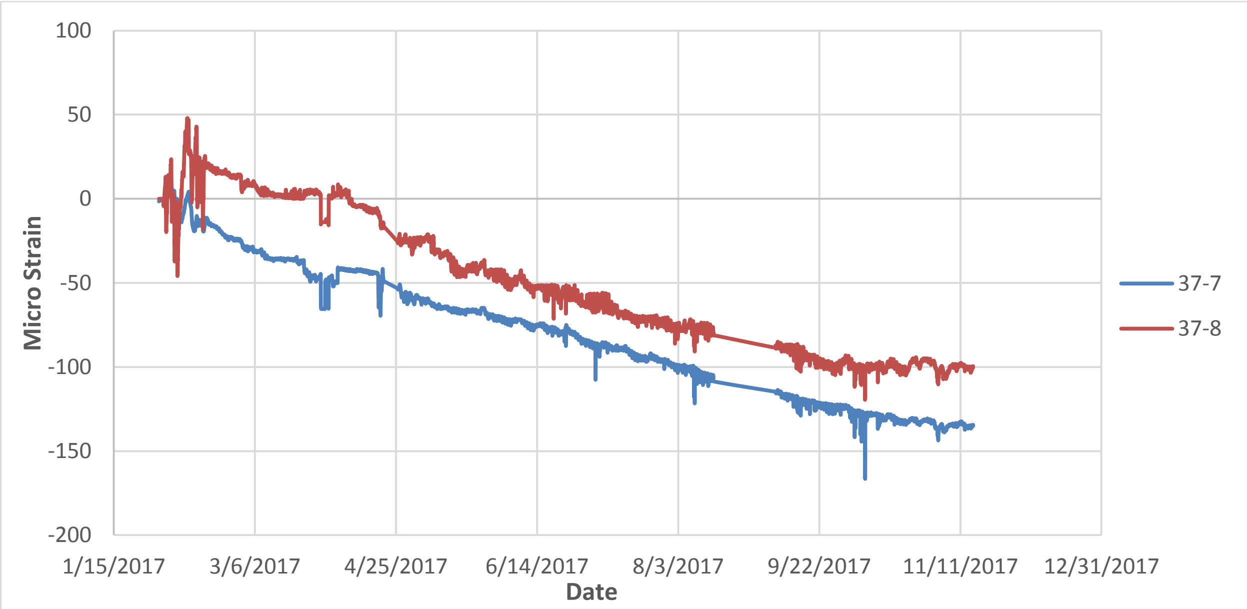
Drill Shaft 37

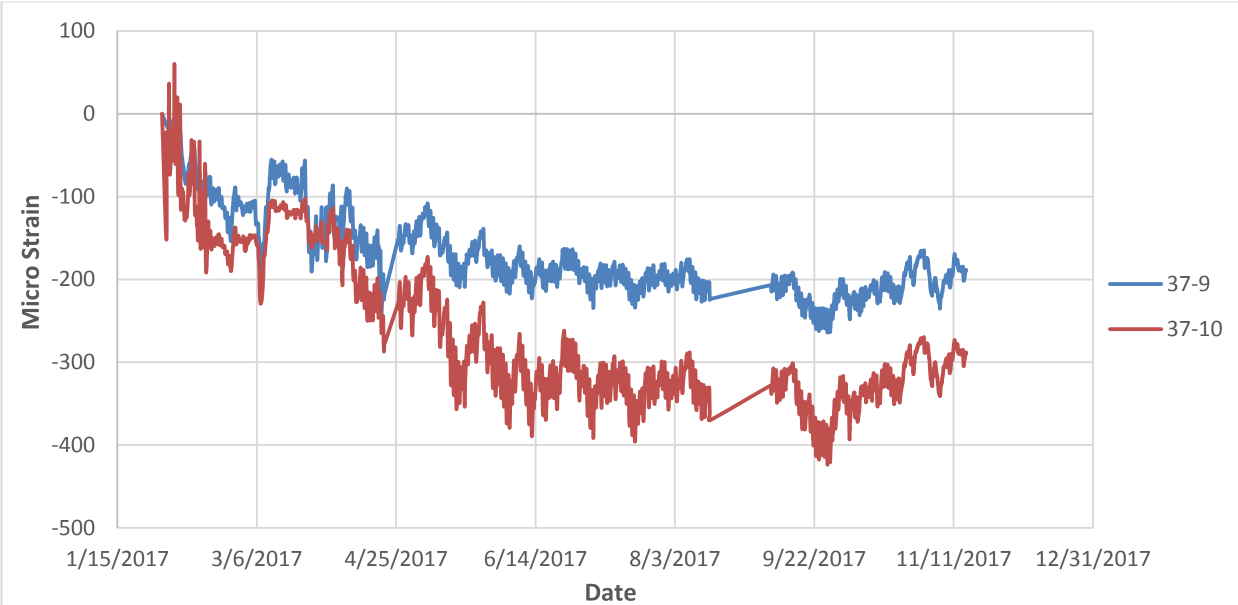
Note: Drill Shaft 37 Strain gages 37-3 was damaged during construction and did not report data. Strain gage 37-5 stopped reporting data in early April.

