UNIVERSITY OF SOUTH FLORIDA

Civil & Environmental Engineering

DEFINING THE UPPER VISCOSITY LIMIT FOR MINERAL SLURRIES USED IN DRILLED SHAFT CONSTRUCTION

BDK84-977-24

FINAL REPORT

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FDOT




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Disclaimer

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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fL	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
kip	kilopound	4.45	kilonewtons	kN

APPROXIMATE CONVERSIONS TO 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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2
kN	kilonewtons	0.225	kilopound	kip

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

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16. Abstract

Drilled shaft construction often requires the use of drill slurry to maintain borehole stability during excavation and concreting. Florida Department of Transportation (FDOT) specifications require that the mineral slurry used for all primary structures must stay within viscosity limits of 30 and 50 sec/qt. This study addressed the rationale for defining the uppermost limit. The lower limit was previously investigated.

Two types of tests were undertaken to assess the effect of the upper viscosity limit on shaft performance. These tests, included: rebar pullout tests and side shear tests where the presence of slurry may impede the structural and geotechnical capacities, respectively. The results of these tests concluded that the presence of any bentonite slurry at the time of concreting reduces the rebar bond. Reductions ranged from 25 to 70% for slurry viscosity of 30 to 90 sec/qt, respectively. Similar tests with polymer slurry showed smaller reductions.

The effect on side shear was evaluated at both model and full scales. Model tests conducted over a wide range of viscosity showed only modest reductions in side shear for shafts cast with 50 sec/qt slurry when compared to shafts cast in 40 sec/qt slurry. However, shafts cast with 90 sec/qt slurry showed a marked increase in side shear.

Full-scale tests were conducted with both mineral and polymer slurry where four different slurries were used (average viscosities were: 40 sec/qt and 74 sec/qt bentonite as well as 50 sec/qt and 131 sec/qt polymer). Those tests showed use of higher viscosity bentonite or polymer slurry had no adverse effects on side shear (again compared to 40 sec/qt). In fact, increases in the unit side shear resistance of 19%, 12%, and 13% were recorded for 74 sec/qt bentonite, 50 sec/qt and 131 sec/qt polymer, respectively.

Finally, physical inspection of shafts with congested cages (6 in. clear space) cast in bentonite slurry indicated that there may exist potential durability issues as pathways/creases of trapped bentonite formed at all rebar locations that extended from the rebar out to the soil/concrete interface. This was most pronounced for slurry with viscosity greater than 40 sec/qt.

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Executive Summary

Construction of drilled shafts in the state of Florida generally requires the excavation to be stabilized either mechanically through the use of permanent or temporary casing or hydrostatically from mineral slurry pressure. Depending on the slurry type (mineral, polymer, or natural), a lower to higher differential fluid level is required. When compared to casing, slurry tends to use less expensive equipment (making it more attractive) but is more prone to complications associated with maintaining the borehole stability.

Until recently, Florida Department of Transportation (FDOT) required mineral slurry to achieve a Marsh funnel viscosity between 28 and 40 sec/qt. Concerns with the lower imit were addressed in a recent study (BDK-84-977-08) that resulted in its increase to 30 sec/qt. After which, the upper limit was conspicuously absent of a similar rationale for its selection. Nationwide, the upper limit ranges widely from 40 to 90 sec/qt again with no apparent supporting evidence. Providing a rationale for the upper limit determination formed the basis of the study.

Two types of tests were undertaken to assess the effect of the upper viscosity limit on shaft performance. These tests, included: rebar pullout tests and side shear tests where the presence of slurry may impede the structural and geotechnical capacities, respectively. The results of these tests concluded that the presence of any bentonite slurry at the time of concreting reduces the rebar bond. Reductions ranged from 25 to 70% for slurry viscosity of 30 to 90 sec/qt, respectively. Similar tests with polymer slurry showed smaller reductions.

The effect on side shear was evaluated at both model and full scales. Model tests conducted over a wide range of viscosity showed only modest reductions in side shear for shafts cast with 50 sec/qt slurry when compared to shafts cast in 40 sec/qt slurry. However, shafts cast with 90 sec/qt slurry showed a marked increase in side shear.

Full-scale tests were conducted with both mineral and polymer slurry where four different slurries were used (average viscosities were: 40 sec/qt and 74 sec/qt bentonite as well as 50 sec/qt and 131 sec/qt polymer). Those tests showed use of higher viscosity bentonite or polymer slurry had no adverse effects on side shear (again compared to 40 sec/qt). In fact, increases in the unit side shear resistance of 19%, 12%, and 13% were recorded for 74 sec/qt bentonite, 50 sec/qt and 131 sec/qt polymer, respectively.

Finally, physical inspection of shafts with congested cages (6 in. clear space) cast in bentonite slurry indicated that there may exist potential durability issues as pathways/creases of trapped bentonite formed at all rebar locations that extended from the rebar out to the soil/concrete interface. This was most pronounced for slurry with viscosity greater than 40 sec/qt.

Although preliminary, and from the durabililty standpoint, the study findings support a bentonite slurry upper viscosity limit of 40 sec/qt and not 50 sec/qt as recommended by the Federal Highway Administration.

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Chapter 1: Introduction

Drilled shafts are cylindrical, cast-in-place concrete, deep foundation elements that can be selected over driven piles on the basis of cost effectiveness, the soil strata encountered, and/or controlling vibrations due to sensitive surroundings. In general, the process of constructing shafts involves the drilled excavation of soil or rock using large diameter augers to form a deep cylindrical void space. Within the excavation, placement of the necessary reinforcing steel is followed by concrete (Figure 1.1). This process requires the in situ soils to act as the formwork and define the shape of the concrete. The greatest concern during this process is maintaining the stability of the excavation walls and preventing the collapse or sloughing of material into the boring during excavation or the concreting process. This project focused on the technique called wet construction, in which the water table is encountered and slurry is introduced to replace the volume of soil removed to prevent side wall collapse.

Figure 1.1 Shaft construction: excavation (left), cage placement (center) and concreting (right)

The stability of a drilled shaft excavation can be maintained mechanically, hydrostatically, or with a combination of both means. Mechanical stability implies the use of a full-length steel casing that holds the soil in place while the construction process is performed within. Upon completion of concreting, the casing is often fully extracted before the concrete cures, and the wet/fluid concrete pushes out against the excavation walls. For this process to be successful, the concrete must still be fluid with sufficient slump to move outward to the excavation walls upon casing extraction to promote side shear resistance.

Hydrostatic stabilization is the process of using fluid to stabilize the excavation. Fluid level is maintained higher than the surrounding ground water table, and thus, the net pressure (or flow) is always directed toward the soil walls to prevent side wall collapse. The fluid can be natural ground water, sea water, or slurry formed by mineral or polymer additives. However, it is never an acceptable practice to allow the ground water to flow in as a means to fill the excavation, as fluids flowing out of the soil will result in side wall collapse.

The selection of slurry products or additives is somewhat controversial as various states permit or restrict the use of some products. In all cases, the slurry pressure within the excavation must be higher than that of the existing ground water. This net pressure differential creates a tendency to flow from the excavation into the soil and not vice versa as noted above. Most commonly, a powdered clay mineral called bentonite is mixed with water to form a slurry with a density slightly higher than water, but with the added advantage of greatly slowing or completely sealing off flow into the surrounding soil while maintaining the pressure differential; this exerts a force against the soil that maintains stability. Polymer slurry products tend to only slow the inflow rate but do not completely seal off the excavation walls.

Although the term slurry can apply to the mixture of in-situ soil and water that forms without the use of additives, this report will restrict the definition of slurry to those fluids that are intentionally mixed from mineral or polymer additives.

With any slurry product, the ratio of product to water volume can be adjusted to meet the needs of the soil conditions encountered. For mineral slurries this ratio can range from 0.5 to 1.0 lb/gal while polymer products may only require $1/100^{th}$ of that required by mineral slurries. In all cases, a thick / viscous fluid results with properties selected on the basis of soil type and permeability (i.e. more viscous for more porous materials). Further, as various products may be more or less effective in achieving a desired level of performance, the amount of material is not as crucial as the resulting properties, specifically viscosity and density.

State and federal specifications have been established to control the slurry properties with the aim of circumventing the potential for problematic shafts. However, despite these efforts (specifications), problems persist. Figure 1.2 shows an example of a shaft that exhibited concrete flow problems, either from fresh concrete or slurry properties.

To date, specifications throughout the Unites States vary from state to state whereby both minimum and maximum values of viscosity are dictated. Many of these values were established on the basis of experience and not science. A recent study (Mullins, et al, 2010) provided a rational explanation for the determination of lower viscosity limits for such specifications. Therein, the viscosity was identified below which flow increased disproportionate to viscosity. The same study noted that no parallel study had been published to establish an upper limit and forms the basis of this study. To establish an upper limit two concerns arise: (1) at what point does the slurry become too thick or heavy to easily displace during concreting and (2) at what point does the slurry viscosity adversely affect the concrete bond with rebar or the surrounding soil.

Figure 1.2 Shaft exhumed to show poor concrete flow performance from slurry properties or fresh concrete properties.

This report discusses the types of testing that are necessary to define an upper viscosity limit. Such a threshold should ensure that slurry viscosity at or below the limit would not adversely affect the overall shaft performance while also remaining cognizant of construction procedures and not being needlessly restrictive or prescriptive. Of the two concerns identified above, this study focused mainly on the second dealing with slurry testing, the bond between concrete and reinforcing steel and the resulting effects on side shear.

The organization of the report is broken into the four ensuing chapters. Chapter 2 provides a background into the use of shafts and reasons for choosing drilled shafts over driven piles, the process of constructing drilled shafts, quality control, slurry products and testing. The variation in state specifications is also presented which highlights the need for a rational upper limit specification. Chapter 3 is broken into three sections discussing the preparation and testing in each focus area: slurry and rebar pullout testing, side shear effects on model shafts constructed with different slurry viscosity, and full scale pull out testing. Sample results from each test matrix are also provided. Chapter 4 discusses the results of the testing from each focus area. Post testing evaluation of the test specimens is also discussed as it pertains to integrity of shaft constructed using the wet / slurry method. And finally, Chapter 5 provides a discussion and summary of the results as well as recommendations for defining an upper viscosity limit and future research or testing that may further the overall understanding of the phenomena observed.

Chapter 2: Background

The following chapter provides a brief history of drilled shafts, and the role slurry plays in the construction of drilled shafts.

2.1 Drilled Shafts

When a traditional spread or shallow footing is unable to carry the required loads a deep foundation is required. Of the many types of deep foundations, two of the most popular are driven piles and drilled shafts. Driven piles are steel, timber or pre-cast concrete elements that are driven to the appropriate depth wherein the pile lengths are determined based on capacity requirements, shipping limitations or physical constraints of the installation method. Drilled shafts, on the other hand, are cast-in-place concrete elements where the practical upper limit of length is 30 to 40 diameters of the shaft (e.g. 4-foot diameter can be 120 to 160-feet deep). The Federal Highway Administration (FHWA) defines a drilled shaft as a *"cast-in-place deep foundation element constructed in a drilled hole that is stabilized to allow controlled placement of reinforcement and concrete"* (FHWA 2010).

Drilled shafts have evolved from caissons which were first used during the late 1800's. Caissons were originally precast foundations that were sunk in place to a depth that provided suitable bearing or cast-in-place in a hand dug braced excavations that were progressively advanced in lengths equivalent to available board lengths used to provide lateral wall stability. The excavation concept for drilled shafts has not been altered much since the 1940's but improvements in technology have allowed the process to become more efficient and a viable option for any type of construction.

Of the aforementioned deep foundations, the drilled shaft can be more cost effective than driven piles in some circumstances. This is due in part to the load carrying capacity of a drilled shaft versus that of a driven pile where large axial and lateral loads can be withstood and the moment capacities are significantly greater. This often allows for fewer elements when using drilled shafts and in turn, allows for an overall smaller cap. For example, in cases exposed to large vessel collision forces, hundreds of piles can be replaced with several drilled shafts.

Drilled shaft construction is also the preferred method when dealing with varying geological strata. Driven piles are restricted to handling and shipping lengths as well as driving criteria set to ensure the piles are not damaged during driving. This is particularly problematic when encountering denser layers near the surface that require drilling prior to driving. This is not an issue with drilled shafts since the elements are cast-in-place, and the boreholes are drilled to the proper depth (reported to over 300 feet) to reach the required capacity.

Drilled shaft construction has other benefits over driven piles wherein minimal vibrations and noise are produced during drilling and concrete placement. This makes drilled shafts more conducive for environments (urban areas) where vibrations are a major concern or when near sensitive structures.

Despite the possible advantages of drilled shafts, they must be constructed properly, but this is where the design and quality control must be addressed. When designing foundations, drilled shafts have the same structural resistance (φ) factor as above ground columns that can be visually inspected. As visual inspection is not possible for underground structures, this highlights the need for quality assurance procedures and test methods to provide the same level of above ground construction practices but for blindly constructed shafts.

2.2 Shaft Construction

Drilled shaft construction is performed in three basic steps: (1) excavation, (2) placement of reinforcing cage, and (3) concreting. The process requires a drill rig capable of drilling to the depth and diameters needed to achieve the design capacity. Drill rigs are typically mechanically or hydraulically driven with telescoping Kelley bars that will vary in length and capacity attached to a multi-flight auger (Figure 2.1). The auger is not continuous-flight, but rather 2 or 3 flights. Once the proper tip elevation is reached, the auger is replaced with a clean out bucket in order to remove any loose material from the bottom of the excavation.

The most important aspect of the construction process is maintaining the integrity of the excavation walls. This is done either mechanically, hydrostatically, or a combination of both. Mechanical stabilization is achieved by inserting a steel casing and drilling inside the casing. The steel casing can either be permanent or temporary. Hydrostatic stabilization (wet construction) involves introducing slurry into the excavation that provides a net outward pressure against the insitu soil and overcomes the ground water tendency to flow inward. Therein, the slurry inside the excavation is typically maintained 4 to 8-feet above the water table depending on the type of slurry. Of these methods, slurry type construction tends to be more cost effective; however, it requires more quality control. When using slurry, a temporary surface casing is often required for the upper portion of the shaft in order to: raise the slurry level, increase the hydrostatic pressure on the walls of the excavation and stabilize near surface soils from construction activities (Figure 2.2).

Figure 2.1 Clean out bucket (left) and flight auger (right) for shaft excavation.

Figure 2.2 Temporary surface casing providing containment for slurry.

Although slurry is most commonly formed by adding dry clay powder to water, slurry can be categorized as mineral, polymer, or natural. Mineral implies that dry clay powder such as bentonite (sodium montmorillonite) or attapulgite (calcium montmorillonite) was used to form the slurry. Attapulgite is used in saline environments. Polymer slurries are typically a form of polyacrylamide and water; and natural slurries are formed when plain water mixes with the natural soil. Plain water is introduced when mechanical stabilization is used to simply offset the inflow of ground water through the bottom of the casing which needlessly loosens the soils below the shaft tip.

The use of slurry to maintain the boring plays several roles, depending on the type of slurry. Primarily, mineral slurry provides lateral stability and a minimum of 4 ft of head differential between the slurry and ground water table is normally recommended. For horizontal drilling or SPT explorations, the slurry provides a method to transport the cuttings to the surface. For drilled shafts, suspended solids in the slurry are discharged with the slurry during concreting. The amount of suspended sand is typically restricted to 4% by volume, but higher viscosity mineral slurry (with higher gel strength) can suspend up to 10% or more without depositing sand on the concrete. When excess sand is found to be present in the slurry, the slurry should be de-sanded in order to reduce the potential of sand pockets from forming in the shaft concrete.

In order for the mineral slurry to function properly, it must be fully hydrated which could take 24 hours or more depending on the mixing method. In such cases, some material goes unused and remains at the bottom of the mixing tanks until it is sufficiently agitated / recirculated into suspension. However, rapid hydration devices are available that perform this step in a matter of minutes (Mullins, 2010).

Polymer slurry acts similarly to mineral slurries, in that it requires a minimum head to maintain the hydrostatic pressure on the excavation walls. However, polymer slurry is thought to require a slightly larger head than that of mineral (e.g. 6 – 8 feet) due to the lower density. Where the mineral slurry suspends the solids by way of mineral gel strength, polymer slurry does not develop gel strength and allows the cuttings to fall-out through the material requiring only cleanout from the bottom of the excavation. Therefore, de-sanding is not necessary, but a sit time may be imposed.

Upon reaching the proper tip elevation, the excavation is cleaned with the clean out bucket and inspected for proper depth and dimensions. Once approved, the reinforcement is lowered into the excavation. Prior to concrete placement, the properties of the slurry are verified, and once approved, the concrete is placed.

Concrete is placed via a tremie pipe or pump line in order to prevent segregation of the concrete; concrete is essentially pumped to the bottom of the excavation through a 6 - 12-inch pipe and the slurry is displaced as the concrete level rises. It was originally thought that as the concrete was placed there was a shearing / scouring effect on the walls of the excavation in turn scrubbing away any filter cake that may have formed (when mineral slurry is used). However, as concrete is placed, it has been shown to fill up the center of the reinforcement cage, and flow outwardly pushing through the reinforcement and then resting against the walls of the excavation (Mullins et al, 2005). This effect was shown to increase with tighter cage spacing and when the tremie pipe was not centered in the opening.

When placing concrete, the tremie must be embedded into the rising concrete level to a depth sufficient to ensure that there is no unwanted segregation. However, until that depth of concrete is achieved within the excavation, some segregation must be expected. The tremie pipe must not be removed at a rate that encroaches on this requirement. As the concrete level rises toward the top of shaft elevation, the slurry is expelled; and concrete overflows from the excavation to ensure all slurry is properly removal.

2.3 Mineral Slurry

Mineral slurry is the most widely used material when employing wet construction methods. Sodium montmorillonite (bentonite) is a natural occurring mineral with a massive absorption capacity which is beneficial in a drilling fluid. The majority of bentonite production in the United States is in the Black Hills area of South Dakota, Montana, and Wyoming (Grim, 1978). This particular bentonite contains higher amounts of the crystallite smectite. The amount of smectite within the bentonite is directly related to performance in that it enhances the absorption capacity of bentonite and results in higher viscosity.

When bentonite is mixed with water, typically keeping a maximum of five percent solids, it creates slurry with properties conducive for drilling. Bentonite changes water from a Newtonian fluid to a non-Newtonian fluid with properties of a Bingham plastic. A Newtonian fluid will maintain the same viscosity regardless of the rate of shear (viscosity can vary with temperature), whereas a non-Newtonian fluids viscosity will vary as the shear rate is varied. A Bingham plastic is a fluid that can have plastic properties and would require a stress to begin flow. The stress required to begin the flow of the material is called the yield point of the fluid (Baker Hughes, 2006). It is these characteristics that allows for the fluid to have gel strength. Gel strength is the ability of the fluid to regain its viscosity after shear thinning, and gel strength allows the slurry to carry the cuttings in suspension. According to the American Petroleum Institute (API), there are two gel strengths measured at 10 seconds and 10 minutes after the material has been agitated (API, 2009). The test requires a viscometer, and it is recommended that the sample be mixed at 600 rpm, sit for the allotted time, then measure the maximum shear stress while rotating at 3 rpm.

When the mineral slurry is introduced into the excavation, it begins to form a filter cake, which is a thin layer, along the walls as it deposits clay particles while flowing into the surrounding soils. This thin layer, along with the higher hydrostatic pressure of the slurry, prevents ground water intrusion which in turn helps to prevent the sloughing the side wall material. As the geology changes, the properties of the slurry must be monitored to ensure there are no adverse changes disabling the filter cake formation. For more porous soils, additional bentonite is typically introduced into the suspension (CETCO, 2013).

2.4 Polymer Slurry

Polymer slurries are formed when polyacrylamide materials are mixed with water (other polymer types exist but are less common). The mixture forms long polymer chains that are vital for proper performance. When mixing polymer slurries, dry powder is introduced at controlled rates into quickly moving water to prevent clumping. Initial mixing is usually performed with a centrifugal pump to provide a constant stream. However, centrifugal pumps tend to shear the long polymer chains, which then require time for the chains to reform. Therefore, recirculation with a diaphragm pump is preferred over more traditional centrifugal pumps.

The performance of polymer slurry is based solely on the viscosity of the material. Where mineral slurries form a filter cake barrier, polymer slurry flows into the walls of the excavation in order to maintain stability and prevents ground water intrusion. As noted earlier, there is no gel strength with polymer slurries so cuttings cannot be carried in suspension. Therefore, all material can be removed more immediately without concern of trapping sand in the shaft concrete. This is also beneficial when reusing the slurry since it reduces the need for de-sanding the slurry.

2.5 Quality Control

When using slurry, mineral or polymer, quality control is needed to ensure that the material will function properly. It is common practice to verify the properties of the slurry prior to introduction into the excavation for viscosity, density, and pH in the field. The same tests are to be performed prior to the placement of concrete as well, but the sand content becomes more important at that time. These test methods are based on the American Petroleum Institute (API) test methods provided in API 13B-1.

2.6 Viscosity (API 13B-1.6, FM 8-RP13B-2)

The viscosity of a fluid is its ability to resist flow under shear stress. Viscosity that is verified with a viscometer is the ratio of shear stress to strain rate. When determining the viscosity in the field, a Marsh funnel is used (Figure 2.3). This determines the time required for one quart of material to pass through a standard funnel (sec/qt). The material tested is passed first through a No. 12 sieve when introduced to the funnel. The Marsh funnel is based on the principles of the falling head flow; therein, fluid flows faster with higher pressure (when the funnel is full) and progressively slows as the pressure decreases (funnel empties) As a result, longer emptying times indicate higher viscosity, but the Marsh funnel test is not a true viscosity test (shear stress/strain rate). The test is simply an indicator of gel strength and/or the presence of clay mineral content. Therefore, the flow times can be affected by the presence of suspended solids.

Figure 2.3 Marsh funnel and cup for determining viscosity.

2.7 Density (API 13B-1.4, FM 8-RP13B-1)

The density of slurry prior to introduction to the bore hole, as well as prior to the placement of concrete is verified with a mud balance (Figure 2.4). Prior to introduction, the slurry must have sufficient density such that the net pressure across the soil/slurry interface maintains wall stability. Prior to concreting, the density should not be too high, whereby the slurry will not be easily displaced by the heavier concrete. There have been no studies to show at what level the slurry may be too heavy, but high density is more commonly attributed to high solids content.

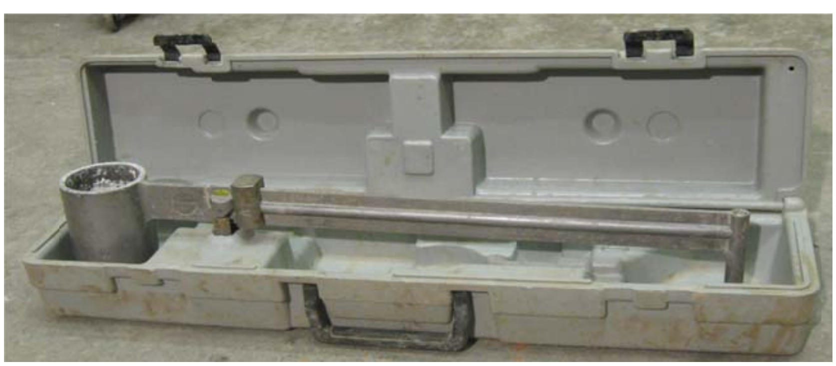


Figure 2.4 Mud balance for determining density.

2.8 Sand Content (API 13B-1.9, FM 8-RP13B-3)

The suspended solids are measured by the sand content test (API, 2009). Sand content is determined by filling a glass vial with a specified amount of fluid, pouring the fluid through a 200 mesh and rinsing the mesh back into the tube for a measurement of retained solids (Figure 2.5). The sand content is measured as a percent of total volume.

Figure 2.5 Test kit for sand content.

2.9 pH Test (API 13B-1.11, FM 8-RP13B-4)

The pH can be verified with either a pH meter or with litmus paper (Figure 2-6). The pH of the mixing water prior to introducing the bentonite powder is important to ensure that the mixing water meets the manufacturer's recommendations (e.g. CETCO, 2013). The pH can negatively affect the hydration of the bentonite if too low, or can hamper the ability of polymer slurry to achieve its desired viscosity.

Figure 2.6 pH meter (left) and litmus strips (right).

2.10 API Filter Press Test (API 13B-1.7.2)

The filter press is typically not mandatory for drilled shaft construction. The filter press is beneficial only for mineral slurry, as it determines the flow rate and filter cake formation. The test measures the time required to pass 25ml of fluid through a filter paper and the filter cake thickness is measured. The output is then 25ml/time elapsed. However, if the time exceeds 30 minutes, the amount of fluid is measured at this time and the filtrate volume/30 min is recorded (Figure 2-7).

Figure 2.7 Bench top filter press.

2.11 State Specifications

Each state provides specifications that limit the viscosity, density, sand content and pH of slurry prior to introduction into the borehole and prior to placement of concrete. FHWA also provides a range for each of the aforementioned tests. In general, state recommended ranges for density, sand content, and pH contents are all consistent with the values set forth by the FHWA. However, specifications for viscosity from each state show that there is quite a variation in the acceptable values that are permitted. Figure 2-8 illustrates the varying viscosities from state to state as well as that from FHWA. The large range of acceptable viscosities is presumably based on empirical data but the rationales are not published with the exception of the recent lower viscosity limit set in Florida (FDOT, 2013). In general, the lower viscosities are similar, but the upper viscosity limit can vary greatly and no rationale for these values is published. A breakdown of all state slurry specifications is provided in Appendix B.

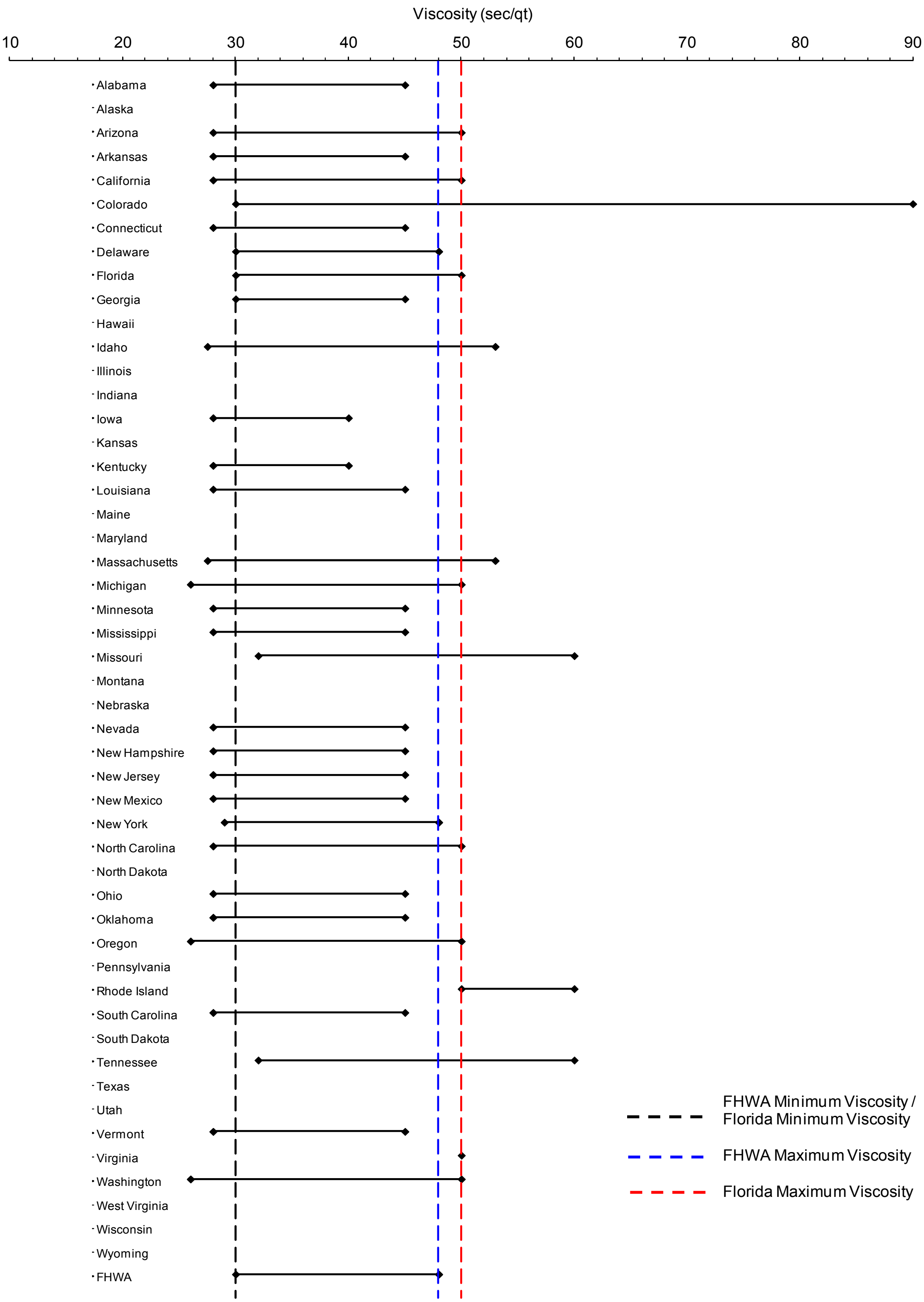


Figure 2.8 Breakdown of available state recommended viscosities.

2.12 Development Length

The development length of a deformed bar can be determined with the equation provided by the American Concrete Institute ACI 318-10 (Equation 2.1) stemming from ACI Committee 408 tasked with determining the bond strength between concrete and steel reinforcement. According to this committee, the bond strength is based on the friction between the concrete and the reinforcement which is affected by the strength of the reinforcement, surface deformation characteristics, system geometry and concrete strength. Any factor or material that interferes with this interface could adversely affect this interface, and in turn reduce the bond strength.

$$L_d = \left[\frac{3}{40}\frac{f_y}{\sqrt{f'_c}}\frac{(\psi_t\psi_e\psi_s\lambda)}{\left(\frac{c_b+K_{tr}}{d_b}\right)}\right]d_b \qquad \text{Equation 2.1}$$

According to ACI 408, there are several formulas to determine the bond strength. The equations use different coefficients, but the variables are similar. This include: the concrete strength, the concrete cover, clear spacing, and surface area of the reinforcement (Equations 2.2 – 2.5), but not steel strength when considering bond.

$$u = 0.083045\sqrt{f'_c}\left[1.2 + 3\frac{c}{d_b} + 50\frac{d_b}{L_d}\right] \qquad \text{Equation 2.2}$$

(Orangun et al, 1977)

$$u = 0.083045\sqrt{f'_c}\left[\left(1.06 + 2.12\frac{c}{d_b}\right)\left(0.92 + 0.08\frac{c_{max}}{c_{min}}\right) + 75\frac{d_b}{L_d}\right] \qquad \text{Equation 2.3}$$

(Darwin et al, 1992)

$$u = 0.265\sqrt{f'_c}\left[\frac{c}{d_b} + 0.5\right] \qquad \text{Equation 2.4}$$

(Australian Standard, 1994)

$$u = 0.083045\sqrt{f'_c}\left[22.8 - 0.208\frac{c}{d_b} - 38.212\frac{d_b}{L_d}\right] \qquad \text{Equation 2.5}$$

(Hadi, 2008)

Where,

$d_b = Bar\ Diameter$

$L_d = Development\ length$

$c = Minimum\ clear\ cover$

$f'_c = Compressive\ strength\ of\ concrete$

$c_{max} = Maximum\ of\ side\ cover, bottom\ cover, clear\ spacing/2$

$c_{min} = Minimum\ of\ side\ cover, bottom\ cover, clear\ spacing/2$

These equations were used to determine the bond strength for this project to both design the pullout equipment and to evaluate the actual measured values (Chapter 3 and 4, respectively).

2.13 Adverse Effects of Wet Construction

Even when following the recommended state specifications, unforeseen complications can still arise. For instance, the contact time for slurry in the excavation is referenced in the FHWA recommendations, and the specified maximum exposure time varies from state to state. FDOT limits bentonite exposure to 36 hours after which the borehole should be over-reamed to remove any filter cake. As some excavations take longer than 36 hours to complete, the bottom 5 feet must be drilled within 12 hours of concreting (FDOT, 2013). This in effect allows the upper most portion of the shaft to be exposed for longer exposure times and degraded side shear between the shaft and soil in those regions, but not in the lower 5 ft.

The plastic properties of the concrete can also affect flow and displacement of the bentonite slurry during concrete placement. FDOT state specification for drilled shaft concrete slump ranges from 7 to 10 inches (FDOT, 2013). However, slump loss is permitted to go as low as 5 inches during concreting. This low slump concrete has been shown to reduce flow resulting in near zero pressure against the soil walls, especially for full length temporary casing applications (Garbin, 2003). This also results in increased potential for anomalies in the concrete outside the cage. Figure 2.9 shows a shaft that was exhumed due to a mismatch in the theoretical and actual concrete volume placed. It clearly shows flow through the cage was compromised. Additionally, there are indications that the suspended solids may have been too high as well.

Figure 2.9 Exhumed drilled shaft displaying concrete flow issues.

According to FHWA, there is *"no reduction in bond strength when using bentonite"* (FHWA, 2010). This statement was based on pullout tests that were performed on concrete panels by Fleming and Sliwinski (1975). For those tests, the bars that were to be in contact with the slurry were attached to the lateral reinforcing, and concrete was cast while in place. In contrast, the pullout specimens not exposed to bentonite were pushed into plastic concrete and not attached to the lateral reinforcement. As other studies have shown that the lateral reinforcement increases the pullout capacity of the reinforcement (ACI, 2003), the results of the two conditions are not comparable and should not have been used to make this conclusion.

Studies performed by Sen and Mullins (1999) showed that the bond between steel H-piles and concrete prestressed piles in seal slabs was affected by the presence of bentonite slurry at the time of seal slab casting (Figure 2.10). In that study, bond was reduced by as much as 50% although the viscosity of the bentonite and the exact bentonite product (pure bentonite or high yield) was not cited.

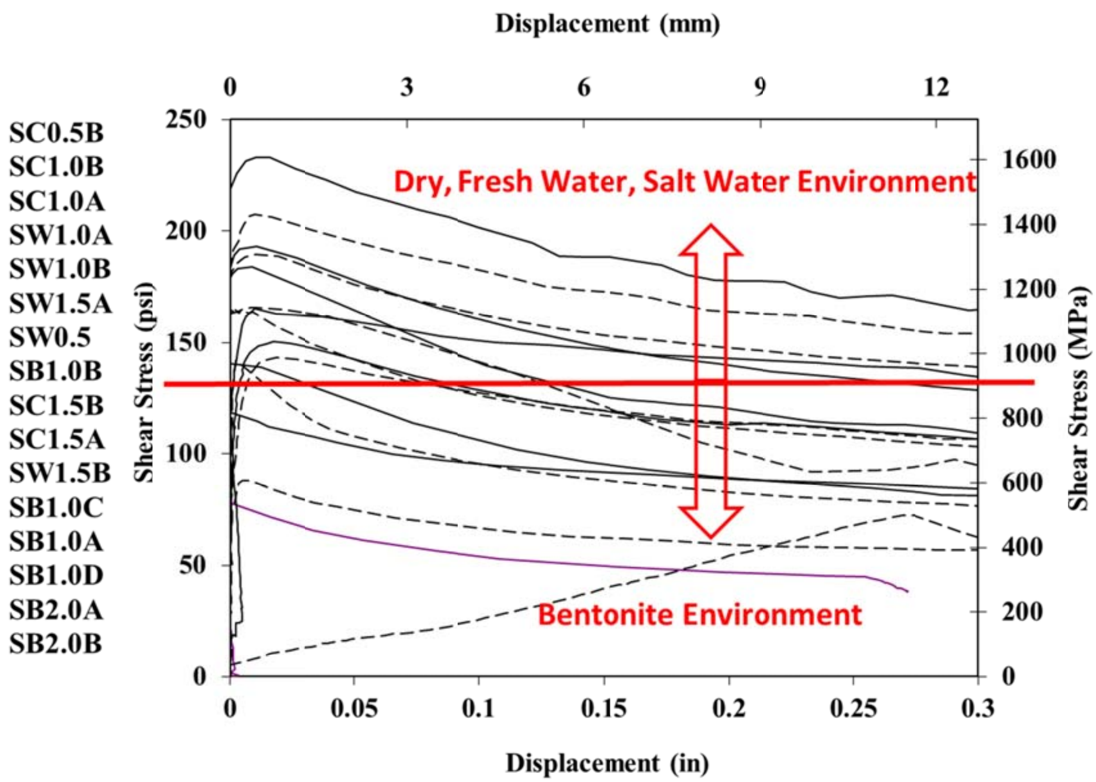


Figure 2.10 Pullout test results from piles embedded in seal slabs cast in various environments (dry as well as submerged in salt water, fresh water, or bentonite slurry).

The purpose of this study was to determine if a mineral slurry upper viscosity limit can be defined below which adverse effects will not occur relating to: rebar bond strength, concreting behavior, and the side shear resistance.

Chapter 3: Test Preparations and Procedures

This chapter discusses the preparation for all testing performed in this study which included: (1) slurry preparation and rebar pullout tests, (2) casting and pullout testing of model shafts in frustum confining vessel, and (3) full scale pullout testing of shafts constructed with various slurries.

3.1 Slurry and Rebar Pullout Testing

3.1.1 Bentonite Testing

In order to determine the amounts of bentonite required to obtain the varying viscosities, small scale (1 gallon) batches of slurry were mixed. Prior to batching slurry, the mixing water was mixed with soda ash to bring the pH within the required range and meet state specifications and manufacturer recommendations (for FDOT this is between 8 and 11, FDOT, 2013). For all slurry mixed during the following experiments the pH was increased to approximately 9.5. In order to encompass all viscosities currently recommended from state specifications the tests were performed as well as extending the testing to 90 sec/quart. The bentonite introduced was increased in increments of 0.1 pounds/gallon until the desired viscosity was obtained (Table 3.1). For the tests performed CETCO's PureGold Gel© was used. This particular brand was chosen based on previous research that indicated more product would be needed to produce comparable viscosities when compared to other brands (Yeasting, 2011). This in turn should provide a worst case scenario as far as percent solids in suspension of the slurry. As Figure 3.1 illustrates, these tests were required due to the non-linear characteristics. Along with the viscosities, the density, pH and temperature were recorded. For the laboratory testing a 100 mL volumetric flask and a digital scale were used to determine the density. This method provided more accurate results and the volume could be more precisely determined. All small scale samples were mixed with a drill press and a paddle blade for a duration of 20 minutes to ensure a homogeneous mixture. Figure 3.2 shows the results for polymer tests for completeness that resulted from both lab and field tests.

Table 3.1 Results for small scale testing to determine bentonite quantities

Bentonite (lb/gal)	pH	Mass/ 100mL (g)	Density (g/mL)	Density (lb/ft^3)	Temp (C°)	Average Viscosity (sec)
0.1	8.34	1001.1	1.0011	62.50	25.0	30.70
0.2	8.34	1018.1	1.0181	63.56	22.1	29.79
0.3	9.13	1013.9	1.0139	63.30	25.0	29.27
0.4	9.10	1016.3	1.0163	63.45	25.0	29.93
0.5	9.11	1020.0	1.0200	63.68	25.0	30.57
0.6	9.16	--			25.0	33.04
0.7	9.09	1036.6	1.0366	64.71	25.0	35.33
0.8	9.04	1045.0	1.0450	65.24	25.0	39.23
0.9	9.05	1050.8	1.0508	65.60	25.0	46.07
1.0	9.16	1059.9	1.0599	66.17	25.0	59.87
1.1	9.12	1061.5	1.0615	66.27	25.0	98.16
1.2	9.09	1073.1	1.0731	66.99	25.0	359.30

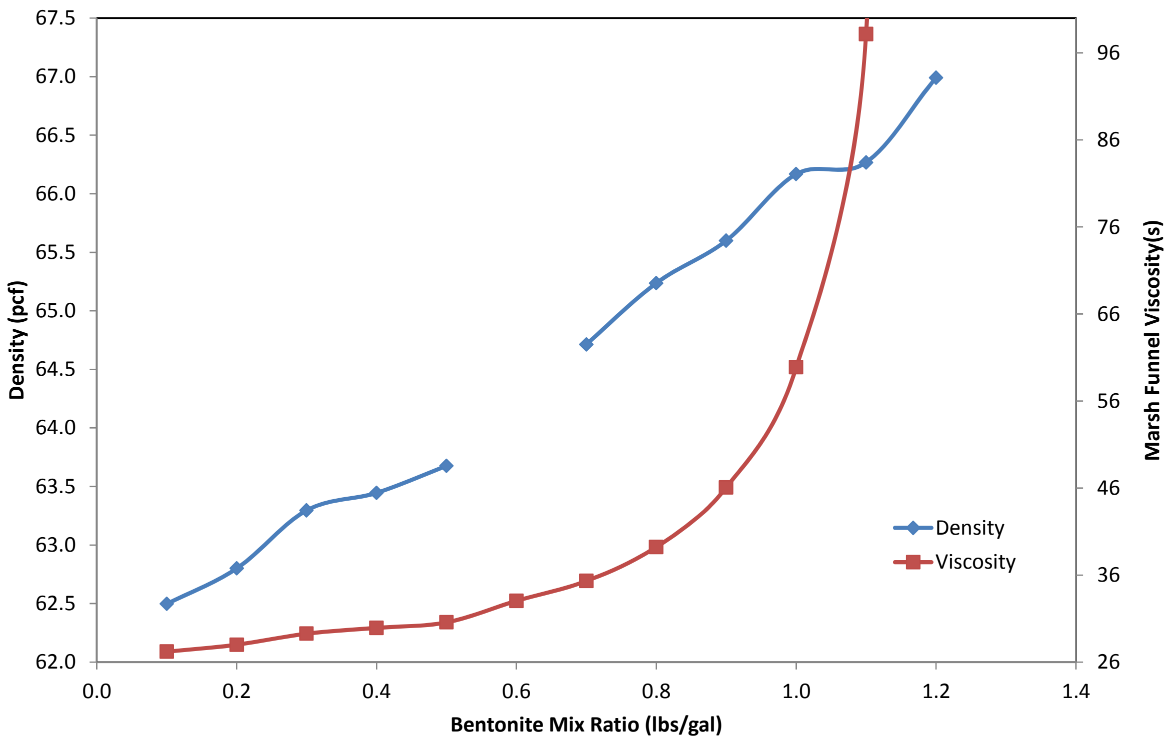


Figure 3.1 Plot of test results illustrating the non-linear relationship.

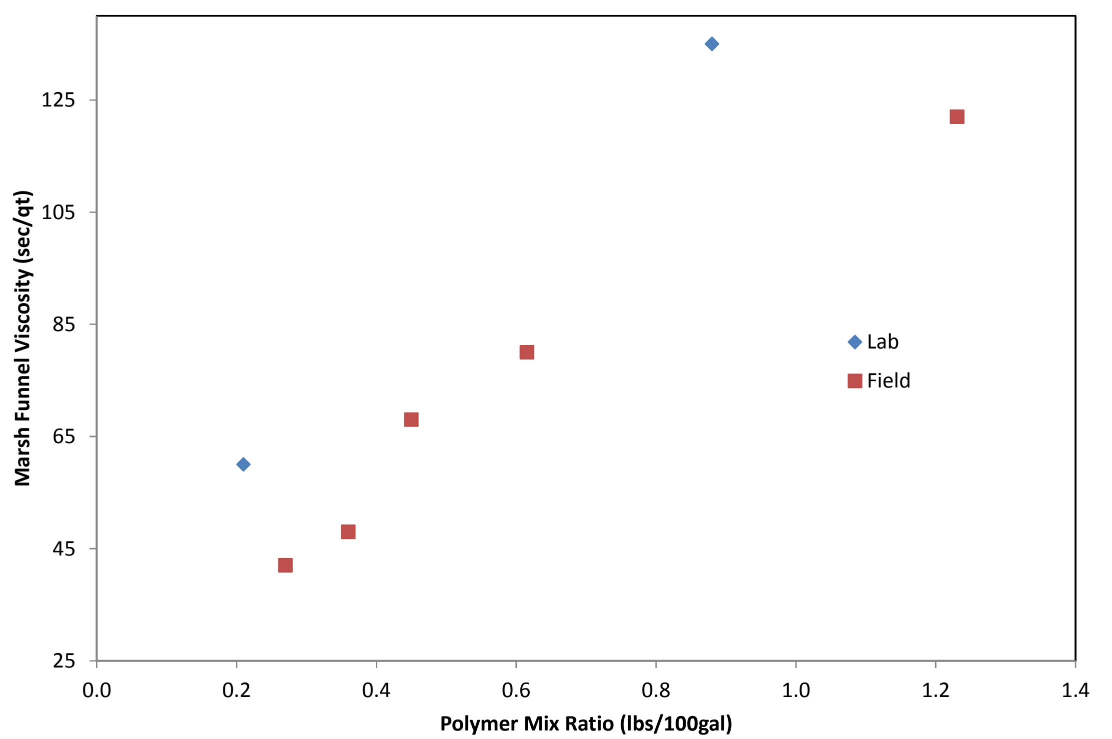


Figure 3.2 Viscosity observed from varied polymer mix ratios.

3.1.2 Form Fabrication

The sizing considerations of the scale model shafts were two-fold: (1) the shafts should be large enough to maximize the sample size and use a full rebar cage to model a congested, within design constraints, reinforcement cage with minimum clearances and openings, and (2) concrete should be tremie placed to replicate field concrete flow conditions. The scale shafts were 24 inches tall, and 42 inches in diameter.

The sidewalls for the shafts were constructed from 18 gauge steel. The steel sheets were cut into 24-inch x 132-inch strips and rolled into a circular shape (Figure 3.3). Once the sheets were rolled, the strips were trimmed and 2-inch x 2-inch x 0.25-inch steel angles were welded to the edges in order to allow the repeated opening and closing of the forms.

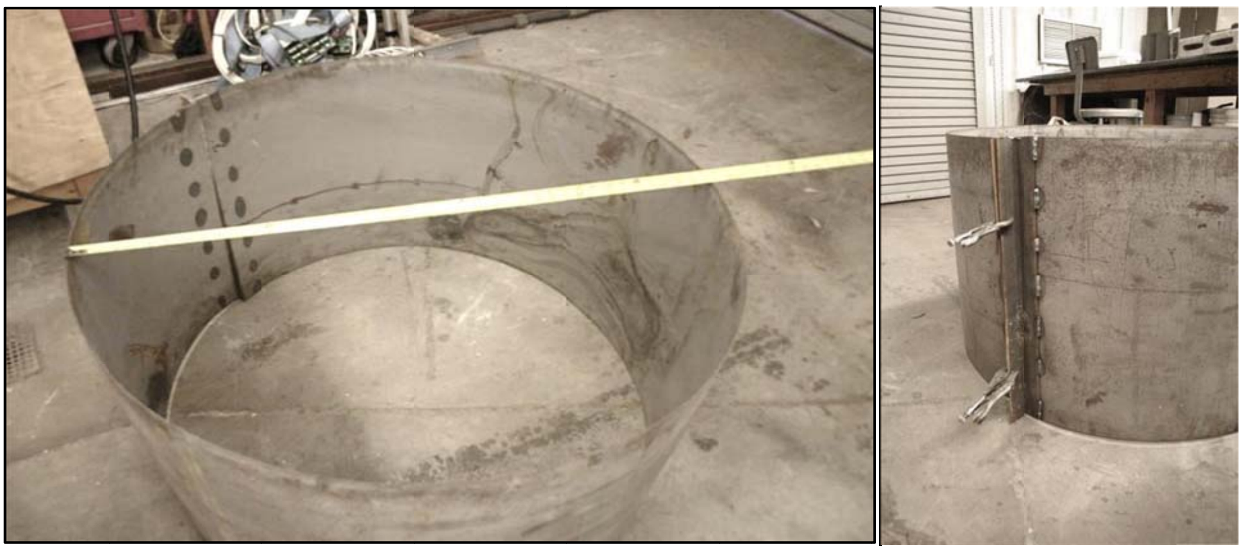


Figure 3.3 18 gauge steel rolled to 42-inch diameter.

Once the sidewalls were completed, ¾ -inch plywood sheets were cut into 4-foot x 4-foot sections and treated with polyurethane in order to achieve a non-absorptive surface. In order to increase repeatability, PVC caps were anchored and, silicon sealed to the plywood base as a means to locate the reinforcement (Figure 3.4). Once the plywood was treated and the PVC caps were installed, the sheets were framed out with 2-inch x 6-inch boards as to dam the flow of slurry during placement in order to pump evacuated slurry into holding tanks. In order to increase the sample numbers for a given pour, a total of six forms were fabricated.

Figure 3.4 Finished form prior to placement of reinforcement.

Each form was sealed with silicone around the base of the form to prevent slurry leakage (Figure 3.4). Once the material had time to cure, a water test was performed in order to ensure that each form was in fact water tight (Figure 3.5).

Figure 3.5 Silicon to seal form (left), water testing to ensure water tight seal (right).

3.1.3 Reinforcing Cage

In order to maximize the congestion and still remain within state specifications, a reinforcement arrangement consisting of 14-No. 8 bars (1.0-inch diameter) vertically, and 2-No. 3 bars were used for the horizontal (stirrups) reinforcement. In addition to the steel stirrups, polyethylene pipe (PEX pipe) was incorporated as a second layer of horizontal reinforcement congestion. The vertical reinforcement was placed in two layers with a minimum of 6-inches of clear spacing between bars. The exterior layer was in place to provide structural reinforcement for the model shafts and was not used for the pullout testing. The steel stirrups were placed on the exterior of the outer layer of vertical reinforcement for confinement purposes, and did not come in contact with the vertical reinforcement to be tested in pullout. PEX pipe (1/2 in) was placed between the vertical reinforcement layers to provide congestion without providing any strength to the pullout rebar specimens. The stirrups were placed 6-inches on center. The PEX pipe was also placed 6-inches on center, however the PEX pipe, non-structural, was placed for the entire depth of the shaft, where the steel, structural, was placed only in the top 10-inches (Figure 3.6).

Figure 3.6 Structural, outer layer, reinforcement (left) and full cage (right).

Each of the vertical reinforcing bars was cut to a length of 4-feet in order to allow enough length for the hydraulic ram, and steel spacers during testing. Each bar to be tested was machined down to 0.865-inches for a length of 3-inches on the upper end. Once machined the bars were threaded for a 0.875-inch nut. This provided a point of resistance for the ram during the pullout testing (Figure 3.7).

Figure 3.7 Reinforcement after machining.

3.1.4 Slurry Preparation

All slurry was mixed a minimum of 24 hours prior to placement in the forms. To maximize the mixing hydration process during mixing, each batch was mixed using the rapid hydration Hootonanny eductor (Figure 3.8). Four different viscosities were chosen for rebar pullout testing (30, 40, 50, and 90 sec/qt). The current most common upper viscosity limits (40 and 50 sec/qt) were tested, corresponding to state and federal limits, respectively. The initial mix ratios were based on previous test data. The 30 sec/qt was achieved with 0.3 lb/gallon of water, 40 sec/qt with 0.8 lb/gallon of water, 50 sec/qt with 0.95 lb/gallon, and the 90 sec/qt with 1.05 lb/gallon.

Figure 3.8 Mixing mineral slurry with Hootonanny® eductor.

The bentonite slurry was mixed with a combination of 3 inch and 2 inch shear pumps. Each batch consisted of 150 gallons (Figure 3.9) for the mineral slurries that were tested. For quality assurance, the viscosities were verified after mixing and again after a setting time of 24 hours.

Figure 3.9 Batches of mineral slurry after mixing.

For comparison, the manufacturer's recommended minimum and maximum viscosities for polymer slurries were tested as well. Shore Pac® was the material chosen for the polymer testing performed. Due to the sensitive nature of the polymer chains, a diaphragm pump with a bubbler system was used to mix and agitate the polymer slurries. The chosen viscosities for the polymer slurry were 60 sec/qt (lower end) and 135 sec/qt (upper end). The polymer mix ratios for the 60 sec/qt mix required 0.21 lb/gallon and 0.88 lb/gallon for the 135 sec/qt mix per manufacturer's recommendations. The polymer slurry was mixed in 300 and 400 gallon batches.

Figure 3.10 60 sec/qt polymer slurry after mixing being agitated with bubbler system.

For every placement, the slurries were tested for density and viscosity at the time of introduction to the forms and again prior to placement of concrete. The viscosities were measured by the Marsh funnel method, as well as with a viscometer. Prior to the placement of concrete, the mineral slurries were tested with the filter press. In order to show the effects of exposure, the maximum permissible set time was used wherein the slurry was allowed to remain in the forms, and in contact with the reinforcement for 12 hours prior to placement of concrete (FDOT, 2013). Slurry was placed in the forms the night prior to the concrete placement (Figure 3.11) with either the shear pump (mineral) or a diaphragm pump (polymer).

Along with the mineral and polymer slurries, two shafts were constructed using only water. These were provided as control samples.

3.1.5 Debonding of Reinforcement

According to the American Concrete Institute (ACI) 318-11, the required development length for a deformed No.-8 bar is 47 inches and can be calculated with the development length equation provided (Equation 2-1). Due to the size of the shafts being constructed, this required length was not attainable. The ACI Committee 408 has performed research to try to determine the force that is required to pull out a deformed bar. These equations were used to approximate the debonded length of the bars for the test specimens (Equations 2.2-2.5).

Figure 3.11 Placing mineral slurry in forms the night prior to placement.

Throughout the project the debonded region was modified in order to ensure the best test results. For the initial placement, a bonded length of 18 inches was used, 2 inches at the bottom and 4 inches at the top of the shaft were debonded with PVC pipe (Figure 3.12). The length was increased in the top of the shaft in order to protect against rupture of the concrete. Due to higher than expected pullout capacity, the debonded length was reduced to 10 inches for the following placement, and finally to 6 inches for all subsequent placements. Debonding was achieved with the use of 1 inch thin-walled PVC pipe cut to length, sealed with tape, and tied in place with plastic ties.