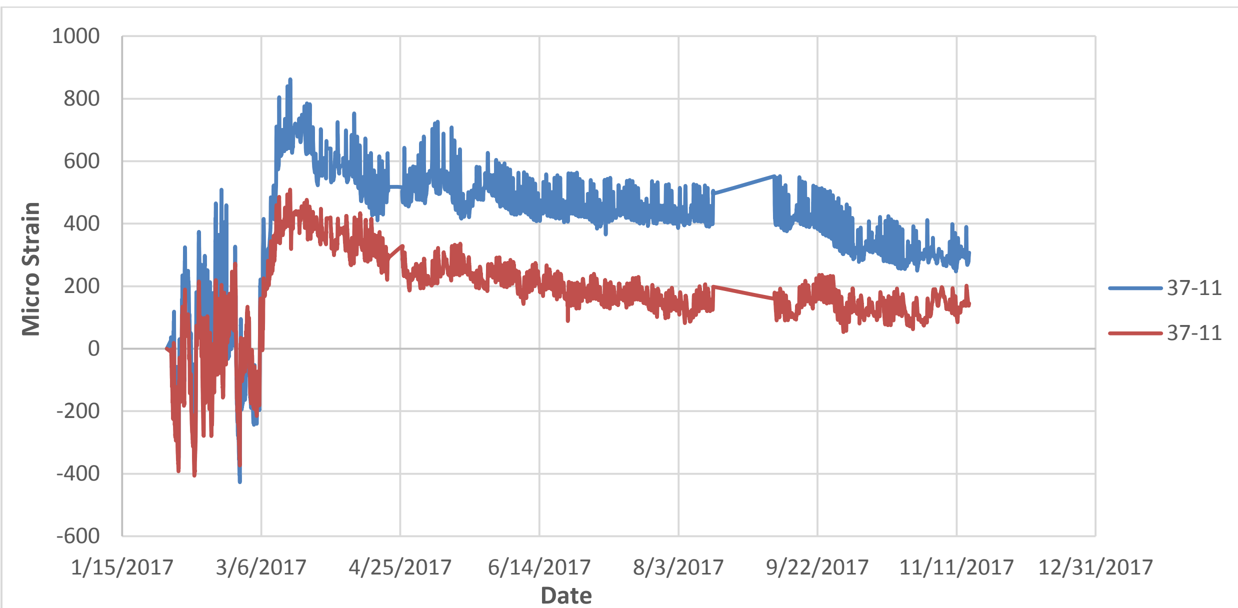





80
60
40
20
0
-20
-40
-60
-80
-100
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
37-5
37-6


100
50
0
-50
-100
-150
-200
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
37-7
37-8


100
0
-100
-200
-300
-400
-500
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
37-9
37-10


1000
800
600
400
200
0
-200
-400
-600
Micro Strain
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
Date
37-11
37-11

Appendix E. Drilled shaft stresses at strain gage positions as computed by SAP2000.

Guide to load abbreviations used in the tables (more than one abbreviation indicates more than one load applied in simulation)

Dead Load-Self weight – activated automatically by the program

DC: Dead Load from superstructure – applied as nodal load on the top of the bearing element

LL: Live load from the superstructure – applied as nodal load on the top of the bearing element

TU: Temperature load from superstructure – applied as load as deflection controlled nodal displacement on the top of the bearing element

EH: Lateral Earth Pressure – applied as triangular horizontal pressure on the back wall of the solid element

LS: Surcharge – applied as rectangular horizontal pressure on the back wall of the solid element

SERVICE: Service Load – all of the above loads combined

Drilled Shaft 27 (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
27-1	7.6	2.41	-239.86	-238.82	66.74	105.49	35.21	81.12	-209.58	-217.35
27-2	-4.12	-3.91	-245.73	-238.45	-31.96	-54.78	-14.49	-81.6	-262.73	-266.66
27-3	147.44	147.24	-267.22	-269.52	952.92	949.58	755.35	781.23	688.68	715.65
27-4	-145.36	-145.02	-266.28	-258.45	-937.85	-924.97	-757.99	-748.07	-1182.99	-1183.87
27-5	32.04	28.52	-61.18	-60.95	142.64	126.16	116.32	114.34	54.44	103.86
27-6	-34.6	-31.46	-65.92	-87.31	-142.45	-183.62	-101.87	-104.09	-195.28	-178.92
27-7	37.03	36.72	-118.33	-113.71	112.85	118.56	57.71	70.74	-9.38	-11.65
27-8	-35.88	-32.14	-98.27	-109.83	-122.49	-91.35	-69.76	-56.93	-194.23	-225.81
27-9	10.21	11.57	-82.01	-82.1	-20.63	-19.32	-37.5	-36.43	-96.11	-99.52
27-10	-10.35	-10.92	-76.83	-76.9	19.48	18.63	36.77	30.85	-54.02	-56.98
947	37.5	41.88	-54.58	-80.82	141.11	167.08	116.67	130.18	52.78	108.53
940	-37.33	-35.49	-78.26	-88.53	-159.68	-195.21	-118.77	-120.59	-198.46	-262.67

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
27-1	52	17	-1654	-1647	460	727	243	559	-1445	-1499
27-2	-28	-27	-1694	-1644	-220	-378	-100	-563	-1811	-1839
27-3	1017	1015	-1842	-1858	6570	6547	5208	5386	4748	4934
27-4	-1002	-1000	-1836	-1782	-6466	-6377	-5226	-5158	-8156	-8162
27-5	221	197	-422	-420	983	870	802	788	375	716
27-6	-239	-217	-455	-602	-982	-1266	-702	-718	-1346	-1234
27-7	255	253	-816	-784	778	817	398	488	-65	-80
27-8	-247	-222	-678	-757	-845	-630	-481	-393	-1339	-1557
27-9	70	80	-565	-566	-142	-133	-259	-251	-663	-686
27-10	-71	-75	-530	-530	134	128	254	213	-372	-393
947	259	289	-376	-557	973	1152	804	898	364	748
940	-257	-245	-540	-610	-1101	-1346	-819	-831	-1368	-1811