Figure 3.12 Reinforcement cage after debonding prior to slurry placement.

3.1.6 Concrete Placement

The concrete used to cast the model shafts was chosen to meet FDOT typically approved shaft mixes with a 28 day compressive strength of 4000 psi, contained 20% to 30% flyash, and had a slump ranging from 7 to 10 inches. Preferred Materials, Inc. was chosen as the concrete supplier and provided a Class IV Drilled Shaft concrete, mix ID 01-1031-01. This FDOT approved mix had a 0.4 water to cement ratio and met the previous requirements.

The concrete placement began within the 12 hours of the slurry placement as previously discussed. The concrete was placed via tremie to simulate concrete placement in the field (Figure 3.13). For quality assurance the plastic properties of the concrete were tested, and 4-inch by 8-inch cylinders were cast in order to verify compressive strength prior to performing pullout tests. Once the concrete placement was completed the tops of the model shafts were leveled and finished for subsequent pullout tests.

Figure 3.13 Placing concrete via tremie.

Upon achieving appropriate compressive strength, the steel forms were removed from the shaft in order to visually inspect for anomalies and imperfections. Once the forms were removed (Figure 3.14) and initial inspection had taken place, the shafts were then pressure washed in order to remove any remaining mineral slurry on the exterior of the concrete that was not displaced by the concreting action. No residual slurry was noted for those shafts cast with polymer slurry.

Figure 3.14 Form removal after shaft achieves suitable compressive strength.

3.1.7 Pullout Testing

Pullout testing was performed with a hydraulic pump and a 30-ton hollow-core hydraulic ram. The hydraulic pump pressure was measured with an inline pressure transducer connected to computerized data acquisition system (Omega DAQ-55). Data was acquired at a sampling rate of 4-Hertz to ensure that the peak load was captured.

The stiffness of the bond was also captured via a displacement transducer attached to the ram to measure the bar pullout movement during loading. Pullout testing was performed after the concrete reached a minimum compressive strength of 4-ksi, and all tests were completed on the same day as the compressive strength testing. During testing, the ram was placed over the bar to be tested, and seated on the previously leveled concrete surface. A 3/8-inch steel plate was placed between the ram and the threaded region of the bar and 2 high-strength nuts were used to hold the steel plate in place (Figure 3.15).

Figure 3.15 Hydraulic ram configured during pullout testing with LVDT.

In all, a total of 126 pullout tests were performed on 18 different shaft specimens. The data acquired from each pullout test was then analyzed to show the effects of stiffness, ultimate capacity, and any trends associated with the bond of the rebar in the various environments.

3.2 Model Shafts in Frustum Confining Vessel

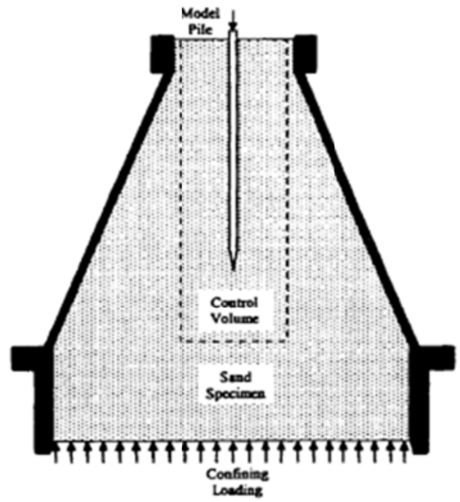
3.2.1 Frustum Confining Vessel (FCV)

The frustum is a conical apparatus which contains an adjustable pressure bladder at its base. This unique device creates the stress gradient similar to that found in the field by inducing pressure to the soil at the base. The stress created increases approximately linearly with depth with the top open to the atmosphere creating a zero stress condition. The pressure within the rubber bladder is created using an air-over-fluid supply system or continuous air supply system which allows for a constant regulation of the pressure at the base.

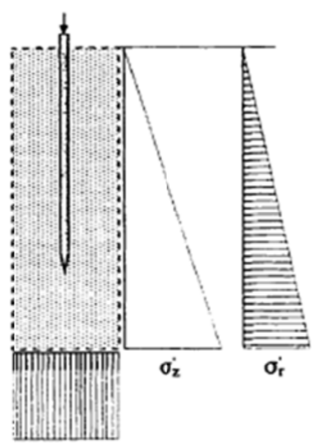
As the stress variation within the soil inside the frustum is near linear in nature, a linear normal force is also implied on the sidewalls of the device (Figure 3.16). The stress attenuation and gradient magnification mechanism is used to determine the maximum value of the normal force at the sidewalls near the base of the frustum. The hydraulic pressure applied to the base of the frustum and measured by a pressure gauge can be related to the maximum value of the normal force distribution of the side of the frustum.

The frustum confining vessel used for this study has approximate dimensions of 56 inches high, a base diameter of 52 inches, and 6.75 inches in diameter at the top. The walls of the frustum are approximately ¾ of an inch thick making the inside diameters of 5.25 inches at the top and 50 inches at the bottom. This allows for the frustum to contain approximately 87 cubic feet of dry sand. The large size of the testing vessel is suitable for scaled shafts of 36 inches long and 4 inches in diameter which helps minimize errors from scaling effects. For this study a 30psi bladder pressure equates to an approximate scale factor of 12, or the full scale prototype shaft for which the model is similar would then be 36ft long and 4ft in diameter.

It is worthy to note that past testing within a FCV used either driven piles or shaft constructed with full length casings. This study was the first to construct a model shaft using drilling slurry to maintain an open hole during excavation.



(a) Schematic of the Frustum Confining Vessel.



(b) Idealized distribution of stresses within a control volume. The purpose of the device is to produce within the control volume a state of stresses similar to those typically found in the field, while controlling the stress levels simultaneously.

Figure 3.16 Schematic and Idealization of pressure in FCV (Sedran, 1999)

3.2.2 FCV Testing Preparation

For the testing of the soil-slurry interaction, the frustum confining vessel was set up to create 4 inch diameter model shafts 36 inches in length in a dry sandy soil. At the onset of the test program, preparation included the complete tear down (Figure 3.17) and reassembly of the frustum apparatus (Figure 3.18) to check for any damage to the vessel and bladder. During the tear down, the interior of the frustum was cleaned and any heavy rust deposits removed from the sidewalls and from under the bladder. For the reassembly, the edges of the bladder were sealed to the base plate using a silicone based adhesive and the main cone placed on top of the base to apply adequate pressure to smooth the edges. Once the bladder was set, the base bolts were torqued to approximately 700 ft-lb.

Figure 3.17 FCV disassembled for inspection and cleaning

Figure 3.18 FCV fully assembled

3.2.3 Soil Preparation

While the frustum was undergoing the cleaning and assembling phase, the sandy soil strata was also being prepared. This consisted of drying, sifting, and storing the sand in a location that did not promote the collection of moisture. The sand was dried indoors by laying down an approximately 10 foot square tarp on the floor with a 6 to 10 inch thick layer of sand. This sand was then allowed to dry for 2-3 days with the aid of low speed fans and twice daily agitation with a rake and shovel. Once the soil was removed of all moisture it was stored indoors in a 5 foot deep and 5 foot square covered container.

3.2.4 Equipment Procurement and Preparation

Other equipment that was fabricated included a 4 inch multi-flight auger, a 4 inch inner diameter casing with slurry holding tank, a 2 inch diameter tremie pipe, a 2 cubic foot hopper with tremie connections, and a loading frame with data collection and monitoring equipment. The multi-flight auger was fabricated to have 3 flights and be attached to a solid half inch rod (Figure 3.19).

It was later determined that fluid transfer ports were needed to reduce the suction force when the auger was removed from the shaft. The auger was then fitted to a hand auger rod and handle with a sliding centralizing device which fit inside the casing during drilling. The casing was also fabricated (Figure 3.20) and included both a slurry holding tank (5 gal bucket) to maintain the height of the slurry during drilling. A drain valve approximately 16 inches above the bottom of the casing was provided to drain off extra slurry before the casing was removed after concreting. The casing / slurry tank assembly was designed to be self-standing and keep a 3 foot minimum head of slurry to maintain the open hole. A 6.5 ft., 2 in. diameter tremie pipe and hopper assembly (Figure 3.21) was created which allowed for the mortar (model concrete) to be mixed and then hoisted into place. An existing compression load frame was modified to also serve as a tension load frame through which the anchor rod could pass for pullout testing (Figure 3.22).

Figure 3.19 Multi-flight auger (4 in diameter)


Figure 3.20 Self-supporting casing with slurry storage tank and relief valve

Figure 3.21 Tremie pipe attached to hopper with quick disconnects

Figure 3.22 Tension/Compression load frame for the FCV

3.2.5 Slurry Preparation

The drilling slurry was prepared in advance and stored in 55 gallon closed containers. The slurry was prepared in two steps. First the mix water was brought to a pH of 9 with the use of soda ash. Then the bentonite powder was slowly added to the water and mixed using a high speed drill with a mixing paddle attachment (Figure 3.23). For the small slurry volume needed, the bentonite powder was manually added in small amounts while mixing to ensure no clumps. Once all of the powder was introduced into the system, the slurry was mixed for a minimum of twenty minutes. Four different viscosities using bentonite were tested: 30, 40, 60, and 90 sec/qt.

Figure 3.23 Preparation of a batch of slurry in 55 gallon drum

A polymer drilling slurry was also created for evaluation and to be used as a control for the data analysis of the model shafts. Due to the inability to process clumps, this slurry was formed by running water through a rapid hydration Hootonanny eductor into a 55 gallon storage container. The target slurry viscosity was 60 to 70 sec/qt.

3.2.6 Construction of Model Shafts

For the construction of each model shaft, the following steps were followed: filling the frustum with dry sand minimizing drop energy; pressurizing the bladder to 30 psi; conducting a CPT in the first 40 inches of the FCV; setting the casing; placing the slurry; drilling the hole; and placing the model shaft.

For each test, the frustum was filled with clean, dry sand. This required removal of any remaining sand from previous tests before the clean sand could be introduced. To insure consistency between tests, the sand was placed in small increments near the sand surface to safeguard against the addition of any compaction energy (Figure 3.24).

Figure 3.24 Addition of dry sand to the FCV

Once the frustum was filled with sand, the bladder was pressurized by supplying a constant air pressure of 30 psi using an air pressure system. This style of pressure system was chosen for two reasons: (1) the fluid used in the air-over-fluid system leaked into the sand strata when pressurized and (2) pullout testing was to be conducted to evaluate the shafts, which didn't require the bladder to be filled with a noncompressible fluid.

With the frustum set and ready for drilling, the work platform was set in place, and then a cone penetration test (Figure 3.25) was conducted to determine the tip stresses versus depth and to rule out sources of variation not associated with slurry viscosity. Figure 3.26 is a typical result from a CPT where the left is the measured tip resistance and the right is the friction ratio.

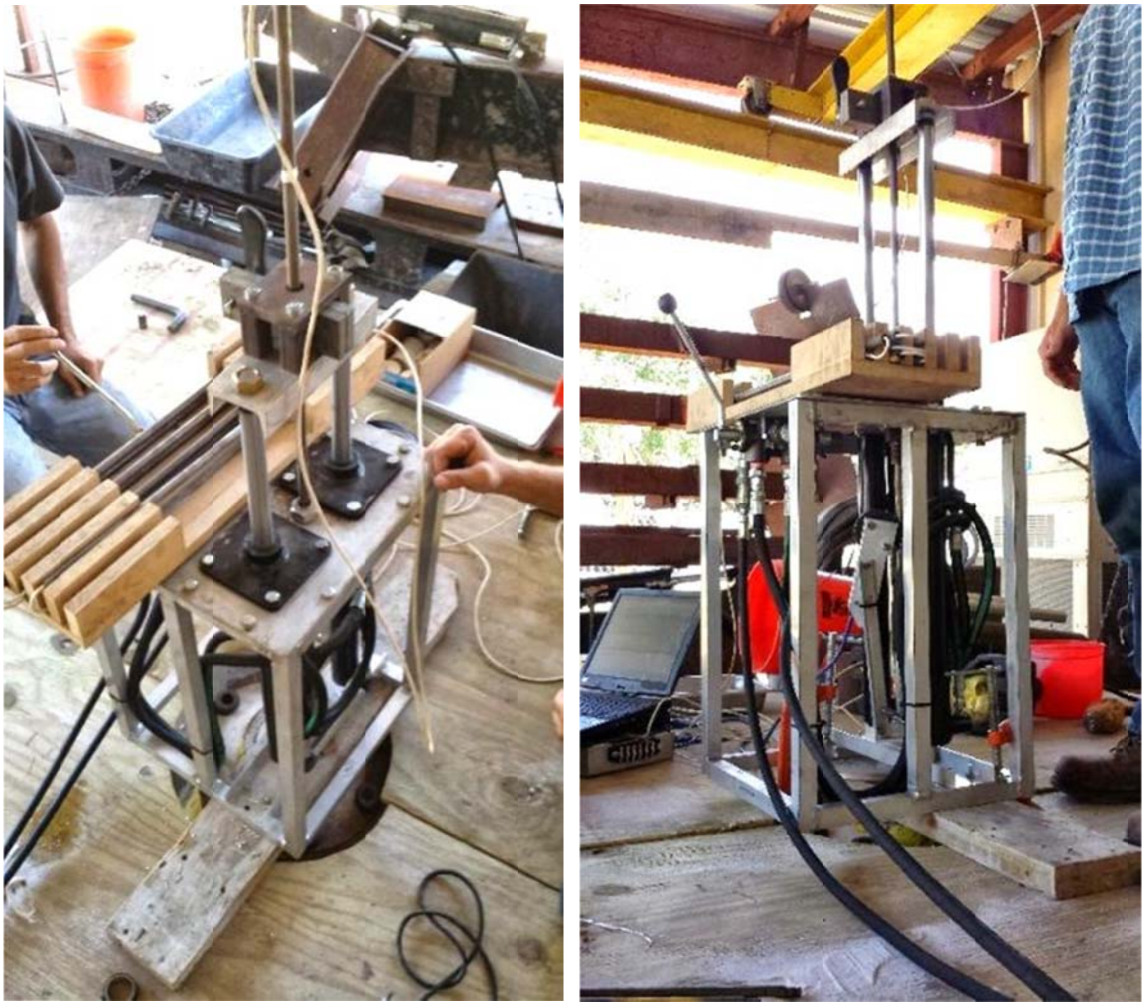


Figure 3.25 Cone penetration test into dry soil strata within FCV

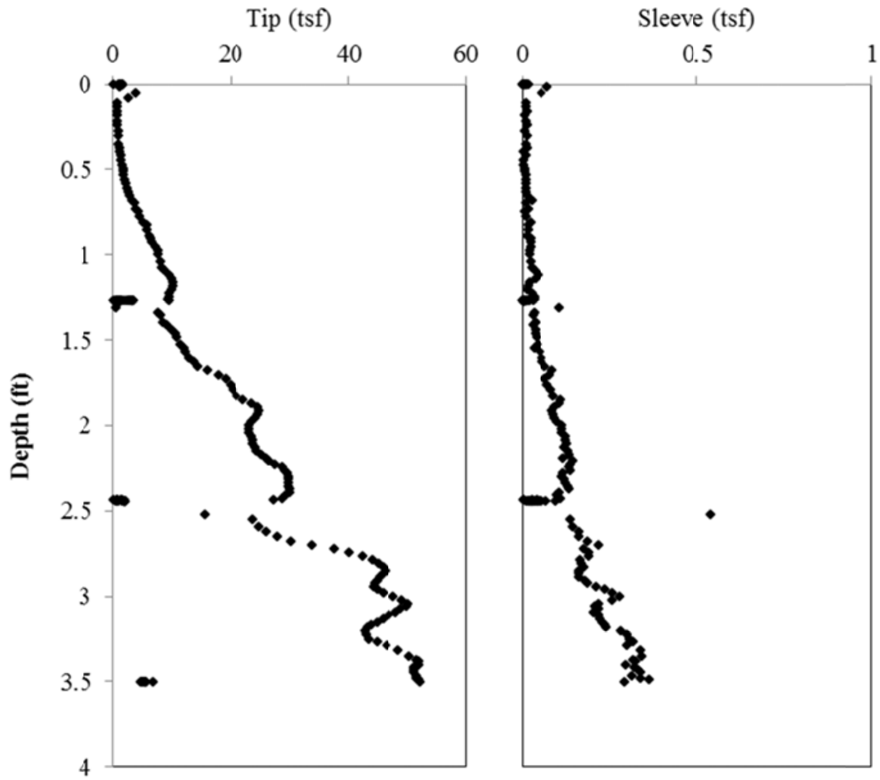


Figure 3.26 Typical CPT sounding for soil strength delineation

This CPT evaluation of the sandy soil was then used to develop a cumulative area under the tip stress curve which graphically represents the load carrying capacity of the soil as seen in Figure 3.27. This process is also done to normalize all of the test shafts and remove the effects of varied soil strength.

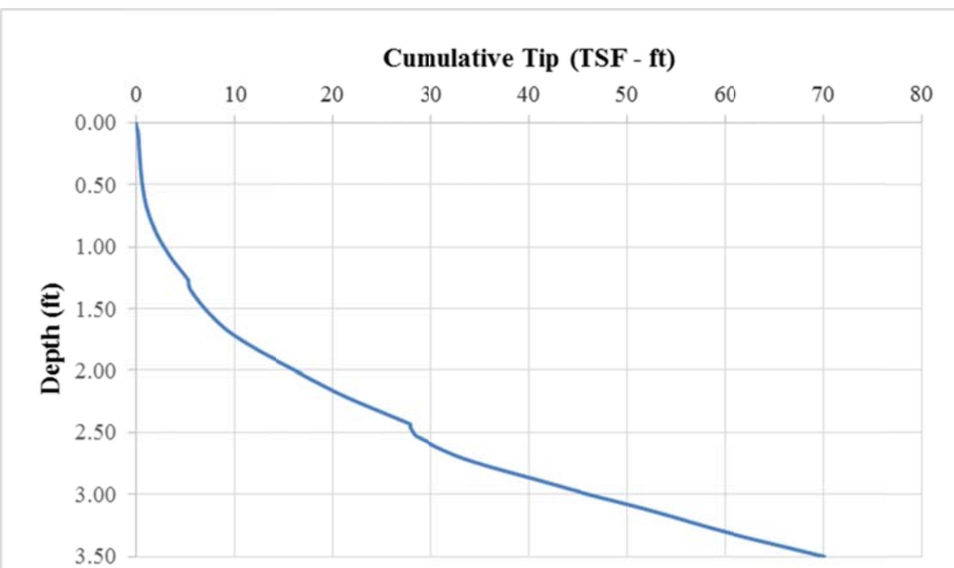


Figure 3.27 Cumulative area under the tip as a function of depth in FCV

After conducting the CPT, drilling of the hole for the model shaft commenced. This process began by setting the casing to a depth of 8 inches within the frustum and securing it in place. A permanent surface casing was placed around the casing to extend the top of shaft up to the load frame and eliminate bonding to the FCV. Slurry was then introduced into the system to maintain a 3 ft minimum head while drilling (Figure 3.28).

Figure 3.28 Casing set in place and filled in excess with drilling slurry (top view of FCV)

Excavation began by placing the auger within the casing and setting the centralizer snug within the temporary casing. After 3 full turns, the auger was removed and the soil was cleaned from the flights (Figure 3.29). A 2 minute wait time was established to allow for the slurry to build up on the sidewalls of the excavation to help prevent collapse due to the higher than normal excavation rate that is possible on such a small scale. This process was repeated until the depth of the hole reached 36 inches. At this point, the open hole was left undisturbed for at least 8 hours before a final cleanout and placement of the fluid concrete.

Concreting was performed using a mortar mix which consisted of 10 lb of Portland cement, 60 lb of Quikrete Mortar Mix, and 15 pounds of water. This mixture was mixed for at least 6 minutes after which a mini slump test was performed (Figure 3.30). If the mini slump diameter was 6.5 inches or greater, then the mixture was transferred into the hopper (Figure 3.31), otherwise water was be added to achieve the desired mini slump diameter. Three mortar cubes were then prepared from the mortar mix according to the proper procedures.

Figure 3.29 Removal of auger after a drilling sequence


Figure 3.30 Mini Slump testing of fresh mortar mix


Figure 3.31 Transfer of fresh mortar mix to tremie hopper

The bottom of the open excavation was then cleaned out with a few turns of the auger. A cap was placed on the bottom of the tremie pipe and then inserted into the open hole. The hopper was then hoisted to the top of the tremie and connected (Figure 3.32). With the tremie on the bottom of the excavation, the hopper valve was opened and concrete placement commenced. Slurry displaced by the mortar flowed out of the drain value on the casing, and once the mortar reached this point in the casing the hopper valve was closed, tremie disconnected, and the hopper, tremie and casing were removed.


Figure 3.32 Connection of tremie pipe to hopper and hose to relief valve

A 1/2in diameter fully treaded rod was then inserted into the shaft the full 36 inches with adequate stick up to connect the pullout device (Figure 3.33). The model shaft was cure for a minimum of 24 hours or until the strength reached 250 psi (minimum strength required to develop the bar).

Figure 3.33 Completed placement of a model shaft

3.2.7 Pullout Testing

Once the model shafts reached sufficient strength, a pullout test was conducted by securing a load frame onto the frustum and connecting an extension rod to the treaded rod within the shaft. A hollow core hydraulic jack was placed on top of a load cell which rested on the load frame (Figure 3.34). A half inch plate was then placed over the rod and secured on top of the jack. The test was monitored by a load cell and two displacement gauges mounted 180° from one another (Figure 3.35). The shaft was then marked to indicate the point at which the shaft extended above the FCV as this length did not contribute to the surface area in contact with the soil. The monitoring equipment was then connected to a data collection system and the test was performed by increasing the pressure via a hand pump. Once the model shaft had been pulled at least 1 inch out of the FCV the test was terminated.

Figure 3.34 Load frame with load cell and hydraulic ram

Figure 3.35 Displacement gauges secured to FCV

Figure 3.36 Overall view of loading setup

3.2.8 Model Shaft Evaluation

After the load test was conducted, the bladder was deflated and upper cone of the FCV was removed to evaluate the slurry filter cake on the sidewalls of the shaft (Figure 3.37). Great care was taken during the excavation of the model shaft from the FCV to not disturb the sand strata that had become moistened from the interaction with the drilling slurry. Once enough of the sand around the shaft has been removed, the filter cake was measured using calipers at three locations along the shaft (Figure 3.38).

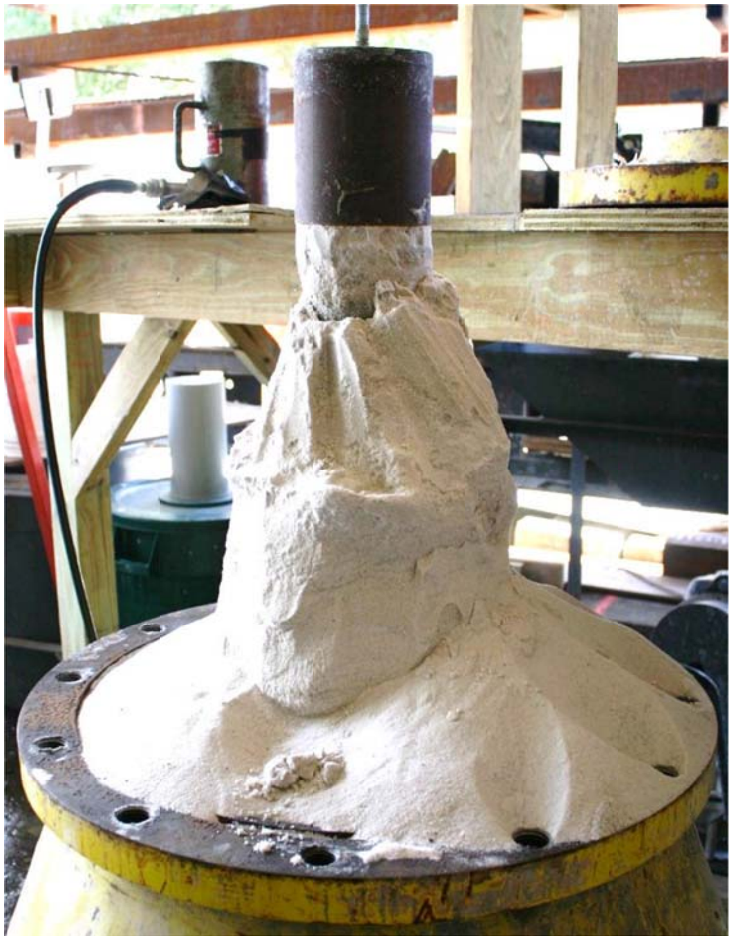


Figure 3.37 Evaluation of model shaft after removal of FCV upper cone

Figure 3.38 Measuring the filter cake

After the shaft was exhumed from the FCV it was washed to remove any remaining slurry filter cake and or sand. The overall length was then determined by measuring from the tip of the shaft to the mark made before the pullout test occurred. Then starting at the same indicating mark on the shaft, the diameter of the shaft was measured every inch in two orthogonal directions. This diameter was then be used to determine the average diameter, cross sectional area, and surface area of each shaft. The FCV bladder was then deflated completely using a vacuum and reset for the next test.

In all, ten model shafts were cast resulting in eight usable data sets. Data from two shafts were discarded: the first method shaft and a second that was inadvertently over pressurized above 30 psi after the shaft had been cast. The data was then analyzed for cumulative area under the CPT tip stress curve, average diameter of the model shaft, length of the shaft, and normalized pullout side shear stress relative to specimen S3-40.

3.3 Field Pullout Testing

Full-scale pullout testing was performed on four different sets of shafts where both mineral and polymer slurry were tested at varied viscosities; in all, twelve shafts were constructed and tested. The test program was performed in two phases.

Phase I provided a baseline for the FDOT upper viscosity limit of mineral slurry, which at that time was 40 sec/qt (this value was increased to 50 sec/qt during of the project, unrelated to the findings of this study). Phase I also included testing a polymer slurry with a viscosity of 60 sec/qt. Although not in the original scope, the FDOT project manager requested similar tests to be performed during the rebar pullout tests discussed earlier.

Phase II tests were performed at the end of the lab study to demonstrate the effects of higher viscosity mineral slurry on side shear resistance. This phase used 74 sec/qt mineral slurry and 131 sec/qt polymer slurry. So in total (Phase I and II), twelve shafts were constructed using four different slurries where each slurry condition was replicated for three shafts.

The overall field testing program involved: (1) CPT testing of the test site to confirm consistency or show where variations existed; (2) design and fabrication of a pullout frame capable of fully extracting the full scale shafts; (3) construction of the test shafts; (4) pullout testing and extraction; and (5) detailed measuring of the constructed shaft dimensions.

3.3.1 CPT Testing

The location of the test site was confirmed to be in the south yard of a local Association of Drilled Shaft Contractors (ADSC) member, R.W. Harris, Inc., in Clearwater, Florida (Figure 3.39). This firm has been supportive with several drilled shaft research projects with the University of South Florida, where many aspects of quality assurance and construction methods have been assessed. These projects dealt with post grouting shaft tips, thermal integrity profiling, viability of voided shafts, rapid hydration of mineral slurries, remote monitoring of foundations, and effects of polymer slurry (Mullins et al., 2012, 2010, 2009a, 2009b, and 2007).

In cooperation with R.W. Harris personnel, an area of the storage yard was selected which provided access to six separate shaft locations per phase that would logistically enable access for both drilling and concreting. Shafts were cast and tested in two phases: Phase I (2012) consisted of six shafts, three 40 sec/qt bentonite and three 50 sec/qt polymer; and Phase II (2013) consisted of six shafts, three 74 sec/qt bentonite and three 131 sec/qt polymer. In each phase, two rows of shaft locations separated by 30 ft were laid out; the individual shaft spacing is 20 ft CTC in each row. The shaft layout locations are shown in Figure 3.40.

Figure 3.39 Test site location in Clearwater, Florida at 123rd Ave N and 44th St N (Google Earth, 2012).

Cone penetration tests (CPT) were conducted at each of the proposed shaft locations using a miniature CPT device (Figure 3.41) to document variations in the soil strength and/or soil types. These types of variations, although usually minimal at close spacing, can affect shaft capacity and can in turn lead to confusing results if not quantified.

Figure 3.40a Phase I shaft layout and location of CPT soundings (Google Earth, 2012).

Figure 3.40b Phase II shaft layout and location of CPT soundings (Google Earth, 2012).

Figure 3.41 Cone penetration testing at Clearwater test site.

A 2-3 ft layer of compacted limestone base was removed with a 2 inch diameter hand auger prior to each sounding and replaced with local soils containing no rock. Soundings B-1, P-2, and B-3 show the presence of some the base course layer which was left in place but removed prior to soundings P-1, B-2, and P-3 to prevent needless damage to the CPT equipment. Each of the six Phase I soundings showed a layer of silty sand for 15ft followed by clay to silty clay (Figure 3.42 and Appendix A). Phase II soundings were similar and are also included in Appendix A.

Although there is general agreement among the soundings, it is apparent that soil strength layering is not exactly the same which can be quantified by the average tip stress, qc. This provides a mechanism to predict capacity variations between locations. Some methods of computing the side shear capacity of drilled shafts use only tip stress values and others use direct measurements of sleeve friction corrected for the difference in the coefficient of friction from a steel / soil interface to a cast-in-place concrete / soil interface. Over the same depth interval the average tip stress is essentially the cumulative area under the tip stress curve divided by the interval length. However, graphically it more clearly shows the differences in cumulative load carrying capacity. Figure 3.43 provides an indication of variations in likely shaft capacity using the cumulative area under the tip stress for both the Phase I and II CPT soundings.

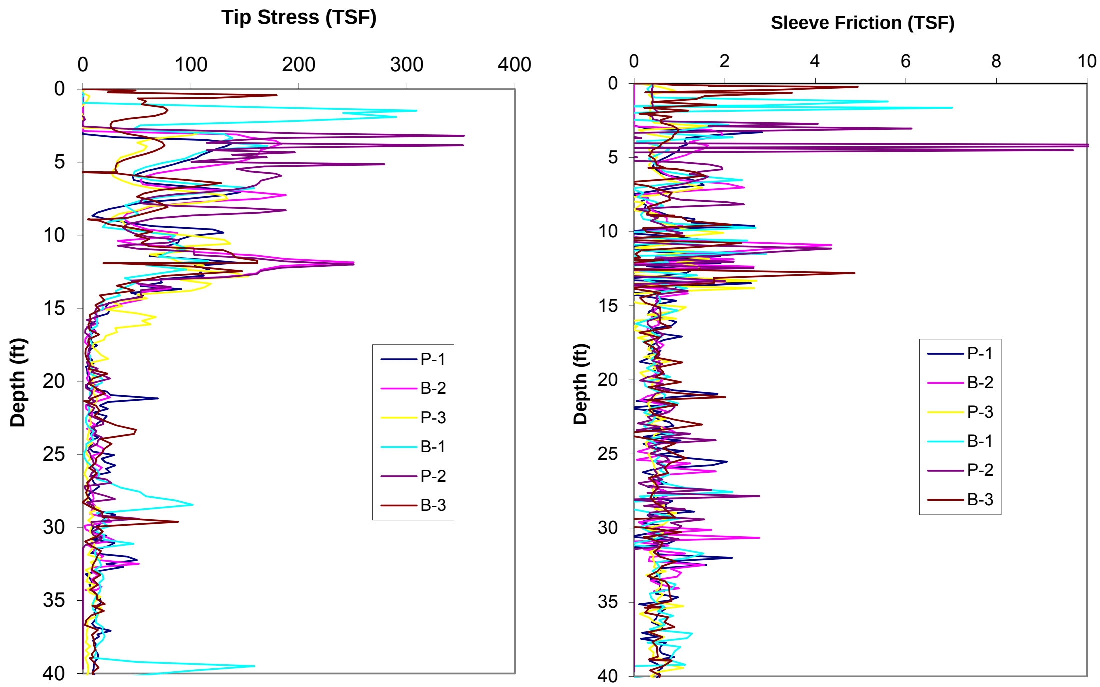


Figure 3.42 CPT tip stress (left) and sleeve friction (right) for each of the Phase I CPT soundings.

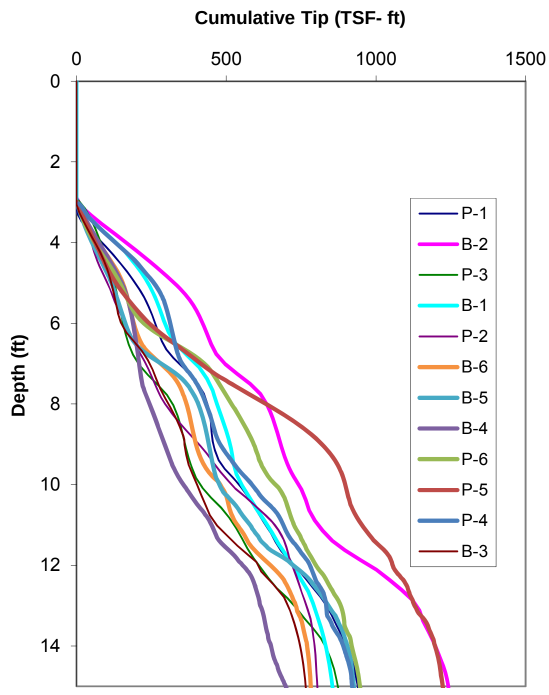


Figure 3.43 Cumulative area under the tip stress curve as a function of depth.

Positions B-2 and P-5 showed the highest cumulative tip area. For the remaining locations, the variation was less significant. Table 3.2 shows each of the CPT locations sorted from highest to lowest potential capacity for both Phase I and II.

Table 3.2 Capacity potential sorted for each phase (highest to lowest)

Cumulative q_c @15ft			
Phase I		Phase II	
Sounding	(TSF-ft)	Sounding	(TSF-ft)
B-2	1264	P-5	1224
P-1	941	B-5	926
P-3	876	P-4	921
B-1	873	B-6	783
P-2	816	B-4	670
B-3	774	P-6	946

3.3.2 Preparations for Shaft Construction and Field Testing

The test program outlined for this study required that shafts be constructed with full-length debonded anchor bars, which would, in effect, load the shaft concrete in compression by applying a tension load to the anchor bar secured at the toe of the shaft. The soil therefore resists by pulling down on the shaft as it is pulled upward, which is typically considered to develop lesser side shear resistance than under typical service loads. However, as all shafts were constructed and tested in the same manner, this serves as a convenient means to compare the shaft capacities and the effect of the slurry used at the time of shaft construction.

<u>Pullout Frame.</u> As the load testing (tension) apparatus could be designed to develop the full capacity of the side shear, it could also be designed to fully extract the shafts for dimensional inspection. As a result, the bulk of the preparations made for this task were in the design and fabrication of the pullout frame as well as the base anchor plates. Preliminary estimates of shaft capacity ranged from 50 to 70 kips based on the target diameter of 18 in. and length of 15 ft. The pullout frame (Figure 3.44) was designed to develop twice the estimated capacity while also providing sufficient vertical clearance to fully extract the shaft during testing. As the pullout tests were performed in two phases, the pullout frame was designed to be self-erecting via hydraulically actuated legs, which expedited transport and assembly.

Figure 3.44 Hydraulically-actuated, self-erecting pullout frame.

<u>Anchor Bar Assemblies Phase I.</u> The anchorage bars were 1in nominal diameter Williams Form 150 ksi fully threaded bars with a minimum ultimate strength of 128 kips (Figure 3.45). The bars were debonded from the shaft to prevent concrete cracking and Poisson necking effects that might affect side shear capacity. For Phase I, debonding was performed using 1-½ in ID SCH 40 PVC pipe which was cut to length and instrumented with thermal integrity wires as shown in Figure 3.45. Although integrity testing was not within the scope of the project, the data collected proved to be valuable in the analysis discussed later.

Thermal wires were strapped to the side of each pipe such that the temperature could be measured on all four sides of the anchor bar / PVC pipe system. For simplicity and to use fewer data collectors, a single thermal wire was looped up and down along the length of the PVC pipe so that a single 60 sensor wire with sensors every 1ft could be used to measure all four sides of the 15 ft central bar (Figure 3.46).

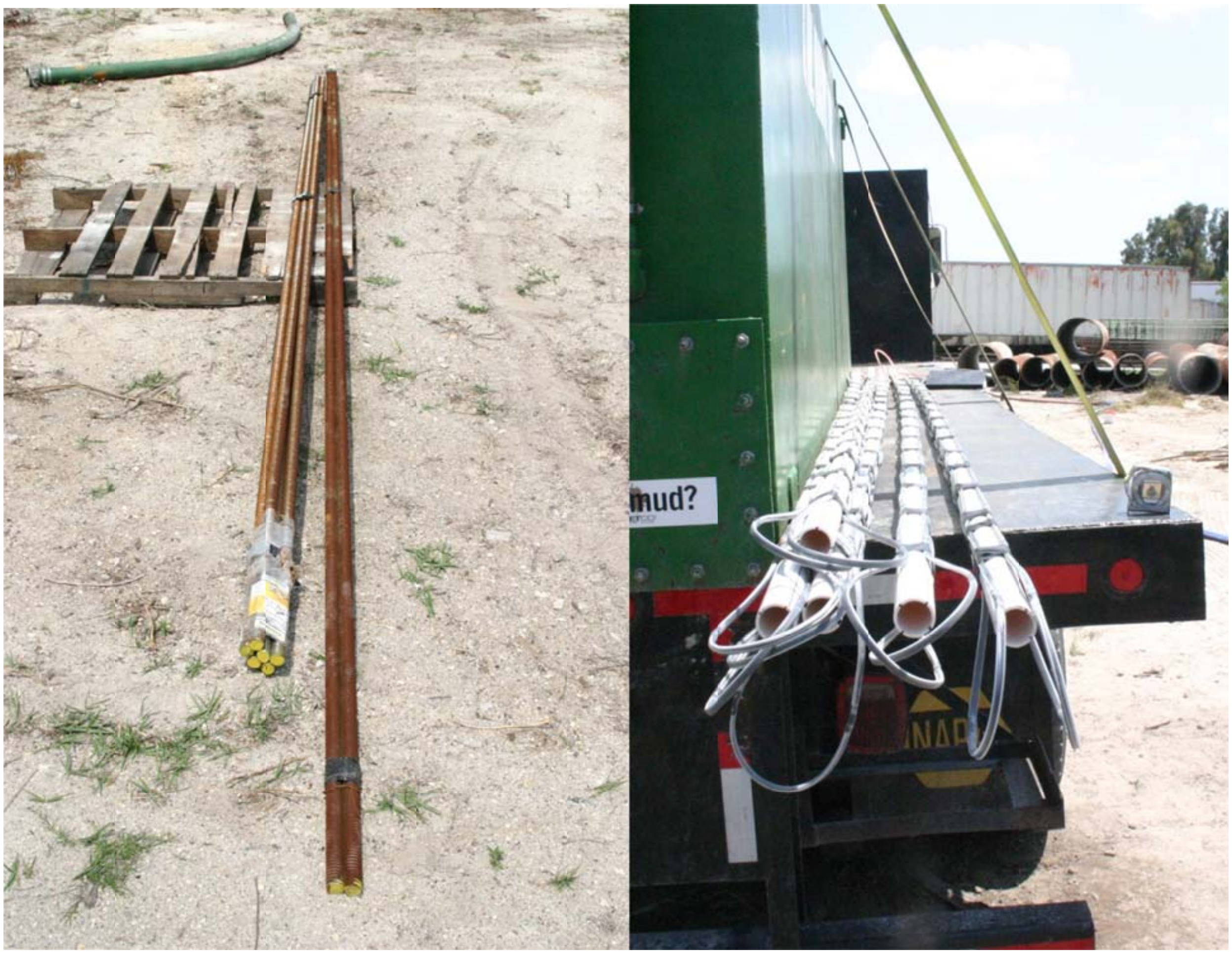


Figure 3.45 Phase I anchors bars as-received (left); PVC pipe instrumented with thermal wires (right).

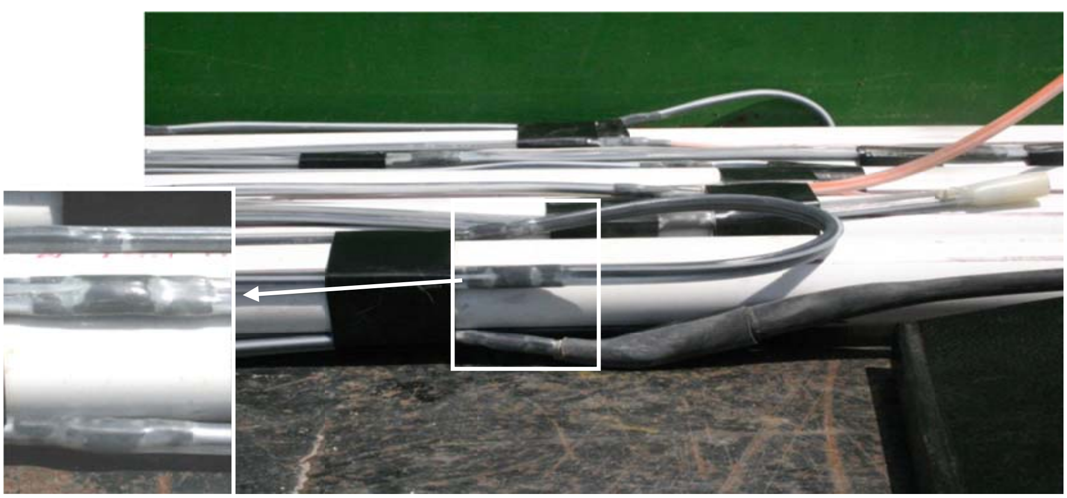


Figure 3.46 Thermal wire looped at the end of the pipe (Phase I).

An anchorage was provided at the toe of each shaft using a 16 in diameter circular plate made of ½ in steel through which the anchor rods where inserted and clamped with nuts on both sides. Figure 3.47 shows the completed anchor bar assemblies.

Figure 3.47 Anchor plates bolted to the base of each threaded bar (nut top and bottom) debonded using PVC pipes (Phase I).

Anchor Bar Assemblies Phase II. Phase II anchor bar assemblies were prepared in a similar fashion with some variations: thermal wires were not used, 1.5 inch steel pipe (not PVC) was used to debond the bar, the anchor plate was increased to ¾ inch thick, and thermal integrity profiling was performed within the steel pipe. To this end, the nut at the base of the anchor plate was welded to the bottom of the plate and the steel pipe to the plate using a welded coupler. Further, to provide access within the 1.5 inch access pipe, the bar was designed for removal (unthreading) from the anchor plate after concreting. This required that a chamber below the anchor nut be provided to prevent soil and water intrusion into the access pipe and to maintain access to the nut. Shear studs were added to each plate to facilitate removal and installation of the threaded anchor bar to allow access for thermal integrity profiling. Figure 3.48 shows the anchor components and assembly.

Figure 3.48 Phase II anchor plate (top left); coupling anchor bar (top right); attaching isolation/integrity pipe (bot left); completed assembly (bot right).

Slurry Preparation. For all shafts (both Phases), *Premium Gel* API 13A Section 9 bentonite powder (no additives) was used to represent a standard 90 barrel (2835 gallons) mineral slurry while *Shore Pac* was used as the selected polymer product for these tests (Figure 3.49).

Both the mineral and polymer materials where prepared and stored in dedicated slurry tanks. The pH of the supply water was adjusted using 6 lb of soda ash in 1000 gal of water to change it from pH 7 to 9 (Figure 3.50).

Bentonite Slurry Phase I. Mineral slurry was produced using the multi-eductor mixing system developed in an earlier FDOT project for the rapid hydration of mineral slurries shown in Figure 3.51. While the manufacturer recommended mix ratio for pure bentonite was 55 lb per 100 gallons to produce a 40 sec/qt viscosity (Phase I), the efficient mixing of the system proved to reduce this amount to 37 lb/100 gallons. As found by the previous study, virtually no material went unmixed and settled to the bottom of the tank thereby reducing the overall quantity needed. Figure 3.52 shows the bentonite immediately after mixing with no clumps of unmixed powder.

Figure 3.49 Slurry products used: Premium Gel pure bentonite (left); Shore Pac polymer (right).

Figure 3.50 1000 gal water tank (left) in which 6 lb of soda ash (right) was used to adjust pH.

Figure 3.51 Multi-eductor mixing system used to mix slurry (Phase I).


Figure 3.52 Bentonite slurry ready for use immediately after mixing (Phase I).

Bentonite Slurry Phase II. The Phase II bentonite slurry was prepared in the same manner with the multi-eductor mixing system (Figure 3.53). With a target viscosity of 50 sec/qt, the manufacturer recommended mix ratio was 60 lb / 100 gallons which was introduced into slurry 24 hr before concreting. The resulting viscosity shortly after introduction was 58 sec/qt. Just prior to introduction the next day, the bentonite had more thorough hydrated to a viscosity of 74 sec/qt. Although higher than the target viscosity, the slurry was used as-is to show adverse effects may not develop as a consequence. This decision was largely based on the small scale model test results which showed no appreciable difference in side shear for mineral slurry with viscosity up to 90 sec/qt (discussed later).

Figure 3.53 Mixing bentonite slurry for Phase II testing.

Polymer Slurry Phase I. The Shore Pac polymer slurry was mixed the next day just prior to commencing the excavation of the polymer shafts and after completing bentonite shaft excavations. The multi-gang eductor system was used to perform initial mixing wherein 2000 gallons of water was re-circulated through the eductors while three, 1 quart scoops (5.4 lb) of dry polymer were drawn into solution (Figure 3.54) which resulted in a viscosity of 42 s/qt. Additional polymer powder (3.6 lb) was slowly added to a moving stream of recirculated slurry to increase the viscosity to the target value (60 s/qt). Table 3.3 shows the results of both slurries, the mix ratios and the effect of small amounts of polymer powder on viscosity (1 quart or 1.8 lb at a time).

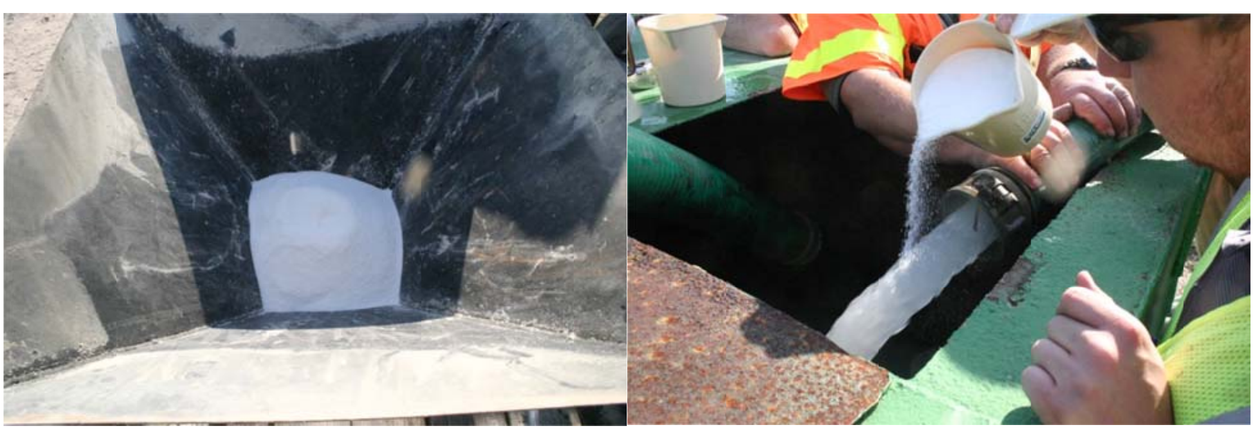


Figure 3.54 Left, 5.4 lb in powder pick-up pan; Right, additional powder added (Phase I).

Polymer Slurry Phase II. The polymer slurry for Phase II was designated to achieve 125 sec/qt which was anticipated to take twice the amount of material as the Phase I slurry (60 sec/qt; 0.45 lb / 100 gal). The required minimum slurry volume to cast the 3 shafts was 141 cu-ft (1060 gal). Two tanks with a total volume of 1300 gal were used in which 8 lb of dry polymer was introduced while filling (0.61 lb / 100 gal). This resulted in a viscosity of 68 sec/qt. To bolster the viscosity to the target 125 sec/qt, the slurry was recirculated through a single eductor using a centrifugal pump. Dry polymer powder was added slowly into the vacuum intake of a single eductor in increments of 2lb until a total of 16lb had been added and the target viscosity was achieved (Figure 3.55). Table 3.4 contains the results of tests performed on both types of slurry for Phase II.

Figure 3.55 Polymer tank (left); adding additional product through eductor (right).

Table 3.3 Slurry test results (Phase I)

Product	Mix Ratio (lb/100gal)	Viscosity (s/qt)	Density (pcf)	Rheometer Tests (lb/100ft^2)			
				300 rpm	600 rpm	Yield Point	Plastic Viscosity
Premium Gel	37	39	65.2	22	28	17	6
Shore Pac	0.27	42	N/A	N/A			
	0.36	48	N/A				
	0.45	59	62.5				

Table 3.4 Slurry test results (Phase II)

Product	Mix Ratio (lb/100gal)	Viscosity (s/qt)	Density (pcf)
Premium Gel	56	74	64.3
Shore Pac	0.61	80	N/A
	0.88	122	62.8

3.3.3 Shaft Construction

The construction approach adopted for this program was designed to compare the effects of varied mineral slurry viscosity on side shear capacity. Additionally, as time in hole and slurry type may affect side shear, shaft excavations were planned to be open for as long as practical without exceeding 12 hrs and polymer slurry was tested as well.

Shaft construction was performed in two phases: Phase I on 4/11/2012 and Phase II on 12/12/2013. On both occasions, construction commenced at first light and concreted starting at 5:00 PM the same day. An 18in auger with 2 in tip extensions, an 18 in cleanout bucket, and 27 in ID (½ in wall thickness) temporary surface casing was selected based on availability. Excavation tools are shown in Figure 3.56.

Figure 3.56 Excavation tools and dimensions.

<u>Phase I.</u> The temporary surface casing was set to an approximate depth of 4 ft for all shafts one day prior to excavation and concreting. However, shaft P-2 was inadvertently excavated slightly more than the rest of the shafts and encountered the water table. Figure 3.57 shows the temporary casings set the day prior to excavation.

Figure 3.57 Shaft locations shown by surface casings set a day in advance (Phase I).

Excavation commenced early the second day starting with shaft B-1 followed by the second and third bentonite shafts. Figure 3.58 shows the initial material extracted from each of those excavations. In general, similar material stratification was noted from all holes. Figure 3.59 shows the bentonite slurry being introduced while Figures 3.60 and 3.61 show the same activities for the polymer shafts.

Figure 3.58 First auger bite from shafts B-1(left), B-2 (center), and B-3 (right).

Figure 3.59 Bentonite slurry pumped-in to replace volume of soil extracted (Shaft B-1).

Figure 3.60 First auger bite from shafts P-1 (left), P-2 (center), and P-3 (right).

Figure 3.61 Polymer slurry being pumped-in to replace volume of soil extracted (Shaft P-1).

All excavations were completed by 12:00 PM (4 hours total); bentonite shafts from 8:00 to 9:30 and the polymer shafts from 10:30 to 12:00. Polymer slurry was mixed while bentonite shafts were being excavated and the same pumping system was cleaned out and used to introduce polymer slurry into the excavations. Upon completion of all shafts, the slurry was left for 5 hours prior to final slurry testing, cleanout procedures, and concreting. Table 3.5 summarizes the results of slurry testing and field measurements just prior to concreting.

Table 3.5 Field measurements and slurry test results at time of concreting

Shaft ID	Length (ft & in)	FDOT Required Slurry Tests			
		Sand Content (%)	Density (pcf)	Viscosity (s/qt)	pH
B1	16'-8"	3	66.5	40	9.5
B2	17'-2"	1.75	65	44	9.5
B3	16'-10"	2.5	65	36	9.5
P1	16'-0"	Trace < 0.25	63	47	10
P2	15'-9"	Trace < 0.25	63	46	10
P3	16'-2"	Trace < 0.25	62.5	56	10

The cleanout process caused the shafts to be slightly over-excavated as shown in Table 3.5 wherein the target depth was 15 ft. Final shaft lengths ranged from 15'-9" to 17'-2".

Note 1: Shaft P-1, slurry was introduced after encountering the water table. Some sloughing was noted prior to pumping in slurry.

Note 2: Shaft P-2, water table was encountered during casing installation the day before excavation.

Due to deeper than anticipated shafts, some of the anchor rods were lengthened to accommodate the as-built conditions. Not all anchor rods could be lengthened, so the anchor bar and anchorages were suspended at the lowest possible elevation. Figures 3.62 and 3.63 show the installation of the anchor rod and concreting.

Figure 3.62 Anchor rod installation.

Figure 3.63 Tremie placed aside suspended anchor bar (top left), slurry displacing during concreting (bottom left), finished shaft with thermal data collector attached (right).

<u>Phase II.</u> Shaft construction for Phase II used the same tools as Phase I but the drill rig was larger with a larger Kelley bar and a pump truck was used in lieu of a traditional tremie. The smaller hard line from the pump truck (6 in nominal diameter) made it easier to keep the anchor bar centered. Additionally, slurry was introduced as early as practical, before the water table was encountered to prevent the sloughing experienced in Phase I.

Figure 3.64 First bite of polymer shaft (left); bentonite shaft (right) during Phase II

Figure 3.65 Anchor bar installation; tremie hose capped before insertion (Phase II)

Figure 3.66 Concrete overflow and slurry displaced on to ground (Phase II)

Figure 3.67 Centering and removal of anchor bar for thermal integrity profiling (Phase II)

3.3.4 Field Pullout Testing

The load frame designed for this project served two purposes: (1) to apply tension loads with a span sufficient to satisfy ASTM recommended guidelines where the reaction feet were 12.5 ft from the shaft (CTC), and (2) to provide enough vertical clearance to fully remove the shafts upon completion of the load test. This chapter discusses the load testing and post testing evaluation of the extracted shafts.

Load Testing. Phase I pullout testing was performed over a two day period corresponding to 50 and 51 days after concreting (5/30-31/2012). The self-erecting load frame was assembled and moved to Shaft P-1 (Figure 3.68). Crane mats were laid out to provide additional bearing capacity beneath each foot of the frame. The short stroke of the jack (4 in) required that a locking nut be added beneath the jack to hold in the elastic compression of the frame, strain in the soil and the elongation of the anchor rod while re-stroking the jack. Without it, the extraction of the shaft required far more load/unload cycles as much of the jack stroke was used to overcome system compliance. This fixture is similar to a detensioning block for releasing prestressing strand and is the box shown in Figure 3.68 beneath the jack.

Figure 3.68 Hydraulically-actuated, self-erecting load frame and 60ton jack equipped with 100ton load cell.

A 30 ft reference beam was oriented orthogonal to the span of the frame on which two displacement transducers were setup to monitor opposite sides of the shaft (Figure 3.69). Loads were applied in increments of 25% ultimate capacity and held for 2.5 min each. This corresponded to 25 kip increments where ultimate capacity was determined after the first test shaft. For the first shaft, lower increments were used until the as-built, site dependent load capacity was established with confidence. The 4 in displacement transducers were removed after the uplift of the shaft exceeded the stroke of the devices. At which point the side shear had been fully developed and the test transitioned into the shaft extraction process.

Figure 3.69 Reference beams with displacement transducers; upward displacement is visible.

Phase II testing was performed in the same manner as Phase I using the same load frame, reference beam, and instrumentation. The only difference in equipment was that a 6 in stroke 60 ton jack was used which replaced the 4 in stroke 60 ton jack used in Phase I.

<u>Extraction.</u> A sequence of lifting the shaft out in 4 in (or 6 in depending on jack used) increments ensued whereby the jack was fully extended, the lock nut below the jack (in the support box, Figure 3.68) was threaded all the way down, the jack retracted, and the upper nut was then threaded down on to the top of the jack and load cell. This process was repeated until no

additional decrease in load was detected which also represented the self-weight of the shaft (about 10 ft upward movement). At which point, the loading frame was removed and the crane lifted the shaft from the ground.

The displacement of the shaft during the full extraction process was tracked by a string-line displacement transducer that measured the position of the jack piston. As all load was locked into the load frame system during the extraction, no rebound of the soil, relaxation of the frame, rod or crane mat / footings movement was experienced. However, the first shaft tested did not have the locking nut below the jack, which necessitated far more loading cycles to extract that shaft (P-1).

The order of load testing was selected based on crane access and to minimize the number of crane lifts and setups required. This resulted in Row A being tested first followed by Row B. Therefore, the Phase I order of testing was as follows: P-1, B-2, P-3, B-1, P-2, and B-3.

With the exception of B-2, all shafts were successfully tested and extracted for inspection. Shaft B-2 was loaded to failure and was extracted approximately 3 in when the anchorage failed at the bottom of the shaft. This was noted by sudden loss of load accompanied by the anchor rod being pulled from the shaft approximately 1 ft. Further, as the shafts were slightly over-excavated and the diameter was larger than that designed (22 in instead of 18 in), the anchor rod and anchorage system was very close to its associated strength limits; the anchor rod capacity was 126 kips, and the ½ in thick bearing plate was 96-120 kips. As a result, shear failure around the bottom nut and washer in the bearing plate most likely caused the sudden failure followed by the nuts splitting up through the bottom of the shaft. The rod was successfully unthreaded from the anchor nuts and showed no damage. However, the rod could not be reinstalled for subsequent attempts to remove the shaft. As thermal integrity wires had been installed this data was reviewed to identify the shaft shape as well as match all data to the extracted shafts. Thermal integrity analyses of the as-built shafts are presented in Appendix I.

The extraction process is depicted in Figure 3.70. Once the load registered by the load cell became constant and decreased no further, the shaft was then set carefully back into the hole, the frame removed, and then the shaft was removed via crane.

Phase II extraction was also performed in the same fashion as Phase I. All shafts were successfully removed for subsequent dimensional examinations; anchor plates were thicker ¾ in steel whereas Phase I used ½ in plates removing the possibility of the same mode of failure experienced for B-2.

Figure 3.70 Extraction process that followed load testing (Shaft P-3).

<u>Dimensional Inspections</u>. Each of the extracted shafts during Phase I and Phase II testing was measured for the exact as-built dimensions to better assess the true unit side shear capacity of each shaft. A large-scale caliper was fabricated to take cross sectional data down the length of these shafts (Figure 3.71). Likewise, the exhumed length of shaft was also recorded.

Figure 3.71 Large-scale caliper used to measure shaft diameter.

Detailed images from all extracted shafts are shown in Appendix G. Appendix H summarizes the as-built dimensions from the excavated shafts.

Chapter 4: Test Results

This chapter discusses the results of the testing that was performed. This includes: the rebar pullout results, model scale side shear testing, and full scale side shear/ pullout tests.

4.1 Rebar Pullout Tests

The rebar pullout tests involved casting specimens in a variety of slurry conditions and as such the slurry properties, concrete properties, pullout resistance, and physical observations of the specimens were all documented and discussed in this section.

4.1.1 Slurry Properties

Prior to placing slurry in the forms and on the evening before concrete placement, the viscosity of each sample was determined with the Marsh funnel and viscometer methods. Both the viscosity and density were tested from each form at the time the slurry was introduced as well as prior to concrete placement. Table 4.1 details the shaft number, as well as the anticipated slurry viscosity. The placement number refers to individual test setups and to an individual concrete truck / strength. Increasing numbers of samples were prepared for subsequent placements.

Table 4.1 Test matrix showing shaft number and target viscosity for each placement

Placement	Shaft	Viscosity (sec/qt)
1	1	40
	2	90
2	3	40
	4	50
	5	90
	6	26 (Water)
3	7	30
	8	40
	9	50
	10	90
	11	60 (Polymer)
	12	60 (Polymer)
4	13	30
	14	30
	15	50
	16	90 (Polymer)
	17	90 (Polymer)
	18	26 (Water)

For the first concrete placement the viscosity was determined only with the Marsh Funnel method, for all subsequent placements the viscosity was first determined via the Marsh Funnel followed by determining the plastic viscosity and gel strength with a viscometer. The subsequent tables provide a breakdown of the slurry properties at the time of slurry placement as well as at the time of concrete placement (Table 4.2 - 4.4). For the first placement only the viscosity was verified to be 40 sec/qt and 90 sec/qt at the time of slurry placement for shafts 1 and 2, respectively.

Table 4.2 Breakdown of slurry properties for model shafts for placement 2

Shaft Number	Sample Time	Viscosity (sec/qt)	Plastic Viscosity (cP)	10 Sec Gel Strength	10 Min Gel Strength	Density (lb/ft^3)	Yield Point
3	Intro	41.15	10.00	33	55.00	65.37	40.51
	Placement	43.81	11.50	0.00	58.00		39.67
4	Intro	51.57	12.88	64.00	66.00	65.29	84.98
	Placement	57.20	15.32	66.00	99.00		72.23
5	Intro	83.90	20.16	135.00	118.00	65.72	138.34
	Placement	108.39	23.99	118.00	180.00		122.77
6		26 (Water)	n/a	n/a	n/a	n/a	n/a

Table 4.3 Breakdown of slurry properties for model shafts for placement 3

Shaft Number	Sample Time	Viscosity (sec/qt)	Plastic Viscosity (cP)	10 Sec Gel Strength	10 Min Gel Strength	Density (lb/ft^3)	Yield Point
7	Intro	30.01	2.80	0.00	4.00	63.21	5.19
	Placement	31.10	4.46	0.00	5.00		2.11
8	Intro	38.10	8.71	18.00	51.00	64.27	32.65
	Placement	41.73	11.74	22.00	55.00		31.16
9	Intro	48.76	14.03	53.00	103.00	64.61	62.88
	Placement	56.72	15.34	54.00	98.00		71.08
10	Intro	80.73	20.84	96.00	172.00	65.17	115.01
	Placement	119.59	22.97	107.00	178.00		130.71
11 Polymer	Intro	65.99	5.75	0.00	0.00	62.03	6.30
	Placement	64.89	5.37	2.00	2.00		8.58
12 Polymer	Intro	66.46	5.77	3.00	3.00	62.09	5..78
	Placement	65.97	5.30	2.00	3.00		9.15

Table 4.4 Breakdown of slurry properties for model shafts for placement 4

Shaft Number	Sample Time	Viscosity (sec/qt)	Plastic Viscosity (cP)	10 Sec Gel Strength	10 Min Gel Strength	Density (lb/ft^3)	Yield Point
13	Intro	29.88	2.59	3.00	5.00	63.41	3.05
	Placement	30.43	3.31	4.00	5.00		4.18
14	Intro	30.22	2.16	3.00	7.00	63.41	11.77
	Placement	31.24	3.32	2.00	5.00		4.51
15	Intro	52.87	13.31	52.00	101.00	65.02	70.94
	Placement	61.37	17.18	48.00	78.00		75.21
16 Polymer	Intro	81.76	7.15	11.00	15.00	61.06	27.58
	Placement	86.76	7.59	10.00	15.00		26.31
17 Polymer	Intro	83.18	7.15	11.00	15.00	61.06	27.58
	Placement	85.05	7.48	10.00	15.00		30.16
18		26 (water)	n/a	n/a	n/a	n/a	n/a

4.1.2 Concrete Properties

Prior to each concrete placement the plastic properties were tested to ensure compliance with FDOT specifications (slump range of 7 to 10-inches, FDOT, 2013). The concrete properties are detailed in Tables 4.5 through 4.8 for placements 1 through 4, respectively. For placement 1, only the slump data was recorded and cylinders were cast between the placement of shaft 1 and shaft 2, and for the subsequent placements the test times were recorded.

Table 4.5 Concrete plastic properties for placement 1

Concrete Data					
Shaft Number	Slurry Type	Viscosity (sec)	Slump (in)	Cylinders	Slurry Contact Time (hours)
1	Bentonite	40	8.50	n/a	12
2	Bentonite	90	8.50	yes	12

The concrete slump throughout the test program ranged from 4.5-inches to 9.5-inches upon arrival at the test site. The properties are specified in the mix design and were noted on the delivery tickets (Appendix C); no adjustment/control was imposed in response to this variability as it was assumed that the same issues could arise in the field under normal drilled shaft construction. However, concrete out of the specified range was rejected.

Table 4.6 Concrete plastic properties for placement 2

Concrete Data							
Shaft Number	Slurry Type	Viscosity (sec)	Slump (in)	Cylinders	Slurry Placed	Casting Time	
						Start	Finish
3	Bentonite	40	9.50	yes	10:04 PM	10:31 AM	10:36 AM
4	Bentonite	50	8.50	n/a	9:06 PM	9:43 AM	9:48 AM
5	Bentonite	90	9.25	n/a	9:35 PM	10:03 AM	10:07 AM
6	Water	26	8.50	yes	9:00 PM	10:57 AM	11:02 AM

Table 4.7 Concrete plastic properties for placement 3

Concrete Data							
Shaft Number	Slurry Type	Viscosity (sec)	Slump (in)	Cylinders	Slurry Placed	Casting Time	
						Start	Finish
7	Bentonite	30	8.25	n/a	9:39 PM	11:03 AM	11:05 AM
8	Bentonite	40	7.75	n/a	10:05 PM	11:13 AM	11:15 AM
9	Bentonite	50	8.50	n/a	10:28 PM	11:20 AM	11:24 AM
10	Bentonite	90	8.00**	yes	9:17 PM	10:52 AM	10:56 AM
11	Polymer	60	7.75	n/a	10:49 PM	11:27 AM	11:29 AM
12	Polymer	60	7.75	yes	11:08 PM	11:38 AM	11:40 AM

** Added approximately 27 gallons of water to obtain slump.

Table 4.8 Concrete plastic properties for placement 4

Concrete Data							
Shaft Number	Slurry Type	Viscosity (sec)	Slump (in)	Cylinders	Slurry Placed	Casting Time	
						Start	Finish
13	Bentonite	50	9.50	n/a	8:31 PM	9:02 AM	9:06 AM
14	Bentonite	30	9.50	yes	8:55 PM	9:17 AM	9:20 AM
15	Bentonite	30	10.00	n/a	9:13 PM	9:29 AM	9:31 AM
16*	Polymer	85	10.00	n/a	9:38 PM	9:38 AM	9:42 AM
17	Polymer	85	9.50	n/a	9:42 PM	9:49 AM	9:55 AM
18	Water	26	10.00	yes	9:22 PM	10:07 AM	10:14 AM

* 2 1/2 hour contact time due to form leaking.

Prior to performing any pullout testing the concrete cylinders cast during the concrete placement were tested to verify the required compressive strength. A minimum of 4-ksi was needed in order to replicate field conditions and to achieve meaningful results during pullout testing. Tables 4.9 through 4.12 provide the compressive strength data for the concrete placements.

Table 4.9 Compressive strength data for placement 1

Sample ID	Break Date	Diameter (in)	Diameter (in)	Area (in^2)	Force (lb)	Strength (psi)
1	4-9-13	4.005	4.032	12.683	80785	6370
2	4-9-13	4.013	4.022	12.677	77570	6119
3	4-9-13	4.064	4.034	12.876	76740	5960
Average Compressive Strength						6150

Table 4.10 Compressive strength data for placement 2

Sample ID	Break Date	Diameter (in)	Diameter (in)	Area (in^2)	Force (lb)	Strength (psi)
1	5-14-13	4.025	4.049	12.800	56130	4385
2	5-14-13	4.059	4.033	12.857	56050	4359
3	5-14-13	4.063	4.023	12.838	54390	4237
4	5-14-13	4.051	4.046	12.873	57290	4450
				Average strength		4358

Table 4.11 Compressive strength data for placement 3

Sample ID	Break Date	Diameter (in)	Diameter (in)	Area (in^2)	Force (lb)	Strength (psi)
1	6-25-13	4.075	4.067	13.016	54083	4150
2	6-25-13	4.080	4.025	12.898	57098	4430
3	6-25-13	4.022	4.000	12.636	62016	4910
4	6-25-13	4.077	4.064	13.013	60180	4620
				Average strength		4530

Table 4.12 Compressive strength data for placement 4

Sample ID	Break Date	Diameter (in)	Diameter (in)	Area (in^2)	Force (lb)	Strength (psi)
1	10/18/13	4.000	4.000	12.566	61170	4870
2	10/18/13	4.080	4.025	12.898	59050	4580
3	10/18/13	4.022	4.000	12.636	60820	4810
				Average strength		4753

4.1.3 Pullout Data

Once the concrete achieved the desired compressive strength, the pullout testing could be performed. Pullout testing was performed on the same day as the compressive strength testing.

The following tables detail the pullout data for each placement. The bonded length for placement 1 was 18-inches. The red shaded areas denote bars that failed in tension. All failures occurred in the threaded region due to the reduced cross section.

Table 4.13 Placement 1 pullout data (load in kips).

Maximum Recorded Pullout Load		
Bar #	**Bentonite**	
	Shaft 1 40 sec	Shaft 2 90 sec
1	58.706	55.724
2	65.360	51.680
3	54.071	51.073
4	56.460	53.133
5	55.160	33.097
6	60.946	53.852
7	49.935	49.367
Max	65.360	55.724
Min	49.935	33.097
Average	57.234	49.704
std dev	5.003	7.604

For placement 2 the bonded length was adjusted from 18-inches to 10-inches based on the calculated values to determine the pullout strength. Again, the red shaded areas denote bars that failed in tension. The bonded length for the water shaft was varied where the shortest length was 8-inches, increasing in 2-inch increments up to 12-inches. Again, all the bar failures occurred in the threaded region of the bar where the cross section was reduced during machining.

Table 4.14 Placement 2 pullout data (load in kips).

Maximum Recorded Pullout Load				
Bar #	Bentonite			Water
	Shaft 3 40 sec	Shaft 4 50 sec	Shaft 5 90 sec	Shaft 6 26 sec
1	40.88	29.36	35.08	54.65
2	40.70	34.68	36.46	51.19
3	37.22	34.56	35.81	55.73
4	40.52	38.96	46.21	54.34
5	33.23	31.62	42.37	51.83
6	26.99	34.17	35.80	55.46
7	38.71	25.52	34.93	56.93
Max	40.881	38.962	46.211	56.933
Min	26.994	25.523	34.927	51.194
Average	36.894	32.697	38.094	54.304
std dev	5.138	4.332	4.405	2.090

For placement 3 the bonded length was again adjusted based on previous test data to a length of 6-inches. Along with determining the pullout strength, for placements 3 and 4 the bar displacement was measured to determine stiffness of the bond between the concrete and reinforcement. Table 4.15 (below) provides the pullout testing data from placement 3, and is followed by the stiffness data in Table 4.16.

Table 4.15 Placement 3 pullout data.

Maximum Recorded Pullout Load (kips)						
Bar #	Bentonite				Polymer	
	Shaft 7 30 sec	Shaft 8 40 sec	Shaft 9 50 sec	Shaft 10 90 sec	Shaft 11 60 sec	Shaft 12 60 sec
1	23.559	26.970	23.998	20.639	32.886	30.233
2	31.575	26.018	18.836	29.715	34.133	42.584
3	22.707	25.242	24.218	20.932	26.757	25.488
4	34.929	24.708	24.117	25.910	41.109	29.595
5	32.530	18.320	20.893	18.518	24.431	36.973
6	28.293	20.599	12.657	27.736	32.836	38.471
7	27.687	27.627	18.947	18.519	34.216	34.244
Max	34.929	27.627	24.218	29.715	41.109	42.584
Min	22.707	18.320	12.657	18.518	24.431	25.488
Average	28.754	24.212	20.524	23.139	32.338	33.941
std dev	4.569	3.454	4.203	4.580	5.445	5.896

Table 4.16 Placement 3 stiffness data.

Recorded Pullout Stiffness (kips/in)						
	Bentonite				**Polymer**	
Bar #	Shaft 7 30 sec	Shaft 8 40 sec	Shaft 9 50 sec	Shaft 10 90 sec	Shaft 11 60 sec	Shaft 12 60 sec
1	184.524	155.147	200.293	178.007	236.414	233.316
2	147.035	95.463	121.542	n/a	229.444	124.058
3	160.456	178.462	133.714	116.327	242.478	183.385
4	118.177	157.900	181.749	146.099	193.904	183.348
5	133.818	134.670	116.816	126.856	98.494	157.599
6	187.597	144.364	79.575	93.945	150.325	129.961
7	154.469	132.983	147.729	103.965	102.648	118.166
Max	187.597	178.462	200.293	178.007	242.478	233.316
Min	118.177	95.463	79.575	93.945	98.494	118.166
Average	155.154	142.713	140.203	127.533	179.101	161.405
std dev	25.273	26.006	40.838	30.666	62.217	41.640

The stiffness was determined by calculating the change in load in the linear portion of the following plots (Figures 4.1 - 4.6).

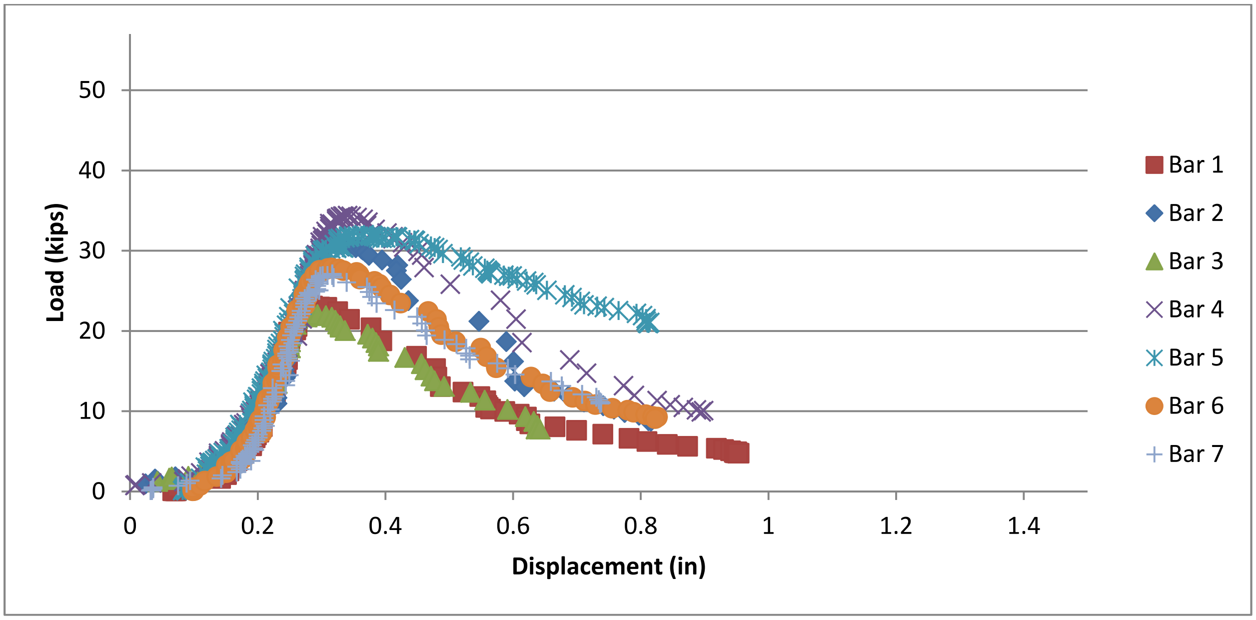


Figure 4.1 Plot of load vs. displacement for shaft 7 (30 sec bentonite).

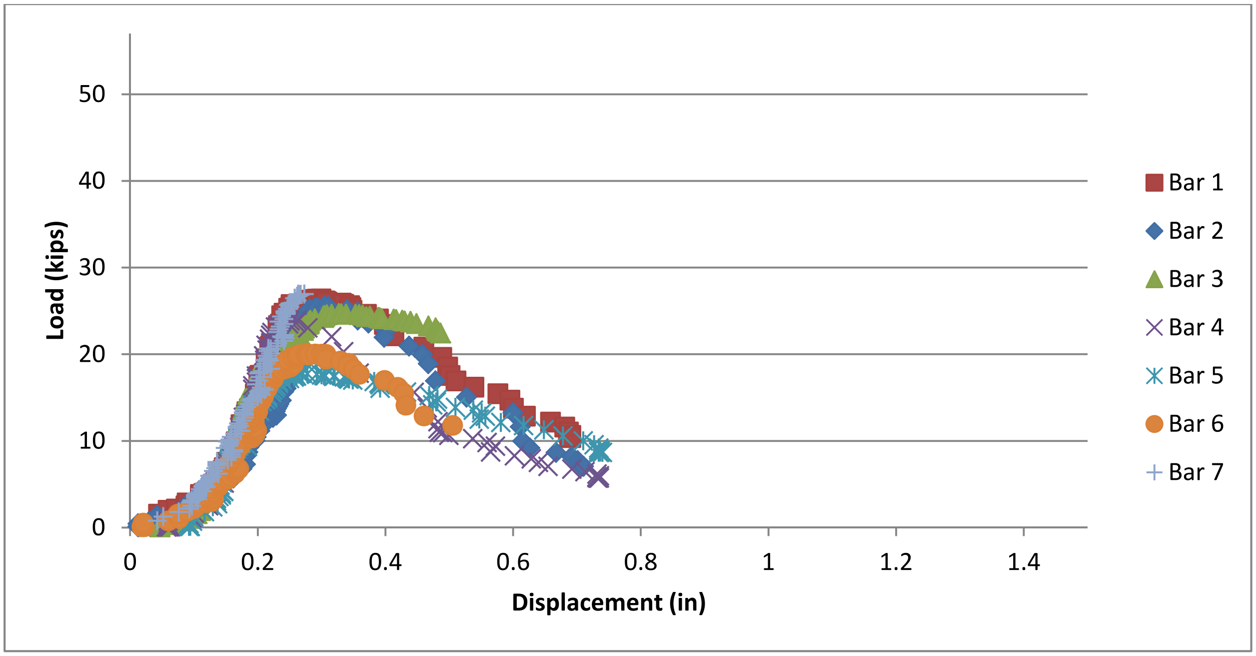


Figure 4.2 Plot of load vs. displacement for shaft 8 (40 sec bentonite).

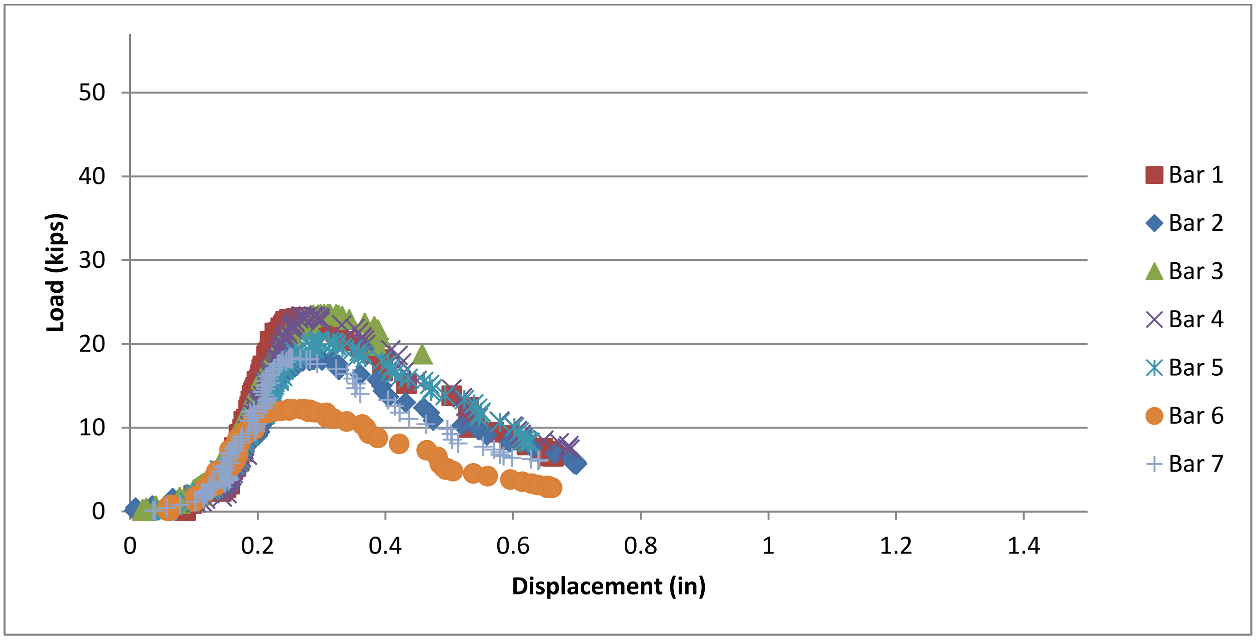


Figure 4.3 Plot of load vs. displacement for shaft 9 (50 sec bentonite).

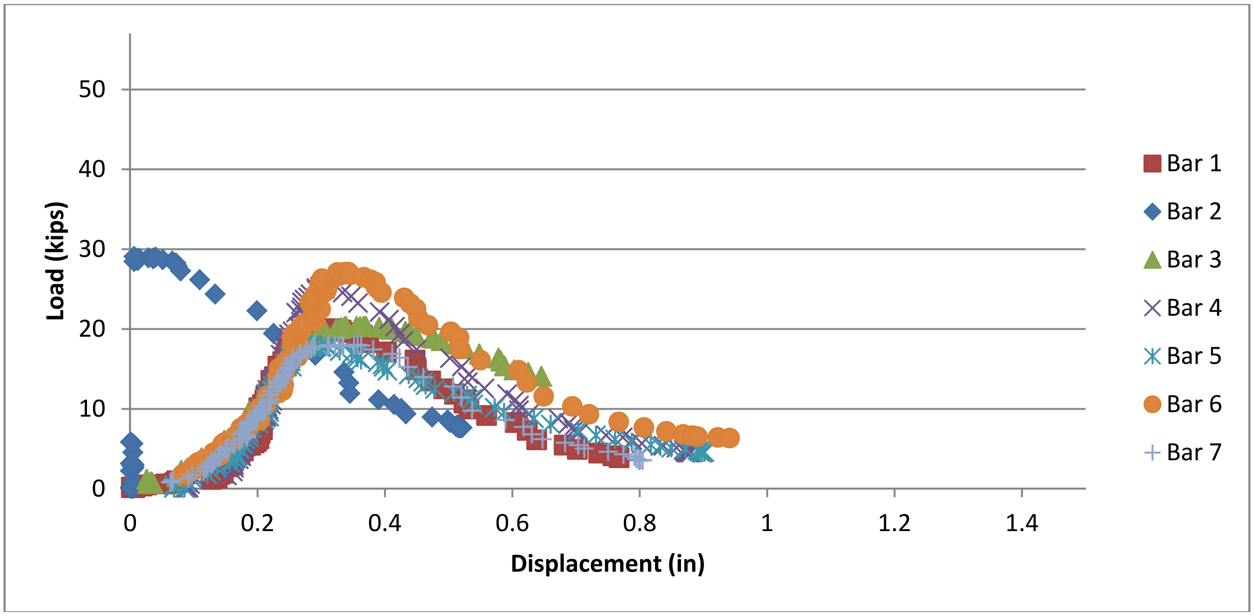


Figure 4.4 Plot of load vs. displacement for shaft 10 (90 sec bentonite).

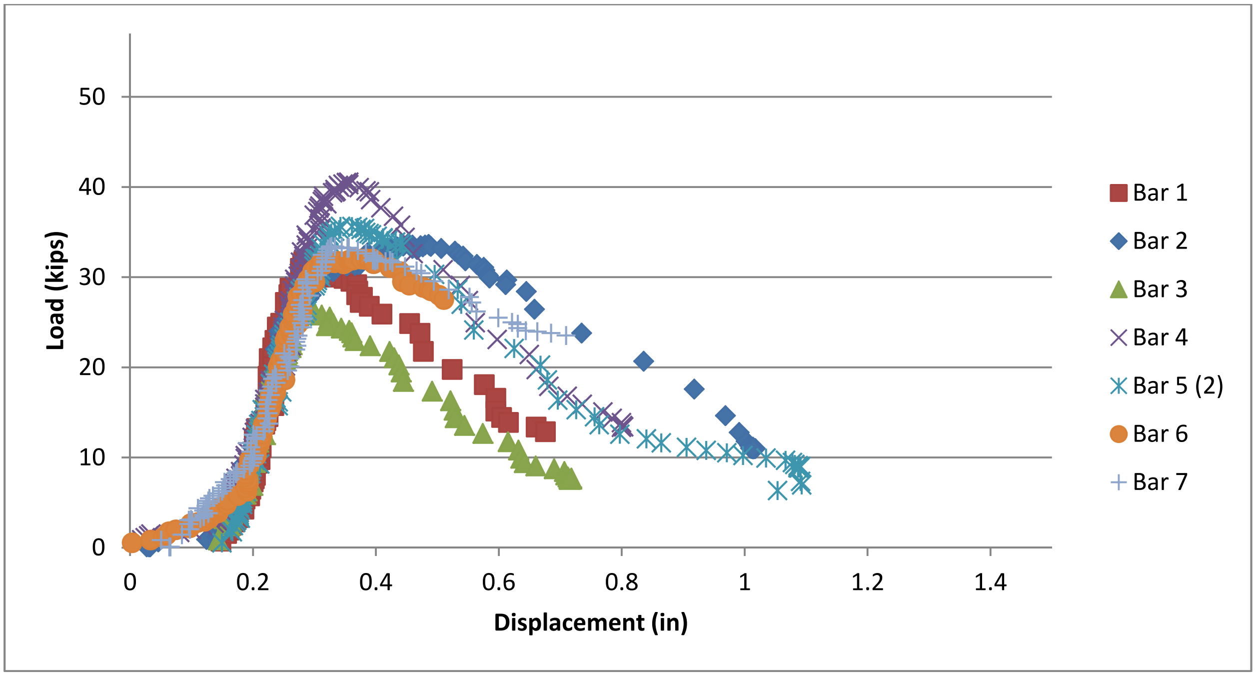


Figure 4.5 Plot of load vs. displacement for shaft 11 (60 sec polymer).

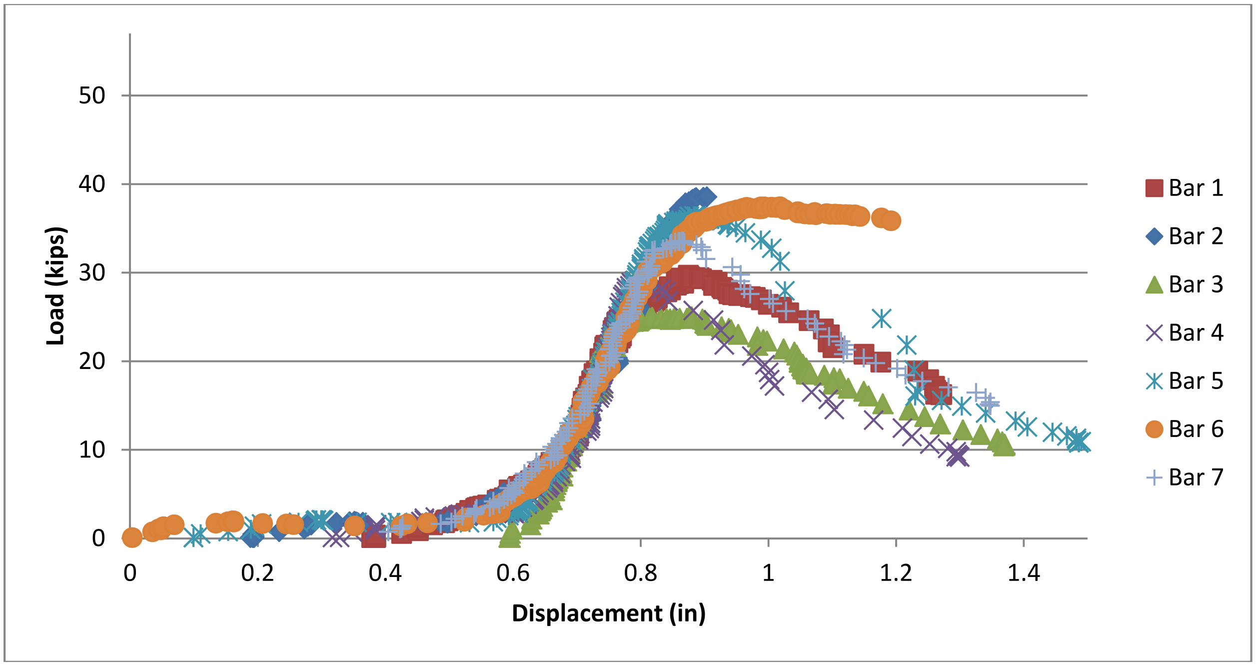


Figure 4.6 Plot of load vs. displacement for shaft 12 (60 sec polymer).

For the fourth and final placement, the bonded length remained 6-inches, however another water shaft was constructed in order to determine a control value for the bond strength due to the tensile failure of the bars in the previous tests. The threads for bar 2 failed and the data was unusable for that particular bar. Table 4.17 (below) provides the pullout testing data from placement four.

Table 4.17 Placement 4 pullout data.

Maximum Recorded Pullout Load (kips)						
Bar #	Bentonite			Polymer		Water
	Shaft 13 30 sec	Shaft 14 30 sec	Shaft 15 50 sec	Shaft 16 85 sec	Shaft 17 85 sec	Shaft 18 26 sec
1	20.000	24.960	21.000	25.590	25.460	37.410
2	25.050	29.210	18.590	24.180	19.110	
3	28.560	27.130	24.540	27.430	24.670	41.500
4	30.040	32.620	21.600	30.880	26.370	27.220
5	25.360	31.530	16.370	23.280	27.740	29.040
6	22.850	24.580	17.130	20.280	25.710	28.060
7	27.590	23.460	19.400	16.900	34.670	41.020
Max	30.040	32.620	24.540	30.880	34.670	41.500
Min	20.000	23.460	16.370	16.900	19.110	27.220
Average	25.636	27.641	19.804	24.077	26.247	34.042
std dev	3.457	3.575	2.819	4.590	4.610	6.678

4.1.4 Physical Defects

Once the forms were removed, the shafts were inspected to check for any defects, anomalies, or buildup of material on the shaft outer surface. Once the surface was inspected, the shafts were then pressure washed in order to remove any residual slurry that remained from the concrete placement. The following figures (Figures 4.7-4.10) illustrate the amount of slurry that remained between the concrete surface and the forms during placement as well as the voids caused by the slurry that was not displaced.

Figure 4.7 The 90 sec/qt bentonite shaft (left) and 40 sec/qt bentonite shaft (right) from placement one following form removal.

Figure 4.8 Buildup encountered at bottom of 90 sec/qt bentonite shaft from placement one.


Figure 4.9 90 sec/qt bentonite shaft after pressure washing.


Figure 4.10 Slurry that was encapsulated in the concrete (90 sec/qt bentonite shaft).

The previous images were from the first placement but were a recurring trend in subsequent concrete placements. Once this trend was noticed the shafts were cored to determine the depth of the visible creases and to determine if any slurry was present between the reinforcement and the concrete.

Selected coring into the side of the shaft specimens (Figure 4.11) was performed at the intersection of creases formed by the longitudinal and lateral steel.

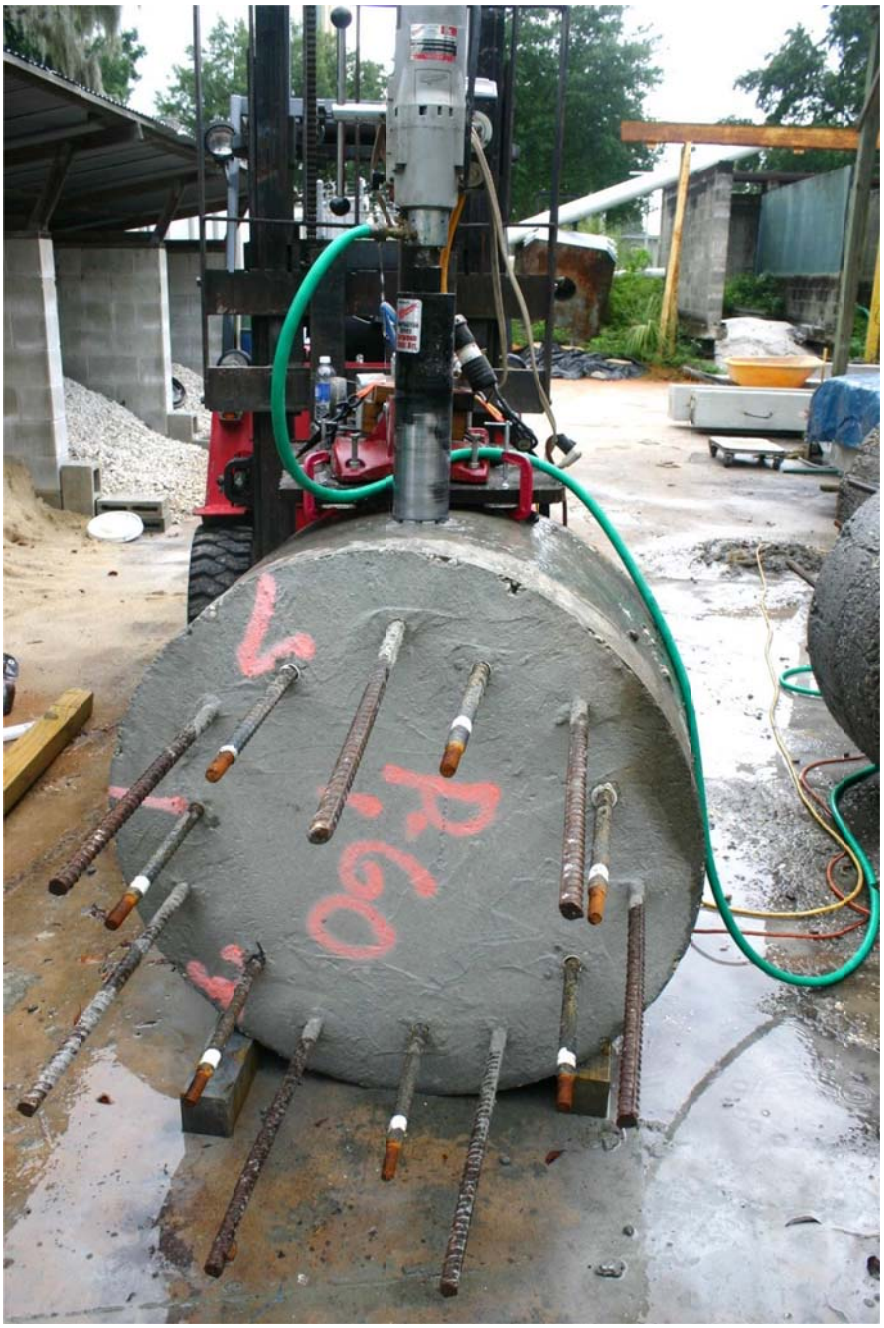


Figure 4.11 Coring performed at the intersection of creases.

Coring revealed that the slurry creases extended to the full depth of the main rebar in all cases (through cover concrete). Cored samples from bentonite samples with 50 sec/qt or higher typically would fall apart along the crease lines upon removal (Figures 4.12).

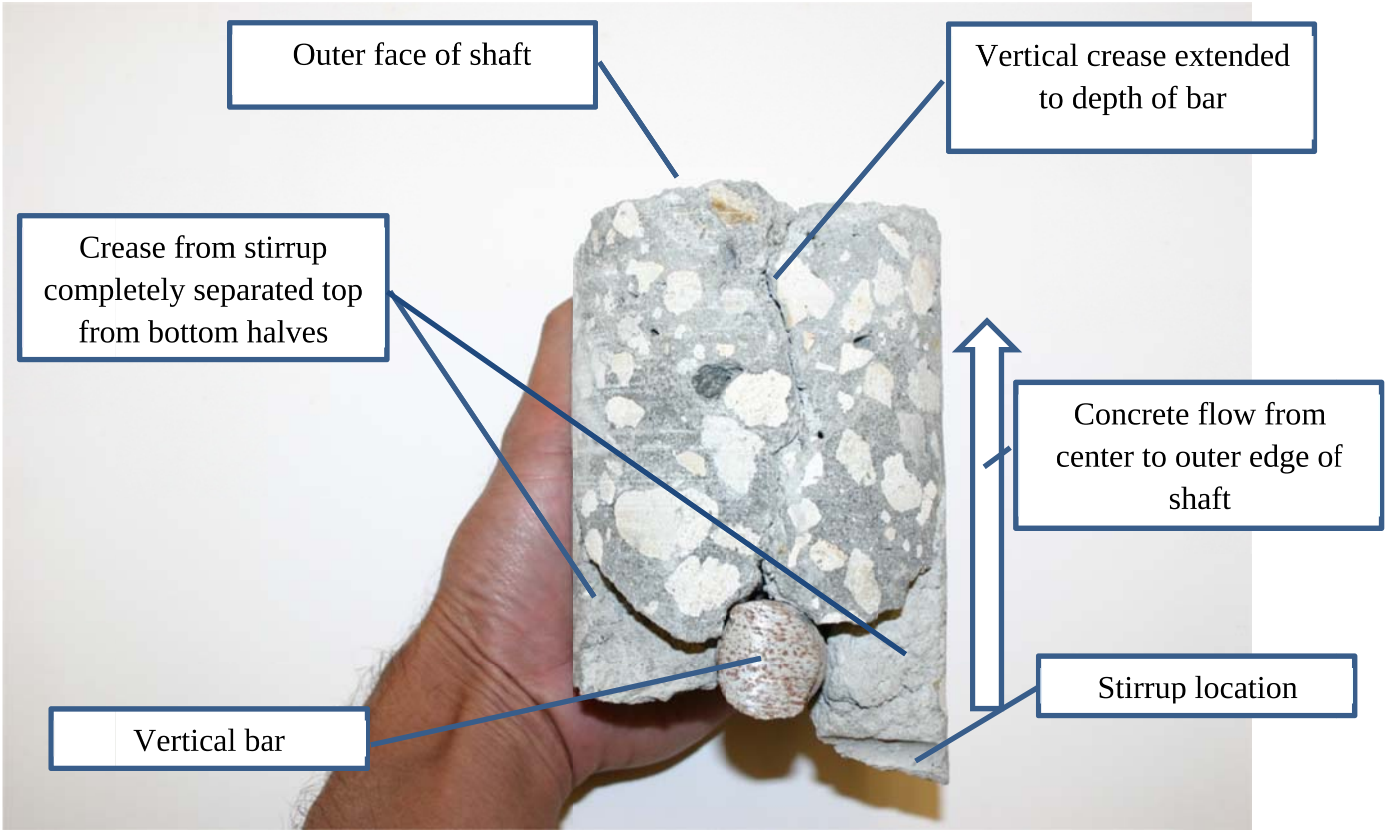


Figure 4.12 Cored sample separated into four parts along creases.

Along the sides of the cored hole in the side of the shaft also confirmed the presence of the bentonite crease to the full depth of the rebar (Figure 4.13). The deformations in the bar made clear imprints in the concrete but there was no apparent adhesion on this surface. Further, when the specimen was pulled away from the rebar, residual bentonite was observed on both faces of the concrete crease and rebar interface.

Specimens cast with water, polymer, or low bentonite viscosity (30 sec/qt) showed minimal, if any, evidence of the crease / pathway to the rebar. Figure 4.14 shows a polymer shaft with no visible signs of cage effects. Images for all shafts constructed can be found in Appendix A.

Figure 4.13 Depth of visible crease (top); slurry present at surface of reinforcement and on both concrete faces (bottom).

Figure 4.14 Shaft cast with 60 sec/qt polymer slurry following pressure washing.

4.2 Model Shaft Tests in FCV

The model shaft tests in FCV involved: casting specimens in various slurry conditions, measuring the variation of the soil strength identified by CPT soundings, pullout / side shear testing, and physical inspection of each specimen cast.

4.2.1 Cone Penetration Tests

Prior to excavation of each model shaft, a CPT sounding of the sandy soil strata was conducted to determine the soil strength within the FCV as subtle variations occur during sand placement. Figure 4.15 details the tip stress versus depth gathered for each of the model shafts created.

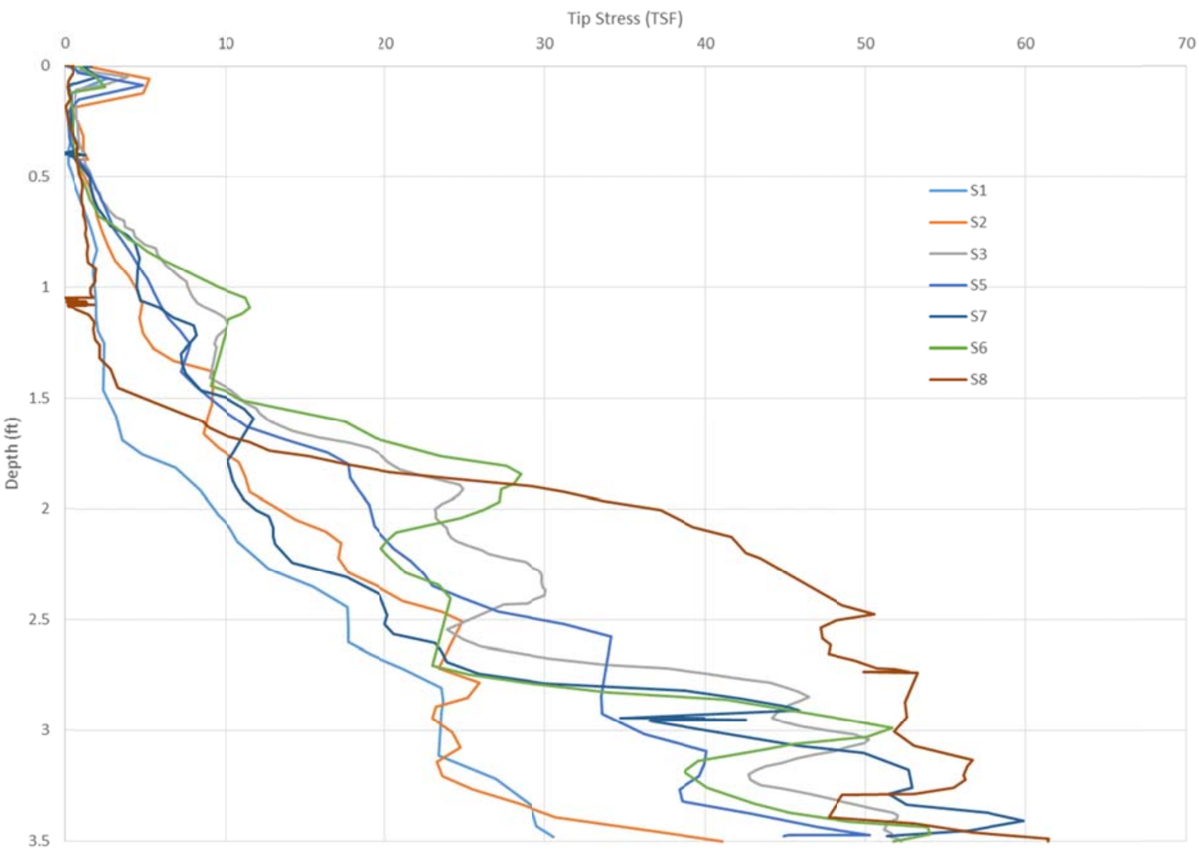


Figure 4.15 CPT Tip Stress Sounding for each model shaft

To better compare all test shafts and the associated viscosity differences, the cumulative area under the cone tip stress curve from each FCV model was computed (Figure 4.16) down to a depth of 3ft (bottom of shaft). Larger values of cumulative tip area would suggest higher side shear would result for a given viscosity. Hence, this provided a mechanism to remove the effects of soil strength variation.

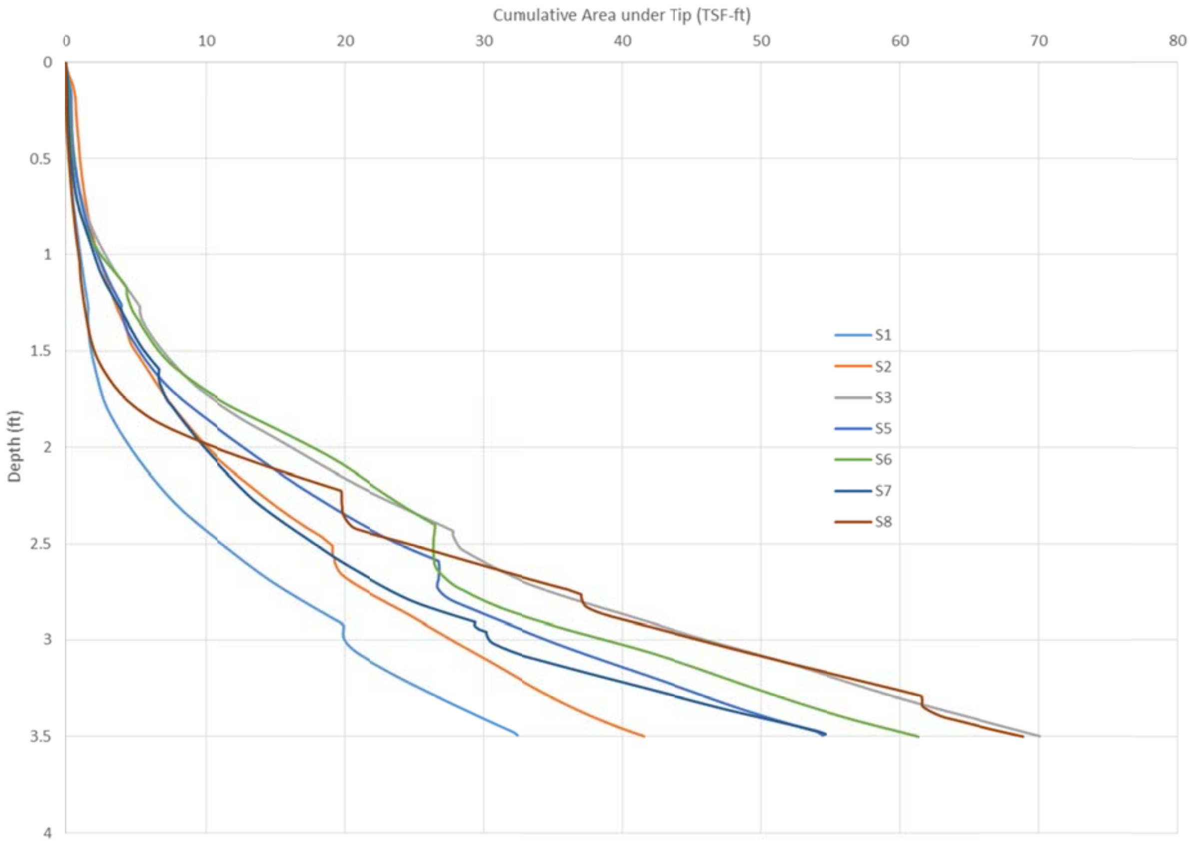


Figure 4.16 Cumulative Area under the Tip for each model shaft

4.2.2 Pullout Data

Once the shaft concrete (mortar) had reached a curing time of 24 hours and a minimum compressive strength of 250 psi, the model shafts could be pulled from the FCV without pulling the anchor bar from the concrete. The load versus displacement results from the pullout testing are shown in Figure 4.17.