Drilled Shaft 29 (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
29-1	4.86	2.53	-231.53	-226.53	27.64	76.65	55.35	54.13	-238.4	-206.79
29-2	-8.53	-4.65	-203.83	-228.14	-42.29	-58.22	-37.61	-46.57	-271.49	-267.82
29-3	68.88	54.8	-216.04	-217.03	404.1	421.59	369.17	336.51	251.94	172.5
29-4	-71.53	-59.73	-209.17	-226.14	-263.39	-377.41	-346.96	-296.42	-602.57	-630.44
29-5	100.87	100.53	-233.13	-242.77	629.24	634.1	524.1	522.43	394.44	415.11
29-6	-102.1	-102.55	-217.62	-246.08	-394.77	-646.76	-518.69	-531.87	-889.12	-876.95
29-7	21.95	20.53	-77.64	-60.2	85.21	87.31	62.71	72.35	29.31	30.18
29-8	-24.72	-23.68	-66.75	-75.71	-54.25	-98.45	-48.68	-70.05	-182.38	-207.3
29-9	26.19	26.26	-79.38	-106.87	63.54	47.78	20.42	26.55	-53.89	-52.43
29-10	-27.01	-26.63	-91.14	-109.84	-19.46	-45.44	-5.8	-22.09	-176.6	-165.76
29-11	9.68	9.75	-71.32	-71.19	-12.64	-15.69	-30.56	-24.68	-93.61	-82.95
29-12	-8.14	-8.54	-55.53	-64.6	1.79	14.05	29.62	24.86	-56.45	-52.84

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
29-1	34	17	-1596	-1562	191	528	382	373	-1644	-1426
29-2	-59	-32	-1405	-1573	-292	-401	-259	-321	-1872	-1847
29-3	475	378	-1490	-1496	2786	2907	2545	2320	1737	1189
29-4	-493	-412	-1442	-1559	-1816	-2602	-2392	-2044	-4155	-4347
29-5	695	693	-1607	-1674	4338	4372	3614	3602	2720	2862
29-6	-704	-707	-1500	-1697	-2722	-4459	-3576	-3667	-6130	-6046
29-7	151	142	-535	-415	588	602	432	499	202	208
29-8	-170	-163	-460	-522	-374	-679	-336	-483	-1257	-1429
29-9	181	181	-547	-737	438	329	141	183	-372	-361
29-10	-186	-184	-628	-757	-134	-313	-40	-152	-1218	-1143
29-11	67	67	-492	-491	-87	-108	-211	-170	-645	-572
29-12	-56	-59	-383	-445	12	97	204	171	-389	-364

Drilled Shaft 31 (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
31-1	-11.76	-11.6	-69.44	-173	-88.47	-76.69	-66.74	-60.72	-251.6	-255.98
31-2	-1.26	-1.24	-185.3	-180.56	-42.88	-37.43	-34.74	-38.29	-218.24	-219.24
31-3	14.22	14.16	-214.65	-186.07	41.39	91.4	81.81	68.71	-110.69	-99.28
31-4	-32.79	-18.82	-193.83	-168.39	-192.09	-164.81	-190.47	-188.73	-403.24	-366.58
31-5	2.87	3.5	-22.22	0.29	6.81	0.76	5.49	3.23	11.32	1.55
31-6	-8.64	-19.29	-58.63	-57.19	-56.57	-66.56	-47.81	-97.05	-127.26	-151.89
31-7	3.64	2.84	-50.76	-61.12	-53.13	-53.76	-56.25	-44.91	-110	-102
31-8	-3.56	-3.99	-86.41	-85.82	12.1	2.92	3.66	-3.13	-101.89	-85.82
31-9	10.64	10.37	-30.56	-33.7	-38.47	13.69	-54.86	21.19	-14.65	-47.08
31-10	-12.89	-13.15	-22.87	-22.84	-49.94	-47.77	-35.12	-32.56	-74.81	-70.51
946	-9.8	-12.11	-57.92	-67.02	-62.36	-95.1	-49.02	-102.56	-128.09	-192.43
937	3.01	2.81	-24.31	0.4	7.92	0.8	6.11	4.1	7.08	2.6
936	1.46	-0.37	5.05	10.57	1.84	0.08	1.21	-1	5.02	-2.27