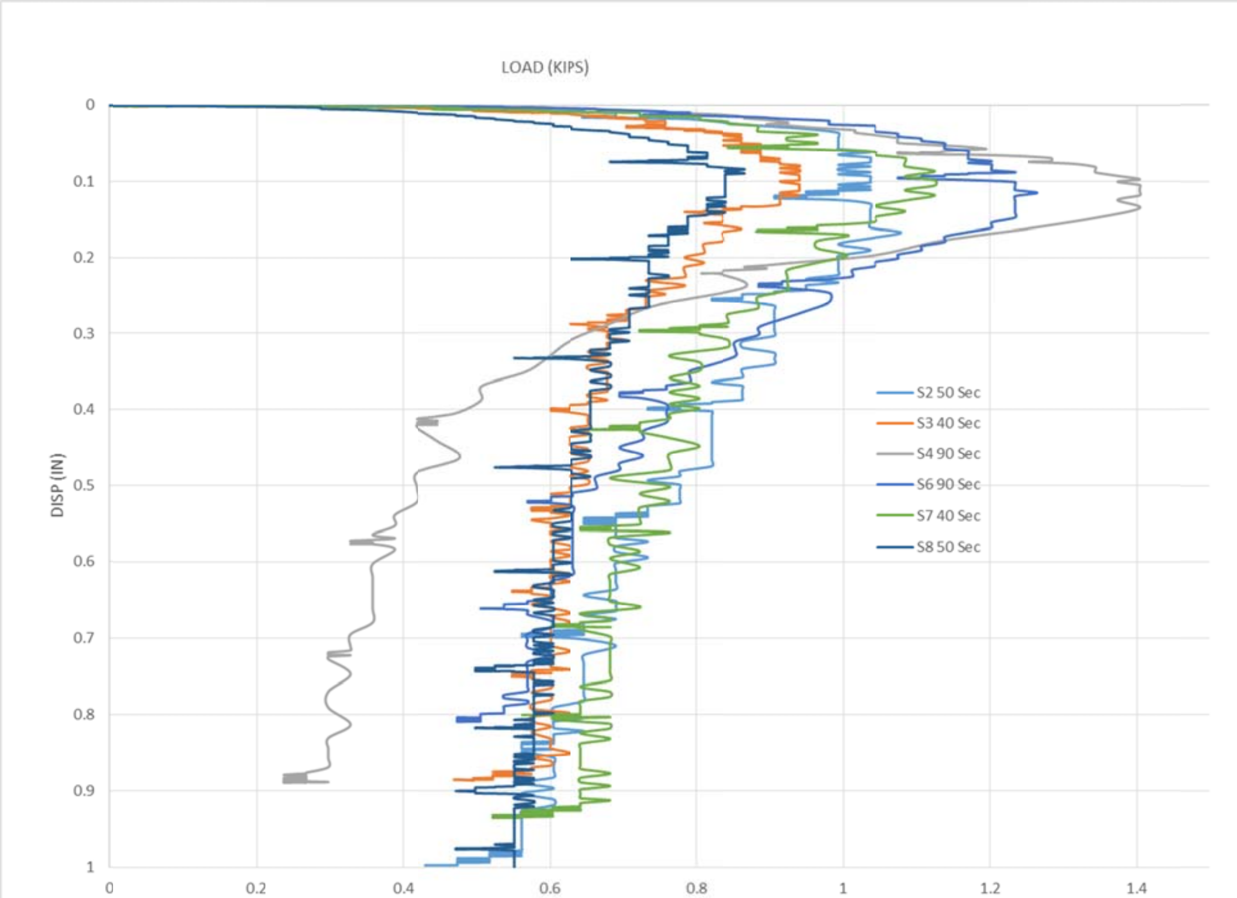


Figure 4.17 Load versus displacement curves from Pullout Testing

4.2.3 Physical Observations

Upon removal of the model shafts from the FCV, the diameter and length of embedment of each shaft were determined. Also any defects such as bulges, pits, or skew were documented and the effects on the pullout performance were considered.

Table 4.18 Model shaft dimensions

ID	Average Diameter	Total Length
	IN	IN
S1	4.260	36
S2	3.909	36
S3	3.898	32.89
S4	3.690	34.95
S5	3.979	36.93
S6	3.848	35.74
S7	3.871	34.45
S8	3.881	38.5

4.2.4 Normalization of Data

All the data was normalized to a single shaft to create comparable data thereby removing effects from inadvertent variations in the FCV soil strength profile. A 40 sec/qt model shaft (S3–40) was selected to be used as the basis of comparison for this testing. To analyze the data, two things were done: (1) the surface area of each shaft was used to convert load to side shear stress by dividing the load by the surface area and (2) the measured side shear was normalized by multiplying the measured values with the cumulative area ratio defined by equation 4.1. The normalized side shear response is shown in in Figure 4.18.

$$q_{normalized} = \frac{Area\ under\ tip\ stress\ curve_{control}}{Area\ under\ tip\ stress\ curve_{measured}}\ q_{measured} \qquad \text{(Equation 4.1)}$$

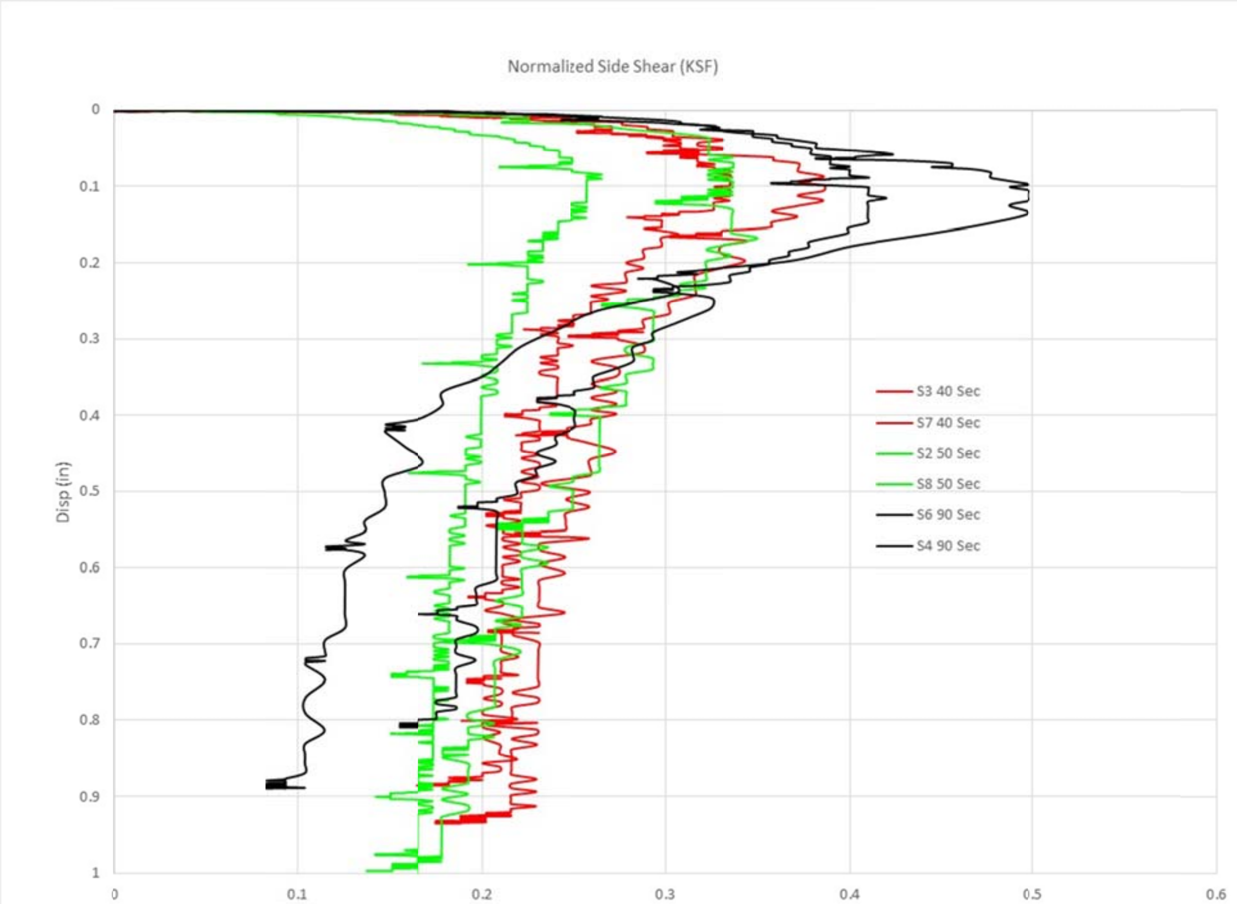


Figure 4.18 Normalized Stress for each model shaft

Somewhat surprisingly, shafts constructed with 90 sec/qt viscosity slurry developed the most ultimate capacity followed by the 40 sec/qt shafts and then the 50 sec/qt shafts. This trend is similar to that of the rebar pullout tests. Residual capacity was also noted for each shaft at an approximate displacement of 1inch. Shaft S5-50 was removed from consideration due to mechanical failure of the pressure regulator controlling the FCV bladder wherein the chamber was permitted to pressurize above 30psi after concreting. Table 4.19 summarizes the normalized results.

Table 4.19 Normalized model shaft capacities

ID	ABS MAX			ABS RESIDUAL @ 1" DISP			Viscosity
	LOAD (KIP)	STRESS (KSF)	STRESS (TSF)	LOAD (KIP)	STRESS (KSF)	STRESS (TSF)	
S2 50 Sec	1.037	0.337	0.168	0.561	0.178	0.089	54.78
S3 40 Sec	0.941	0.335	0.168	0.627	0.209	0.105	44.62
S4 90 Sec	1.404	0.498	0.249	0.299	0.104	0.052	88.41
S5 50 Sec	2.188	0.669	0.335	1.094	0.343	0.171	50
S6 90 Sec	1.234	0.410	0.205	0.538	0.186	0.093	93.38
S7 40 Sec	1.125	0.386	0.193	0.643	0.215	0.108	37.49
S8 50 Sec	0.841	0.257	0.129	0.552	0.165	0.082	51.26

Figures 4.19 and 4.20 show the effects of slurry viscosity on the normalized ultimate and residual capacity, respectively.

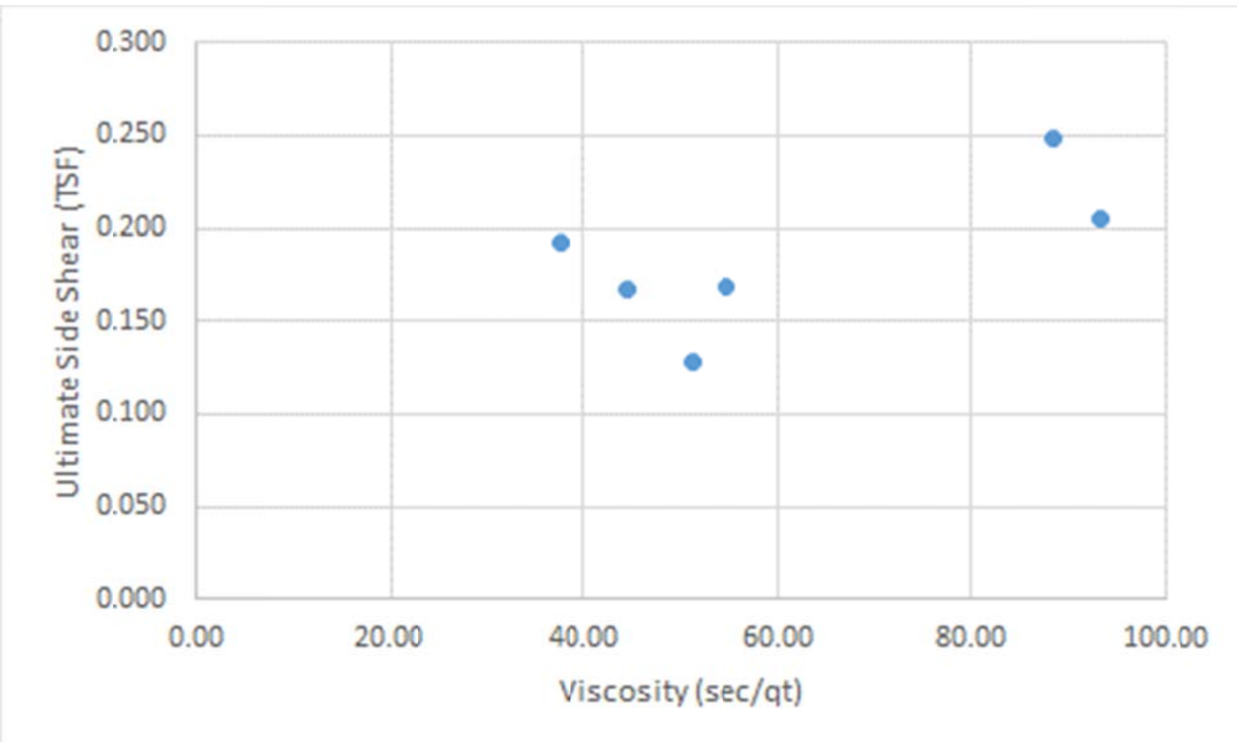


Figure 4.19 Ultimate side shear from model tests versus mineral slurry viscosity.

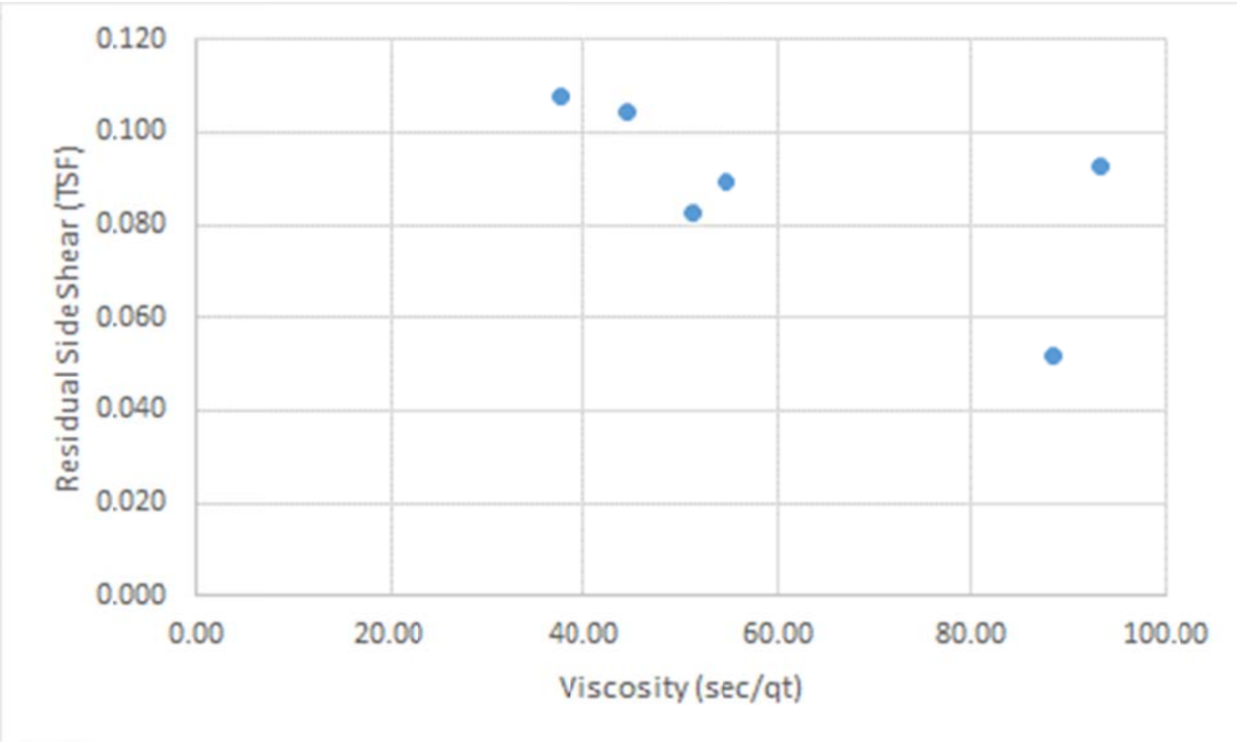


Figure 4.20 Residual side shear from model tests versus mineral slurry viscosity.

4.3 Full Scale Pullout Tests

Phase I. The measured load and displacement from each of six test shafts, as well as, the as-built measured dimension of the extracted shafts were evaluated to compare the 50 sec/qt polymer shafts to the 40 sec/qt bentonite shafts in two ways: initial stiffness and side shear capacity.

As noted in Chapter 3, load and displacement data was collected for upwards of 100 in of extraction for four of the six shafts. The first 3 inches were monitored precisely using displacement transducers mounted to the reference beam. However, the subsequent displacement response was computed from the jack stroke / position data monitored using a string line displacement gage (rheostatic displacement transducer); this data is not considered to be as precise with regards to actual upward displacement, but does provide an indication of when the shaft became fully disengaged from the soil.

Raw data from a single load test, for the first 3 to 4 inches of displacement, is shown in Figure 4.21. This data represents the total load measured by the load cell versus the average displacement measured by the two displacement transducers. The raw data for all shafts is provided in Appendix F.

Note that the excessive number of load/unload/reload cycles required for Shaft P-1 in Appendix F was simply due to the lack of the locking nut preventing rebound and the associated downwards displacement during extraction. The locking nut system was added after the first load test (P-1).

<u>Phase II.</u> The measured load and displacement of all shafts tested in Phase II was recorded in the exact same fashion as in Phase I. This phase increased the scope of review to scrutinize the effects of high viscosity bentonite and polymer slurry on side shear.

<u>Evaluation.</u> In order to compare shaft performance based on the effects of slurry, the average side shear resistance experienced by each shaft was determined. Side shear was computed according to Equation 4-1, as follows:

$$\text{Unit Side Shear} = \frac{\text{Measured Load - Dead Load}}{\text{Side Surface Area}} \qquad \text{(Equation 4.2)}$$

With the exception of Shaft B-2, the surface area of each shaft was computed from the post-extraction measurements taken from the as-built shafts. As Shaft B-2 could not be extracted and measured, these values were computed from estimated dimensions based on analysis of thermal data, the results of which are provided in Appendix I.

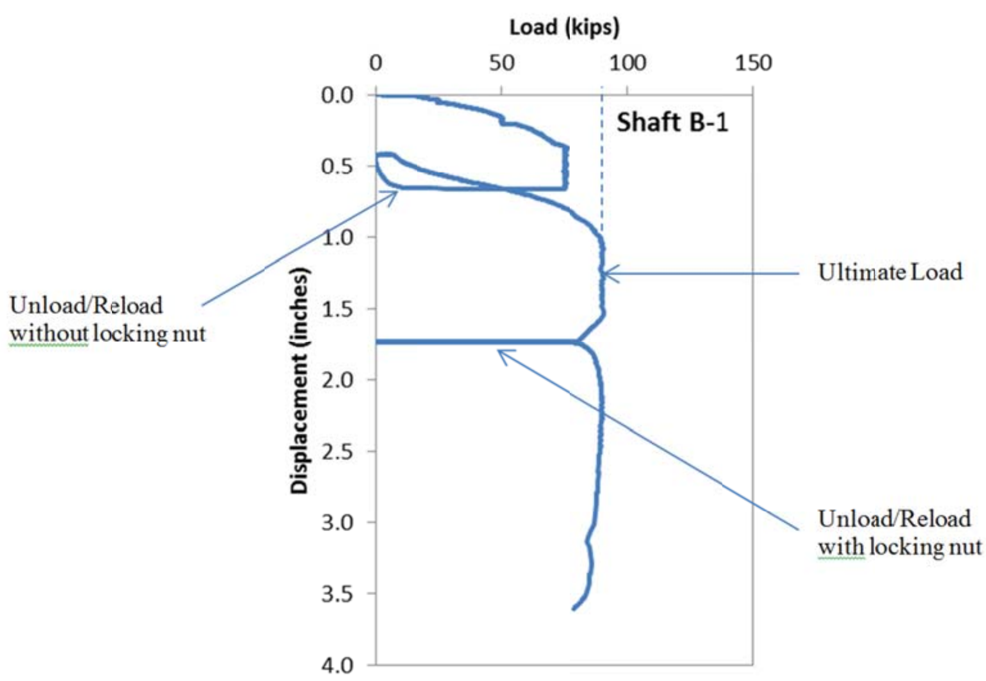


Figure 4.21 Load versus displacement data for Shaft B-1.

With the exceptions of Shafts P-1 and B-2, the dead load of each shaft was determined by examining the load cell measurements near the end of the extraction process. Once each shaft had been extracted a sufficient amount, side shear resistance was no longer present, and the resistance being experienced by the load cell was that of the shaft dead load only. Plots of load versus time, with identified dead load, are provided in Appendix F. Due to the absence of the locking nut during the test of Shaft P-1, extraction to this point was not possible with the load cell in place as the shaft would fall back into the soil and could not be clearly held above the ground. In the case of Shaft B-2, the dead load could not be determined from load cell measurements due to the failure of the anchor rod. The dead loads of Shaft P-1 and B-2 were estimated based on the volumes calculated from their as-built measurements and the average unit weight of the other four shafts. Again, the volume of Shaft B-2 was calculated based on estimated dimensions from thermal analysis.

Each of the load versus displacement responses shown in Appendix F was converted to unit side shear as shown in Figure 4.22 using Equation 4-2. For clarity, the unload/reload cycles were removed to produce a load displacement envelope for each shaft (Figure 4.23). This curve is based on the end of each load holding period to include any effects of creep. This is more representative of actual structural loading.

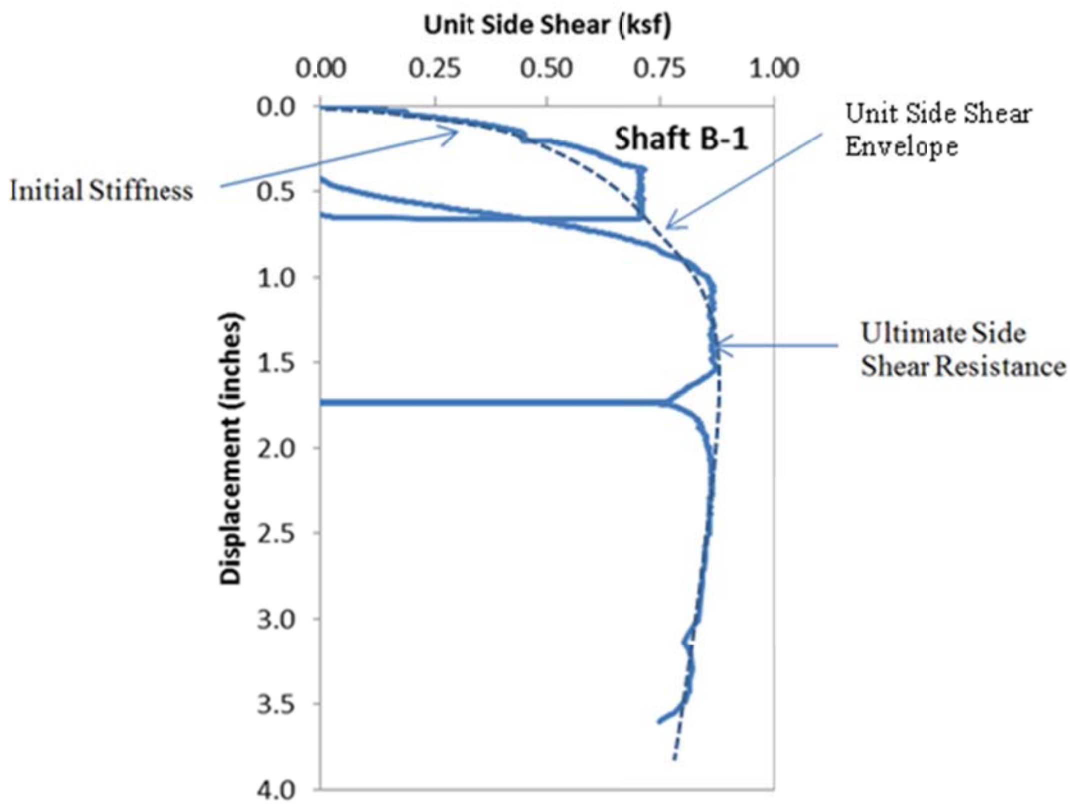


Figure 4.22 Unit side shear versus displacement graph for Shaft B-1.

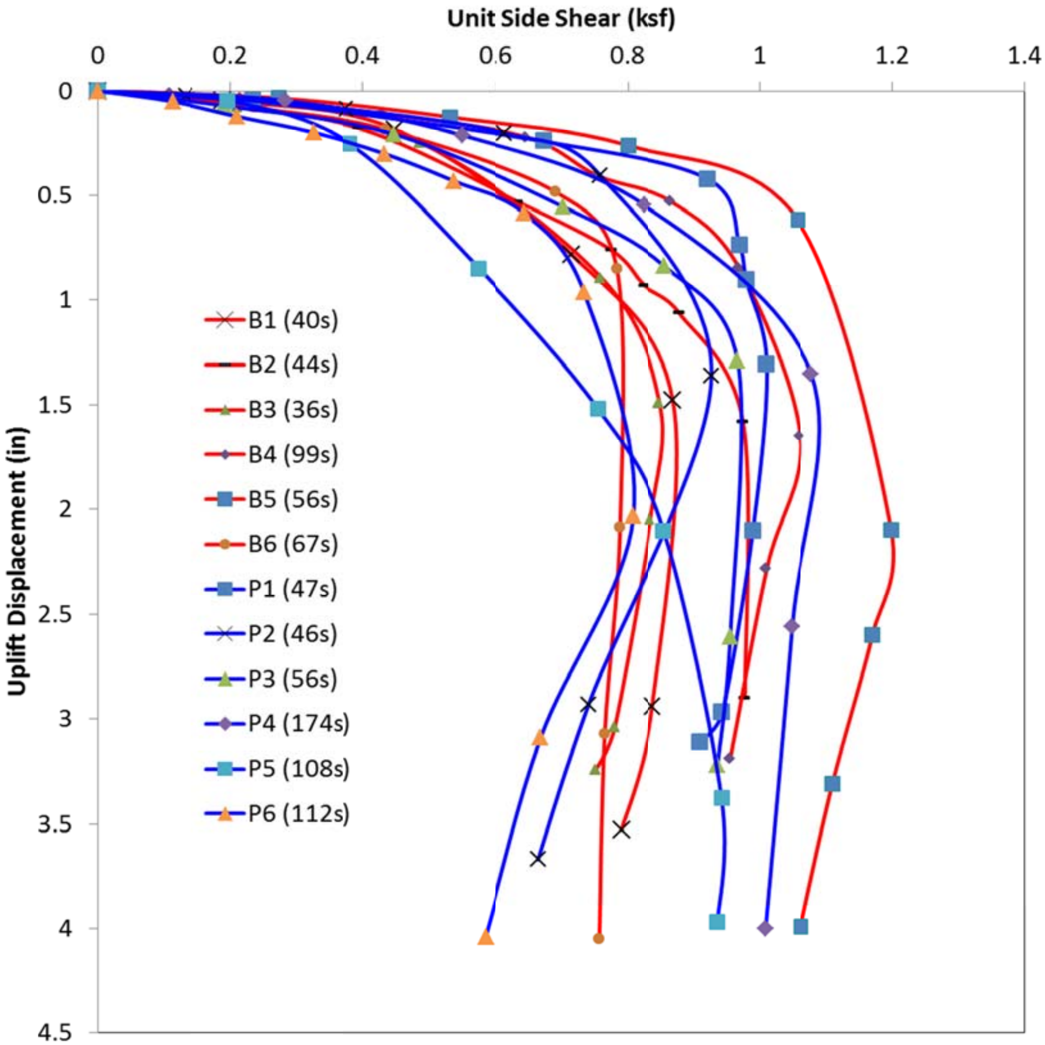


Figure 4.23 Unit side shear envelopes for all shafts superimposed.

A summary of the shaft parameters which includes the measured loads and corresponding side shear values at displacements of 0.25, 0.5, and 1 in are shown in Table 4.20. These values are not normalized for local strength noted by CPT tests (discussed in next chapter).

Table 4.20 Unit capacity at various displacements along with ultimate capacity for each shaft.

	Length (ft)	Viscosity (sec/qt)	Side Surface Area (ft^2)	correction	Total Volume (ft^3)	Calculated Dead Load (kips)	Observed Min. Load (kips)	Displacement (in)	Total Load (kips)	Side Shear (ksf)
Shaft B-1	15.4	40	95.5	1.01	48.1	6.7	7.6	0.25	62.28	0.58
								0.50	75.19	0.72
								1.00	89.22	0.86
Shaft B-2	14.2	44	104.3	0.88	56.0	8.8	N/A	0.25	62.94	0.52
								0.50	65.49	0.54
								1.00	100.12	0.87
Shaft B-3	14.7	36	90.7	1.26	45.3	6.3	6.6	0.25	50.26	0.49
								0.50	74.96	0.76
								1.00	76.70	0.78
Shaft P-1	15.4	47	97.0	1.22	49.7	6.9	N/A	0.25	68.60	0.64
								0.50	97.93	0.94
								1.00	103.43	1.00
Shaft P-2	14.8	46	104.9	0.74	60.9	8.4	11.1	0.25	90.31	0.78
								0.50	100.31	0.88
								1.00	102.54	0.90
Shaft P-3	15.5	56	97.2	1.09	49.5	6.9	7.3	0.25	59.84	0.55
								0.50	56.14	0.51
								1.00	97.39	0.93
Shaft B-4	16.2	99	99.2	1.63	46.0	6.9	13.8	0.25	68.7	0.69
								0.50	80.2	0.81
								1.00	99.5	1.00
Shaft B-5	17.0	56	101.0	1.23	46.6	7.0	15.4	0.25	75.10	0.74
								0.50	100.20	0.99
								1.00	119.00	1.18
Shaft B-6	14.7	67	87.0	1.46	42.6	6.4	13.4	0.25	60.00	0.69
								0.50	68.80	0.79
								1.00	70.40	0.81
Shaft P-4	15.7	174	98.2	1.24	45.7	6.9	15.6	0.25	62.30	0.63
								0.50	74.70	0.76
								1.00	100.40	1.02
Shaft P-5	17.4	108	106.4	0.93	55.8	8.4	14.2	0.25	43.25	0.41
								0.50	60.16	0.57
								1.00	70.37	0.66
Shaft P-6	15.1	112	93.5	1.21	47.7	7.1	14.1	0.25	45.80	0.49
								0.50	59.90	0.64
								1.00	69.10	0.74

The length shown for each was based on measured lengths after the shafts were exhumed with the exception of B-2. The length of B-2 was determined from the measurements during excavation and just prior to concreting.

Chapter 5: Conclusions

State and federal specifications and quality control measures are implemented as means to ensure a minimum level of attention is focused on construction practices. The expectation is that if observed, the anticipated design capacity, durability and serviceability will result. For drilled shaft construction this is largely true, however, many variables associated with construction practices and specification limits are either unaccounted for or simply assigned on the basis of past experience (no known catastrophe as a result). For instance, a shaft constructed with full length temporary casing is likely to perform differently from that which used slurry. The effects of vibrated versus oscillated casing on side shear are similarly unknown. Design approaches do not address such construction effects.

A recognized mechanism for implementing new technology is to compare the performance of the new foundation element with the performance of the present practice. This trial and error / Edisonian technique has merit, and it is the goal of all standards to have a supporting rationale based on science. This study was initiated to better define the upper viscosity limit for mineral slurry used in drilled shaft construction. To this end, the effects of thicker slurry on the rebar bond and side shear were explored. However in so doing, the study may also have uncovered unforeseen complications pertaining to possible degradation in corrosion resistance / durability.

5.1 Pullout Testing

Based on the collected data, the bond strength between the concrete and reinforcement was reduced up to 70% in some bentonite cases. This can be attributed to the buildup of slurry on the reinforcement as well as the absence of concrete connectivity outside the rebar cage. The effect of increasing viscosity can be seen in the series of images shown in Figures 5.1 - 5.3. These images were taken after one of the concrete placements was aborted as concrete did not meet the specified requirements. These figures depict the amount of slurry that can adhere to the reinforcement.

Figure 5.1 Residual slurry noticed on reinforcement 30 second (left), 40 second (right).

Figure 5.2 Residual slurry noticed on reinforcement 30 second (left), 50 second (right).

Figure 5.3 Residual slurry noticed on reinforcement 30 second (left), 90 second (right).

The residual slurry coating appeared less prominent as the apparent viscosity was reduced; however in all cases it was still noticeable.

Based on the results, it is assumed that this buildup is not fully removed during the concrete placement and in turn causes the reduced bond strength. Figure 5.4 shows the average loss of bond strength caused by the bentonite slurry may actually be worse for mid-values of viscosity in the range of 60 to 90 sec/qt. Figure 5.5 shows the analogous results for polymer slurry. The viscosity values noted correspond to that measured at the time of concrete placement. There was a noticeable increase in viscosity between placement in the forms and the placement of concrete for the higher viscosity slurry mixes due to the increased hydration time.

Using a theoretical upper bound of 0.5f'c, only the pure water and polymer shafts came close to that value and in such cases the water environment causes a 10-15% loss in bond. However, if water is used as the reference upper limit, the percent loss becomes slightly less. Bond loss in the bentonite samples ranged from 40% to 70% for 30 and 90sec/qt slurry, respectively. These effects were more prevalent for the bentonite slurry than the polymer slurry. Note that the effect of varied concrete strength was normalized by dividing the pullout shear stress by the f'c of that sample. Hence, all bond strengths are shown relative to the unconfined compression strength. Likewise, the bond length was also taken into account in the normalized bond strength equation shown.

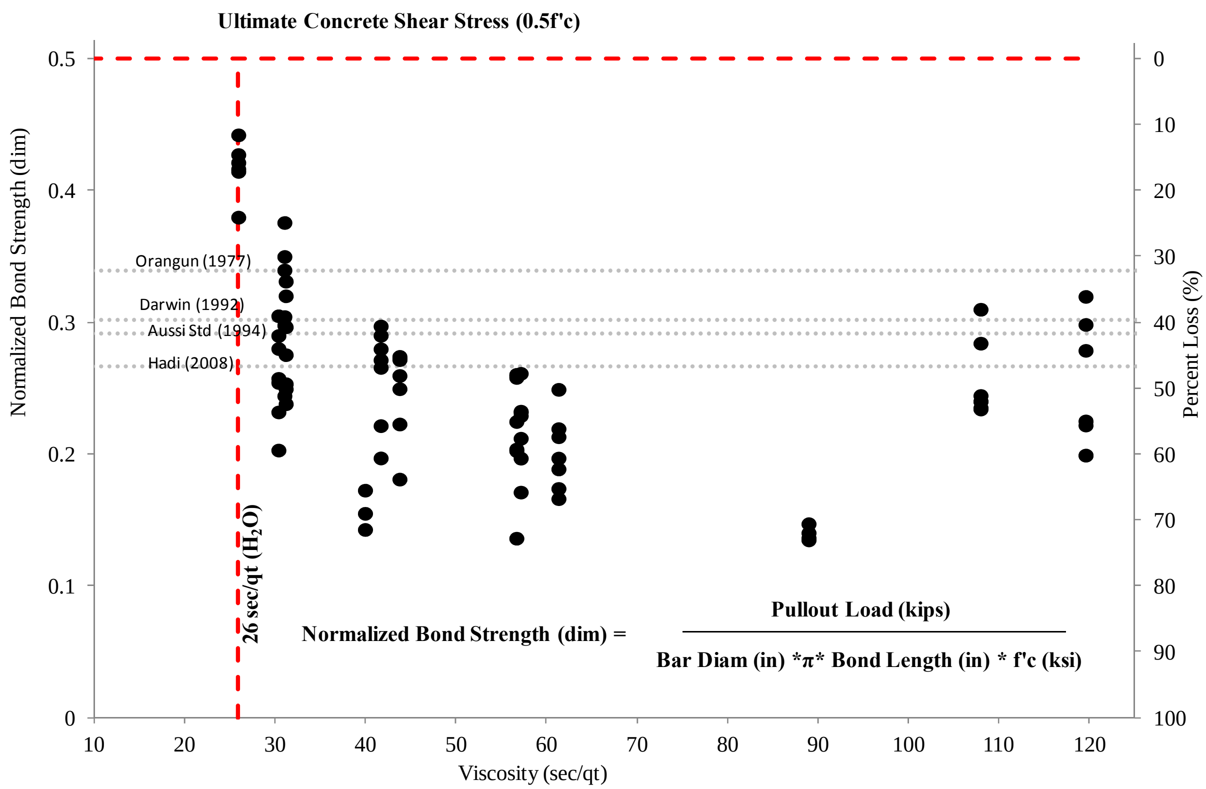


Figure 5.4 Comparison of pullout test results using bentonite slurry.

The pullout bond for the polymer slurry specimens tended to be higher than that of the bentonite specimens with average bond losses on the order of 25% to 50% for 60 and 90 sec/qt, respectively. However in some cases, the bond values noted for 60 sec/qt polymer specimens exceeded that of the pure water (Figure 5.5).

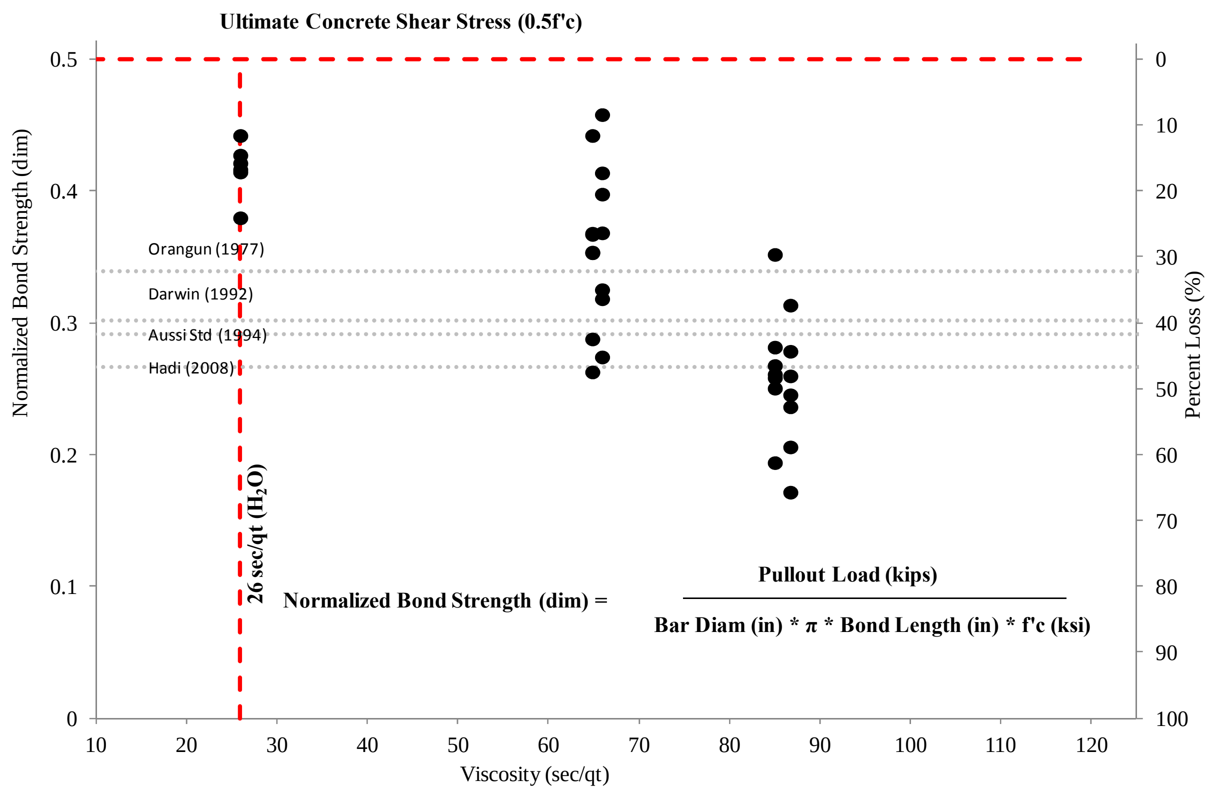


Figure 5.5 Comparison of pullout test results using polymer slurry.

5.2 Durability

In addition to the loss of bond strength, the pullout specimens revealed possible permeability issues with the hardened concrete. Due to the flowing action of the concrete around the rebar, the bentonite slurry was encapsulated by the concrete, projecting to the outer surface the location of each piece of reinforcement. The encased slurry could potentially provide a direct pathway between the exterior of the shaft and the reinforcement for chloride or sulfate attack. Cores taken at the intersection of the creases split into quarters along the visible lines in the 50 and 90 sec/qt shafts. The 30 and 40 sec/qt cores did not split, however showed visible signs of poor consolidation around the reinforcement as well as creases at the surface. The cores that were cut from the shaft cast with water and polymer did not show any signs of poor consolidation, nor did it show any visible defects in the concrete. Figures 5.6 - 5.9 illustrate the encapsulation potential caused by slurry in the shafts. Poor consolidation was also noted. Figure 5.10 shows the preferred concrete flow path which is up, then out after sufficient lateral pressure has developed to drive the concrete through the resisting cage matrix. This flow explains the mechanism that formed the creases and is in keeping with previous studies that showed similar concrete movement using a down-hole borescope.


Figure 5.6 Visible creases in 90 sec/qt bentonite shaft (all specimens in Appendix A).


Figure 5.7 Polymer shafts showed little signs of separations (60 sec/qt).

Figure 5.8 Poor consolidation around reinforcement in 40 sec/qt bentonite slurry shaft.

Figure 5.9 Encapsulated bentonite slurry in 50 sec/qt shaft caused core to fall into four pieces defined by intersecting creases.

Figure 5.10 Flow of concrete around reinforcement during placement of 60 sec/qt polymer shaft.

5.3 Side Shear Effects

The study conducted two levels of testing to investigate the effects of slurry viscosity on side shear capacity. Model scale results in the frustum confining vessel showed modest reductions in capacity with increased slurry viscosity from 40 to 50 sec/qt. However, samples cast in the thicker 90 sec/qt slurry developed the highest ultimate side shear capacities (Figure 5.11).

In full scale tests, the capacity of each shaft shown in Table 4.20 was compared to the specific CPT profile using the algorithms outlined by the model scale testing program. But in this case, all penetration soundings were normalized to the average of all six soundings and not one specific shaft. The normalized soil strengths are shown in Table 5.1 for each of the six Phase I cumulative qc values presented in Table 3.2. Again using this approach CPT B-2 showed significantly higher soil strength (36% higher than average).

The average bentonite and polymer shaft capacities from Table 4.20 (Phase I) were divided by the average normalized soil strength from Table 5.1 and plotted versus the respective displacement (Figure 5.12). This resulted in the average normalized side shear resistance of the 50 sec/qt polymer shafts being 27% higher than the average normalized side shear resistance of the 40 sec/qt bentonite shafts.

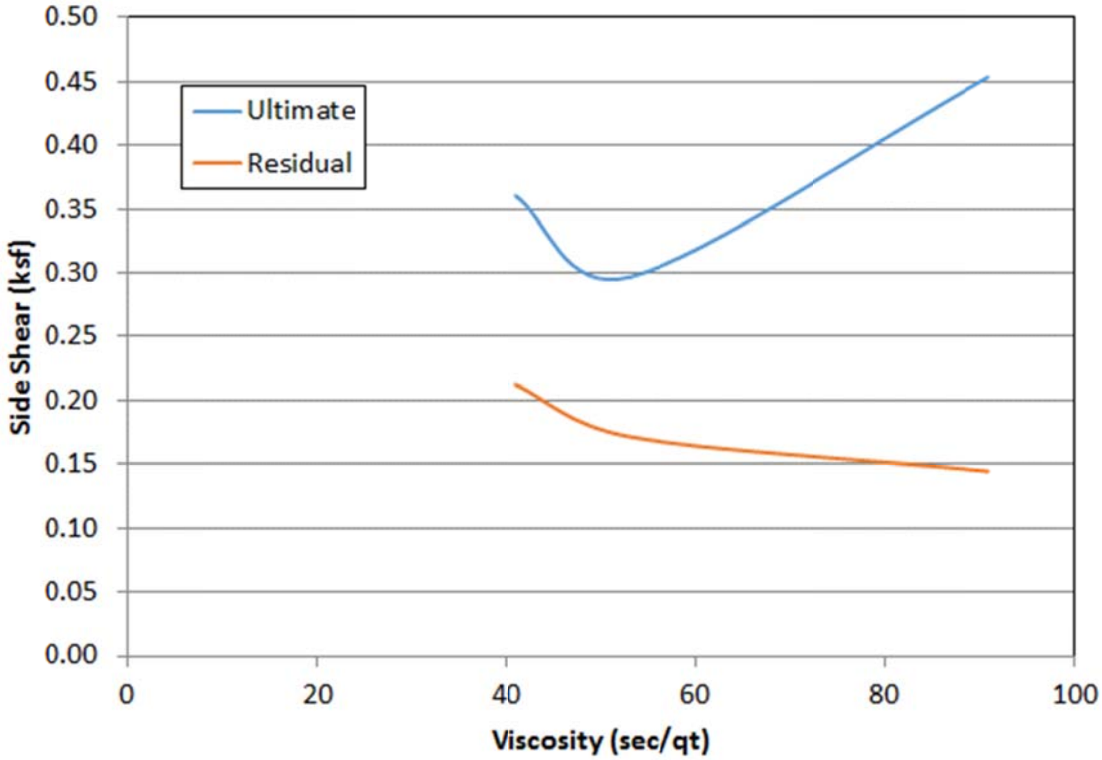


Figure 5.11 Side shear capacity versus mineral slurry viscosity

Table 5.1 Normalized soil resistance at each CPT sounding location (Phase I).

Shaft ID	Normalized Ultimate Side Shear (ksf)
P-1	1.03
B-2	1.36
P-3	0.95
B-1	0.93
P-2	0.88
B-3	0.84

Phase II pullout testing resulted in viscosity values that ranged more widely than Phase I for both bentonite and polymer. Both slurry materials (bentonite and polymer) were prepared the day before excavation where the bentonite slurry had an initial viscosity of 50 sec/qt and the polymer had an initial viscosity of 100 sec/qt. Target values were 50 and 125 sec/qt, respectively. The following day, the bentonite slurry had increased to 74 sec/qt and the polymer was recirculated to introduce additional polymer powder raising it to 122 sec/qt. While the intent was to construct three shafts under near identical conditions, viscosity tests at the time of concrete placement ranged from 56 to 99 sec/qt and 108 to 174 sec/qt for the bentonite and polymer, respectively. This was attributed to thicker material at the bottom of the holding tanks.

Shaft B-4 with the thickest slurry (99 sec/qt) was the first bentonite shaft constructed where slurry was drawn from a bottom-of-tank fitting. Shaft P-6 was the last polymer shaft constructed where slurry was drawn from the middle of the tank through a hose over the top of tank; the last shaft therefore pulled in the thickest material from the bottom consisting in some cases of clumped balls of poorly hydrated polymer (174 sec/qt viscosity).

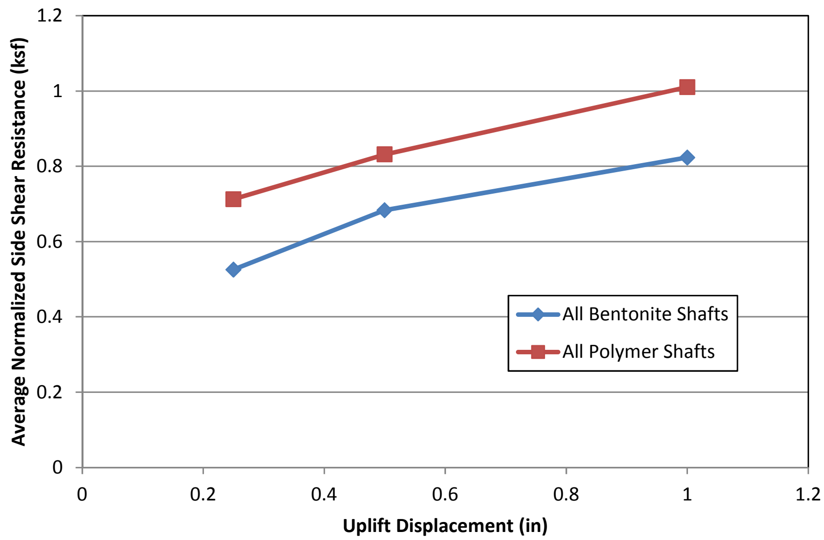


Figure 5.12 Comparison of bentonite and polymer side shear resistance normalized for local soil strength (Phase I).

Where Phase I results could be easily plotted in the form shown in Figure 5.12 (all viscosities were similar for each slurry type), the wide range of viscosity values demonstrated when considering all 12 shafts made it more reasonable to plot the results as function of viscosity (Figure 5.13). No appreciable affects from slurry type or viscosity is readily apparent.

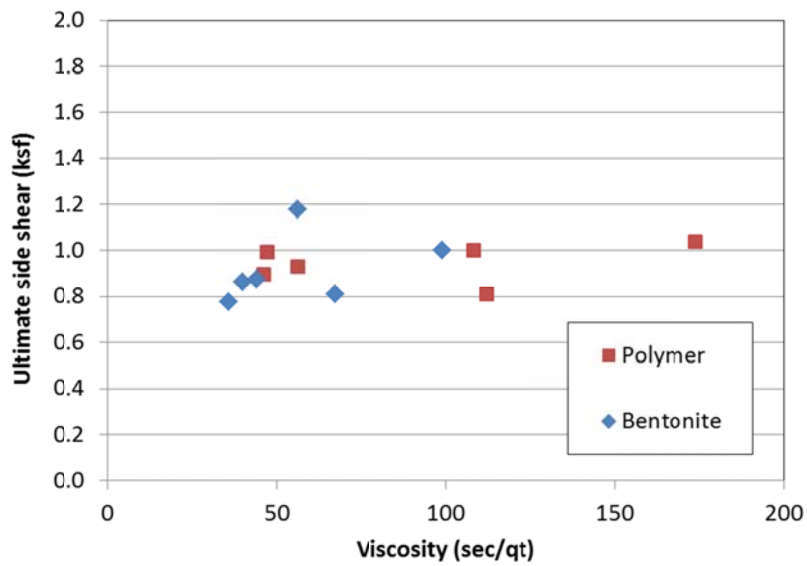


Figure 5.13 Ultimate side shear determined from measured load and surface area.

Table 5.1 shows the same data both as-measured and using an adjustment factor for local CPT strengths. For example, a CPT adjustment factor of 1.12 means that the local CPT soil strength was 12% weaker than the average of all 12 CPT strength profiles.

Table 5.2 Ultimate side shear for Phase I and Phase II with and without local CPT adjustments.

Shaft ID	Viscosity		Ultimate Side Shear (as-measured)			Adjusted Side Shear			
	(sec/qt)	Avg.	(ksf)	Average (ksf)	% Increase	CPT Adj. Factor	(ksf)	Average (ksf)	% Increase
B1	40	40	0.86	0.84	0	0.91	0.79	0.79	0
B2	44		0.87			0.79	0.69		
B3	36		0.78			1.13	0.88		
B4	99	74	1.00	1.00	18.9	1.47	1.48	1.28	63.1
B5	56		1.18			1.11	1.31		
B6	67		0.81			1.32	1.06		
P1	47	50	1.00	0.94	12.3	1.10	1.10	0.87	10.6
P2	46		0.90			0.67	0.60		
P3	56		0.93			0.98	0.91		
P4	174	131	1.04	0.95	13.3	1.12	1.16	0.96	22.2
P5	108		1.00			0.84	0.84		
P6	112		0.81			1.09	0.88		

5.4 Conclusions

This study tested the pullout resistance of 126 rebar specimens cast in 18 different shaft specimens as well as the side shear resistance of twelve shafts with nominal dimensions of 16ft long and 22in diameter constructed using either mineral or polymer drilling slurry. Rebar specimens cast in mineral slurry showed degraded bonded which may require consideration from a structural perspective.

Full scale side shear tests were conducted where six of the twelve shafts were constructed using each type of slurry (polymer slurry stabilized or mineral slurry stabilized) and where the excavations were left open with slurry in place for an extended period of time. Subsequent to load testing, the shafts were extracted from the ground whereby the diameter and length could be measured to ascertain the exact surface area contributing to the side shear resistance. Additionally, the soil type and strength distribution at each shaft location was delineated using a cone penetrometer to provide further insight into variations that often occur in load testing.

Phase I. Test results showed similar performance in the comparison of stiffness and ultimate load resistance with a 24% increase in initial stiffness and a 6% increase in ultimate capacity is noted as a result of polymer use. One bentonite and one polymer shaft (B-2 and P-2) exhibited higher capacity than the rest due to a stronger soil strength profile and a bulge, respectively. These findings are summarized below (Table 5.3) where the average of all bentonite and all polymer shafts are computed with and without the effects of the higher capacity shafts. However, when considerations for local increases or decreases in soil strength are considered, a 27% increase in side shear resulted from the 50sec/qt polymer slurry relative to the 40sec/qt bentonite slurry (Figure 5.12).

Table 5.3 Initial stiffness and ultimate capacity of mineral and polymer slurry shafts (Phase I).

Comparison Type	Average Bentonite Capacities		Average Shore Pac Capacities	
	All B-Series	w/o Shaft B-2	All P-Series	w/o Shaft P-2
Initial Stiffness (ksf/in)	2.11	2.13	2.62	2.36
Ultimate Capacity (ksf)	0.93	0.87	0.99	1.00

Excavation stability (resulting from slurry type) showed similar capabilities where all shafts showed some irregularities along the length of the shaft. The irregularities either stemmed from water table sloughing where slurry was not introduced in time or less pronounced undulations from the bottom of casing to the shaft toe. Water table sloughing resulted in bulging in the regions just below the temporary surface casing. In one instance, the excavation was left open overnight below the bottom of the temporary casing. In another, the drilling process started before slurry could be introduced. In cases where slurry was introduced prior to encountering the water table, no significant difference was noted as a result of slurry type. These findings support the importance of proper sequencing with regards to the addition of slurry for any type of wet shaft construction.

Phase II. All shafts were compared to the average unit side shear capacity of shafts constructed with bentonite slurry having viscosity of 40 sec/qt in Phase I. In all cases, shafts performed better than the control shaft conditions where thick bentonite (74 sec/qt) performed the best. Different schools of thought exist when comparing side by side shafts where the load tests results should be adjusted to account for varied soil conditions using SPT or CPT results. Or, variations noted by SPT or CPT can be subject to scaling errors and direct corrections may be inappropriate. In any event, by applying or by not applying such corrections, no adverse effects on side shear capacity were noted by using higher than 40 sec/qt viscosity bentonite slurry (the previous FDOT state upper viscosity limit). No adverse effects were noted from the use of polymer slurry either.

It is unclear to what extent the creases formed by entrapped bentonite slurry may affect long-term durability/corrosion resistance of shafts cast with bentonite slurries. No concern is apparent for the shafts constructed with polymer slurry.

5.5 Further Considerations

For this project a slump of 8-inches to 9.5-inches was used, also, the time the reinforcement was exposed to slurry was maximized but kept within the Florida Department of Transportation's drilled shaft requirements. Given the opportunity, it would be beneficial to explore higher slump concrete in order to minimize the creases noted from the flow of concrete. These trends could be verified with x-ray diffraction of the material encountered between the exterior of the shaft and the reinforcing in order to determine if bentonite is present and to what extent. Further testing could be done on the polymer and water shafts in order to see if there is a localized higher water/cement ratio at these locations as well.

Comparative studies of shafts constructed where bentonite was 1hr and 24hrs in the excavation show reduction in side shear capacity. But within that time span less is known. Given the negligible fluid loss during both the lab and field studies, it is conceivable that all degradation of side shear occurs very early on which is in keeping with findings from filter press tests performed in previous studies. If true, there should be no further increase in "filter cake" thickness beyond the first couple of hours. Hence, over-reaming may never be necessary if the traditional 24hr performance is suitable.

In order to determine the severity of the creases that were encountered, it would be beneficial to perform chloride diffusion testing on the existing specimens in order to determine the permeability of the concrete where the bentonite was not displaced. It is the opinion of the principle investigator that the creases formed in this study along with the images depicted in Figures 1.2 and 2.9 are the norm and not the exception. The act of extracting a surface casing simply obliterates the lines making them undetectable during routine shallow excavations.

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APPENDIX A: PHOTO DOCUMENTATION

Figure A.1 Steel testing form, 42-inches in diameter.

Figure A.2 Steel testing form, 24-inches in height.

Figure A.3 Steel form, clamped, welded angle closures.

Figure A.4 Bottom of form after polyurethane and cap placement.

Figure A.5 Form with structural reinforcement prior to placement of pullout steel.

Figure A.6 Final reinforcement configuration prior to slurry placement.

Figure A.7 Typical debonding for reinforcement.

Figure A.8Verifying water tight seal of form.

Figure A.9 Re-circulating mineral slurry prior to placement in form.

Figure A.10Testing plastic properties of fresh concrete.

Figure A.11 Placing concrete for shaft 2, 90 sec/qt mineral slurry.

Figure A.12 Placing concrete for shaft 1, 40 sec/qt mineral slurry.

Figure A.13 Shaft 1 (right) and shaft 2 (left) after pressure washing.

Figure A.14 Form layout for placements 2-4.

Figure A.15 Shaft 6 (water) after pressure washing.

Figure A.16 Shaft 3, 40 sec/qt mineral slurry after pressure washing.

Figure A.17 Shaft 4, 50 sec/qt mineral slurry after pressure washing.

Figure A.18 Shaft 5, 90 sec/qt mineral slurry after pressure washing.

Figure A.19 Shaft 7, 30 sec/qt mineral slurry after pressure washing.

Figure A.20 Shaft 8, 40 sec/qt mineral slurry after pressure washing.

Figure A.21 Shaft 9, 50 sec/qt mineral slurry after pressure washing.

Figure A.22 Shaft 10, 90 sec/qt mineral slurry after pressure washing.

Figure A.23 Shaft 11, 60 sec/qt polymer slurry after pressure washing.

Figure A.24 Shaft 13, 30 sec/qt mineral slurry after pressure washing.

Figure A.25 Shaft 15, 50 sec/qt mineral slurry after pressure washing.

Figure A.26 Shaft 17, 85 sec/qt polymer slurry after pressure washing.

Figure A.27 Shaft 18, water shaft after pressure washing.

Figure A.28 Core from shaft 6, water.

Figure A.29 Core from shaft 11, 60 sec/qt polymer.

Figure A.30 Core from shaft 7, 30 sec/qt mineral slurry.

Figure A.31 Core from shaft 8, 40 sec/qt mineral slurry.

Figure A.32 Core from shaft 9, 50 sec/qt mineral slurry.

Figure A.33 Core from shaft 10, 90 sec/qt mineral slurry.

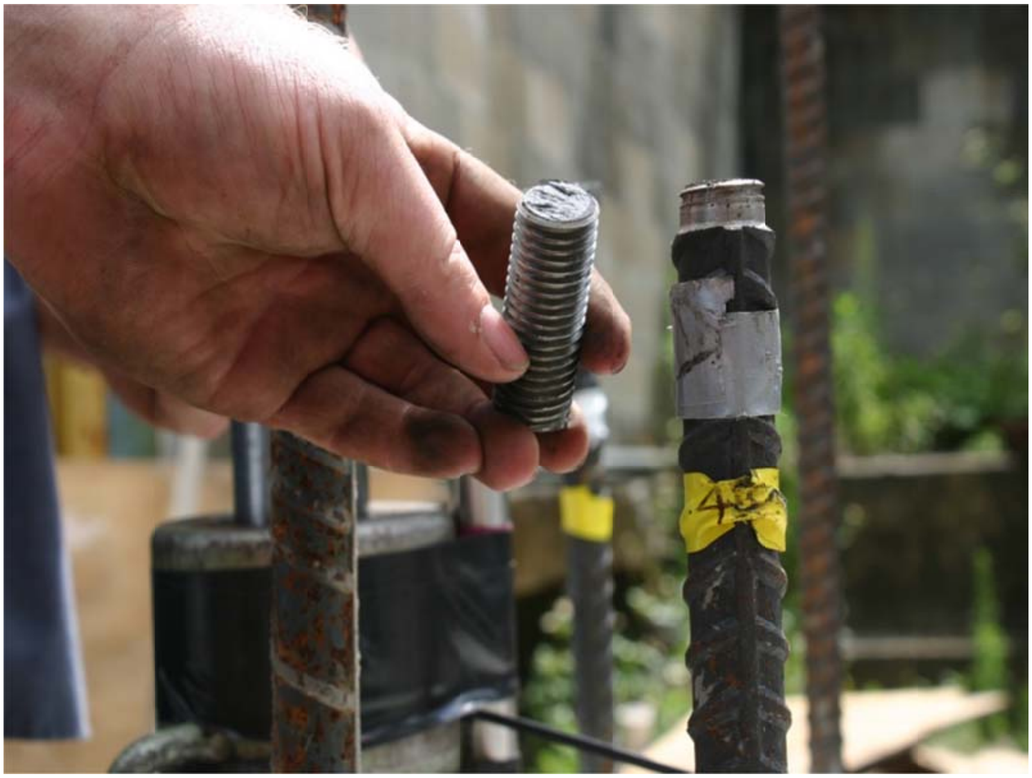


Figure A.34 Bar failure from water shaft 6, water.

APPENDIX B: STATE SPECIFICATIONS

Table B.1 Alabama Slurry Specifications

Mineral Slurry Specifications
(Sodium Bentonite or Attapulgite in Fresh Water)

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3** - 69.1** {1030* - 1110**}	64.3** - 75.0** {1030** - 1200**}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH Meter
Sand Content Percent by Volume	N/A	N/A	N/A

**Increase by 2 pounds per cubic foot {32 kg/m^3} in salt water
a. Tests should be performed when the slurry temperature is above 39° F.
b. If desanding is required, sand content shall not exceed 4 percent (by volume) at any point in the bore hole as determined by the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alabama has no polymer slurry specifications		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Source: United States. Alabama Department of Transportation. *Standard Specifications for Highway Construction. 2012.*
Their 2012 is still the most current, so no change was made
http://www.dot.state.al.us/conweb/specifications.htm
http://www.dot.state.al.us/conweb/doc/Specifications/2012%20DRAFT%20Standard%20Specs.pdf

Table B.2 Alaska Slurry Specifications

Mineral Slurry Specification

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alaska has no specification for drilled shaft slurry		
Viscosity Seconds/qt {Seconds/L)			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alaska has no specification for drilled shaft slurry		
Viscosity Seconds/qt {Seconds/L)			
pH			
Sand Content Percent by Volume			

Source: United States. Alaska Department of Transportation and Public Facilities. *Standard Specifications for Highway Construction.* 2004.
Their 2004 version is still the latest...
http://www.dot.state.ak.us/stwddes/dcsspecs/pop_hwyspecs_english.shtml

Table B.3 Arizona Slurry Specifications

Mineral Slurry Specifications
(Sodium Bentonite in Fresh Water[a])

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0*	Density Balance
Yield Point {Pascals} Or Viscosity Seconds/qt	Bentonite 1.25 – 10 28 – 50	10 Maximum 28 – 50	Rheometer Marsh Cone
pH	7 – 12	7 – 12	pH paper, pH meter
Sand Content Percent by Volume	0 – 4	0 – 2	API Sand Content Kit

* 85 lb/ft^3 maximum when using Barite.

a. Range of results above 68°F.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Arizona has no polymer slurry specifications. Only mentions: "The level of polymer slurry shall be maintained at or near the ground surface or higher, if required to maintain boring stability."		
Yield Point {Pascals} Or Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: United States. Arizona Department of Transportation. *Standard Specifications for Road and Bridge Construction*. 2008.

Their 2008 version is still the latest, no change in requirements
http://azdot.gov/business/ContractsandSpecifications/Specifications

Table B.4 Arkansas Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 – 75	None Specified	Mud Balance ASTM D4380
Viscosity (Seconds/qt) {Seconds/L}	28 – 45	None Specified	API RP13B-1 Section 2 Marsh Funnel and Cup
pH	8 – 11	None Specified	ASTM D4972
Sand Content Percent by Volume	4% Maximum	N/A	(Sand Screen Set) ASTM D4381

a. Range of results at 60°F (20°C).

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 Maximum (fresh water applications)	N/A	(Mud Balance) ASTM D4380
Viscosity Seconds/qt {Seconds/L}	40 to 90 (or as approved by the Engineer)	N/A	API RP13B-1 Sect. 2 (Marsh Funnel & Cup)
pH	8-10	N/A	ASTM D4972
Sand Content Percent by Volume	1 % maximum	1% Max	(Sand Screen Set) ASTM D4381

a. Range of results at 60°F (20°C).

Source: United States. Arkansas State highway and Transportation Department. *Special Provision Job No. 110229 Slurry Displacement Drilled Shaft*. 2005.

Table B.5 California Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3* – 69.1*	64.3* - 75.0*	Mud Weight (Density) API 13B-1 Section 1
Viscosity Seconds/qt	(Bentonite) 28 – 50 (Attapulgite) 28 – 40	None Specified	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10.5	8 – 10.5	Glass Electrode pH meter, pH paper
Sand Content Percent by Volume	Volume≤4.0	Volume≤4.0	Sand, API 13B-1, Section 5

* When approved by the Engineer, slurry may be used in salt water, and the allowable densities may be increased by up to 2 lb/ft^3. Slurry temperature shall be at least 40°F when tested.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	The physical properties of synthetic slurries should be carefully monitored during drilling of the hole and before concrete placement. Because these slurries in general do not suspend particles, the permissible density and sand content values are much lower than those allowed for mineral slurries. The density and sand content values should be tested and the values maintained within the limits stated in the contract specifications to allow for quick settlement of suspended materials. The synthetic slurry's pH value should be tested and maintained within the limits stated in the contract specifications to prevent destabilization of the slurry.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Water Slurry Specification

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3		63.5	Mud Weight (Density) API 13B-1 Section 1
Sand Content Percent by Volume		Volume≤ 0.5	Sand, API 13B-1, Section 5

If authorized, you may use salt water slurry. The allowable density of the slurry may be increased by 2 lb/ft^3.
Source: United States. California Department of Transportation Division of Engineering Services. *Foundation Manual*. 2010.

Table B.6 Colorado Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density g/ml	Less than 1.10	Less than 1.10	Mud Weight (Density) API 13B-1 Section 1
Viscosity Seconds/qt	(Bentonite) 30-90 seconds Or less than 20cP	None Specified	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10.5	8 – 10.5	pH indicator paper Strips or electrical pH meter
Sand Content Percent by Volume	Less than 5%	Less than 5%	Screen

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density g/ml	No specification for Polymer Slurries		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: United States. Colorado Department of Transportation. *Permanent Changes to Project Dated Special Provisions, Revision of Section 503.* 2006.

Table B.7 Connecticut Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3* – 69.1*	64.3* - 75.0*	Density Balance
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Increase by 2 lb/ft^3 in salt water.

Polymer Slurry Specifications

<table>
<tr><th>Property (Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test Method</th></tr>
<tr><td>Density lb/ft³</td><td colspan="3" rowspan="3">Connecticut has no polymer slurry specifications.

“If polymer slurry, or blended mineral-polymer slurry, is proposed, the Contractor’s slurry management plan shall include detailed provisions for controlling the quality of the slurry, including tests to be performed, the frequency of those tests, the test methods, and the maximum and/or minimum property requirements that must be met to ensure that the slurry meets its intended functions in the subsurface conditions at the construction site and with the construction methods that are to be used. The slurry management plan shall include a set of the slurry manufacturer’s written recommendations and shall include the following tests, as a minimum: Density test (API 13B-1, Section 1), viscosity test (Marsh funnel and cup, API 13B-1, Section 2.2, or approved viscometer), pH test (pH meter, pH paper), and sand content test (API sand content kit, API 13B-1, Section 5).”</td></tr>
<tr><td>Viscosity Seconds/qt</td></tr>
<tr><td>pH</td></tr>
</table>

Source: United States. Connecticut Department of Transportation. *Connecticut DOT Guide Drilled Shaft Spec.* 2009.

Table B.8 Delaware Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	63.55 – 68.51 {1025 – 1105}	63.55 – 74.41 {1025 – 1200}	Density Balance
Viscosity Seconds/ft {Seconds/L}	849.5 – 1359.2 {30 – 48}	849.5 – 1359.2 {30 – 48}	Marsh Cone
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	1 MAX	4 MAX	200 Sieve Retain

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined. Refers to FHWA guidelines.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: Keith Gray (Bridge Engineer, DELDOT), email message to author, March 7, 2009.

Table B.9 Florida Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64 – 73* 66 – 75** {1030 – 1170*} {1060 – 1200**}	N/A	Mud Density Balance FM 8-RP13B-1
Viscosity Seconds	30 - 50	N/A	Marsh Cone Method FM 8-RP13B-2
pH	8 – 11	N/A	Electric pH meter, pH paper FM 8-RP13B-4
Sand Content Percent by Volume	4% or less	N/A	FM 8-RP13B-3

* Fresh water @ 68°F (20°C)

** Salt water @ 68°F (20°C)

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	62 to 64 lb/ft3 (fresh water) 64 to 66 lb/ft3 (salt water)	62 to 64 lb/ft3 (fresh water) 64 to 66 lb/ft3 (salt water)	Mud Density Balance FM 8-RP13B-1
Viscosity Seconds/qt {Seconds/L}	Range Published By The Manufacturer for Materials Excavated	Range Published By The Manufacturer for Materials Excavated	Marsh Cone Method FM 8-RP13B-2
pH	Range Published By The Manufacturer for Materials Excavated	Range Published By The Manufacturer for Materials Excavated	Electric pH meter, pH paper FM 8-RP13B-4
Sand Content Percent by Volume	0.5% or less	0.5% or less	FM 8-RP13B-3

a. Range of results at 68° F
b. The Engineer will not allow polymer slurries during construction of drilled shafts for bridge foundations.
c. Materials manufactured expressly for use as polymer slurry for drilled shafts may be used as slurry for drilled shaft excavations up to 60 inches in diameter installed to support mast arms, cantilever signs, overhead truss signs, high mast light poles or other miscellaneous structures.

d. A representative of the manufacturer must be on-site or available for immediate contact to assist and guide the construction of the first three drilled shafts at no additional cost to the Department.
e. Use polymer slurry only if the soils below the casing are not classified as organic, and the pH of the fluid in the hole can be maintained in accordance with the manufacturer's published recommendations.

Source: United States. Florida Department of Transportation . *Standard Specifications for Road and Bridge Construction*. 2014.

Table B.10 Georgia Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	66 – 73 {1060 – 1170}	N/A	N/A
Viscosity Seconds/qt {Seconds/L}	30 – 45 {32 – 48}	N/A	Marsh Funnel
pH	8 – 11	N/A	N/A
Sand Content Percent by Volume	N/A	4%	N/A

a. Perform sand content tests on slurry samples taken from the bottom of the shaft after placement of the reinforcing cage, but immediately before pouring concrete. Do not place concrete until all testing produces acceptable results.
b. If sidewalls are unstable, or if artesian flow is present, use a weighing additive to increase the slurry density
c. pH may be adjusted with soda ash.
d. When sand content exceeds 4%, desanding or other equipment must be used.
e. Tests must be performed at 39°F (4°C), slurry temperature.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 – 67 {1025 – 1073}	N/A	N/A
Viscosity Seconds/qt {Seconds/L}	30 – 125 {32 – 132}	N/A	Marsh Funnel
pH	8 – 11	N/A	N/A
Sand Content Percent by Volume	N/A	≤1	N/A

A weighing additive may be used to increase the density of the polymer slurry if the sidewalls are unstable or if artesian flow is present.

Source: United States. State of Georgia Department of Transportation. *Special Provision Section 524 – Drilled Caisson Foundations*. 2006.

Table B.11 Hawaii Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Slurry Drilling is not permitted*		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Slurry Drilling is not permitted*		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

*Wet Construction Method – This method includes using water to maintain stability of shaft perimeter while advancing excavation to final depth, and placing reinforcing cage and shaft concrete.

Reuse drilling water only if permitted by the Engineer and contingent upon control of unit weight to no more than 62.5 pounds per cubic foot and Marsh funnel viscosity to not more than 27 seconds per quart, at the time drilling water is introduce into the borehole.

Source: United States. State of Hawaii Department of Transportation. *Standard Specifications*. 2005.

Table B.12 Idaho Slurry Specifications Special Provisions

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64 to 75	N/A	Mud Weight (Density) API 13b-1,Section 1
Viscosity Seconds/qt	26 to 50	N/A	Marsh Funnel API 13b-1, Section 2.2
pH	8 – 11	N/A	N/A
Sand Content Percent by Volume	N/A	4.0 Max	Sand API 13b-1 Section 5

Quality control testing will be by the contractor. Slurry temperature shall be at least 40°F when tested.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States Idaho Transportation Department. *Special Provision S501-20A SP Bridge-Drilled Shaft -2013*.

Table B.13 Illinois Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Illinois Department of Transportation. *Standard Specifications for Bridge Construction*. 2012.

Table B.14 Indiana Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 - 69.1	N/A	Density Balance
Viscosity Seconds/qt	28 - 45	N/A	Marsh Cone
pH	8 – 11	N/A	pH paper or meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Indiana Department of Transportation. *Standard Specifications. 728-B-203 Drilled Shaft Foundations* 2013

Table B.15 Iowa Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 – 75 {1030 – 1200}	64 – 75 {1030 – 1200}	Slurry Density Materials I.M. 387
Viscosity Seconds/gal {Sec./L}	104 - 201 (27.5 – 53)	104 - 201 (27.5 – 53)	Marsh Funnel and Cup Materials I.M. 387
pH	8 – 11	8 – 11	pH paper
Sand Content Percent by Volume	≤ 4	≤ 4	Sand Content Test Materials I.M. 387

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	62-63 {995 – 1010}	62-63 {995 – 1010}	Slurry Density Materials I.M. 387
Viscosity Seconds/gal {Sec./L}	136-227 (36-60) 231-252 (61-66.5) (dry sand/gravel)	136-227 (36-60) 231-252 (61-66.5) (dry sand/gravel)	Marsh Funnel and Cup Materials I.M. 387
pH	8 – 11	8 – 11	pH paper
Sand Content Percent by Volume	< 2	< 2	Sand Content Test Materials I.M. 387

Source: United States. Iowa Department of Transportation. *Standard Specifications* 2012.

Table B.16 Kansas Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Kansas Department of Transportation. *Standard Specifications for State Road and Bridge Construction*. 2007.

Table B.17 Kentucky Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined. Refer to FHWA Guidelines		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Kentucky Transportation Cabinet. *Special Note 11C for Excavation and Embankment*. 2008.

Table B.18 Louisiana Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 69.1 {1030 – 1107} (fresh water)	64.3 – 75.0 {1030 – 1202} (fresh water)	Mud Balance API 13B Section 1
Viscosity Seconds	28 – 45	N/A	Marsh Funnel API 13B Section 2
pH	8 – 11	8 – 11	pH paper, pH meter API 13B Section 6
Sand Content Percent by Volume	4	4	Sand Screen Set API 13B Section 4

a. Slurry shall not stand for more than 4 hours in the excavation without agitation.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 (kg/m3)	63-64 (1010-1026) (fresh water)	63-64 (1010-1026) (fresh water)	Mud Balance (API 13B- Sec 1)
Viscosity Seconds	45 MIN	N/A	Marsh Funnel (API 13B- Sec 2)
pH	8 – 10	8 - 10	pH Paper pH Meter (API 13B-Sec6)
Sand Content Percent by Volume	1 MAX	1 MAX	Sand Screen Set (API 13B- Sec 4)

a. The slurry shall not stand for more than 4 hours in the excavation without agitation

Source: United States. Louisiana Department of Transportation. *Drilled Shaft Inspection Manual, Shaft Construction.* 2006.

Table B.19 Maine Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Maine Department of Transportation. *Standard Specifications*. 2002.

Table B.20 Maryland Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Maryland Department of Transportation. *Standard Specifications for Construction and Materials.* 2008.

Table B.21 Massachusetts Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 { kg/m^3}	64-75 {1030-1200}	64-75 {1030-1200}	Mud Density API 13B- Sec. 1
Viscosity Seconds/qt {Sec./L}	26-50 {27.5-53}	26-50 {27.5-53}	Marsh Funnel and Cup API 13B- Sec. 2.2
pH	8 – 11	8 - 11	Glass Electrode, pH Paper, pH Meter
Sand Content Percent by Volume	4 MAX	4 MAX	Sand Content API 13B- Sec 5

* To be increased by 2 lb/ft3 (32 kg/m3) in salt water or brackish water.

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3
{kg/m^3}</td><td colspan="3" rowspan="4">Natural or synthetic slurry shall have specific properties at the time of mixing and of concreting that are in conformance with the written recommendations of the manufacturer and the Contractor’s Drilled Shaft Installation Plan. The Contractor shall perform the required tests at the specified frequency and shall provide slurry that complies with the maximum and/or minimum property requirements for the subsurface conditions at the site and with the construction methods that are used. Whatever product is used, the sand content at the base of the shaft excavation shall not exceed 1% when measured by the API sand content test, immediately prior to concreting.</td></tr>
<tr><td>Viscosity
Seconds/qt
{Seconds/L}</td></tr>
<tr><td>pH</td></tr>
<tr><td>Sand Content
Percent by Volume</td></tr>
</table>

Water Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3</td><td colspan="3" rowspan="4">The use of water slurry without full length steel casings will only be allowed if approved in writing by the Engineer. In that case, all of the properties of mineral slurry shall be met, except that the maximum density shall not exceed 70 lb/ft3 (1120 kg/m3). Mixtures of water and on-site soils shall not be allowed for use as a drilling slurry, since particulate matter falls out of suspension easily and can contaminate the concrete.</td></tr>
<tr><td>Viscosity
Seconds/qt</td></tr>
<tr><td>pH</td></tr>
<tr><td>Sand Content
Percent by Volume</td></tr>
</table>

Source: United States. Massachusetts Department of Transportation. *Standard Specifications*. 2012.

Table B.22 Michigan Slurry Specifications

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	< 63	< 63	Density Balance
Viscosity Seconds/qt	33-43	33-43	Marsh Cone
pH	8 – 11	8-11	pH meter, pH paper
Sand Content Percent by Volume	< 1	< 1	API 13B-1

a. Slurry temperature shall be at least 40°F when tested.
b. Use of mineral slurry in sat water installations will not be allowed.

Source: United States. Michigan Department of Transportation. *Standard Specifications for Construction.* 2012.

Table B.23 Minnesota Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/qt {Seconds/L}			
pH			

a. Mineral slurries shall be employed in the drilling process unless other drilling fluids are approved by the Engineer.

Source: United States. Minnesota Department of Transportation. *Standard Bridge Special Provisions.* 2005.

Table B.24 Mississippi Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3* – 69.1* {1030* – 1105*}	64.3* – 75.0* {1030** – 1200*}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Increase by 2 lb/ft^3 (30 kg/m^3) in salt water.

a. Tests should be performed when slurry temperature is above 41°F (5°C).

b. If desanding is required, sand content shall not exceed 4% (by volume) at any point in the borehole as determined by the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Mineral slurries shall be employed when slurry is used in the drilling process, unless other drilling fluids are approved in writing by the Engineer. No Polymer Specification Available.		
Viscosity Seconds/qt {Seconds/L}			
pH			

Source:United States. Mississippi Department of Transportation. *Special Provision No. 907-803-18M, Deep Foundations*. 2007.

Table B.25 Missouri Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	63.5 – 66.8 {1017 – 1129}	63.5 – 70.5 {1017 – 1129}	Density Balance
Viscosity Seconds/qt {Seconds/L}	32 – 60 {34 – 60}	32 – 60 {34 – 60}	Marsh Funnel
pH	8 – 10	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	<4	<10	API Sand Content Kit
Maximum Contact Time* Hours	N/A	4	N/A

a. All values without agitation and sidewall cleaning.
b. Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.
c. All values for freshwater without additives.

Polymer Slurry Specifications

Emulsified Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	< 63 {1009}	< 63 {1009}	Density Balance
Viscosity Seconds/qt {Seconds/L}	33 – 43* {35 – 45}*	33 – 43* {35 – 45}*	Marsh Funnel
pH	8 - 11	8 - 11	pH Paper or pH Meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation and Sidewall Cleaning	72 hrs		

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

Dry Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	< 63 {1009}	< 63 {1009}	Density Balance
Viscosity Seconds/qt {Seconds/L}	50 – 80* {53 – 85}*	50 – 80* {53 – 85}*	Marsh Funnel
pH	7 - 11	7 - 11	pH Paper or pH Meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation and Sidewall Cleaning	72 hrs		

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

a. All values for freshwater without additives.

Source:United States. Missouri Department of Transportation. *Supplemental Specifications to 2013 Missouri Standard Specifications for Highway Construction.* 2013.

Table B.26 Montana Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Mineral slurry use not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry must be in conformance with Manufacturer's recommendations		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

The following synthetic slurries are approved as slurry systems:

Product	*Manufacturer*
Novagel	Geo-Tech Services, LLC 220 North Zapata Highway, Suite 11A Laredo, TX 78043-4464
ShorePac GCV	CETCO 1500 West Shure Drive Arlington Heights IL, 60004
SlurryPro CDP	KB International, LLC Suite 216, 735 Broad Street Chattanooga, TN 37402-1855
Super Mud*	PDS Company 8140 East Rosecrans Ave. Paramount, CA 90723-2754

*Approval as a product applies to the liquid product only.

Submit other proposed synthetic slurry products for approval. Submit proposed additives for approval.

Source: United States. Montana Department of Transportation. *Special Provisions: Synthetic Slurry for Drilled Shafts*. 2011.

Table B.27 Nebraska Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Mineral slurry not allowed without engineer approval.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Manufacturer specifications required upon engineer approval.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: Jordan Larsen (Nebraska Department of Roads Bridge Foundation Engineer) in discussion with author, August 2013

Table B.28 Nevada Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kN/m^3}	64.0-68.8 {10.1-10.8}	64.0-74.6 {10.1-11.8}	Density Method API 13B-1 Section 1
Viscosity* Seconds/qt	28 – 45	28 – 45	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, Glass Electrode pH meter
Sand Content Percent by Volume	4 MAX	4 MAX	N/A

* The Marsh Funnel Test is conducted using one quart of fluid, not one liter.

a. Testing shall be performed when the slurry temperature is above 40°F (4°C).

b. The sand content shall not exceed 4% (by volume) at any point in the bore hole as determined by the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kN/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity* Seconds/qt			
pH			

Source:United States. Nevada Department of Transportation. *Standard Specifications for Road and Bridge Construction*. 2001.

Table B.29 New Hampshire Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kN/m^3\}$	64.3 – 69.1* {410 – 440*}	64.3 – 75.0* {410 – 478*}	Density Balance
Viscosity Seconds/qt {Seconds/0.945L}	28 – 45 {28 – 45}	28 – 45 {28 – 45}	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Upper limit assumes that the slurry is being reused after having been treated. Initial mixing of mineral powder and fresh water should be no higher than 65.5 lb/ft^3 (717 kN/m^3) unless additional density is obtained with weighting agents. Increase by 2 lb/ft^3 (12.5 kN/m^3) in salt water.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kN/m^3\}$	64.3 – 69.1* {410 – 440*}	64.3 – 75.0* {410 – 478*}	Density Balance
Viscosity Seconds/qt {Seconds/0.945L}	28 – 45 {28 – 45}	28 – 45 {28 – 45}	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter

* Upper limit assumes that the slurry is being reused after having been treated. Initial mixing of mineral powder and fresh water should be no higher than 65.5 lb/ft^3 (717 kN/m^3) unless additional density is obtained with weighting agents. Increase by 2 lb/ft^3 (12.5 kN/m^3) in salt water.

Source: United States. New Hampshire Department of Transportation. *Standard Specifications.* 2010.

Table B.30 New Jersey Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1*	64.3 – 75.0*	Mud Balance API 13B ASTM D 4380
Viscosity Seconds/qt	28 – 45*	28 – 45*	Marsh Funnel and Cup API 13B Section 2
pH	8 – 11	8 – 11	pH paper, Glass-Electrode pH meter API 13B Section 6
Sand Content Percent by Volume	4 MAX	4 MAX	Sand Screen Set API 13B Section 4 ASTM D 4381

* Increase by 2 lb/ft^3 in salt water.

a. Perform tests when slurry temperature is above 40°F.

b. Ensure that the sand content does not exceed 4% (by volume) at any point in the borehole as determined by the API sand content test when the slurry is introduced.

c. Perform tests to determine density, viscosity and pH value during the shaft excavation to establish a consistent working pattern. Perform a minimum of 4 sets of tests during the first 8 hours of slurry use. When the results show consistent behavior, the Contractor may decrease the testing frequency to 1 set per every 4 hours of slurry use.

d. One sec/qt = 1.06 sec/L.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available.		API 13B-1, Section 1
Viscosity Seconds/qt {Seconds/L}			(Marsh funnel and cup, API 13B-1), Section 2.2 or approved viscometer
pH			pH meter, pH paper
Sand Content Percent by Volume			API sand content kit, API 13B-1, Section 5

Provide a slurry management plan to the RE that includes a set of the slurry manufacturer's written recommendations and results of the following tests, as a minimum:

1. Density Test (API 13B-1, Section 1).
2. Viscosity Test (Marsh funnel and cup, API 13B-1), Section 2.2 or approved viscometer.
3. pH Test (pH meter, pH paper).
4. Sand Content Test (API sand content kit, API 13B-1, Section 5).

Also include the tests to be performed, the frequency of those tests, the test methods, and the maximum and minimum property requirements that must be met to ensure that the slurry meets its intended functions. Ensure that all test reports are signed, and provide them to the RE on completion of each drilled shaft.

Source: United States. New Jersey Department of Transportation. *Standard Specifications for Road and Bridge Construction*. 2007.

Table B.31 New Mexico Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	N/A	64.0 – 75.0	Density Balance
Viscosity Seconds/qt	28 – 45	N/A	Marsh Cone
pH	8 – 10	8 – 10	pH paper
Sand Content Percent by Volume	N/A	0 – 4	API Method

a. Perform tests when the slurry temperature is above 40 °F.
b. Premix the slurry according to the manufacturer's directions. Prevent the slurry from "setting up" in the shaft. Dispose of the slurry offsite in accordance with Section 107.14.8, "Disposal of Other Materials and Debris."

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	62.4 - 64	62.4 - 64	Density Balance
Viscosity Seconds/qt	50-120	50-120	Marsh Cone
pH	8 – 11.7	8 – 11.7	pH paper
Sand Content Percent by Volume	0-1	0 – 1	API Method

a. Premix the slurry according to the manufacturer's directions. Prevent the slurry from "setting up" in the shaft. Dispose of the slurry offsite in accordance with Section 107.14.8, "Disposal of Other Materials and Debris."
b. Perform tests when the slurry temperature is above 40 °F.
c. Table pertains to Emulsified or Dry Phpa Polymer

Source: United States. New Mexico State Department of Transportation. *Standard Specifications for Highway and Bridge Construction.* 2007.

Table B.32 New York Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	1030 – 1106	1030 – 1200	Density Balance
Viscosity Seconds/L	29 – 48	29 – 48	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

<table>
<tr><th>Property (Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test Method</th></tr>
<tr><td>Density kg/m^3</td><td colspan="3" rowspan="3">Polymer Slurry. Provide a polymer slurry with sufficient viscosity and gel characteristics to hold the hole open, and transport excavated material to a suitable screening system. Polymer slurry may be made from PHPA (emulsified), vinyl (dry), or natural polymers. Desand the polymer slurry so that the sand content is less than 1 percent (by volume) prior to concrete placement, as determined by the American Petroleum Institute sand content test.</td></tr>
<tr><td>Viscosity Seconds/L</td></tr>
<tr><td>pH</td></tr>
</table>

Source: United States. New York State Department of Transportation. Standard Specifications. 2008.

Table B.33 North Carolina Slurry Specifications

Define "slurry" as bentonite or polymer slurry. Mix bentonite clay or synthetic polymer with water to form bentonite or polymer slurry.

Bentonite Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 72	64.3 – 72	Mud Weight API RP[b]13B-1 Section 4
Viscosity Seconds/qt	28 – 50	28 – 50	Marsh Funnel and Cup API RP[b]13B-1 Section 6.2
pH	8 – 11	8 – 11	Glass Electrode pH meter API RP[b] 13B-1 Section 9
Sand Content Percent by Volume	Vol≤4	Vol≤2	Sand API RP[b] 13B-1 Section 9

a. Slurry temperature of at least 40°F (4.4°C) required.
b. American National Standards Institute/ American Petroleum Institute Recommended Practice
c. Increase density requirements by 2 lb/ft^3 in salt water
d. pH paper is also acceptable for measuring pH.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	≤64	≤64	Mud Weight API RP[b] 13B-1 Section 4
Viscosity Seconds/qt	32 – 135	32 - 135	Marsh Funnel and Cup API RP[b] 13B-1 Section 6.2
pH	8 – 11.5	8 – 11.5	Glass Electrode pH meter API RP[b] Section 11
Sand Content Percent by Volume	≤0.5	≤0.5	Sand API RP[b] 13B-1 Section 9

a. Slurry temperature of at least 40°F (4.4°C) required.
b. American National Standards Institute/ American Petroleum Institute Recommended Practice
c. Increase density requirements by 2 lb/ft^3 in salt water
d. pH paper is also acceptable for measuring pH.

The following polymer slurries are approved for use:

Product	**Manufacturer**
Shore Pac	CETCO Construction Drilling Products 2870 Forbs Avenue Hoffman Estates, IL 60192 (800) 527-9948

https://connect.ncdot.gov/resources/Geological/Lists/GEOTechApprvlList/Attachments/2/SHORE%20PAC%20Technical%20Data.pdf

Terragel	Geo-Tech Services, LLC 220 North Zapata Highway Suite 11A-449A Laredo, TX 78043 (210) 259-6386

https://connect.ncdot.gov/resources/Geological/Lists/GEOTechApprvlList/Attachments/32/Terragel%20Technical%20Data.pdf

SlurryPro CDP	KB International, LLC 735 Broad Street Suite 209 Chattanooga, TN 37402 (423) 266-6964

https://connect.ncdot.gov/resources/Geological/Lists/GEOTechApprvlList/Attachments/3/SlurryPro%20CDP%20Technical%20Data.pdf

Super Mud	PDS Co., Inc. 105 West Sharp Street El Dorado, AR 71731 (800) 243-4755

https://connect.ncdot.gov/resources/Geological/Lists/GEOTechApprvlList/Attachments/4/Super%20Mud%20Technical%20Data.pdf

Super Mud Dry	PDS Co., Inc. 105 West Sharp Street El Dorado, AR 71731 (800) 243-475

https://connect.ncdot.gov/resources/Geological/Lists/GEOTechApprvlList/Attachments/5/Super%20Mud%20Dry%20Technical%20Data.pdf

Source: United States. North Carolina Department of Transportation. *Standard Specifications*. 2012.

Table B.34 North Dakota Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Table B.35 Ohio Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

a. Range of values for 68°F.

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry
Introduction</th><th>In Hole at Time of
Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3
$\{kg/m^3\}$</td><td colspan="3" rowspan="3">Only use polymer slurry after demonstrating to the Engineer that the stability of the hole perimeter can be maintained while advancing the excavation to its final depth by excavating a trial hole of the same diameter and depth as that of the production shafts. Use the same polymer slurry in the trial hole as proposed for the production shafts. If using different sizes of the shafts at the project, use the same size trial hole as that of the largest diameter shaft, except the depth of the trial hole need not be more than 40 feet (12 meters). Only one trial hole per project is required. Do not use the trial hole excavation for a production shaft. After completing the trial hole excavation, fill the hole with sand. The acceptance of the polymer slurry does not relieve the Contractor of responsibility to maintain the stability of the excavation. Polymer slurry shall conform to the manufacturer‟s requirements.</td></tr>
<tr><td>Viscosity
Seconds/qt
{Seconds/L}</td></tr>
<tr><td>pH</td></tr>
</table>

Source: Ohio Department of Transportation. *Construction and Material Specifications.* 2013.

Table B.36 Oklahoma Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1200}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

a. Perform tests when slurry temperature is above 40°F [4°C]

b. Density values are for fresh water. Increase density values 2.0 lb/ft^3 [32 kg/m^3] for salt water

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	62.4 – 63 {1000 – 1010}	62.4 – 63.5 {1000 – 1017}	Density Balance
Viscosity Seconds/qt {Seconds/L}	30 – 40 {32 – 42}	30 – 40 {32 – 42}	Marsh Cone
pH	9 – 11	9 – 11	pH paper, pH meter
Sand Content Percent by Volume	< 1	< 1	N/A

a. Perform tests when slurry temperature is above 40°F [4°C]

b. Density values are for fresh water. Increase density values 2.0 lb/ft^3 [32 kg/m^3] for salt water

Source: United States. Oklahoma Department of Transportation. *Standard Specifications Book.* 2009.

Table B.37 Oregon Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64 – 75	64 – 75	Mud Density API 13B-1 Section 1
Viscosity Seconds/qt	26 – 50	26 – 50	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter, Glass Electrode
Sand Content Percent by Volume	4 MAX	4 MAX	Sand API 13B-1 Section 5

a. Maintain slurry temperature at 40°F or more during testing.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	**(b) Synthetic Slurries** - Select synthetic slurries from the QPL. Use synthetic slurries according to the manufacturer's recommendations and the Contractor's quality control plan. The sand content of synthetic slurry shall be less than 2.0 percent (API 13B-1, Section 5) prior to final cleaning and immediately prior to concrete placement.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume	<2	<2	Sand API 13B-1 Section 5

a. Maintain slurry temperature at 40°F or more during testing.

Water Slurry

Water may be used as slurry when casing is used for the entire length of the drilled shaft. Use of water slurry without full-length casing will only be allowed with the Engineer's approval.

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	70 MAX	70 MAX	Mud Density API 13B-1 Section 1
Sand Content Percent by Volume	2 MAX	2 MAX	Sand API 13B-1 Section 5

a. Do not use blended slurries.

Source: United States. Oregon Department of Transportation. *Standard Specifications*. 2008.

Table B.38 Pennsylvania Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Table B.39 Rhode Island Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Table B.40 South Carolina Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Cone API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

a. Perform tests when the slurry temperature is above 40° F.
b. If desanding is required, do not allow sand content to exceed 4% (by volume) at any point in the borehole as determined by the American Petroleum Institute Sand Content Test (API 13B-1, Section 5).

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Cone API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter

Source: United States. South Carolina Department of Transportation. *Standard Specifications for Highway Construction*. 2007.

Table B.41 South Dakota Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. South Dakota Department of Transportation. *Standard Specifications*. 2004.

Table B.42 Tennessee Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63.5 – 66.8	63.5 – 70.5	Density Balance
Viscosity Seconds/qt	32 – 60	32 – 60	Marsh Funnel
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	Vol<4	Vol<10	API Sand Content Kit
Maximum Contact Time Hours	N/A	N/A	N/A

Polymer Slurry Specifications

Emulsified Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	< 63	< 63	Density Balance
Viscosity Seconds/qt {Seconds/L}	33-43*	33-43*	Marsh Funnel
pH	8 - 11	8 - 11	pH paper or meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation or Sidewall Cleaning	72 hrs	72 hrs	

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

Dry Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	< 63	< 63	Density Balance
Viscosity Seconds/qt {Seconds/L}	50 – 80*	50 – 80*	Marsh Funnel
pH	7 - 11	7 - 11	pH paper or meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation or Sidewall Cleaning	72 hrs	72 hrs	

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.
Source: United States. Tennessee Department of Transportation. *Special Provisions Item 625: Drill Shaft Specifications.* 2006.

Table B.43 Texas Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Specific Gravity	≤1.10	≤1.15	
Viscosity Seconds/qt {Seconds/L}	N/A	≤45	
pH			
Sand Content Percent by Volume	Vol≤1	Vol≤6	

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Specific Gravity	"Do not use PHPA (partially hydrolyzed polyacrylamide) polymeric slurry or any other fluid composed primarily of a polymer solution."		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Source: United States. Texas Department of Transportation. *Standard Specifications*. 2004.

Table B.44 Utah Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry drilling is not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry drilling is not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Utah Department of Transportation. *Standard Specifications*. 2012.

Table B.45 Vermont Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 47}	28 – 45 {30 – 47}	Marsh Cone API 13B-1 Section 2.2
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	≤4	Sand API 13B-1 Section 5

a. These tests shall be done per the American Petroleum Institute RP 13B-1 Standard Procedure for field testing Water Based Drilling Fluids.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	63 – 64 {1009 – 1025}	63 – 64 {1009 – 1025}	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	45 min {48 min}	45 min {48 min}	Marsh Cone API 13B-1 Section 2.2
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	< 1	Sand API 13B-1 Section 5

a. These tests shall be done per the American Petroleum Institute RP 13B-1 Standard Procedure for field testing Water Based Drilling Fluids.
b. Range of values for polymer slurry at 68° F [20° C]
c. The use of a blended mineral-polymer slurry is not permitted.
d. Polymer slurry (vinyl (dry) or natural polymers) shall be made from Partially-Hydrolyzed Polyacrylamide Polymer (PHPA) (emulsified). The polymer slurry product must be approved for use by the Agency.

Source: United States. Vermont Agency of Transportation. *Bennington AC NH 019-1(51) Construction Special Provisions*. 2009.

Table B.46 Virginia Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63 – 65	65 – 67	Mud Balance API 13B-1 Section 1
Viscosity Seconds/qt	50 max.	50 max.	Marsh Cone Method API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	0.3% max	1% max	API 13B -1

a. Density values shall be increased by two pounds per cubic foot (lb/ft^3) in salt water.
b. At time of concreting, sand content at any point in the drilled shaft excavation shall not exceed 1% (by volume); test for sand content as determined by the American Petroleum Institute.
c. Minimum mixing time shall be 15 minutes.
d. Storage time to allow for hydration shall be minimum of 4 hours.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63 – 65	65 – 67	Mud Balance API 13B-1 Section 1
Viscosity Seconds/qt	50 max.	50 max.	Marsh Cone Method API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	0.3% max	1% max	API 13B -1

a. Density values shall be increased by two pounds per cubic foot (lb/ft^3) in salt water.
b. At time of concreting, sand content at any point in the drilled shaft excavation shall not exceed 1% (by volume); test for sand content as determined by the American Petroleum Institute.
c. Minimum mixing time shall be 15 minutes.
d. Storage time to allow for hydration shall be minimum of 4 hours.

Source: United States. Virginia Department of Transportation. *Special Provisions for Drilled Shafts*. 2010.

Table B.47 Washington Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63 – 75	63 – 75	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt	26 – 50	26 – 50	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	Glass electrode, pH paper, pH meter
Sand Content Percent by Volume	4 MAX	4 MAX	Sand API 13B-1 Section 5

a. Use of mineral slurry in salt water installations will not be allowed.
b. Slurry temperature shall be at least 40 F when tested.

Water Slurry Specifications

Water without site soils may be used as slurry when casing is used for the entire length of the drilled hole. Water slurry without full length casing may only be used with the approval of the Engineer.

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	65 MAX	65 MAX	Mud Weight (Density)API 13B-1 Section 1
Sand Content Percent by Volume	1 MAX	1 MAX	Sand API 13B-1 Section 5

Use of water slurry in salt water installations will not be allowed.
Slurry temperature shall be at least 40ºF when tested.

Synthetic Slurry Specifications

Synthetic slurries shall be used in conformance with the manufacturer's recommendations and shall conform to the quality control plan specified in Section 6-19.3(2)B, item 4. The synthetic slurry shall conform to the following requirements:

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64 MAX	64 MAX	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt	32-135	32-135	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	6 -11.5	6 -11.5	Glass electrode, pH paper, pH meter
Sand Content Percent by Volume	1 MAX	1 MAX	Sand API 13B-1 Sec 5

Source: United States. Washington State Department of Transportation. *Bridge Special Provisions.* 2014.

Table B.48 West Virginia Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	When the use of slurry is anticipated, details of the methods to mix, circulate, and de-sand slurry. Any request to use a slurry displacement method for the construction of caissons shall also provide information for the Engineer's approval as follows: 1. Detailed description of proposed construction method. 2. Concrete mix, as modified for use with the slurry displacement method. 3. Components and proportions in proposed slurry mixture. 4. Tests proving slurry mixture will not degrade rock or interfere with bond. 5. Methods to agitate slurry mixture prior to concrete placement. 6. Methods to clean slurry mixture for re-use. 7. Disposal methods for used slurry.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specific polymer slurry specifications		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. West Virginia Department of Transportation. *West Virginia Division of Highways: Supplemental Specifications.* 2000.

Table B.49 Wisconsin Slurry Specifications

Mineral Slurry Specifications

Property at 68°F Units	At the Time of Slurry Introduction into the Drilled Shaft	Before Concrete Placement in the Drilled Shaft	Test Method
Density in Fresh Water (lb/ft^3) (a)	64 to 69	64 to 75	Density Balance
Viscosity (seconds per quart)	28 to 45	28 to 45	Marsh Funnel
pH	7 to 11	7 to 11	pH paper or meter
Sand Content (%) (b)	4 maximum	10 maximum	200 Sieve Retain

Polymer Slurry Specifications

Property at 68°F Units	At the Time of Slurry Introduction into the Drilled Shaft	Before Concrete Placement in the Drilled Shaft	Test Method
Density in Fresh Water (lb/ft^3) (a)	63 or less	63 or less	Density Balance
Viscosity (seconds per quart)	50 minimum	50 minimum	Marsh Funnel
pH	8 to 11	8 to 11	pH paper or meter
Sand Content (%)	2 maximum	10 maximum	200 Sieve Retain

Source : United States. Wisconsin Department of Transportation. Standard Specification, 2013.

Table B.50 Wyoming Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. State of Wyoming Department of Transportation. *Standard Specifications*. 2010.

Table B.51 Federal Highway Administration Slurry Specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 72	N/A	Mud Weight Density Balance (API 13B-1)
Viscosity Seconds/L	28 – 50	N/A	Marsh Funnel and Cup (API 13B-1)
pH	8 – 11	N/A	pH paper, pH meter
Sand Content Percent by Volume	4 MAX	N/A	Sand Content API 13B-1

Note: Density values shown are for fresh water. Increase density values 2 pounds per cubic foot for saltwater. Perform tests when slurry temperature is above 40 °F. If desanding is required, sand content shall not exceed 4 percent by volume at any point in the bore hole according to the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	≤64	N/A	Mud Weight Density Balance (API 13B-1)
Viscosity Seconds/L	32 to 135	N/A	Marsh Funnel and Cup (API 13B-1)
pH	8 – 11.5	N/A	pH paper, pH meter
Sand Content Percent by Volume	≤ 1.0	N/A	Sand Content API 13B-1

Source: United States. United States Department of Transportation Federal Highway Administration. *Drilled Shafts: Construction Procedures and LRFD Design Methods*. 2010.

APPENDIX C: REBAR PULLOUT CONCRETE INFORMATION

CEMEX

Brooksville South Plant
10311 CEMENT PLANT ROAD
Brooksville, Fl 34601
Phone (352) 799-7881 / FAX (352) 799-6088

CEMENT MILL TEST REPORT

Cement Identified as: AASHTO M85, Type I, Type II and Type II (MH), C-150

Date of Report: 01/04/12

Production Period:
Beginning: 1-Dec-12
Ending: 31-Dec-12

Silo 1,2,4,5,13,15

CHEMICAL REQUIRMENTS ASTM C114 and AASHTO M 85	Test Results	Specifications	AASHTO M 85, ASTM C 150 Type I	TYPE II	TYPE II (MH)	ASTM C-1157 GU
Silicon Dioxide (SiO_2) %	20.1	Minimum	—	—	—	—
Aluminum Oxide (Al_2O_3) %	4.9	Maximum	—	6.0	6.0	—
Ferric Oxide (Fe_2O_3) %	3.9	Maximum	—	6.0	6.0	—
Calcium Oxide (CaO) %	64.5		—	—	—	—
Magnesium Oxide (MgO) %	0.7	Maximum	6.0	6.0	6.0	—
Sulfur Trioxide (SO_3) % [A]	2.8	Maximum	3.5	3.0	3.0	—
Loss on Ignition (LOI) %	2.4	Maximum	3	3	3.0	—
Insoluble Residue (IR) %	0.50	Maximum	0.75	0.75	0.75	—
Alkalies (Na_2O equivalent) %	0.41	Optional Max	0.60	0.60	0.60	—
Carbon Dioxide in cement (CO_2) %	1.10					
Limestone % in cement (ASTM C150 A1)	2.7	Maximum	5	5	5	—
$CaCO_3$ in limestone % (2.274 x %CO_2 LS)	86	Minimum	70	70	70	—
Inorganic Processing Addition (Kiln dust) (%)	3.0	Maximum	5	5	5	—
Potential Phase composition [D]						
Tricalcium Silicate (C_3S) %	61		—	—	—	—
Dicalcium Silicate (C_2S) %	10		—	—	—	—
Tricalcium Aluminate (C_3A) %	6	Maximum	—	8	8	—
Tetracalcium Aluminoferrite (C_4AF) %	12		—	—	—	—
(C_3S + 4.75 C_3A)	90	Maximum	—	—	100	—
(C_4AF + 2C_3A) or (C_4AF + C_2F) %	24	Maximum	—	—	—	—
PHYSICAL REQUIRMENTS						
(ASTM C204) Blaine Fineness, cm2/g	3972	Minimum	2600	2600	2600	—
(ASTM C204) Blaine Fineness, cm2/g	3972	Maximum	—	—	4300 [B]	—
(ASTM C430) -325 Mesh %	95.8		—	—	—	—
(ASTM C191) Time of Setting (Vicat) Initial Set, minutes	105	Min / Max	45 / 375	45 / 375	45 / 375	45 / 420
(ASTM C185) Air Content of Mortar %	5.2	Maximum	12	12	12	—
(ASTM C151) Autoclave Expansion %	-0.020	Maximum	0.80	0.80	0.80	0.80
(ASTM C187) Normal Consistency %	25.0		—	—	—	—
(ASTM C1038) Expansion in Water % *	0.011	Maximum	0.020	0.020	0.020	0.020
(ASTM C186) 7 day Heat of Hydration cal/g [C]	76	Informational				
(ASTM C109) Compressive Strength, psi (Mpa)						
1 Day	2266 (15.6)		—	—	—	—
3 Days	4148 (28.6)	Minimum	1740 (12.0)	1450 (10.0)	1450 (10.0)	1890 (13.0)
7 Days	5236 (36.1)	Minimum	2760 (19.0)	2470 (17.0)	2470 (17.0)	2900 (20.0)
28 Days [C]	6324 (43.7)	Minimum	—	—	—	4060 (28.0)

A As per note D of table 1. SO_3 limit may be exceeded demonstrating expansion according to ASTM C 1038 <= 0.020
B Blaine limits does not apply if Sum of C3S + 4.75* C3A <= 90
C Test results for this period not available. Most recent test result provided.
D Adjusted per A 1.6
* Required only if SO_3 exceeds limit of table 1.
This Cement contains Limestone.

Physical Testing completed by: KW, ES
Chemical Testing completed by: KW, ES, RP

Cemex hereby certifies that this cement meets or exceeds the chemical and physical specifications of:
x AASHTO M 85 Type I and Type II and ASTM C150 Type I and Type II
x AASHTO M 85 Type II (MH) and ASTM C150 Type II (MH)
x ASTM C-1157 GU
x Florida Spec 921

Oliver Sohn
Oliver Sohn
Quality Control Manager

We certify that the above described data represents the materials used in the cement manufactured during the production period indicated.
Cemex is not responsible for the improper use or workmanship that may be associated with the use of this cement.

Figure C.1 Page 1 of cement mill certificate.

CEMEX

Brooksville South Plant
10311 CEMENT PLANT ROAD
Brooksville, Fl 34601
Phone (352) 799-7881 / FAX (352) 799-6088

CEMENT MILL TEST REPORT

Cement Identified as: AASHTO M85, Type I, Type II and Type II (MH) , C-150

Date of Report: 01/04/12

Production Period:
Beginning: 1-Dec-12
Ending: 31-Dec-12

Silo 1,2,4,5,13,15

ADDITIONAL DATA

Inorganic Processing Addition

Type	Baghouse Dust
Amount (%)	3.0
SiO2 (%)	18.77
Al2O3 (%)	7.38
Fe2O3 (%)	2.8
CaO (%)	71.71
SO3 (%)	0.24

Base Cement Phase Composition

C3S (%)	63
C2S (%)	10
C3A (%)	6
C4AF (%)	12

Figure C.2 Page 2 of cement mill certificate.