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
31-1	-81	-80	-479	-1193	-610	-529	-460	-419	-1735	-1765
31-2	-9	-9	-1278	-1245	-296	-258	-240	-264	-1505	-1512
31-3	98	98	-1480	-1283	285	630	564	474	-763	-685
31-4	-226	-130	-1336	-1161	-1324	-1136	-1313	-1301	-2780	-2527
31-5	20	24	-153	2	47	5	38	22	78	11
31-6	-60	-133	-404	-394	-390	-459	-330	-669	-877	-1047
31-7	25	20	-350	-421	-366	-371	-388	-310	-758	-703
31-8	-25	-28	-596	-592	83	20	25	-22	-703	-592
31-9	73	71	-211	-232	-265	94	-378	146	-101	-325
31-10	-89	-91	-158	-157	-344	-329	-242	-224	-516	-486
946	-68	-83	-399	-462	-430	-656	-338	-707	-883	-1327
937	21	19	-168	3	55	6	42	28	49	18
936	10	-3	35	73	13	1	8	-7	35	-16

Drilled Shaft 35 (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
35-1	-5.07	1.53	-111.04	-111.25	11.74	11.87	20.49	27.65	-117.64	-123.82
35-2	3.31	3.16	-111.53	-113.81	-27.99	-11.53	-21.39	-33.45	-119.86	-129.4
35-3	-10.41	-10.29	-92.22	-92.92	423.54	340.92	434.92	433.88	313.75	326.64
35-4	12.84	11.14	-125.49	-121.79	-152.99	-472.3	-465.83	-437.52	-410.69	-594.1
35-5	-2.61	-2.74	-31.46	-37.52	147.01	142.78	154.38	144.13	110.69	114.34
35-6	3.3	2.8	-46.53	-43.49	-175.35	-160.74	-175.07	-174.94	-209.1	-214.63
35-7	-0.61	-0.73	-13.68	-13.74	34.51	36.4	34.38	36.33	22.5	21.43
35-8	0.92	1.08	-25.97	-24.65	-79.86	-82.17	-78.26	-40.22	-101.32	25
35-9	-0.13	-0.34	-12.78	-14.48	19.93	22.07	22.43	20.29	6.46	9.32
35-10	-1.57	-1.78	-8.19	-7.92	-31.46	-30.12	-31.04	-30.68	-42.5	-36.36

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
35-1	-35	11	-766	-767	81	82	141	191	-811	-854
35-2	23	22	-769	-785	-193	-79	-147	-231	-826	-892
35-3	-72	-71	-636	-641	2920	2351	2999	2991	2163	2252
35-4	89	77	-865	-840	-1055	-3256	-3212	-3017	-2832	-4096
35-5	-18	-19	-217	-259	1014	984	1064	994	763	788
35-6	23	19	-321	-300	-1209	-1108	-1207	-1206	-1442	-1480
35-7	-4	-5	-94	-95	238	251	237	250	155	148
35-8	6	7	-179	-170	-551	-567	-540	-277	-699	172
35-9	-1	-2	-88	-100	137	152	155	140	45	64
35-10	-11	-12	-56	-55	-217	-208	-214	-212	-293	-251