Preferred
MATERIALS, INC.

Delivery Ticket for Structural Concrete

Financial Project Number	N/A	Serial #	7526992
DOT Plant Number	10-410	Date	May 8, 2013
Concrete Supplier	Oldcastle Southern Group / Preferred Materials, Inc.	Delivered to	USF/DANNY WINTERS
		Phone #	
Phone Number	800-331-3375	Address;	LAUREL & HOLLEY
Address	1811 N. 57th Street Tampa, FL 33619		USF

84097010

Truck # 4195	DOT class CL IV DS 4000 EQUL	DOT mix ID [illegible]	Cubic yards this load 4
allowable jobsite Water 13.58	Time loaded 8:44 AM	Mixing revolutions 78	Cubic yards total today 4
Chloride Test Results:		Chloride Test Date:	

Cement			Flyash / Slag			
American	TYPEI/ II	2075	ProAsh	F		1020
source	Type	amount-lbs	source	Type		amount-lbs
Coarse agg			Air admixture			
87-089	2.90	6400	Euclid	AEA-92S		12
Pit num.	%moisture	amount-lbs	source	brand	Type	amount-oz.
Fine agg.			Admixture			
16-659	3.20	4500	Euclid	WR	D	216
Pit num.	% moisture	amount-lbs	source	brand	Type	amount-oz.
		0.00				
ICE	Lbs.	Gal.	Admixture			
Batch water			Euclid	Viscstol	F	
Amount	799.0	96	source	brand	Type	amount
	Lbs.	Gal.				

Issuance of this ticket constitutes certification that the concrete batched was produced and information recorded in compliance with Department specifications for Structural Concrete

W363-620-53-391-0
CTQP Technician Identification number

Signature of batch plant operator

Arrival on jobsite		Number of revolutions upon arrival at job site	
Water added at job site(gal or lbs)		Additional mixing revs. With added water	
Time concrete completely discharged		Total number of revolutions	
Initial slump	Initial air	Initial concrete temp	Initial W/C ratio
Accept. Slump	Accept. Air	Accept. Concrete temp	Accept W/C ratio

Issuance of this ticket constitutes certification that the maximum specified water cementitious ratio was not exceeded and the batch was delivered and plaved in compliance with Department specification requirements

CTQP Technician Identification number

Signature of contractors representative

Figure C.3 FDOT batch ticket for placement 1.

Preferred
MATERIALS, INC.

Delivery Ticket for Structural Concrete

Financial Project Number	N/A	Serial #	7528042
DOT Plant Number	10-410	Date	June 5, 2013
Concrete Supplier	Oldcastle Southern Group / Preferred Materials, Inc.	Delivered to	KEVIN JOHNSON
		Phone #	
Phone Number	800-331-3375	Address;	HOLLEY & PLUM DR
Address	1811 N. 57th Street Tampa, FL 33619		USF

Truck # 4282	DOT class CL IV DS 4000		DOT mix ID 01-1031-01			Cubic yards this load 6	
allowable jobsite Water 20.52		Time loaded 8:11 AM	Mixing revolutions 78			Cubic yards total today 6	
Chloride Test Results:			Chloride Test Date:				
Cement			Flyash / Slag				
American	TYPEI/ II	3120	ProAsh	F		1525	
source	Type	amount-lbs	source	Type		amount-lbs	
Coarse agg			Air admixture				
87-089	3.00	9680	Euclid	AEA-92S		18	
Pit num.	%moisture	amount-lbs	source	brand	Type	amount-oz.	
Fine agg.			Admixture				
16-659	4.10	6680	Euclid	WR	D	372	
Pit num.	% moisture	amount-lbs	source	brand	Type	amount-oz.	
		0.00					
ICE	Lbs.	Gal.	Admixture				
Batch water			Euclid	Viscstol	F		
Amount	1132.0	136	source	brand	Type	amount	
	Lbs.	Gal.					

Issuance of this ticket constitutes certification that the concrete batched was produced and information recorded in compliance with Department specifications for Structural Concrete

W 363-620-53-391-0
CTQP Technician Identification number

Signature of batch plant operator

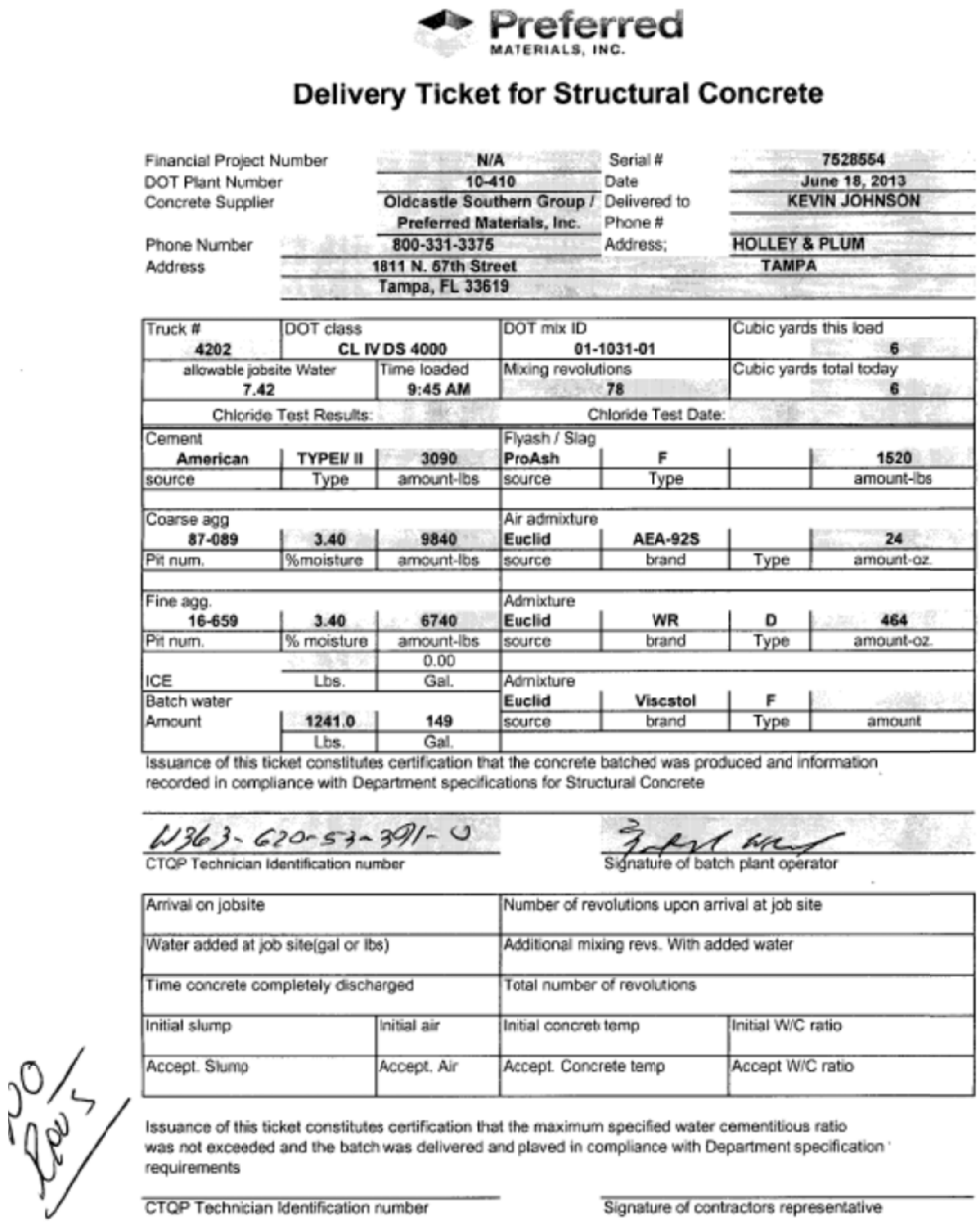
Arrival on jobsite		Number of revolutions upon arrival at job site	
Water added at job site(gal or lbs)		Additional mixing revs. With added water	
Time concrete completely discharged		Total number of revolutions	
Initial slump	Initial air	Initial concreti temp	Initial W/C ratio
Accept. Slump	Accept. Air	Accept. Concrete temp	Accept W/C ratio

Issuance of this ticket constitutes certification that the maximum specified water cementitious ratio was not exceeded and the batch was delivered and plaved in compliance with Department specification requirements

CTQP Technician Identification number

Signature of contractors representative

Figure C.4 FDOT batch ticket for placement 2.



Preferred
MATERIALS, INC.

Delivery Ticket for Structural Concrete

Financial Project Number	N/A	Serial #	7528554
DOT Plant Number	10-410	Date	June 18, 2013
Concrete Supplier	Oldcastle Southern Group / Preferred Materials, Inc.	Delivered to	KEVIN JOHNSON
		Phone #	
Phone Number	800-331-3375	Address;	HOLLEY & PLUM
Address	1811 N. 57th Street		TAMPA
	Tampa, FL 33619		

Truck # 4202	DOT class CL IV DS 4000		DOT mix ID 01-1031-01		Cubic yards this load 6	
allowable jobsite Water 7.42		Time loaded 9:45 AM	Mixing revolutions 78		Cubic yards total today 6	
Chloride Test Results:			Chloride Test Date:			
Cement			Flyash / Slag			
American	TYPE I/ II	3090	ProAsh	F		1520
source	Type	amount-lbs	source	Type		amount-lbs
Coarse agg			Air admixture			
87-089	3.40	9840	Euclid	AEA-92S		24
Pit num.	%moisture	amount-lbs	source	brand	Type	amount-oz.
Fine agg.			Admixture			
16-659	3.40	6740	Euclid	WR	D	464
Pit num.	% moisture	amount-lbs	source	brand	Type	amount-oz.
		0.00				
ICE	Lbs.	Gal.	Admixture			
Batch water			Euclid	Viscstol	F	
Amount	1241.0	149	source	brand	Type	amount
	Lbs.	Gal.				

Issuance of this ticket constitutes certification that the concrete batched was produced and information recorded in compliance with Department specifications for Structural Concrete

W363-620-53-391-0
CTQP Technician Identification number

Signature of batch plant operator

Arrival on jobsite		Number of revolutions upon arrival at job site	
Water added at job site(gal or lbs)		Additional mixing revs. With added water	
Time concrete completely discharged		Total number of revolutions	
Initial slump	Initial air	Initial concrete temp	Initial W/C ratio
Accept. Slump	Accept. Air	Accept. Concrete temp	Accept W/C ratio

20 Revs

Issuance of this ticket constitutes certification that the maximum specified water cementitious ratio was not exceeded and the batch was delivered and plaved in compliance with Department specification requirements

CTQP Technician Identification number

Signature of contractors representative

Figure C.5 FDOT batch ticket for placement 3.

Preferred
MATERIALS, INC.

Delivery Ticket for Structural Concrete

Financial Project Number	N/A	Serial #	7531916
DOT Plant Number	10-410	Date	September 20, 2013
Concrete Supplier	Oldcastle Southern Group / Preferred Materials, Inc.	Delivered to	KEVIN JOHNSON
		Phone #	
Phone Number	800-331-3375	Address;	4202 E FOWLER AVE
Address	1811 N. 57th Street Tampa, FL 33619		TAMPA

Truck # 3972	DOT class CL IV DS 4000	DOT mix ID 01-1031-01	Cubic yards this load 5
allowable jobsite Water 30.41	Time loaded 8:00 AM	Mixing revolutions 78	Cubic yards total today 5
Chloride Test Results:		Chloride Test Date:	

Cement			Flyash / Slag			
American	TYPEI/ II	2565	ProAsh	F		1255
source	Type	amount-lbs	source	Type		amount-lbs
Coarse agg			Air admixture			
87-089	2.50	8040	Euclid	AEA-92S		17
Pit num.	%moisture	amount-lbs	source	brand	Type	amount-oz.
Fine agg.			Admixture			
16-659	3.10	5540	Euclid	WR	D	387
Pit num.	% moisture	amount-lbs	source	brand	Type	amount-oz.
		0.00				
ICE	Lbs.	Gal.	Admixture			
Batch water Amount	924.0	111	Euclid	Viscstol	F	
	Lbs.	Gal.	source	brand	Type	amount

Issuance of this ticket constitutes certification that the concrete batched was produced and information recorded in compliance with Department specifications for Structural Concrete

4363-620-53-391-0 [illegible]

CTQP Technician Identification number — Signature of batch plant operator

Arrival on jobsite 845		Number of revolutions upon arrival at job site 115	
Water added at job site(gal or lbs)		Additional mixing revs. With added water	
Time concrete completely discharged		Total number of revolutions	
Initial slump	Initial air	Initial concrete temp	Initial W/C ratio
Accept. Slump	Accept. Air	Accept. Concrete temp	Accept W/C ratio

Issuance of this ticket constitutes certification that the maximum specified water cementitious ratio was not exceeded and the batch was delivered and plaved in compliance with Department specification requirements

CTQP Technician Identification number — Signature of contractors representative

Figure C.6 FDOT batch ticket for placement 4.

APPENDIX D: FRUSTUM MODEL SCALE TESTING

CPT Soundings
Load vs Displacement Graphs

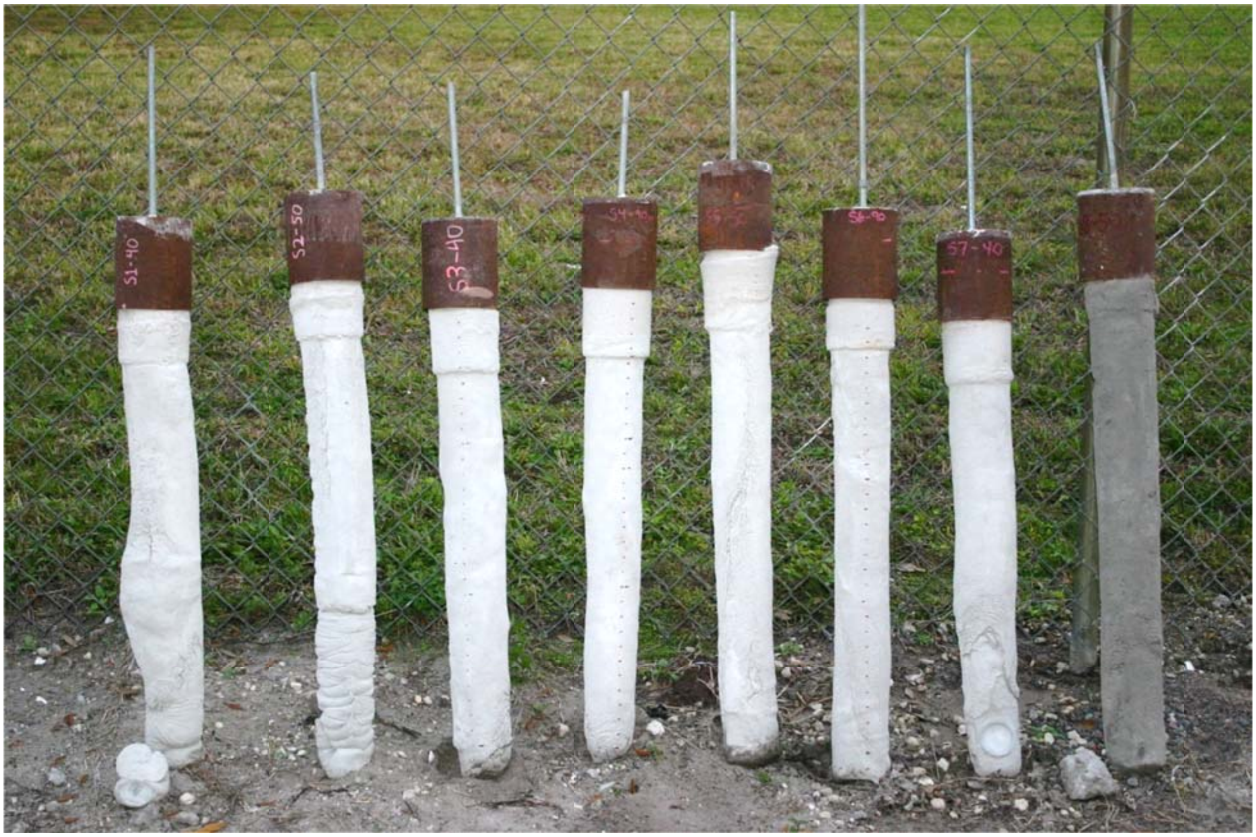


Figure D.1 Model Shafts

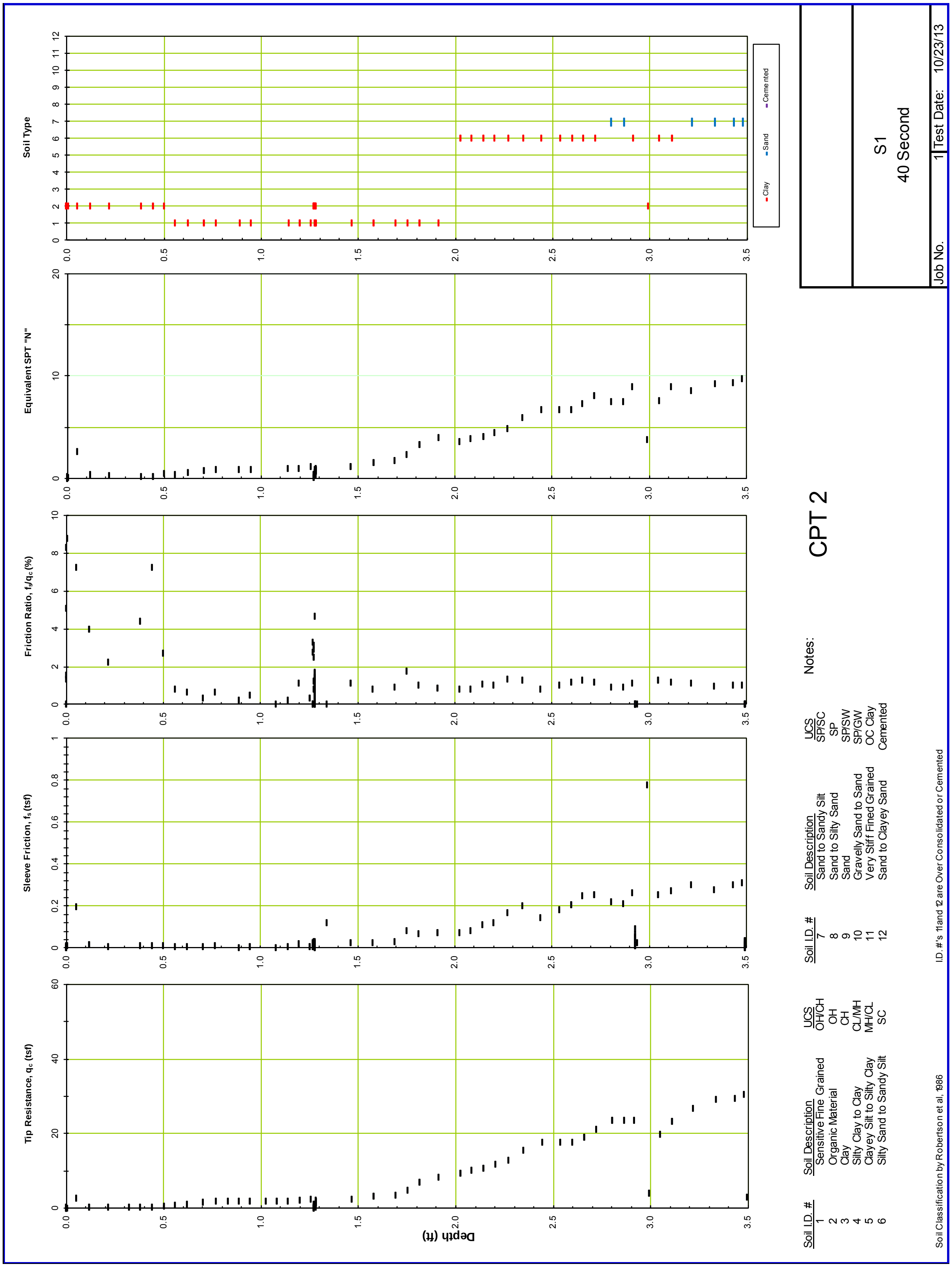


Figure D.2 CPT data prior to casting S1 – 40 (40 sec/qt)

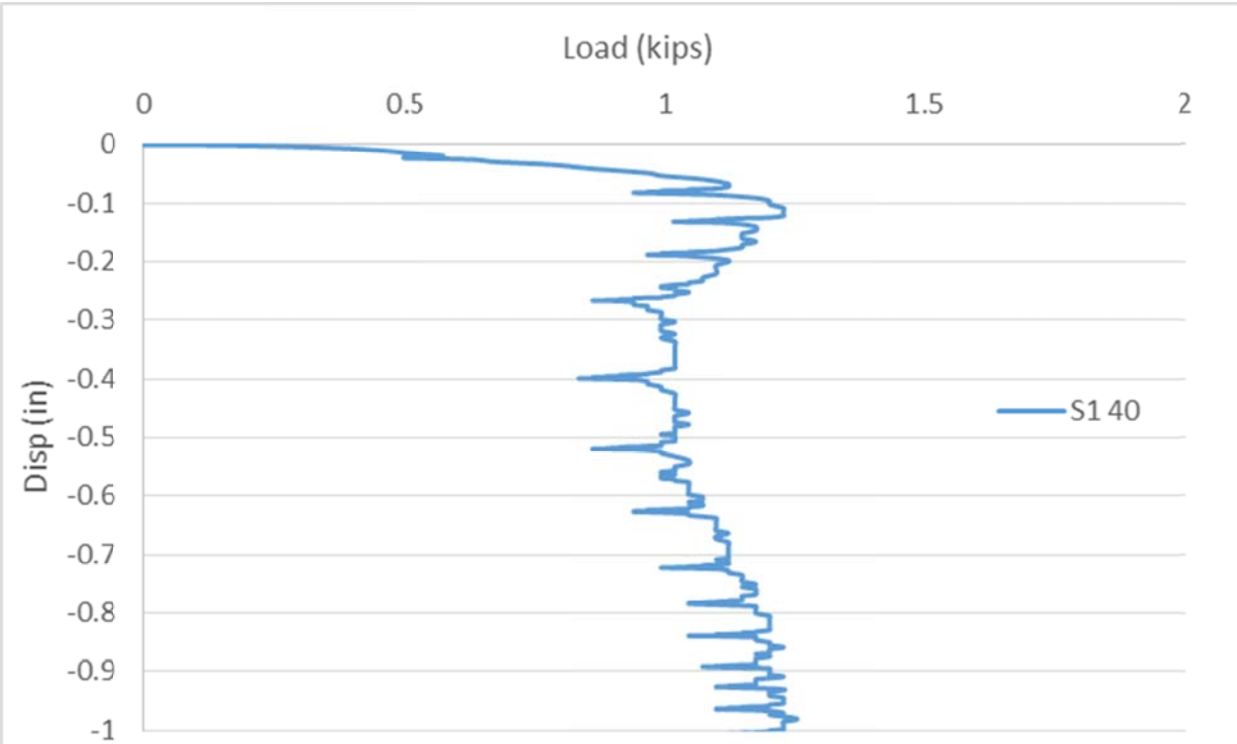


Figure D.3 Pullout data for model shaft S1 – 40 (40 sec/qt)

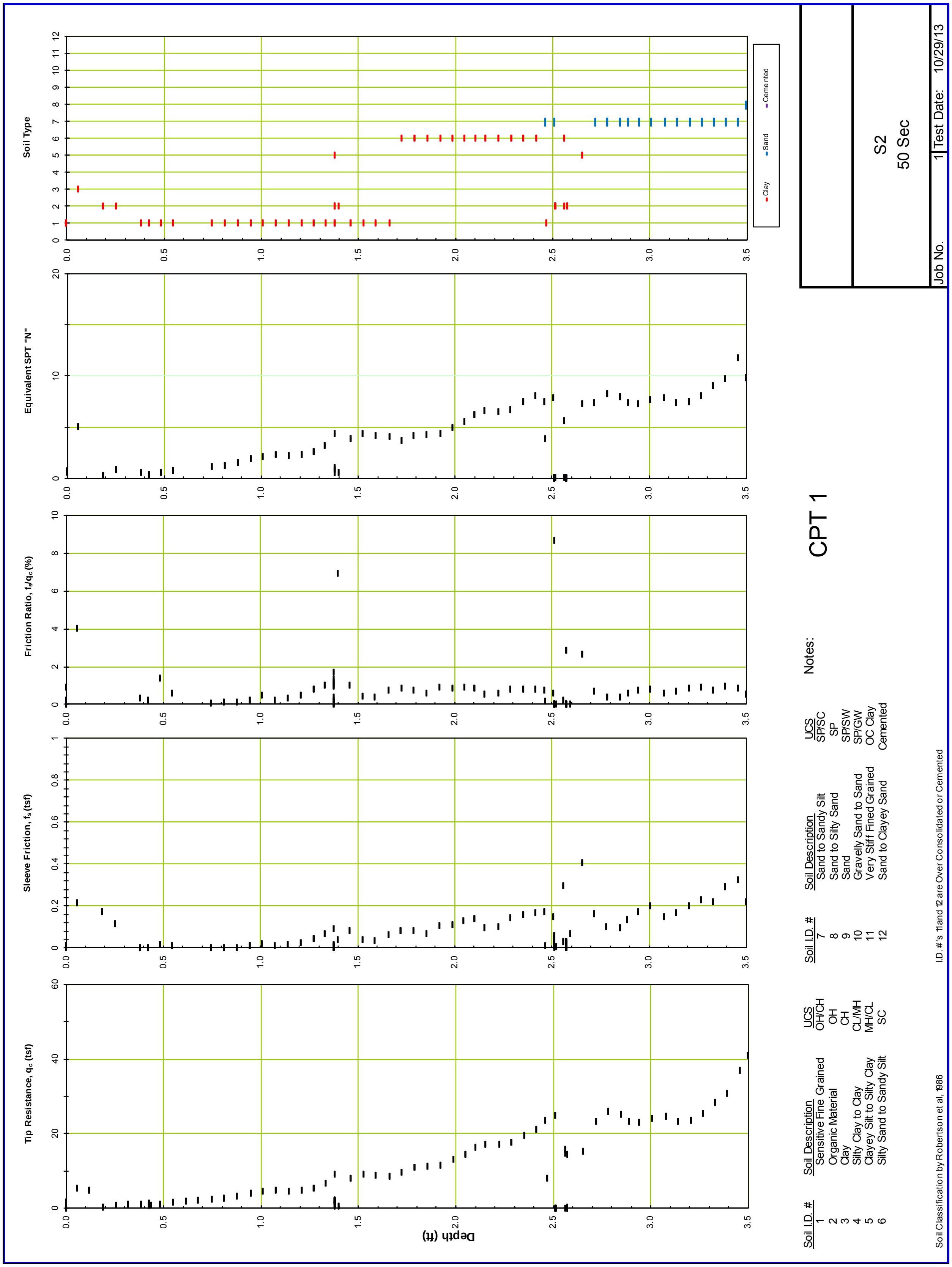


Figure D.4 CPT data prior to casting S2- 50 (50 sec/qt)

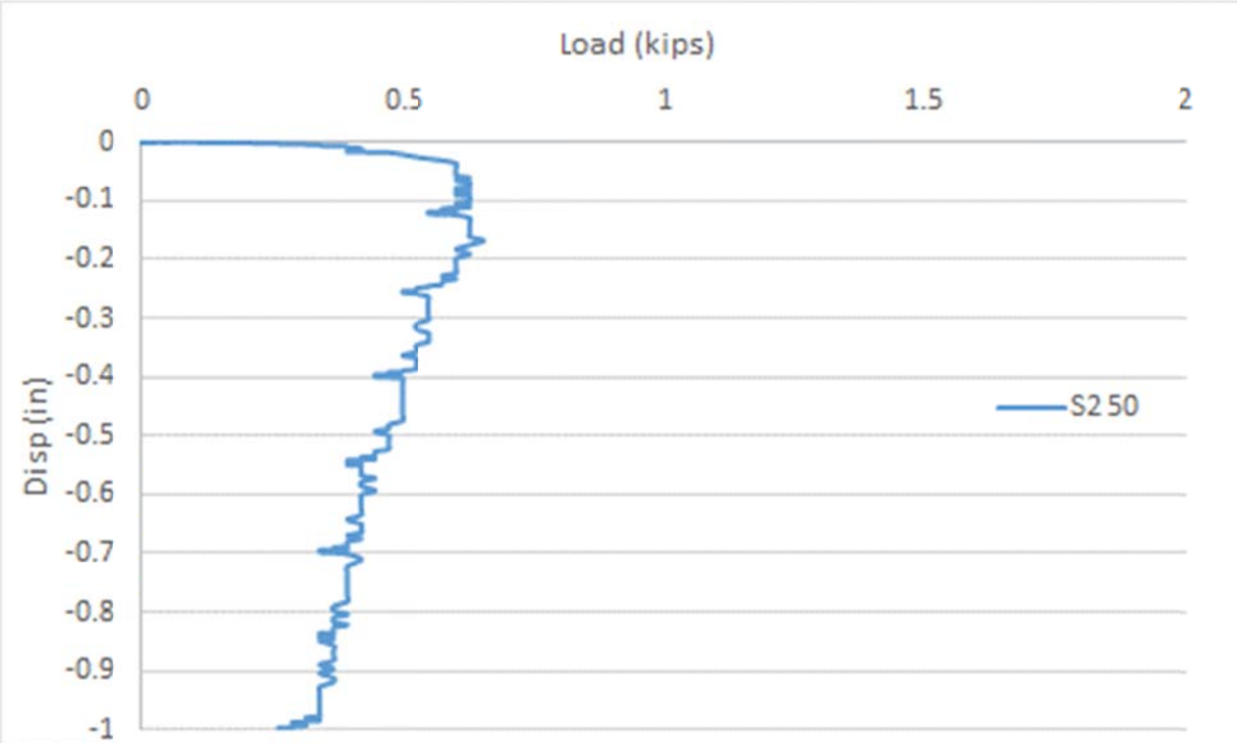


Figure D.5 Pullout data for model shaft S2 – 50 (50 sec/qt)

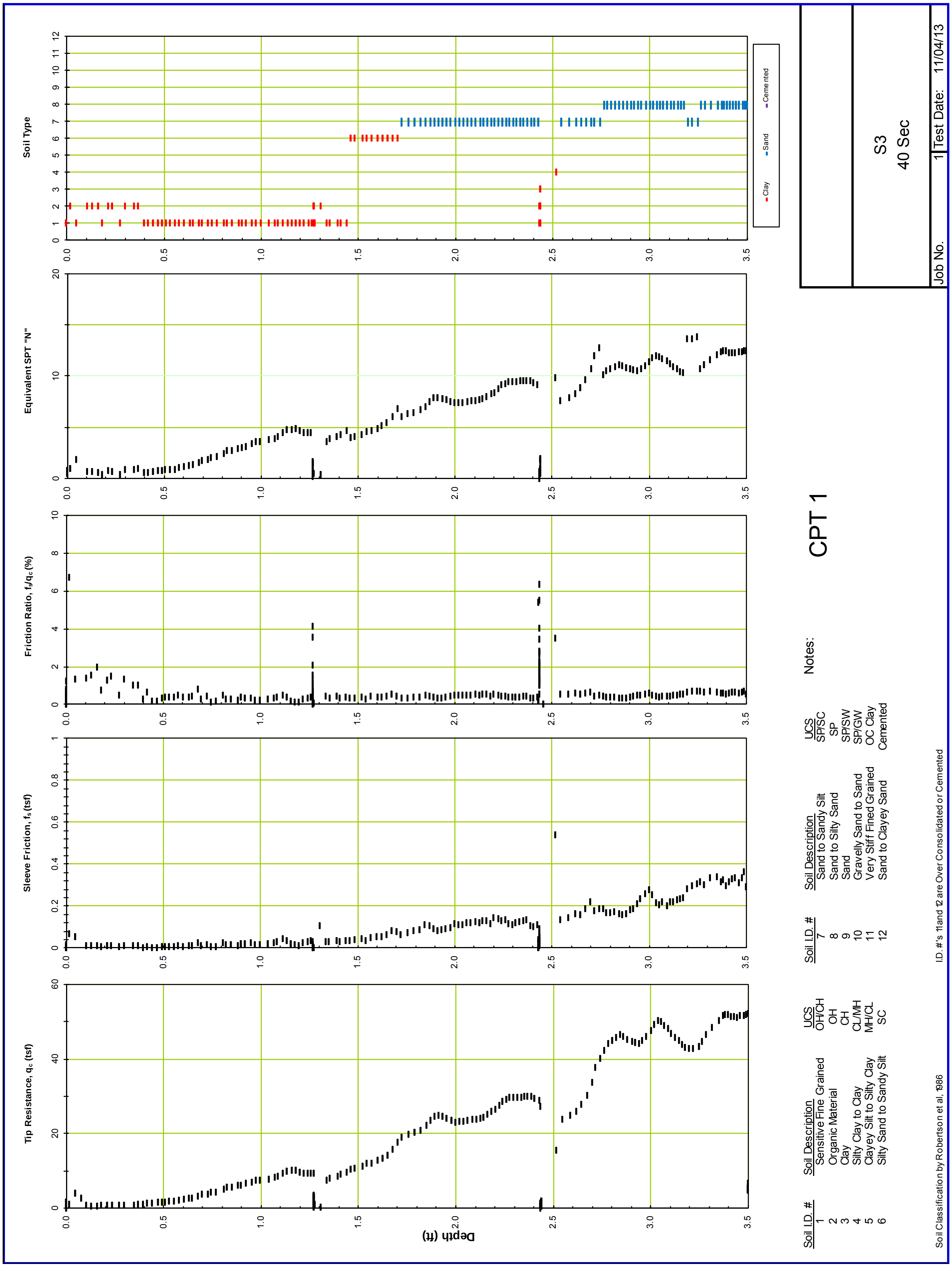


Figure D.6 CPT data prior to casting S3- 40 (40 sec/qt)

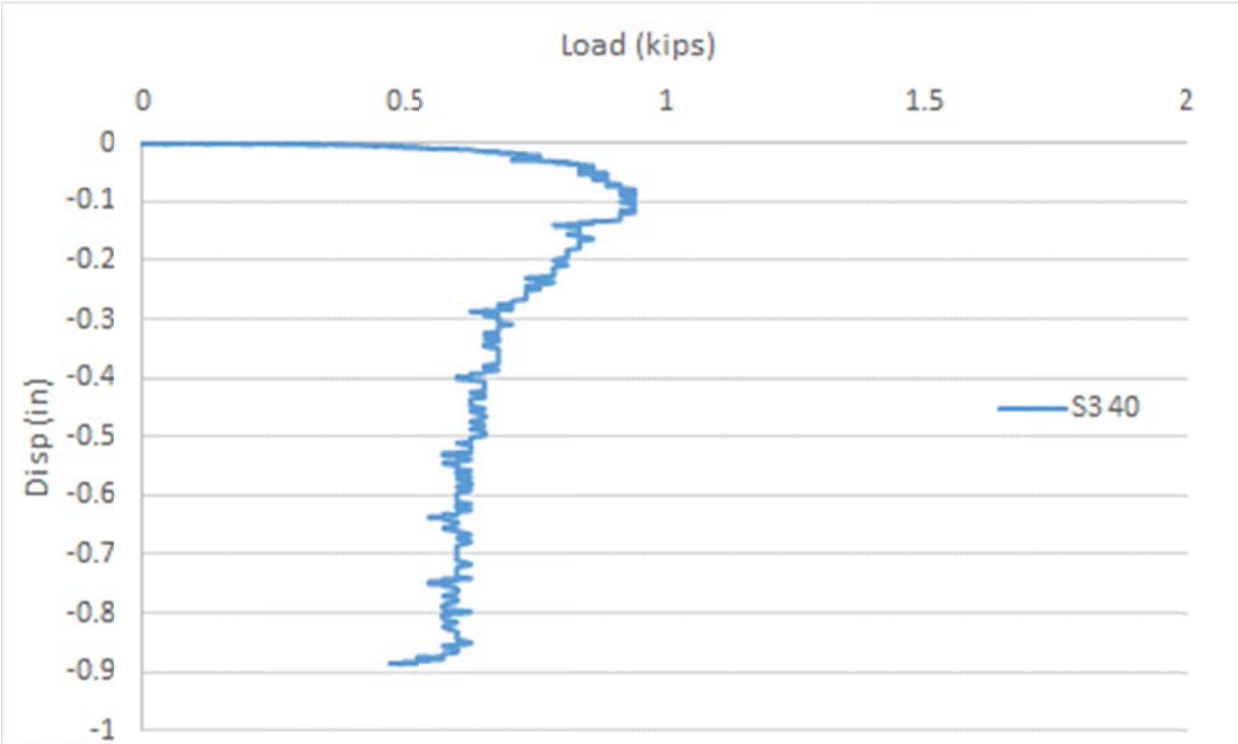


Figure D.7 Pullout data for model shaft S3 – 40 (40 sec/qt)

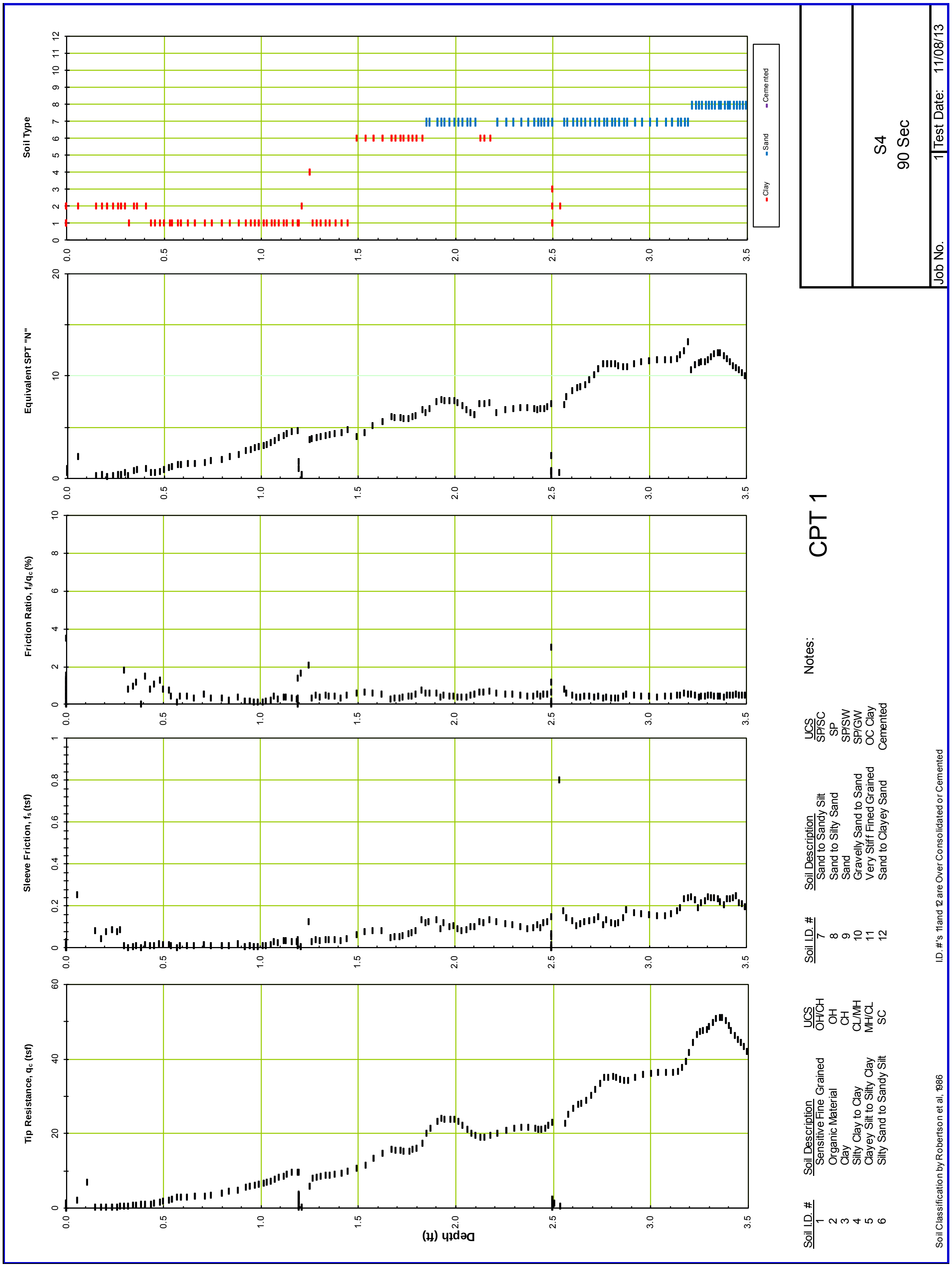


Figure D.8 CPT data prior to casting S4- 90 (90 sec/qt)

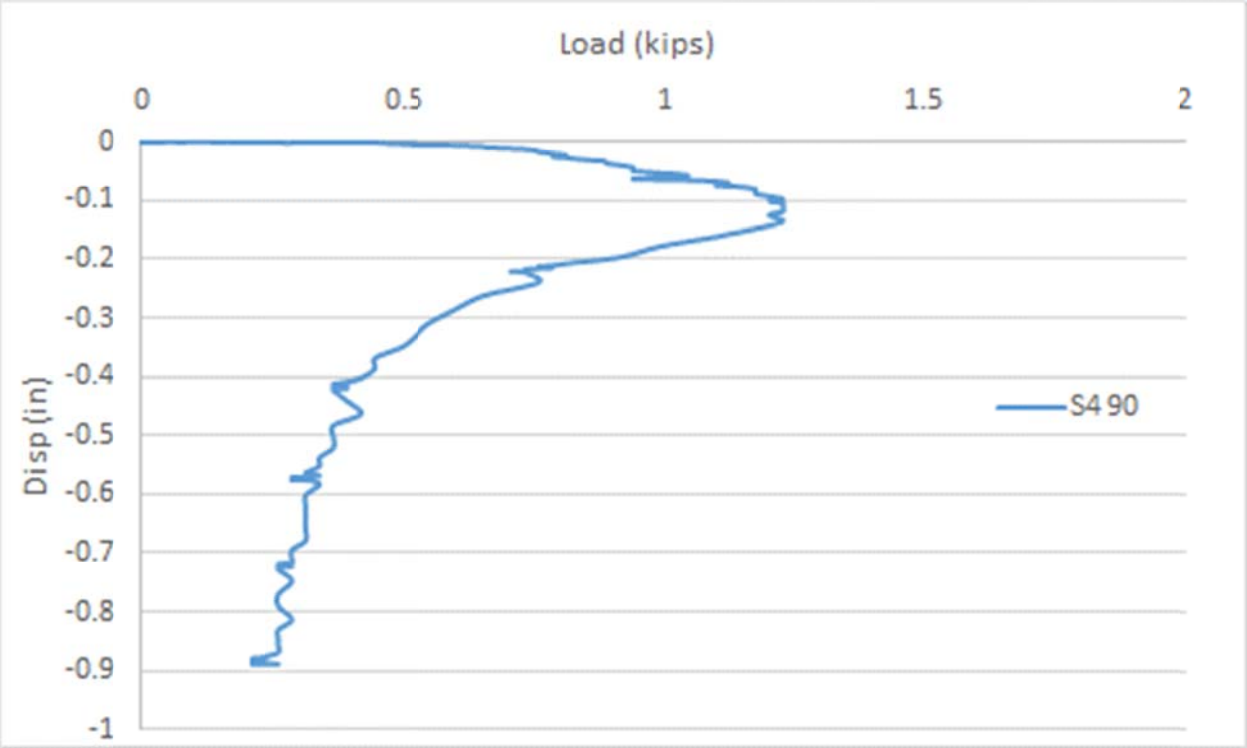


Figure D.9 Pullout data for model shaft S4 – 90 (90 sec/qt)

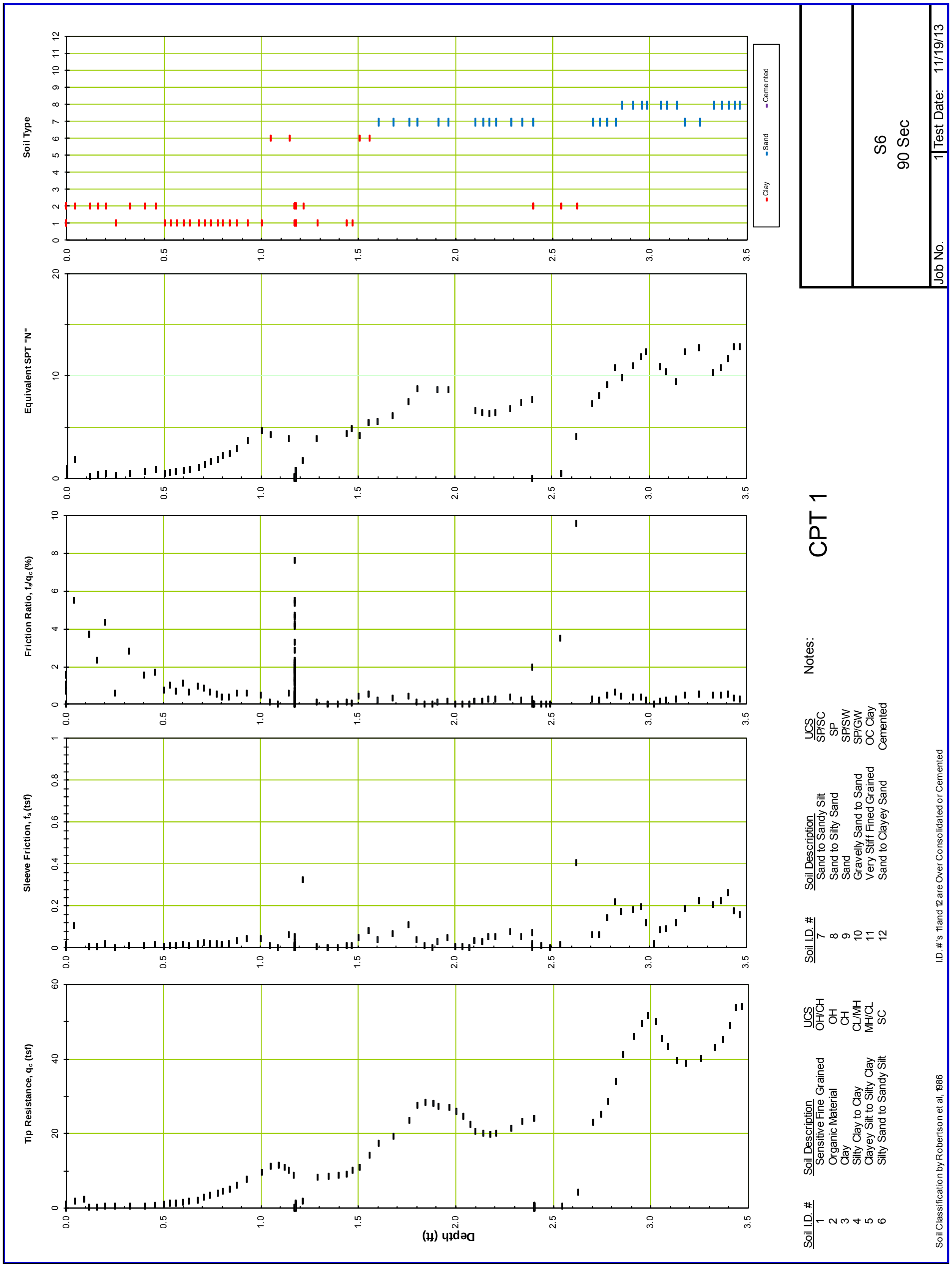


Figure D.10 CPT data prior to casting S6- 90 (90 sec/qt)

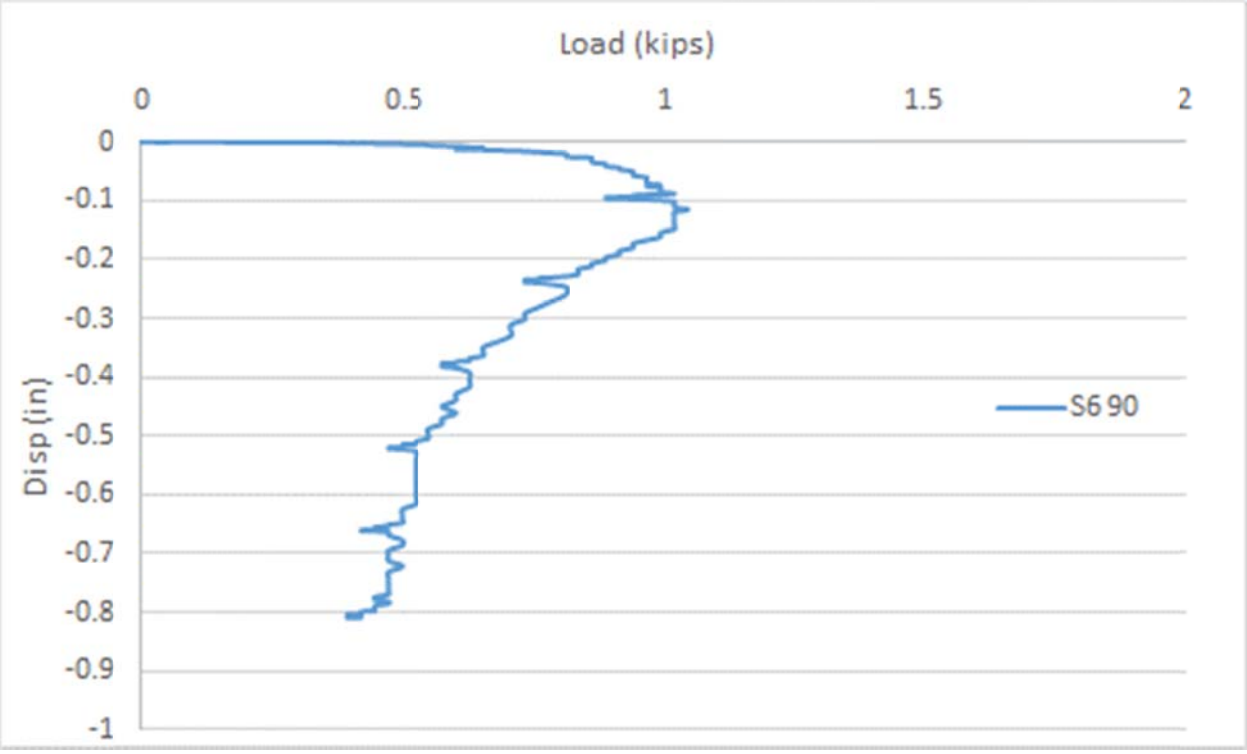


Figure D.11 Pullout data for model shaft S6 – 90 (90 sec/qt)

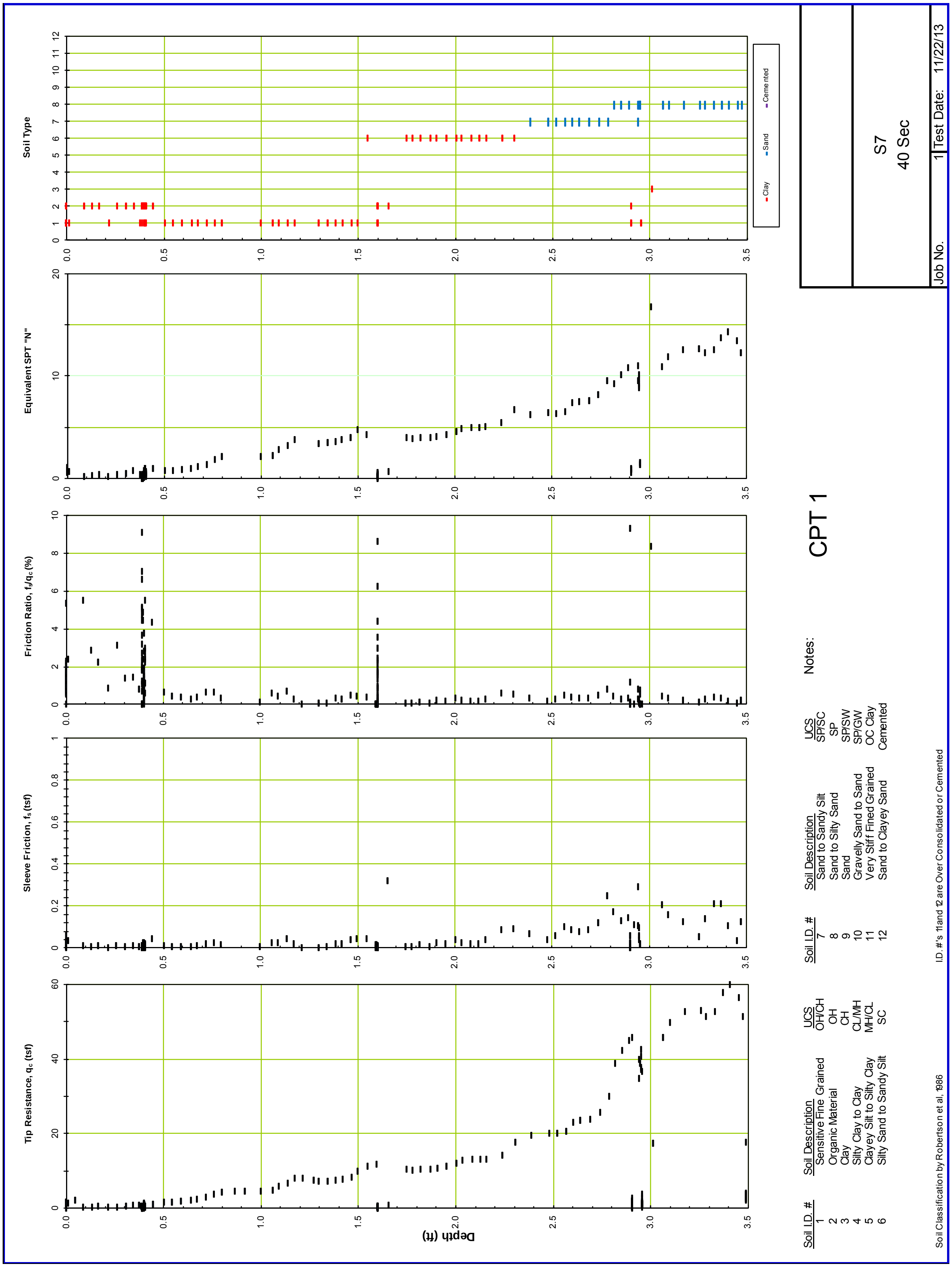


Figure D.12 CPT data prior to casting S7- 40 (40 sec/qt)

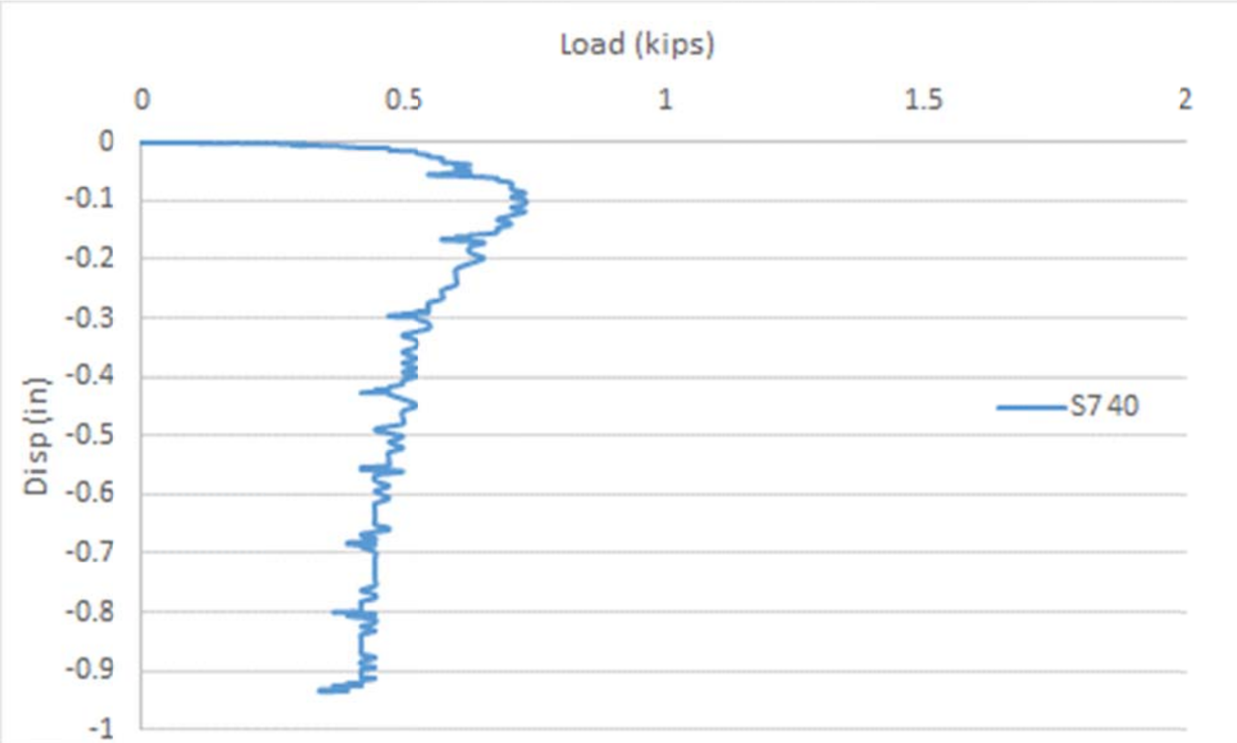


Figure D.13 Pullout data for model shaft S7 – 40 (40 sec/qt)

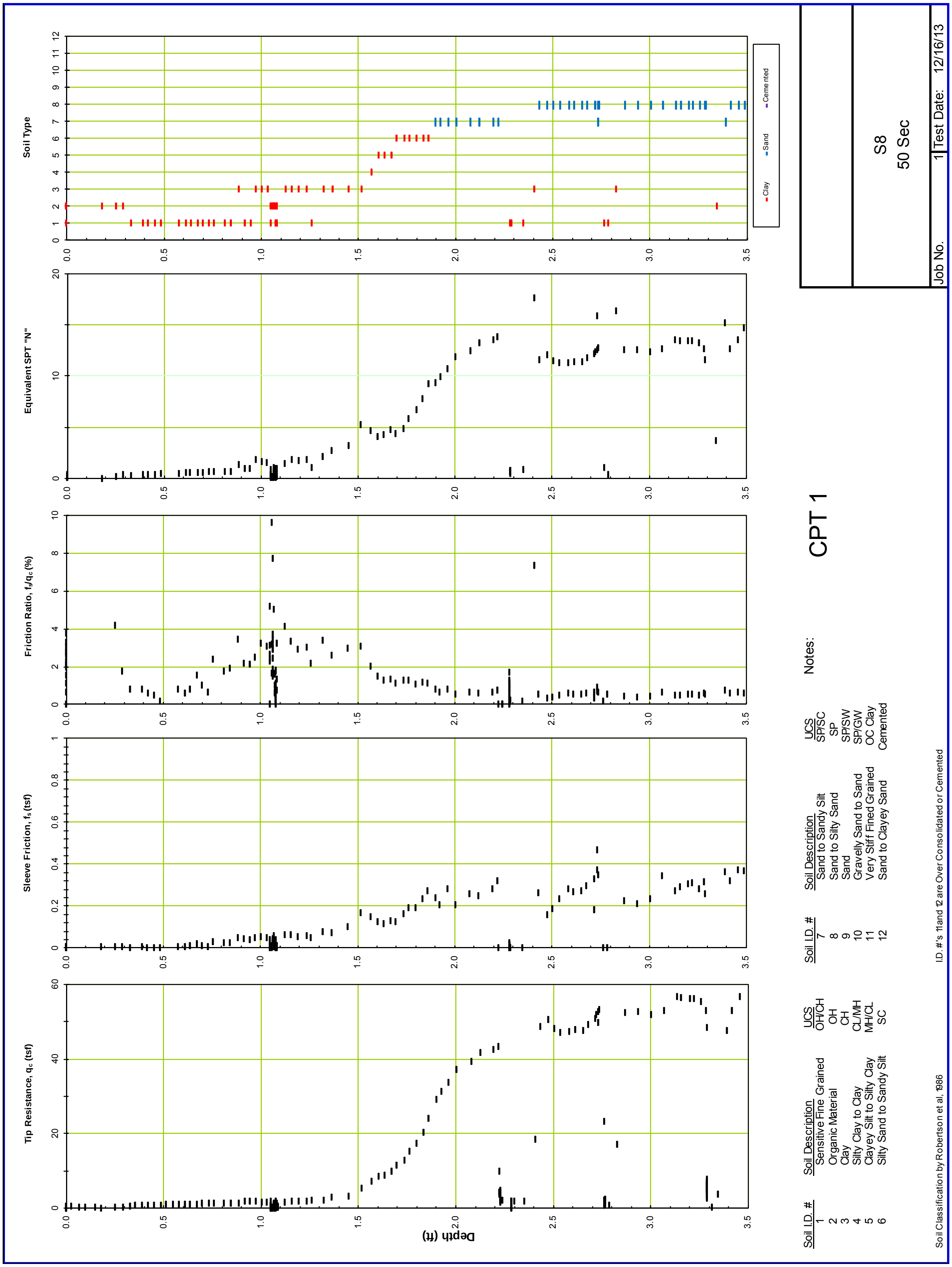


Figure D.14 CPT data prior to casting S8- 50 (50 sec/qt)

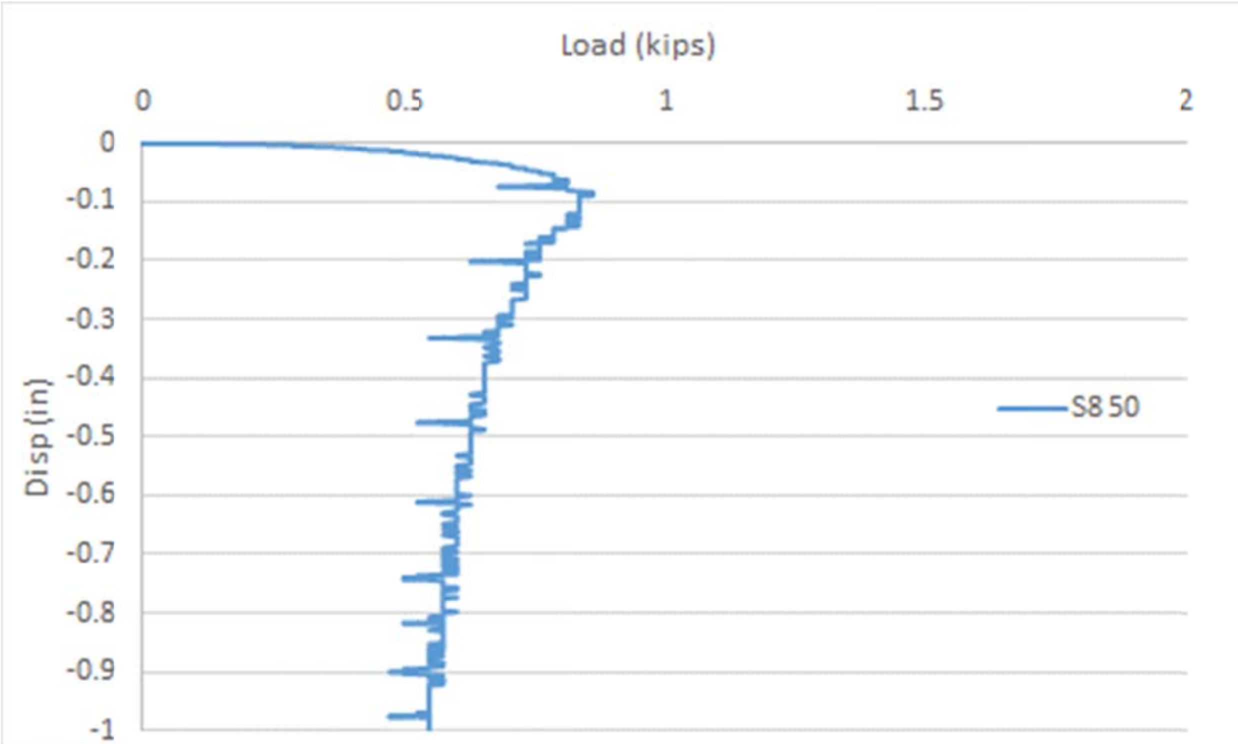


Figure D.15 Pullout data for model shaft S8 – 50 (50 sec/qt)

APPENDIX E: CONE PENETRATION TEST RESULTS

Phase I: P-1, P-2, P-3, B-1, B-2, and B-3
Phase II: B-4, B-5, B-6, P-4, P-5, and P-6

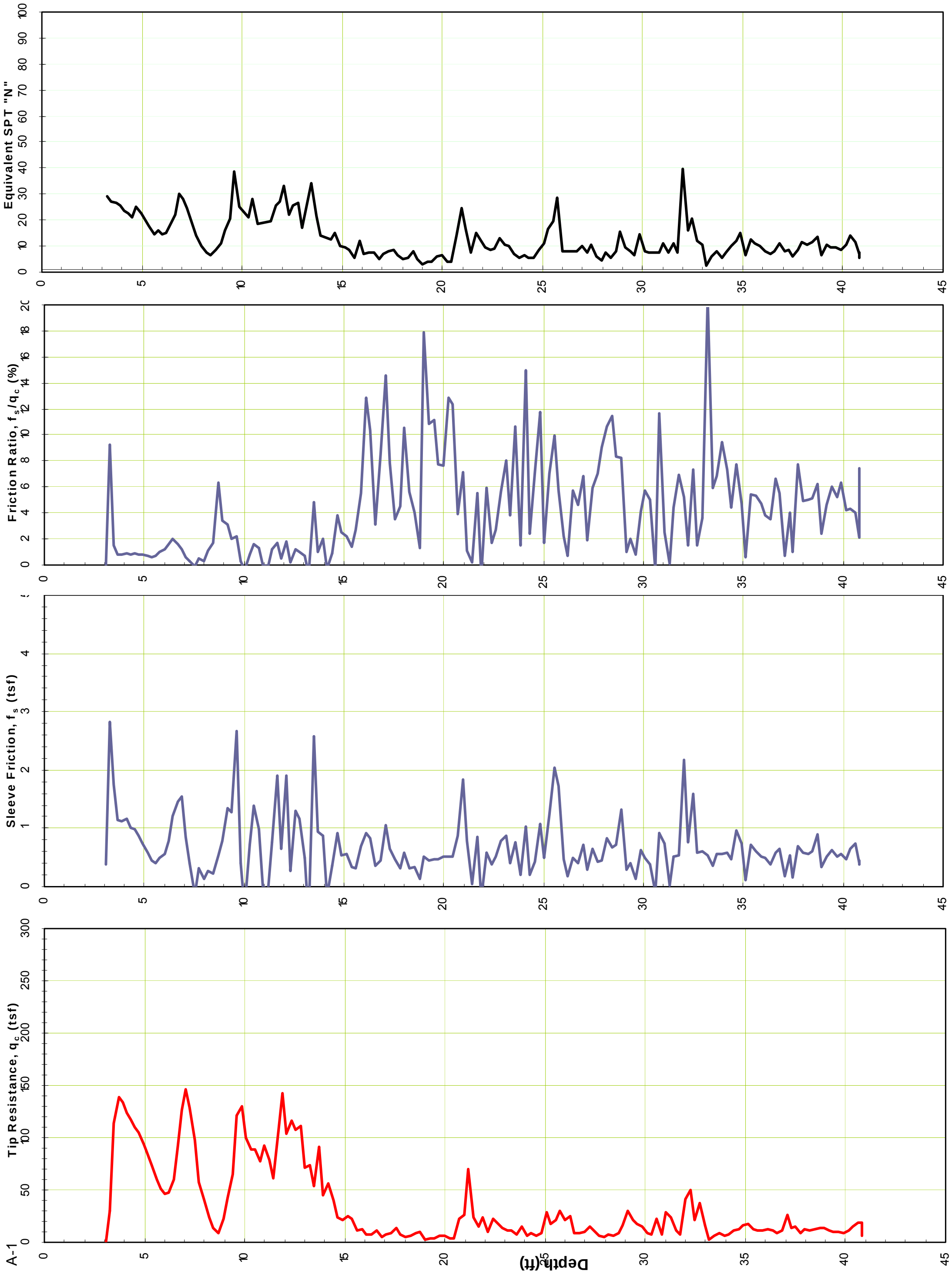


Figure E.1 CPT sounding for Shaft P-1 (Phase I).

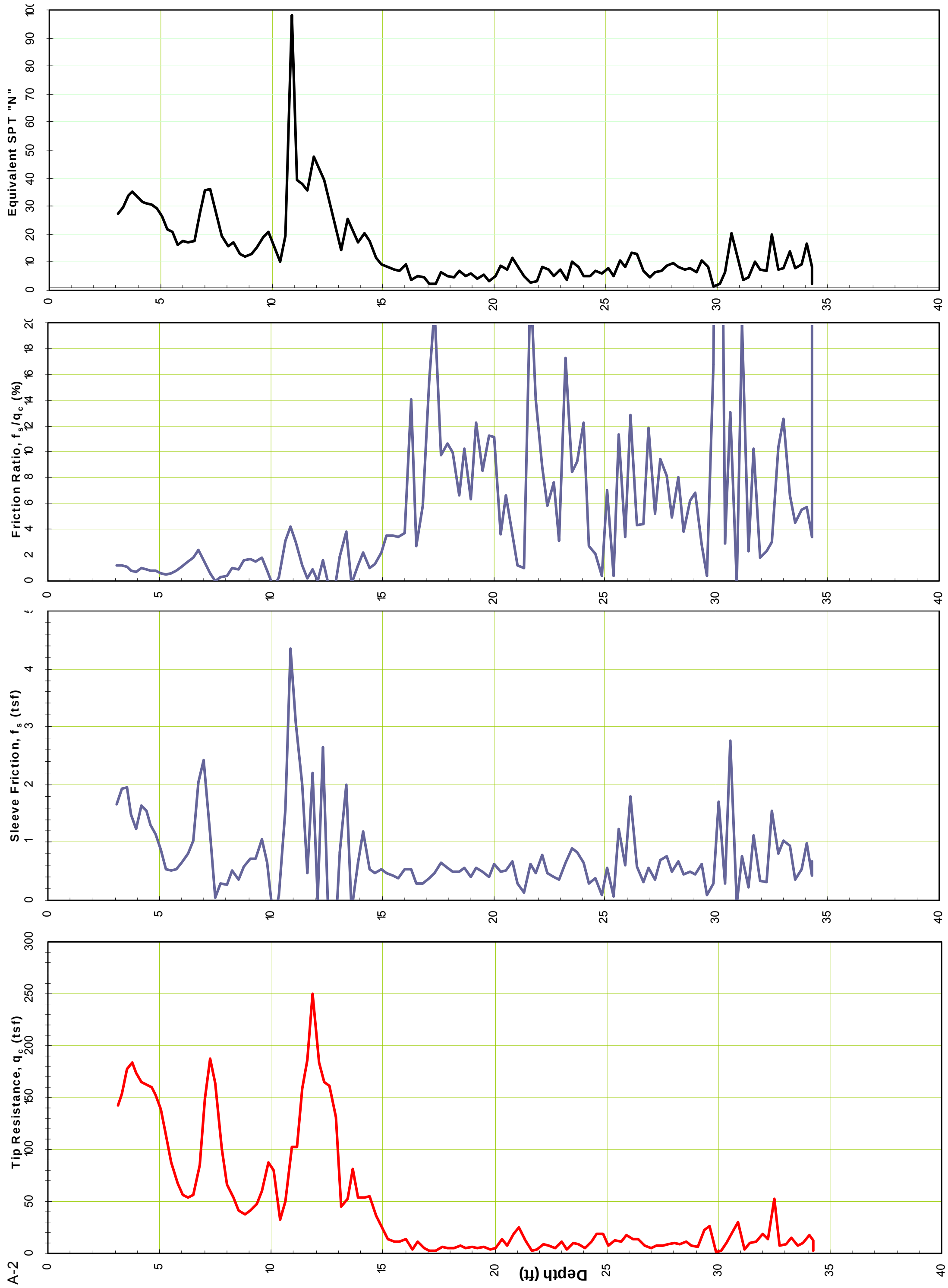


Figure E.2 CPT sounding for Shaft B-2 (Phase I).

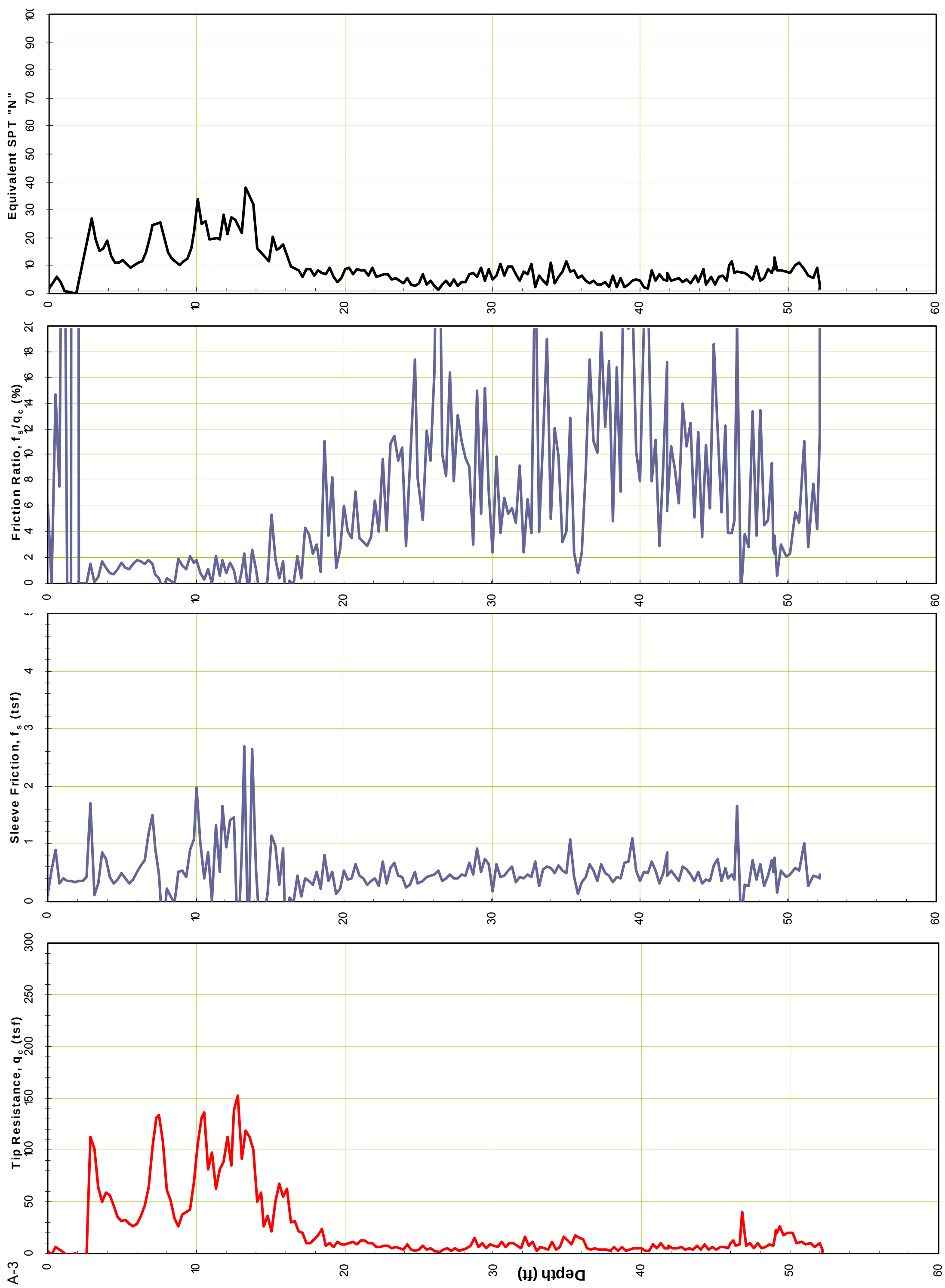


Figure E.3 CPT sounding for Shaft P-3 (Phase I).

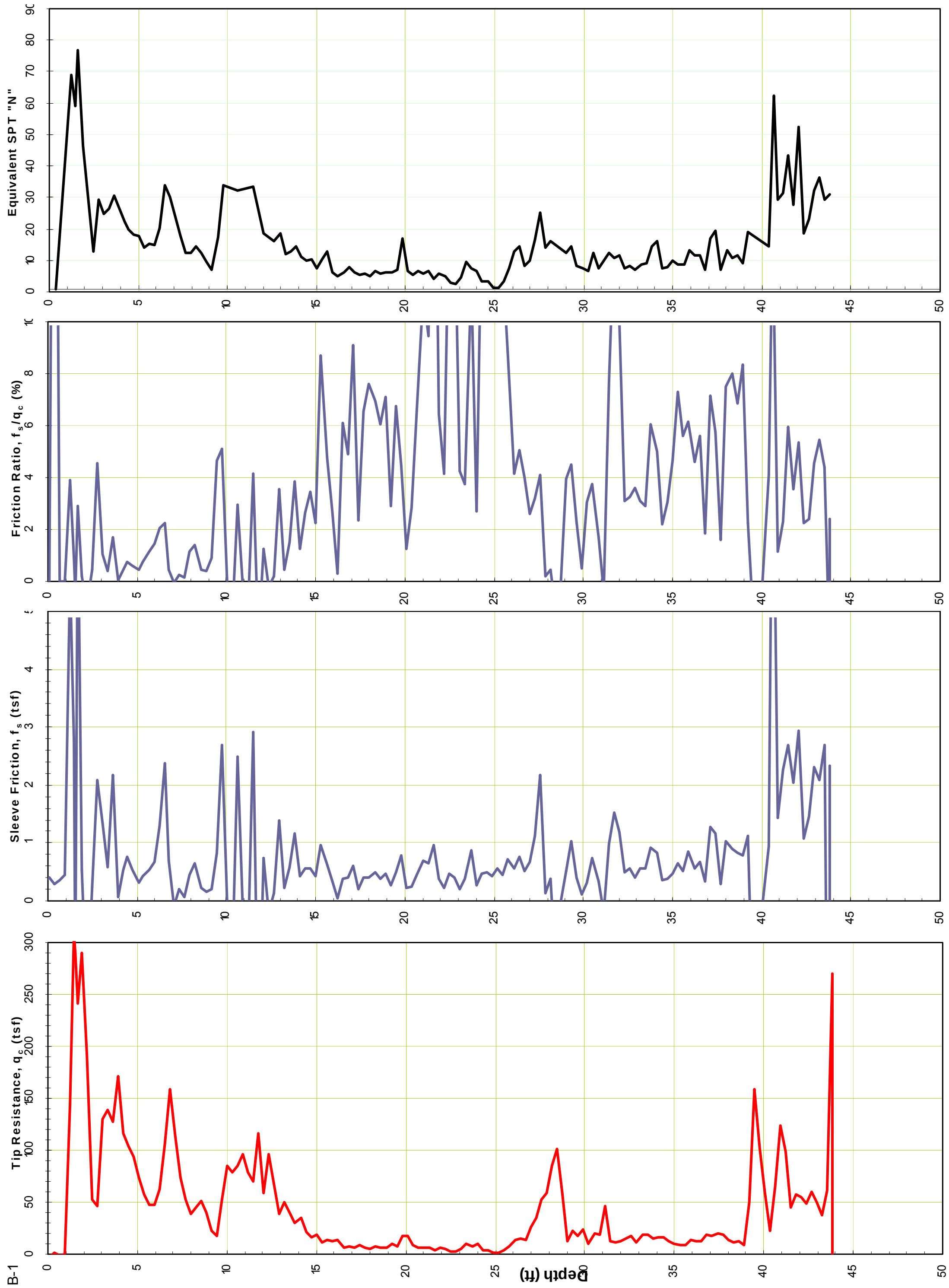


Figure E.4 CPT sounding for Shaft B-1 (Phase I).

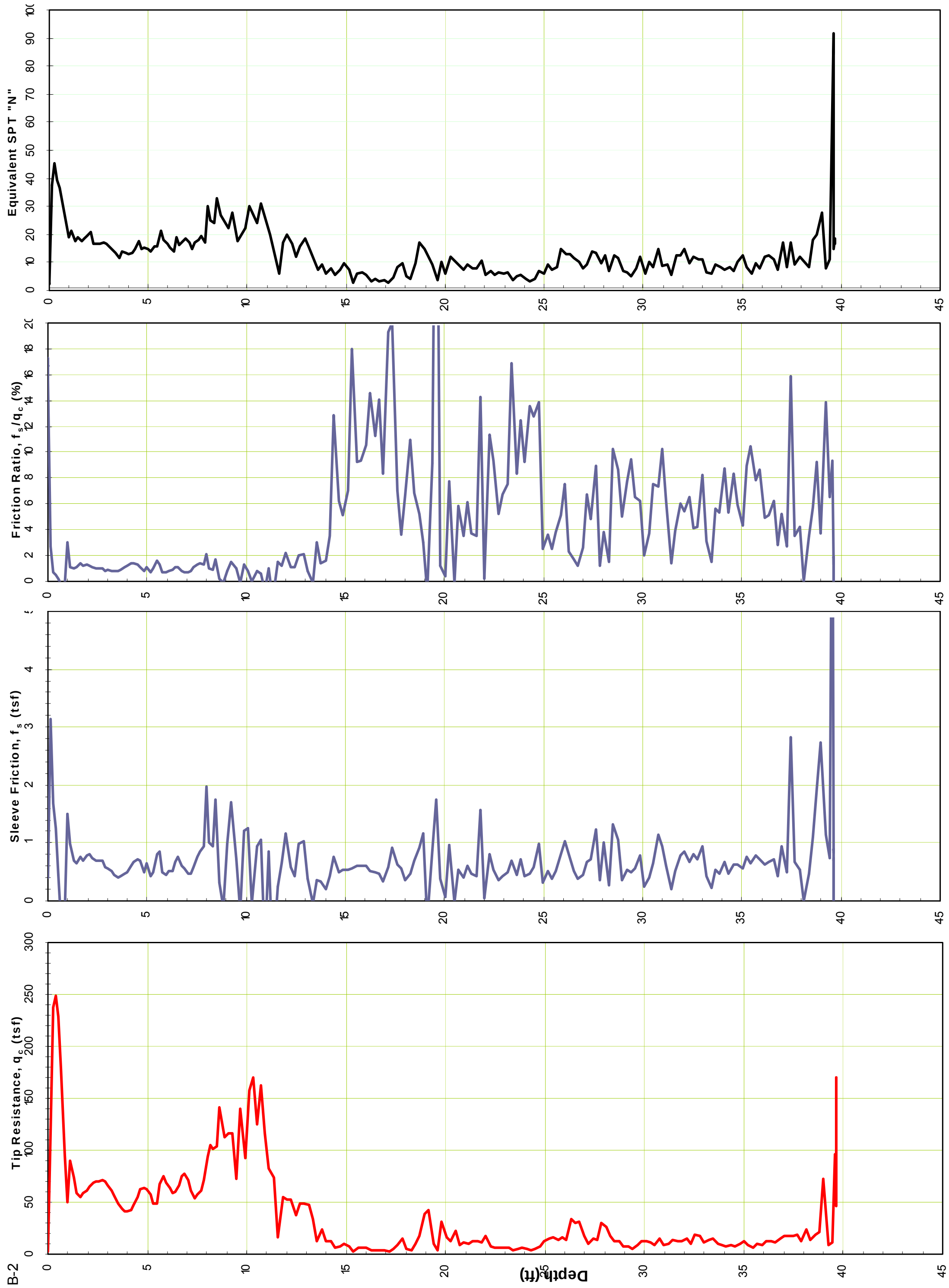


Figure E.5 CPT sounding for Shaft P-2 (Phase I).

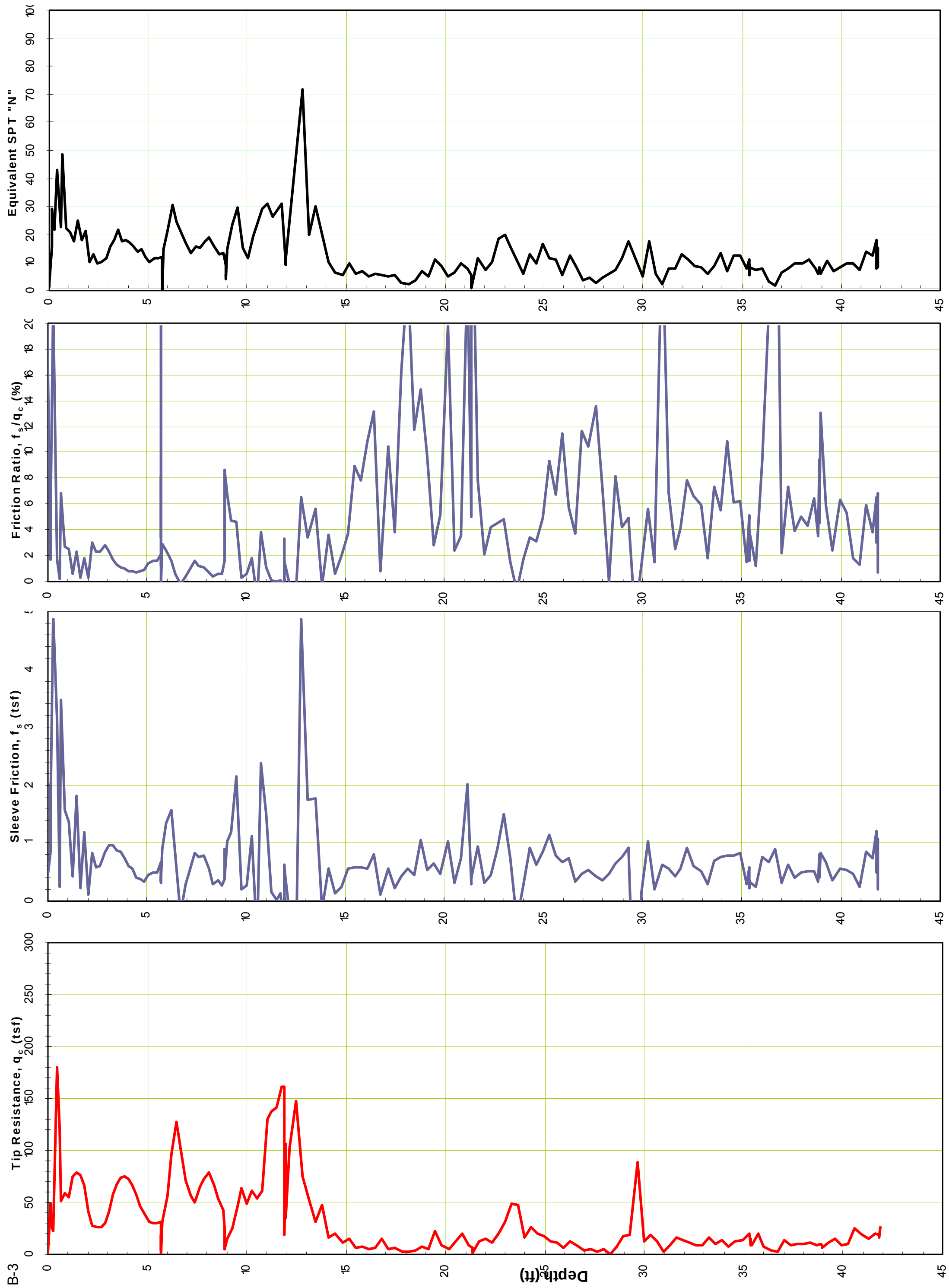


Figure E.6 CPT sounding for Shaft B-3 (Phase I).

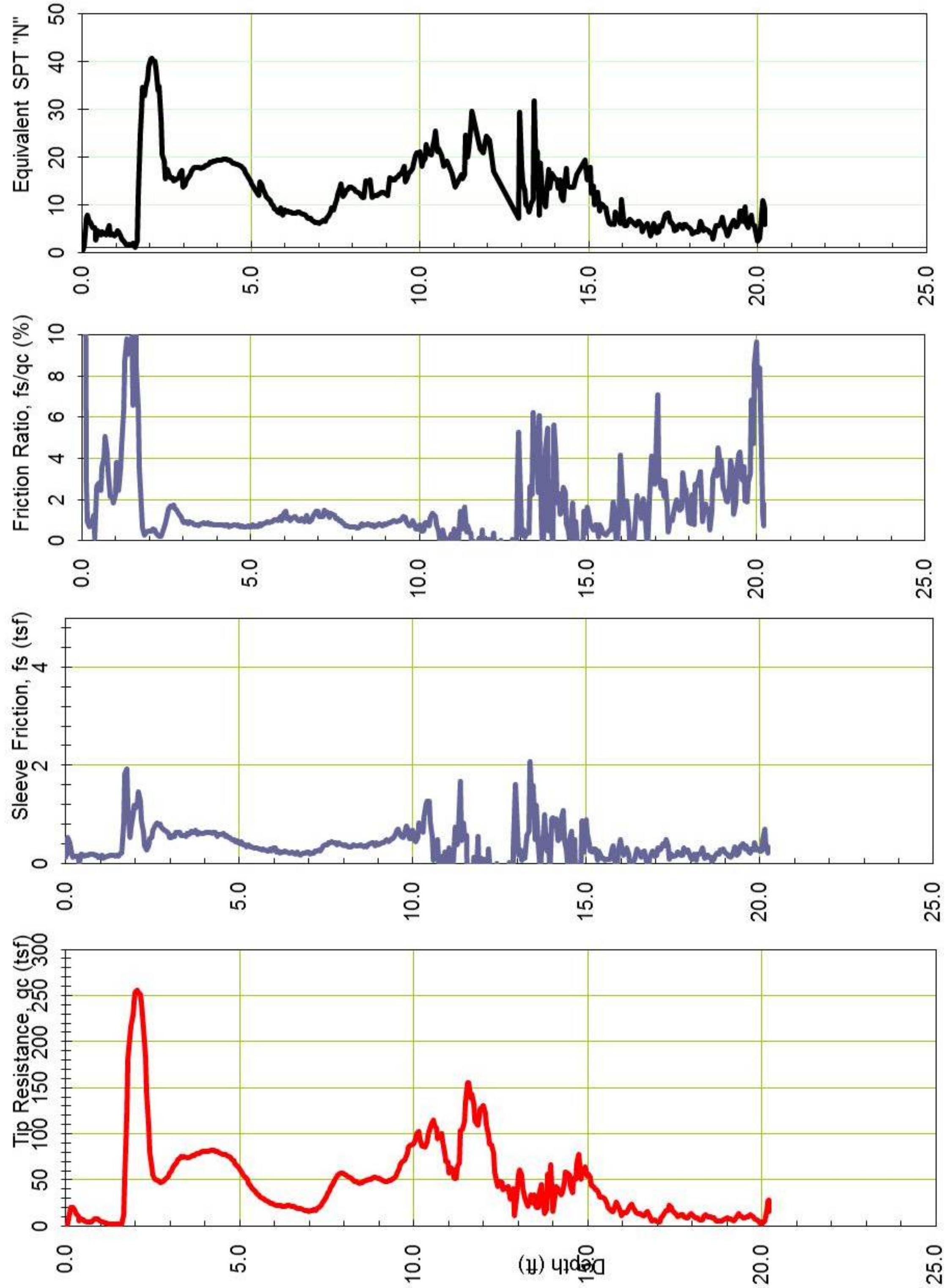


Figure E.7 CPT sounding for Shaft B-4 (Phase II).

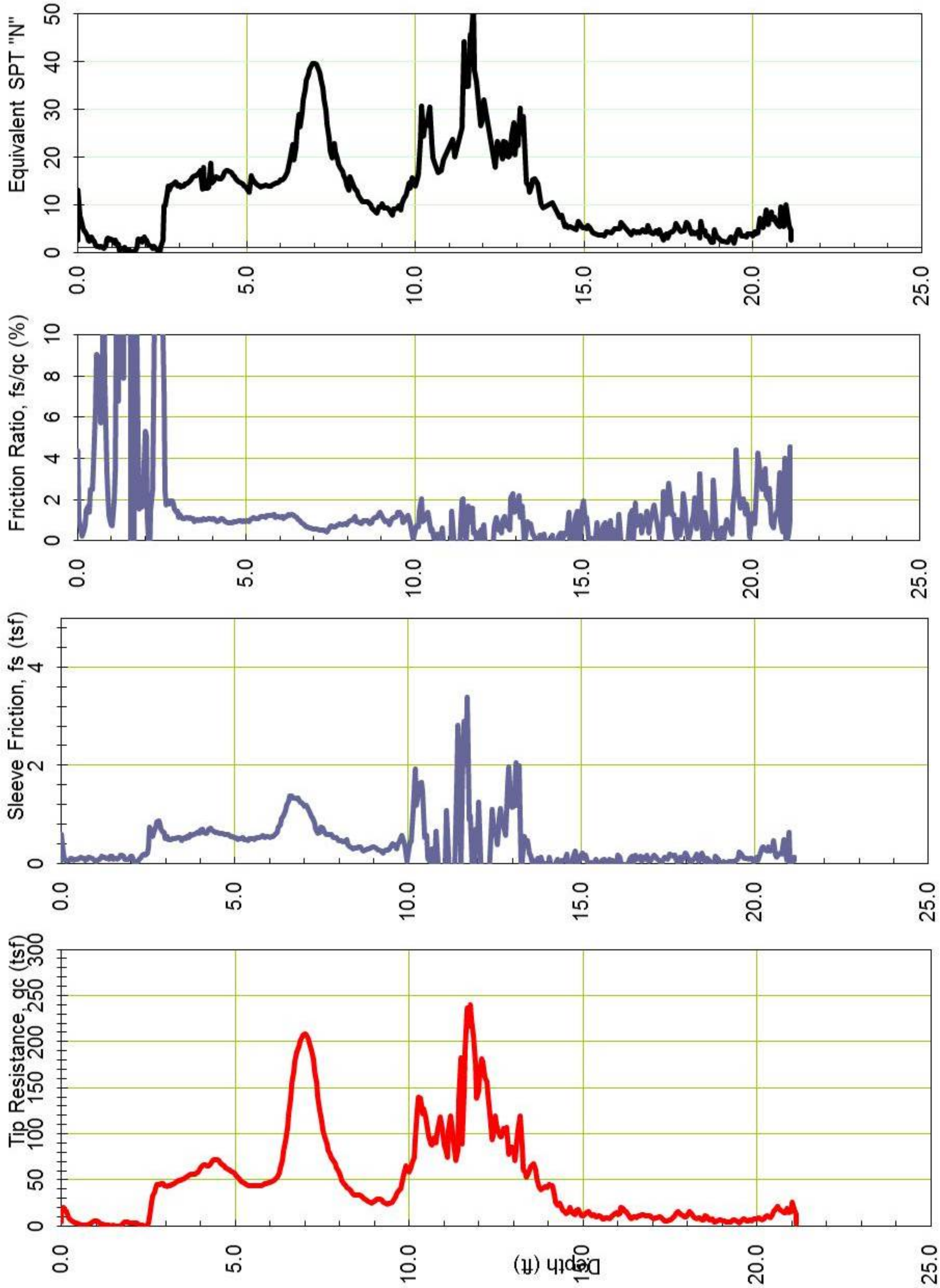


Figure E.8 CPT sounding for Shaft B-5 (Phase II).

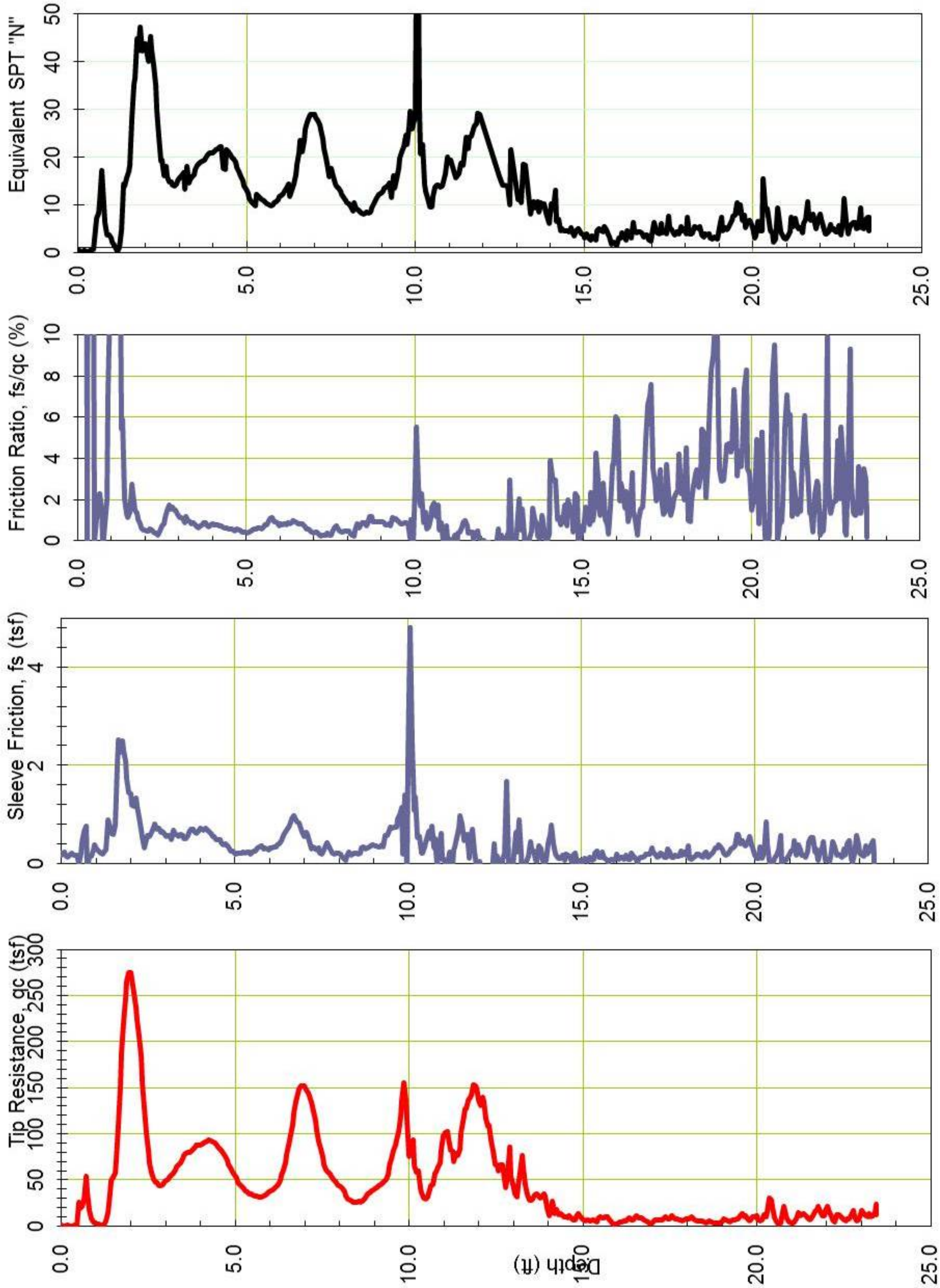


Figure E.9 CPT sounding for Shaft B-6 (Phase II).

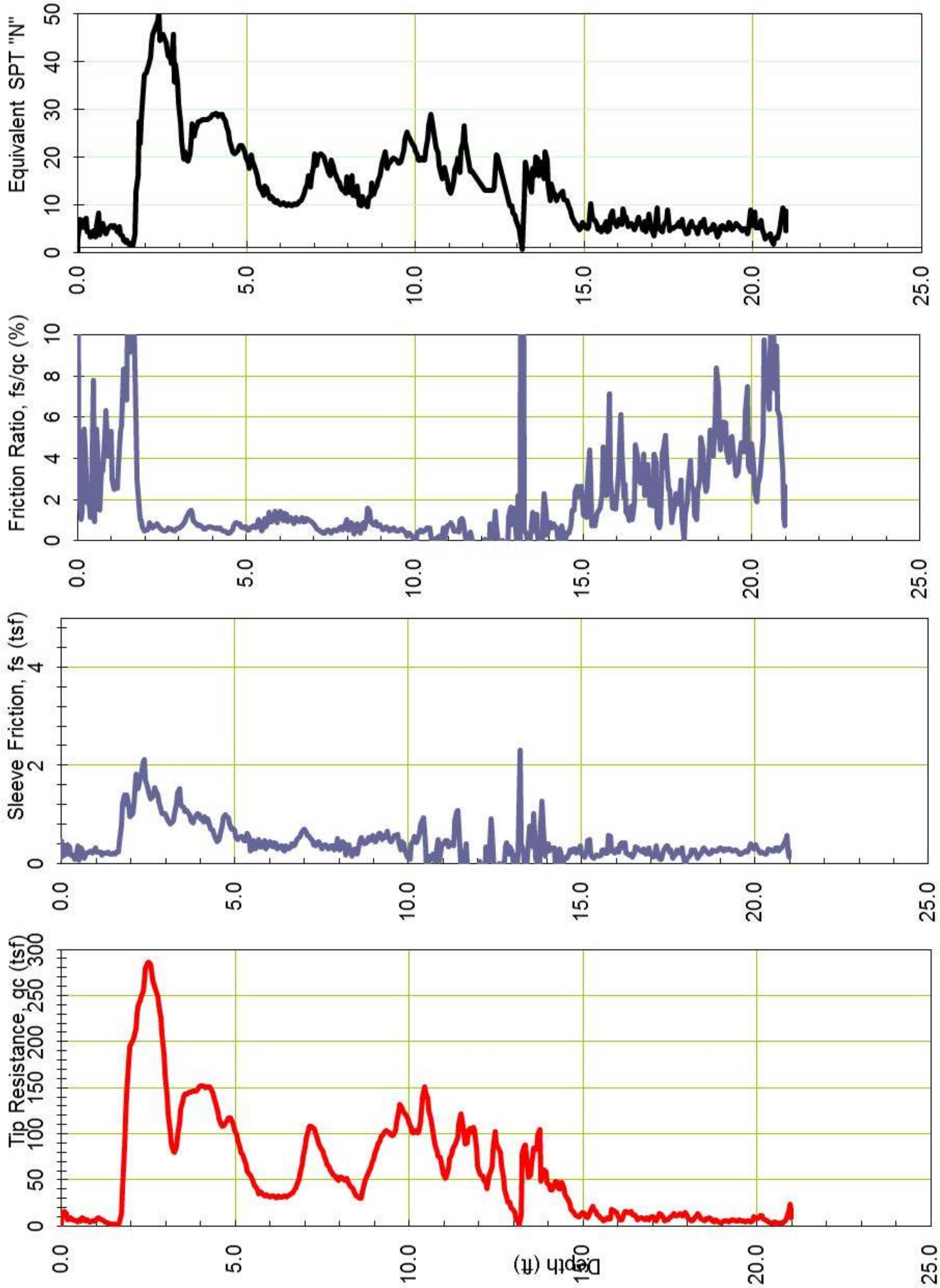


Figure E.10 CPT sounding for Shaft P-4 (Phase II).

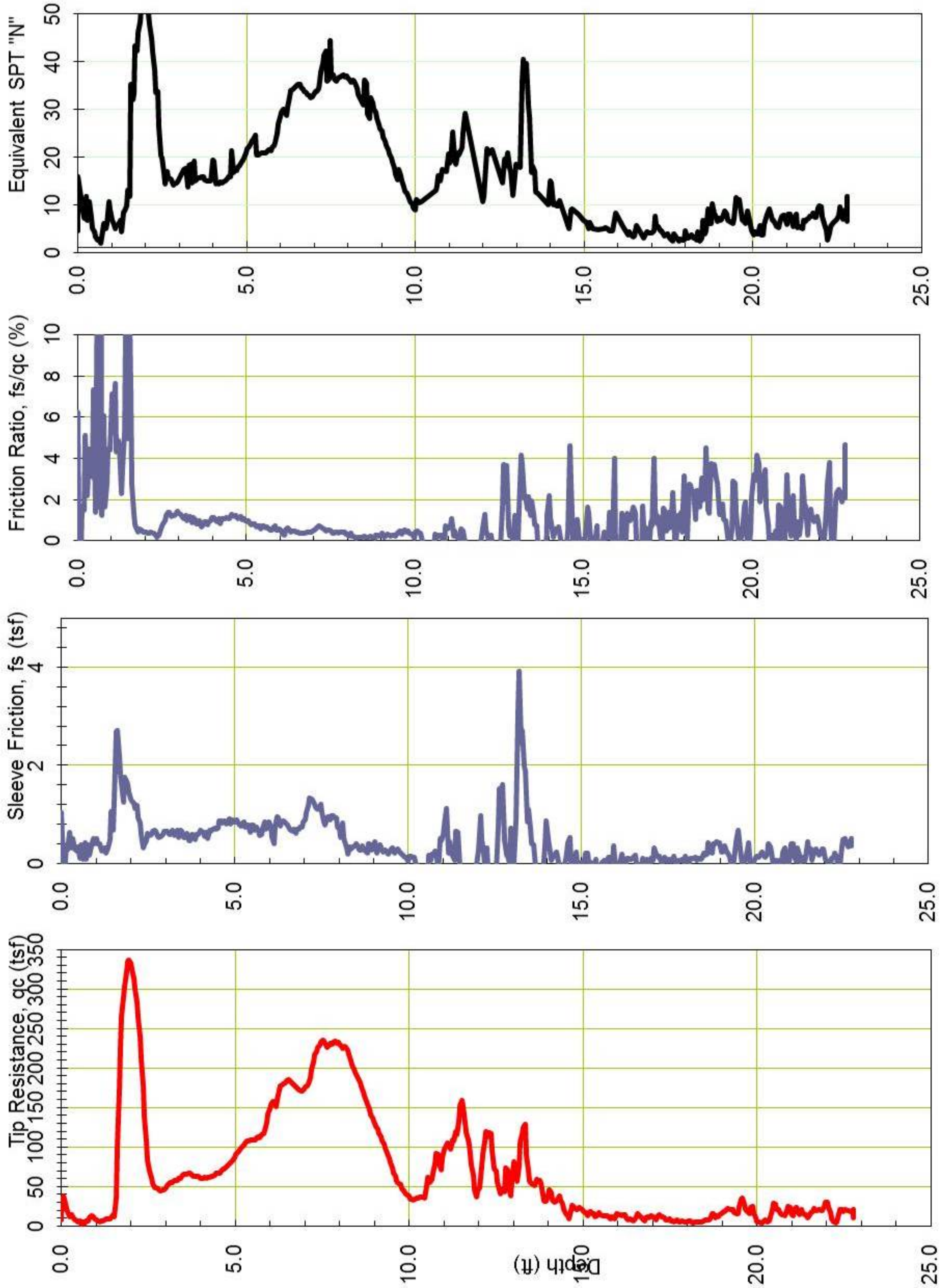


Figure E.11 CPT sounding for Shaft P-5 (Phase II).