Drilled Shaft 37 (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
37-1	5.69	3.46	-36.81	-71.83	65.28	100.71	62.15	90.33	95.17	224.61
37-2	5.61	5.58	-38.92	-37.82	-21.42	-43.21	-14.47	-10.76	-82.65	-26.66
37-3	0.65	3.07	-20	-20.12	719.23	556.01	761.27	583.72	574.79	652.63
37-4	10.78	10.08	-46.2	-45.54	-28.14	-450.71	-439.94	-511.91	-748.02	-679.86
37-5	-2.59	-2.34	-12.99	-14.35	1034.67	1042.88	1014.4	1039.93	1024.44	1034.89
37-6	12.4	12.92	-54.37	-53.49	-714.05	-830.45	-974.02	-973.69	-1008.33	-1007.15
37-7	-1.41	-1.1	-0.76	-1.25	117.84	112.55	109.97	119.84	77.99	126.78
37-8	2.23	1.82	-13.1	-8.64	-139.08	-130.76	-161.6	-137.46	-208.61	-150.15
37-9	0.73	0.45	-16.04	-14.52	409.31	411.98	413.73	410.28	401.6	396.7
37-10	4.11	3.99	-27.45	-27.73	-369.34	-368.16	-369.21	-377.58	-382.01	-395.95
37-11	-0.13	-0.35	-12.92	-12.95	17.84	17.63	14.61	19.33	5.33	6.62
37-12	1.47	1.44	-14.03	-15.16	-84.97	-56.06	-85.04	-84.03	-95.76	-97.45
949	0.11	-0.22	0.88	-0.67	-37.93	-31.68	-33.1	-24.01	-29.72	-38.02
948	-3.1	0.31	-3.58	-5.29	-69.45	-80.87	-88.13	-93.88	-70.9	-86.44
944	0.55	0.72	-0.39	-4.7	-42.22	-56.13	-49.78	-54.86	-54.26	-63.6

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
37-1	39	24	-254	-495	450	694	429	623	656	1549
37-2	39	38	-268	-261	-148	-298	-100	-74	-570	-184
37-3	4	21	-138	-139	4959	3834	5249	4025	3963	4500
37-4	74	69	-319	-314	-194	-3108	-3033	-3529	-5157	-4687
37-5	-18	-16	-90	-99	7134	7190	6994	7170	7063	7135
37-6	85	89	-375	-369	-4923	-5726	-6716	-6713	-6952	-6944
37-7	-10	-8	-5	-9	812	776	758	826	538	874
37-8	15	13	-90	-60	-959	-902	-1114	-948	-1438	-1035
37-9	5	3	-111	-100	2822	2841	2853	2829	2769	2735
37-10	28	28	-189	-191	-2547	-2538	-2546	-2603	-2634	-2730
37-11	-1	-2	-89	-89	123	122	101	133	37	46
37-12	10	10	-97	-105	-586	-387	-586	-579	-660	-672
949	1	-2	6	-5	-262	-218	-228	-166	-205	-262
948	-21	2	-25	-36	-479	-558	-608	-647	-489	-596
944	4	5	-3	-32	-291	-387	-343	-378	-374	-439

Other Gages (English units top, metric units bottom)

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)	initial (psi)	final (psi)
938	0.05	0.06	-0.28	-0.25	-0.12	-1.85	0.68	-1.87	-2.91	-0.78
939	0.03	-0.06	-0.05	-0.03	-0.84	-0.78	1.39	-0.52	0.93	-0.68
941	3.6	2.68	-0.13	0.09	59.76	53.78	58.54	53.36	55.91	56.41
942	4.02	2.38	0.09	-0.32	19.19	24.2	27.21	24.68	35.13	22.72
943	2.4	0.85	1.11	1.25	18.03	39.63	34.82	36.31	41.82	41.31

Strain gage	TU		DC LL		TU EH LS		EH LS		SERVICE	
	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)	initial (kPa)	final (kPa)
938	0.34	0.41	-1.93	-1.72	-0.83	-12.76	4.69	-12.89	-20.06	-5.38
939	0.21	-0.41	-0.34	-0.21	-5.79	-5.38	9.58	-3.59	6.41	-4.69
941	24.82	18.48	-0.90	0.62	412.03	370.80	403.62	367.90	385.49	388.93
942	27.72	16.41	0.62	-2.21	132.31	166.85	187.61	170.16	242.21	156.65
943	16.55	5.86	7.65	8.62	124.31	273.24	240.08	250.35	288.34	284.82