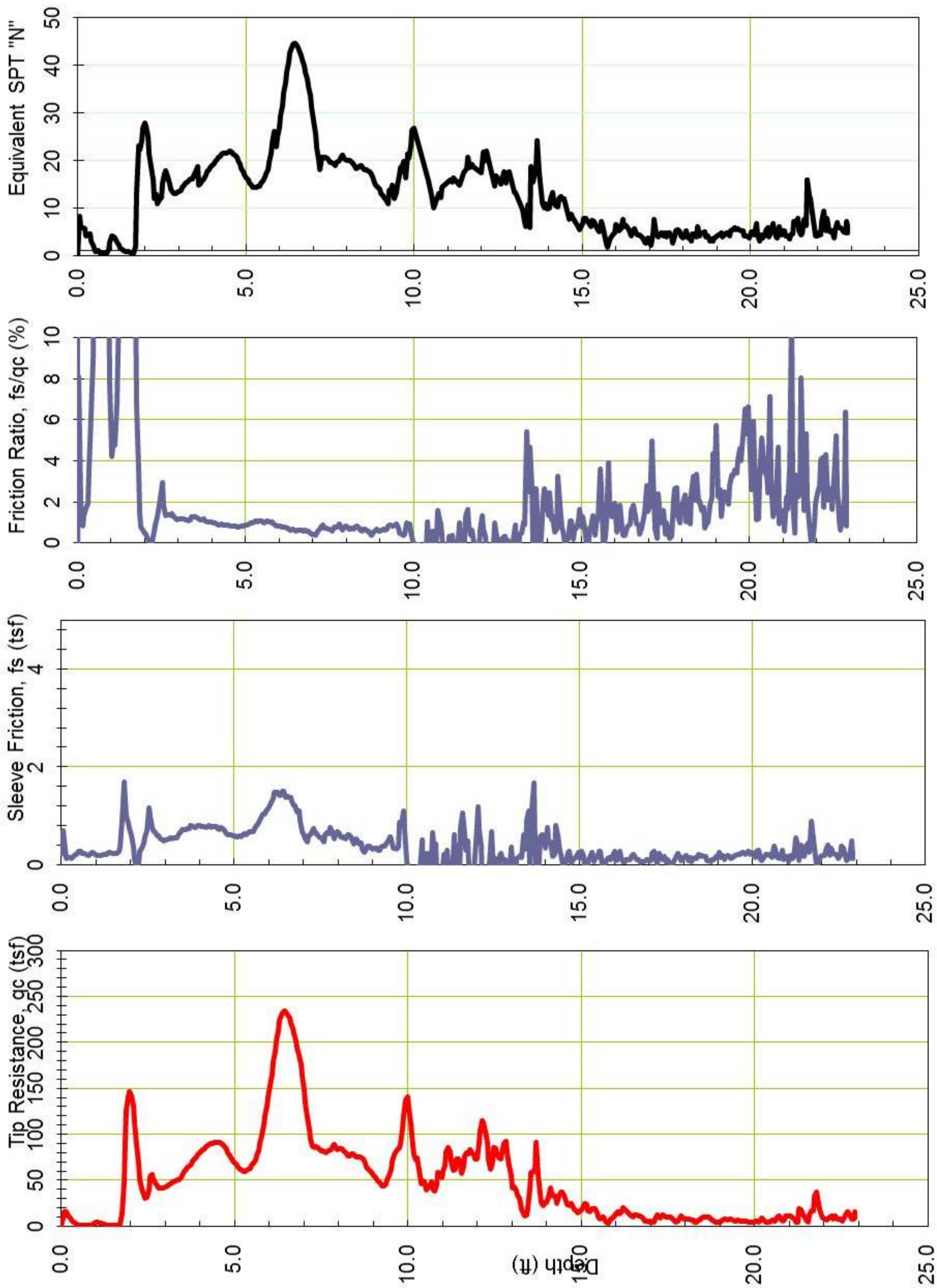


Figure E.12 CPT sounding for Shaft P-6 (Phase II).

APPENDIX F: PHASE I and II LOAD TEST RESULTS

Phase I
Shafts B-1, B-2, B-3, P-1, P-2, and P-3

Phase II
Shafts B-4, B-5, B-6, P-4, P-5, and P-6

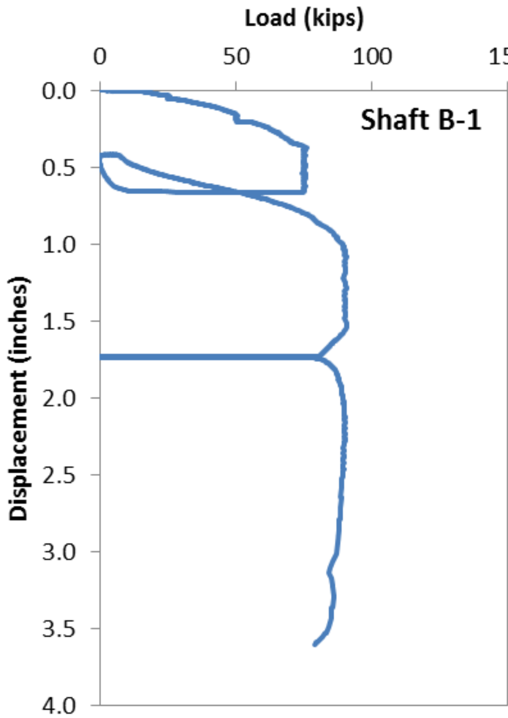


Figure F.1 Load vs. Displacement data for Shaft B-1

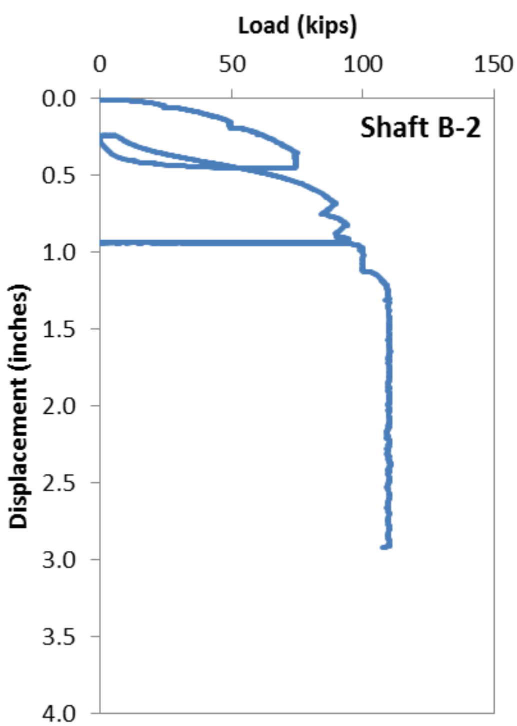


Figure F.2 Load vs. Displacement data for Shaft B-2

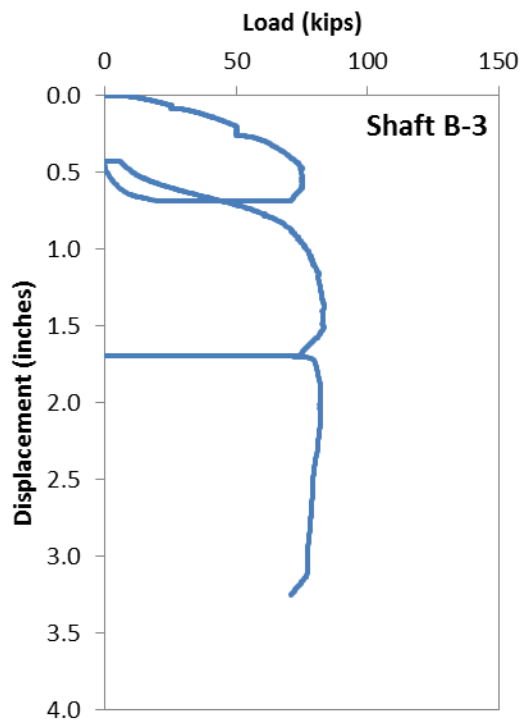


Figure F.3 Load vs. Displacement data for Shaft B-3

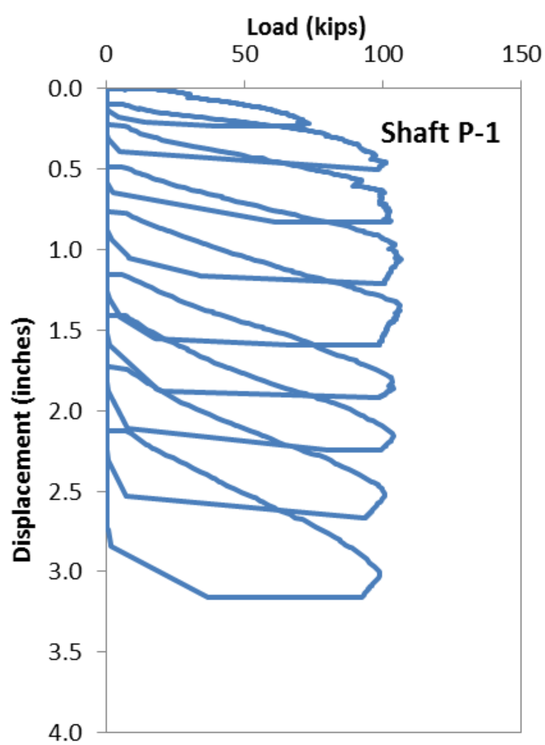


Figure F.4 Load vs. Displacement data for Shaft P-1

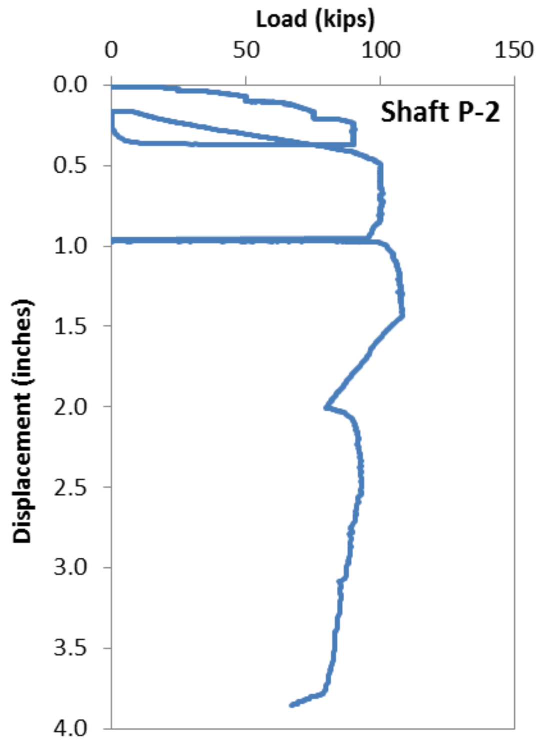


Figure F.5 Load vs. Displacement data for Shaft P-2

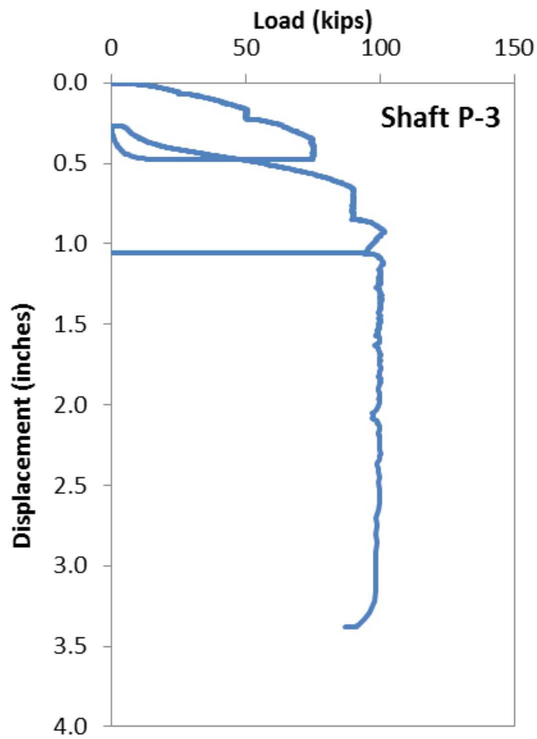


Figure F.6 Load vs. Displacement data for Shaft P-3

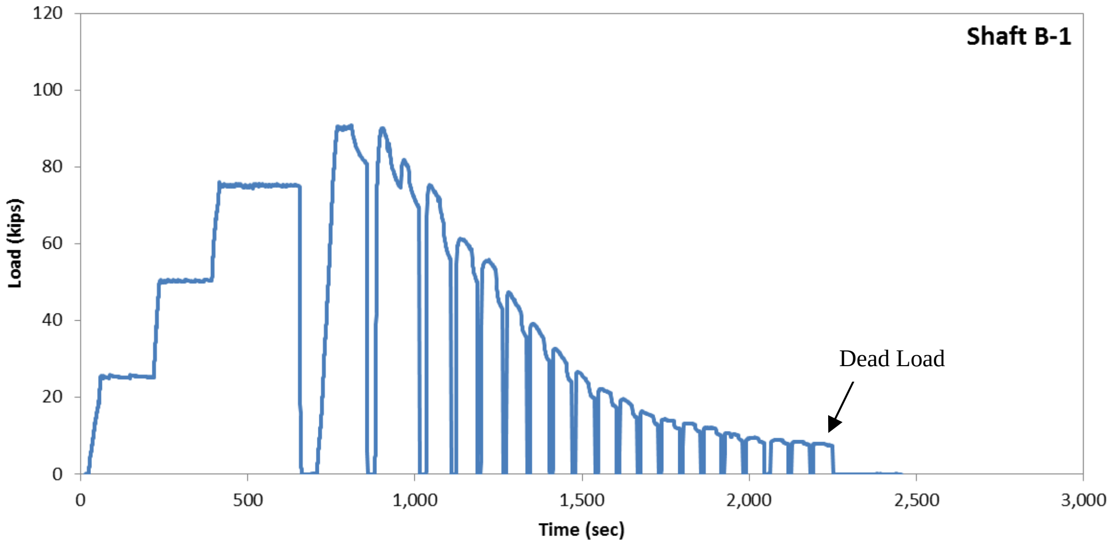


Figure F.7 Extraction data for Shaft B-1

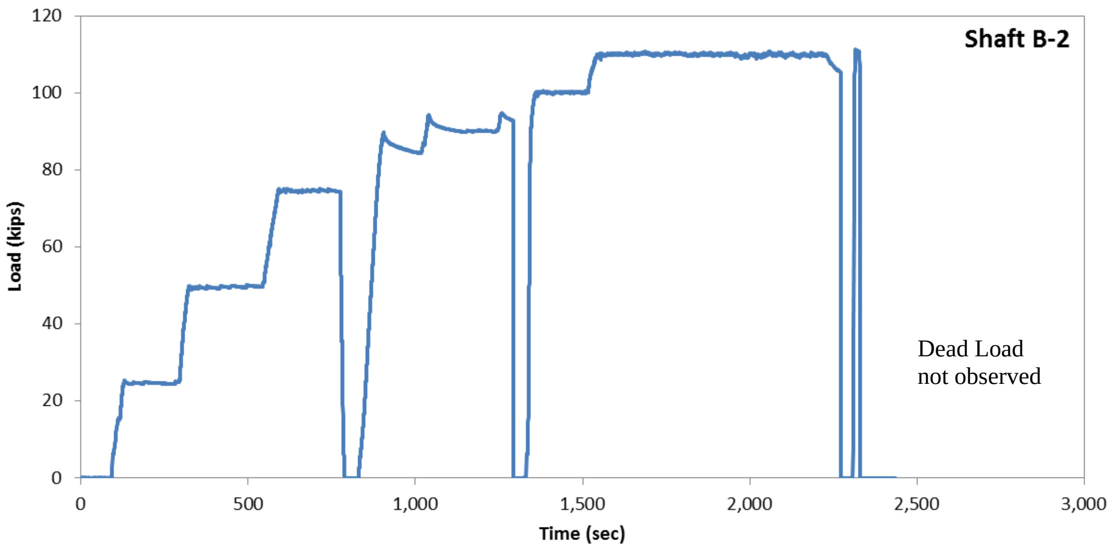


Figure F.8 Extraction data for Shaft B-2

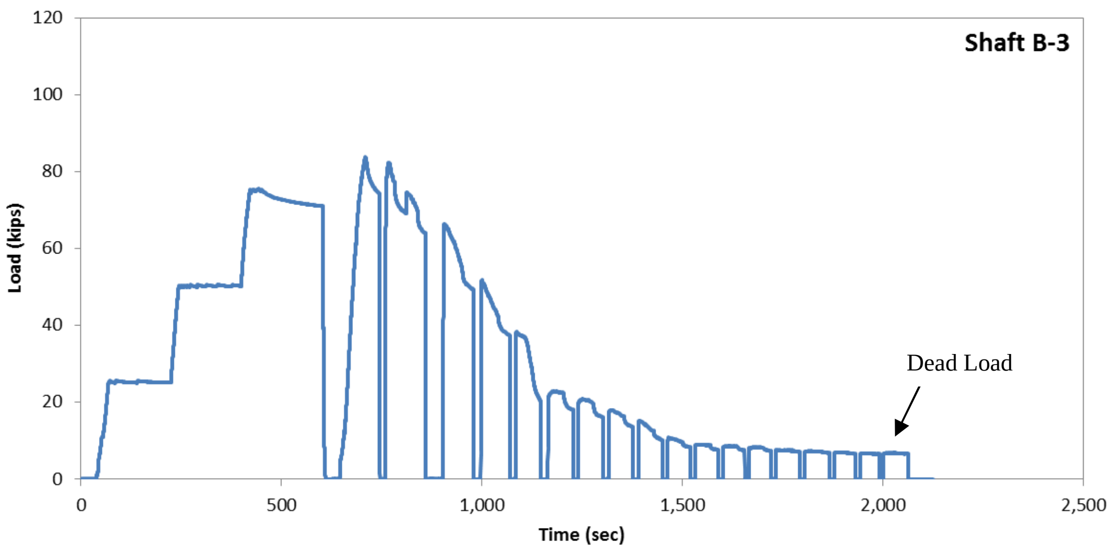


Figure F.9 Extraction data for Shaft B-3

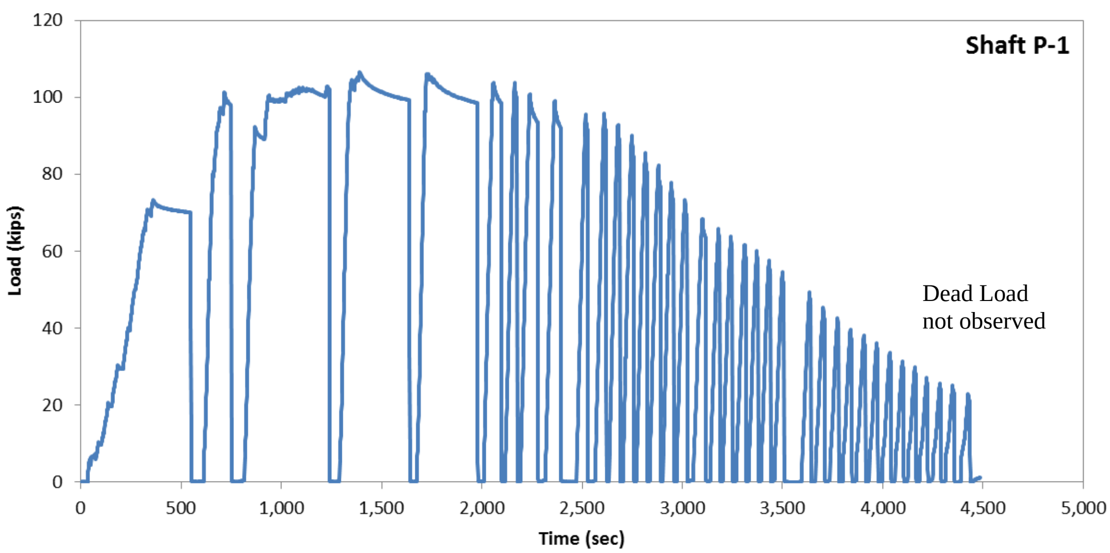


Figure F.10 Extraction data for Shaft P-1

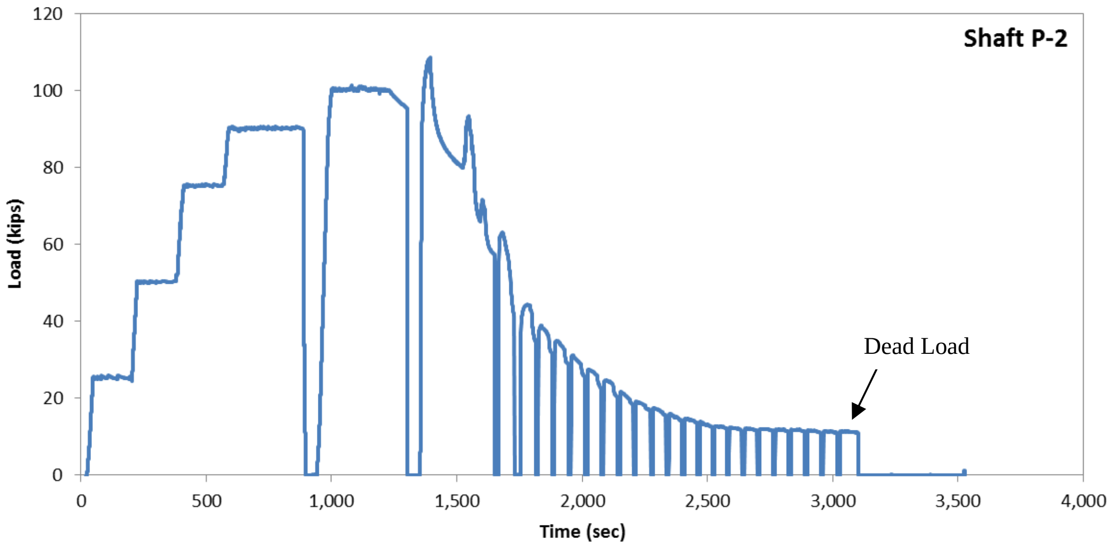


Figure F.11 Extraction data for Shaft P-2

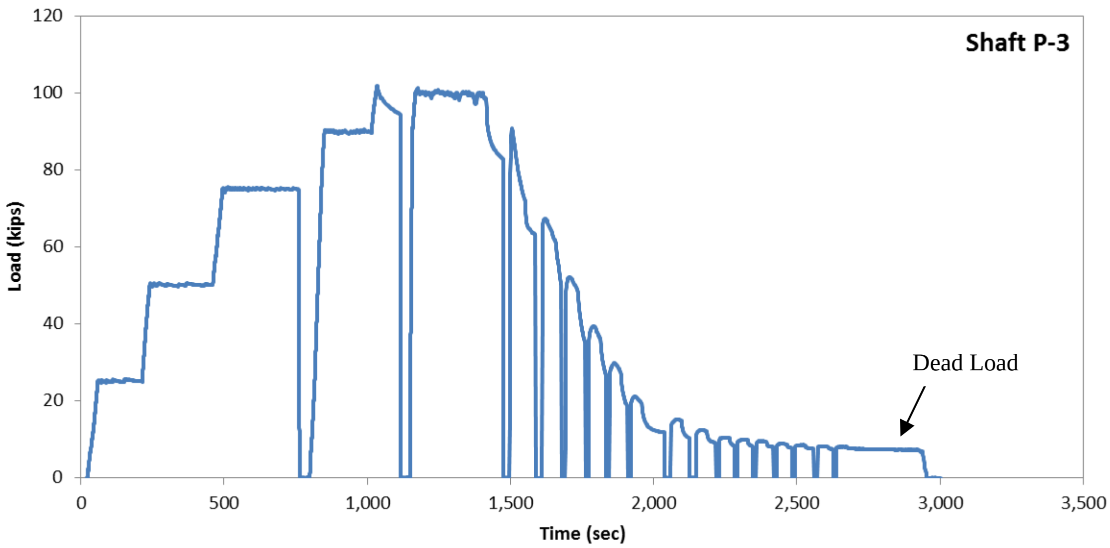


Figure F.12 Extraction data for Shaft P-3

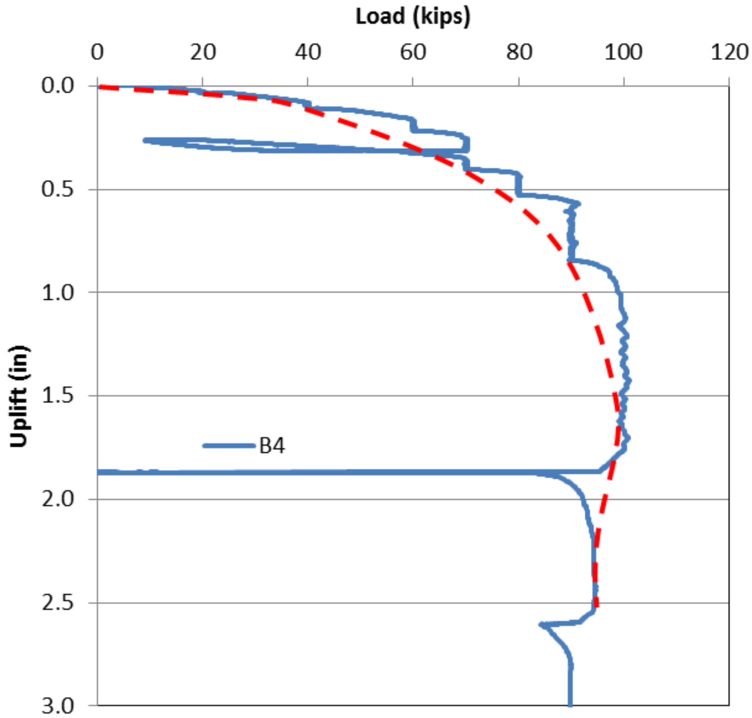


Figure F.13 Load vs. Displacement data for Shaft B-4

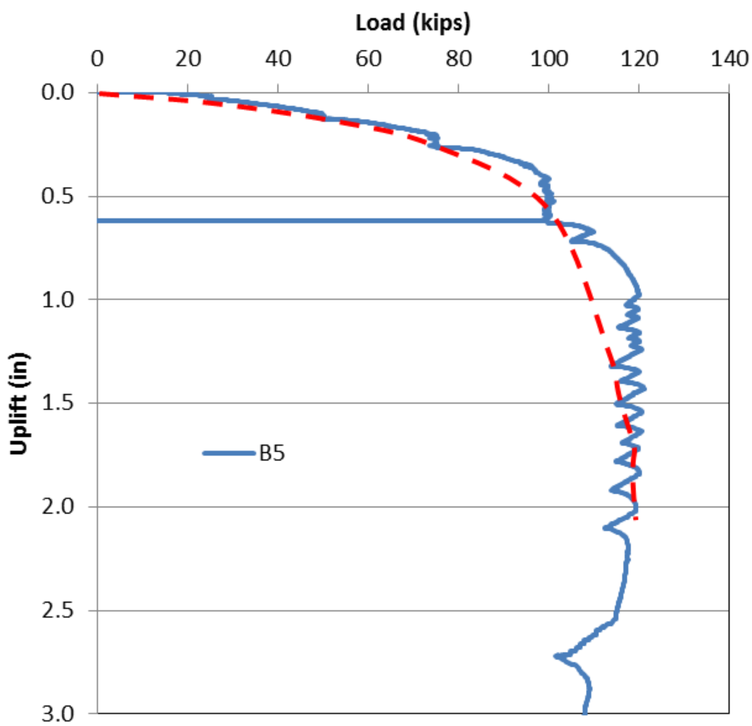


Figure F.14 Load vs. Displacement data for Shaft B-5

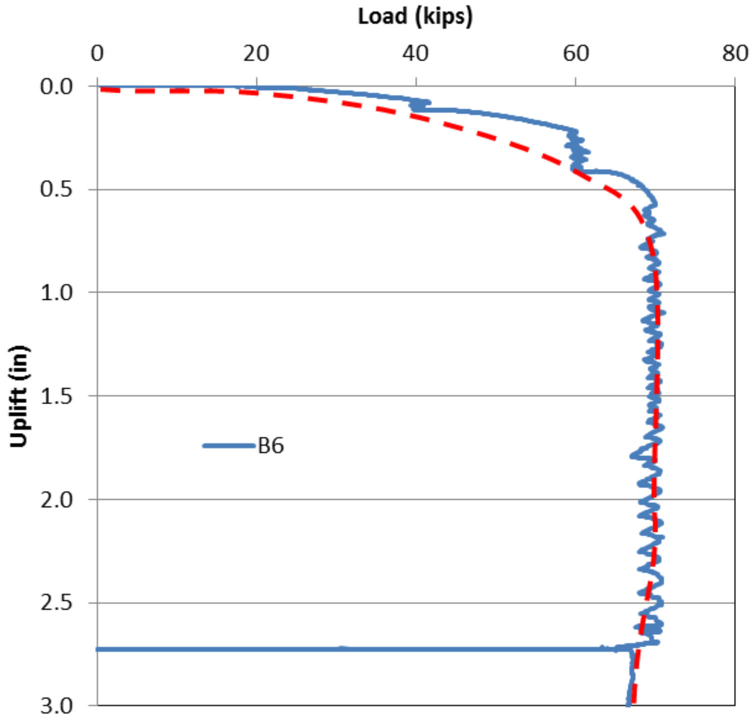


Figure F.15 Load vs. Displacement data for Shaft B-6

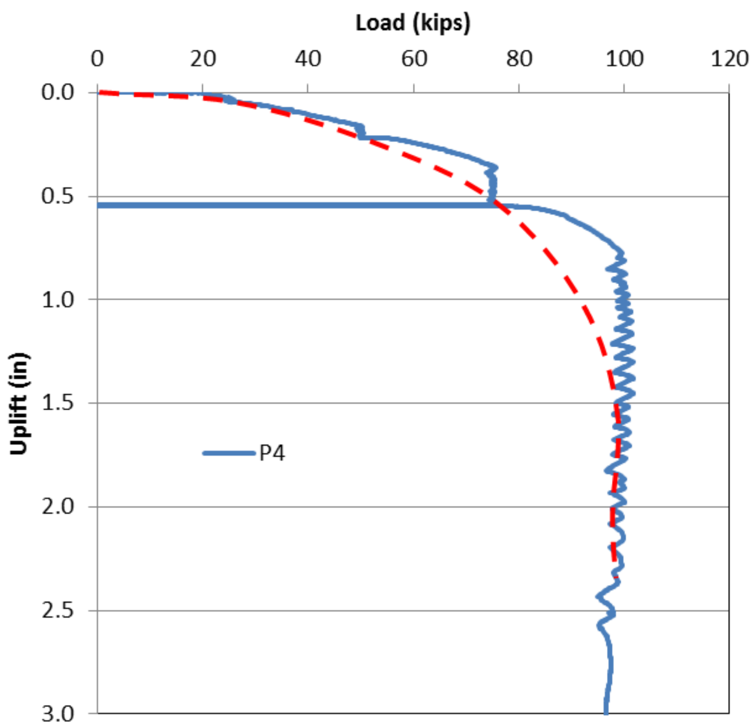


Figure F.16 Load vs. Displacement data for Shaft P-4

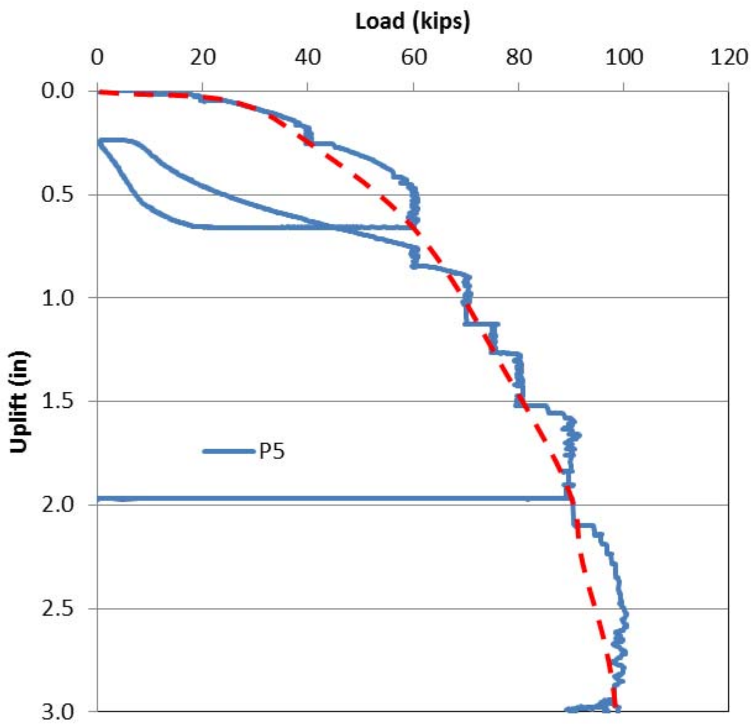


Figure F.17 Load vs. Displacement data for Shaft P-5

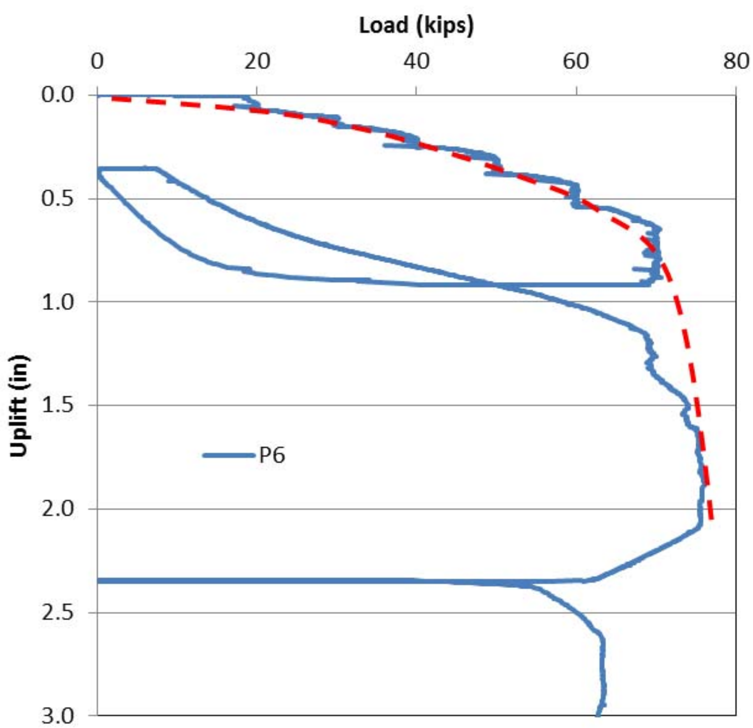


Figure F.18 Load vs. Displacement data for Shaft P-6

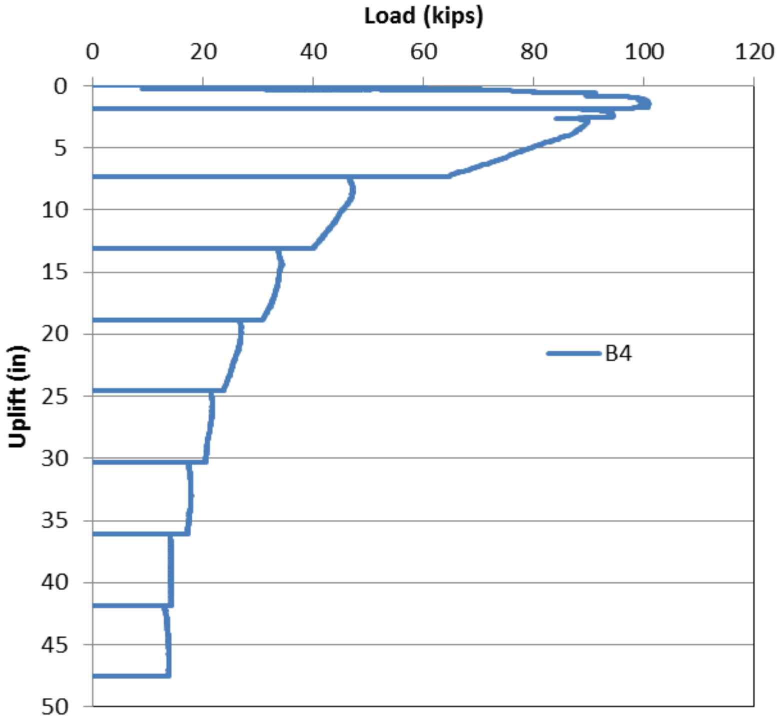


Figure F.19 Extraction data for Shaft B-4

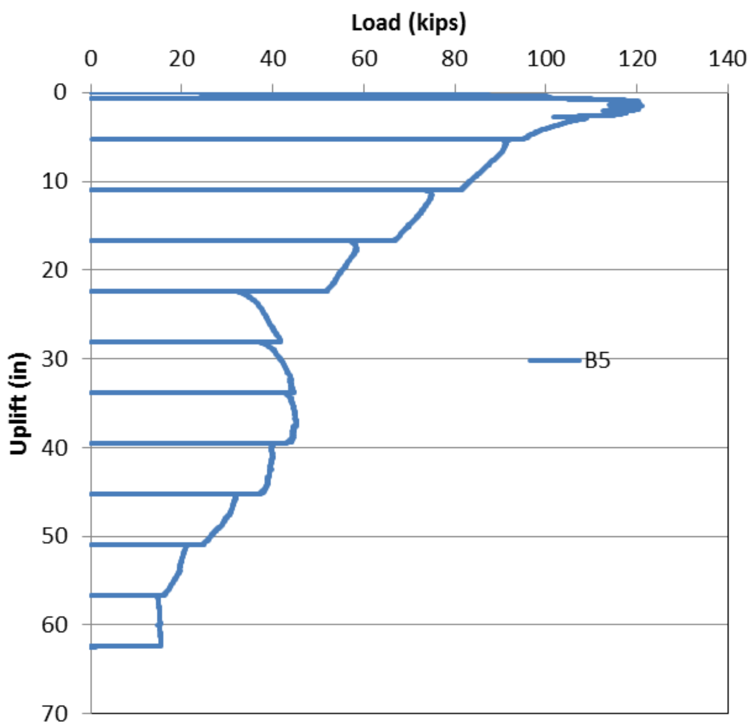


Figure F.20 Extraction data for Shaft B-5

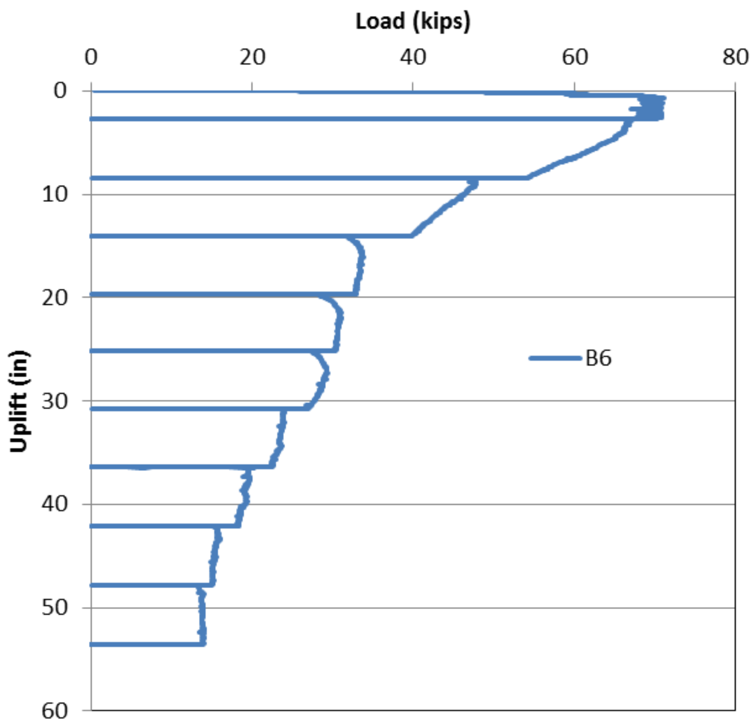


Figure F.21 Extraction data for Shaft B-6

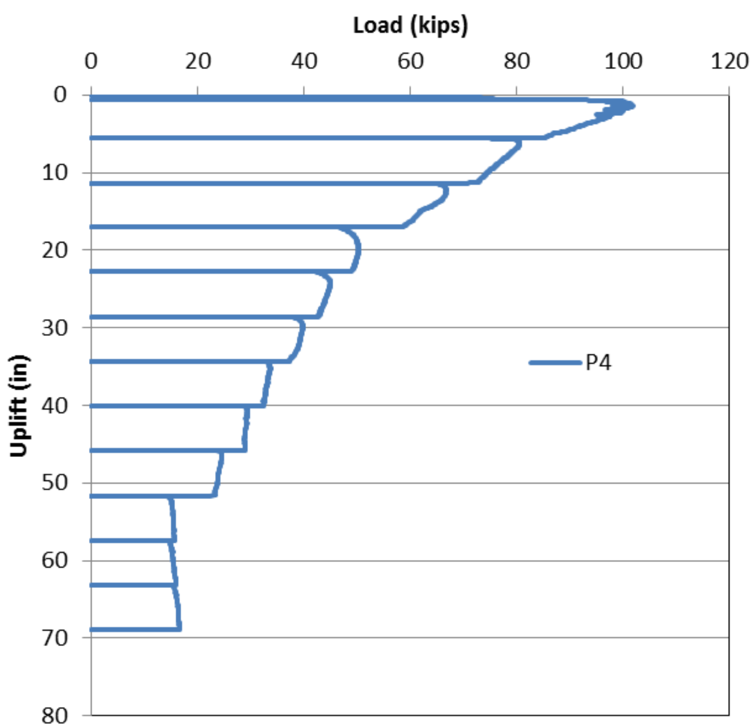


Figure F.22 Extraction data for Shaft P-4

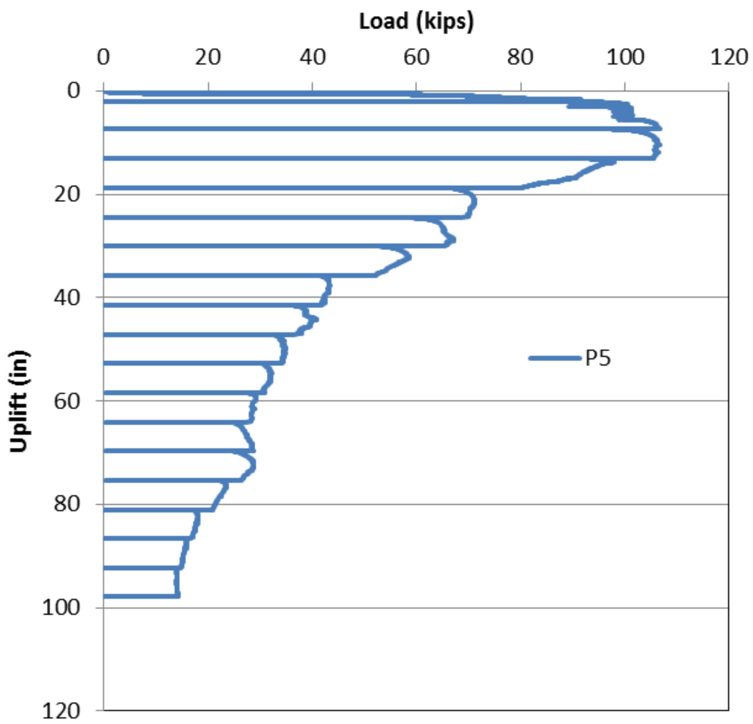


Figure F.23 Extraction data for Shaft P-5

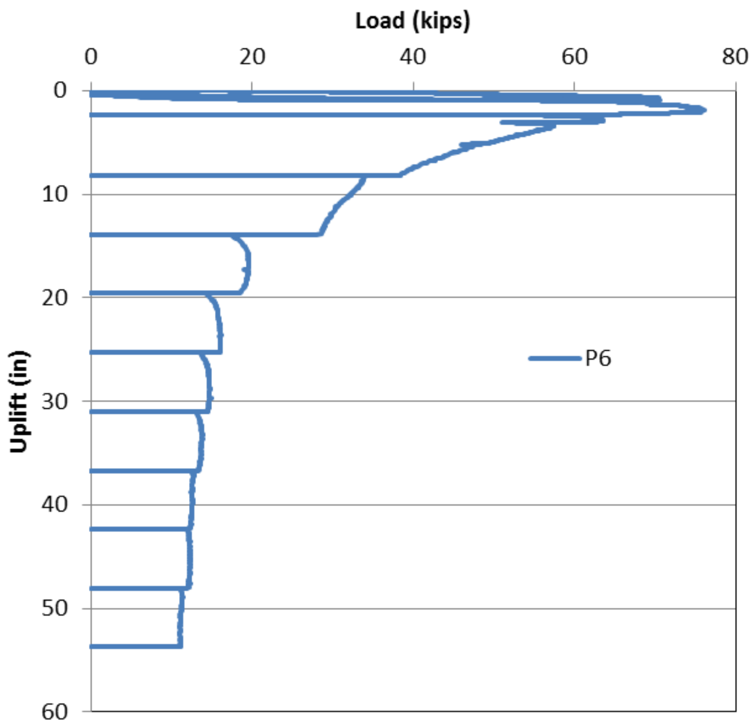


Figure F.24 Extraction data for Shaft P-6

APPENDIX G: PHASE I and II EXTRACTED SHAFT IMAGES

Phase I
Shafts B-1, B-3, P-1, P-2, and P-3

Phase II
Shafts B-4, B-5, B-6, P-4, P-5, and P-6

Figure 0.1 Shaft B-1 top, toe, side view top, middle, bottom (from top to bottom).

Figure 0.2 Shaft B-3 top, toe, side view top, middle, bottom (from top to bottom).

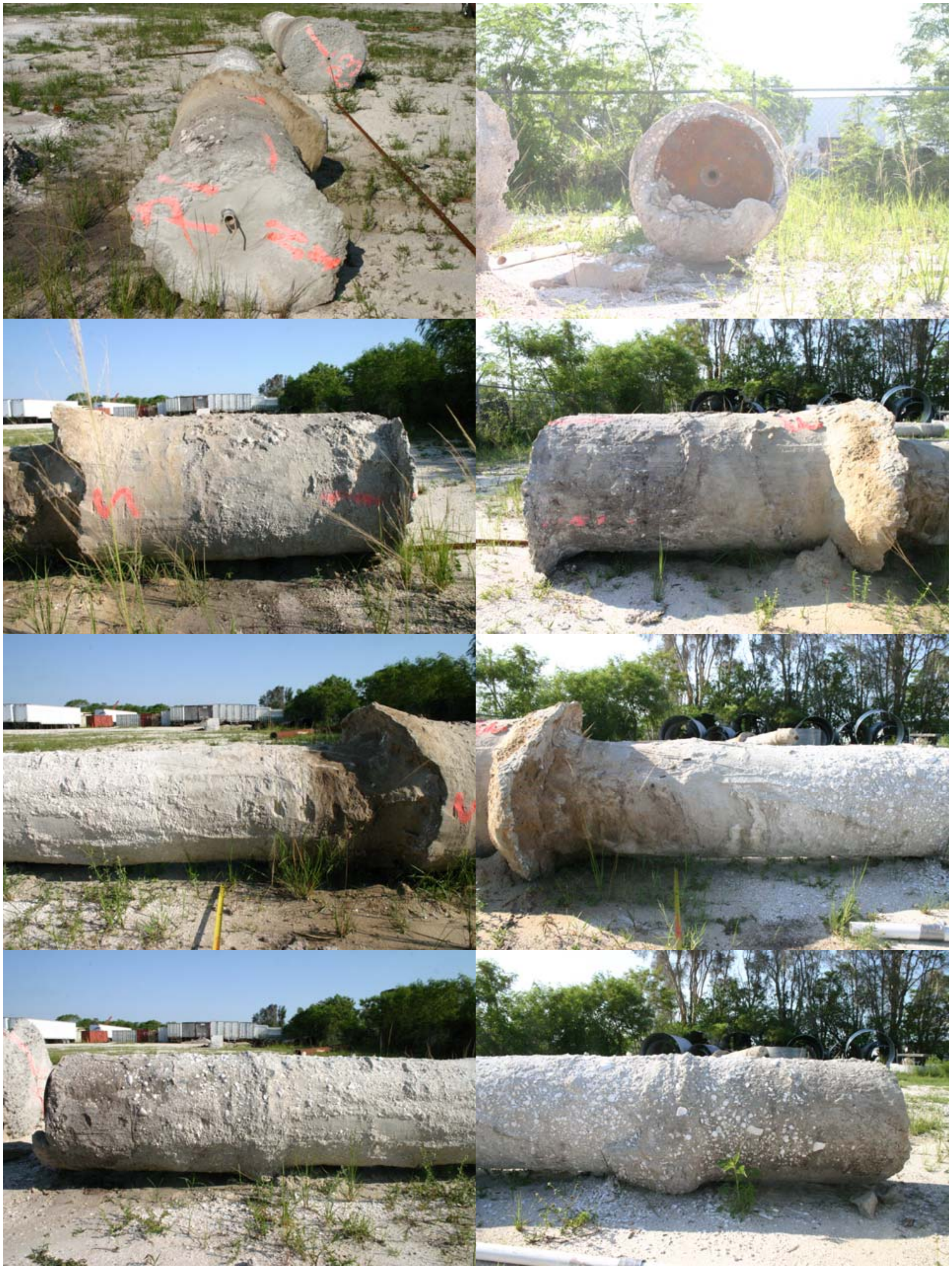


Figure 0.3 Shaft P-1 top, toe, side view top, middle, bottom (from top to bottom).

Figure 0.4 Shaft P-2 top, toe, side view top, middle, bottom (from top to bottom).

Figure 0.5 Shaft P-3 top, toe, side view top, middle, bottom (from top to bottom).

Figure G-6 Shaft B-4 top, toe, side view top, middle, bottom (from top to bottom).

Figure G-7 Shaft B-5 top, toe, side view top, middle, bottom (from top to bottom).

Figure G-8 Shaft B-6 top, toe, side view top, middle, bottom (from top to bottom).

Figure G-9 Shaft P-4 top, top elevated, toe, side view top, middle, bottom (from top to bottom).

Figure G-10 Shaft P-5 top, toe, side view top, middle, bottom (from top to bottom).

Figure G-11 Shaft P-6 top, toe, side view top, middle, bottom (from top to bottom).

APPENDIX H: PHASE I and II AS-BUILT SHAFT DIMENSIONS

Shafts B-1, B-2, B-3, P-1, P-2, and P-3

Shaft B-1

Measured Length: 15’ 4 ½”

Depth (ft)	Diameter (in)		
	D1	D2	AVG
0.0	27.5	27.5	27.5
0.5	28.25	29.5	28.875
1.0	29	29.5	29.25
1.5	28.25	29.75	29
2.0	28	29.5	28.75
2.5	28.5	29	28.75
3.0	28.5	28.75	28.625
3.5	28.25	28.5	28.375
4.0	28.75	28.5	28.625
4.5	23	25.5	24.25
5.0	22	22.75	22.375
5.5	21.75	21.5	21.625
6.0	22.5	23.5	23
6.5	21.5	21	21.25
7.0	21.5	21	21.25
7.5	21	21.5	21.25
8.0	21	21.75	21.375
8.5	21.5	21.5	21.5
9.0	22	21	21.5
9.5	22.25	21	21.625
10.0	22	21	21.5
10.5	21.5	21	21.25
11.0	21.75	21	21.375
11.5	22	21.75	21.875
12.0	23	22.25	22.625
12.5	22.25	22	22.125
13.0	22	22	22
13.5	22	22.25	22.125
14.0	22.25	22	22.125
14.5	22	22	22
15.0	20.75	20.5	20.625
15.4	20.75	20.5	20.625

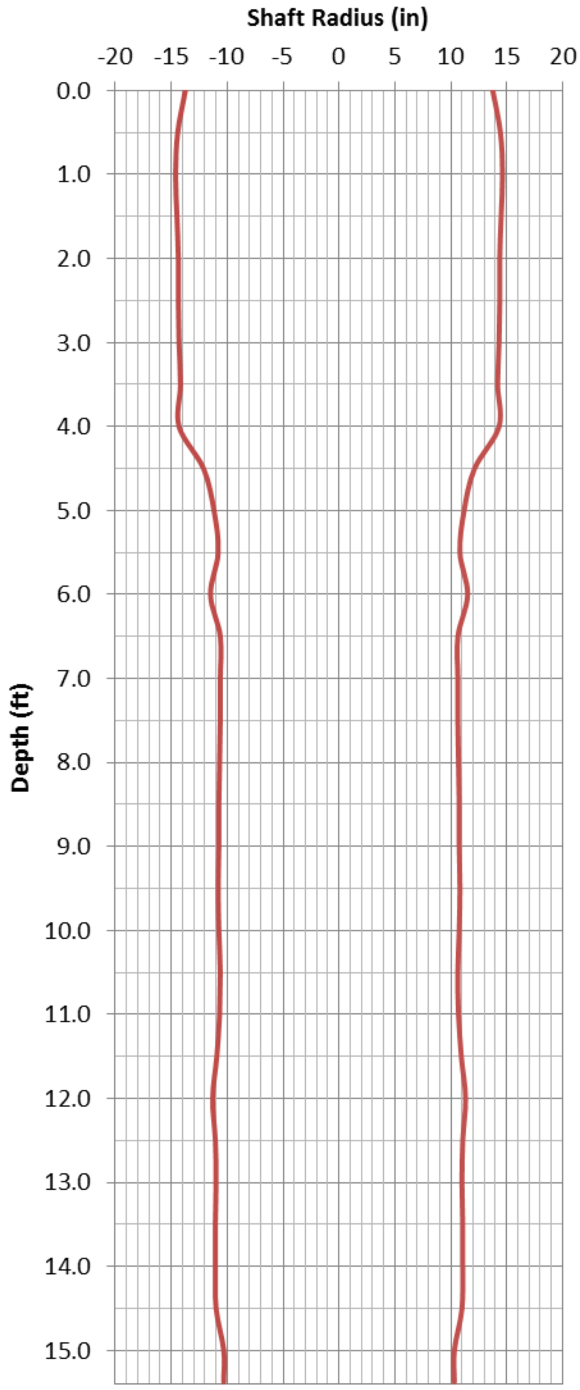


Figure H.1 Shaft B-1 caliper measurements and graphical representation of shaft shape.

Shaft B-2

See Appendix I for dimensions of Shaft B-2 as estimated from thermal data.

Shaft B-3

Measured Length: 14’ 8”

Depth (ft)	Diameter (in)		
	D1	D2	AVG
0.0	27.5	30	28.75
0.5	28.5	28.25	28.375
1.0	28.25	28	28.125
1.5	28.25	28	28.125
2.0	28.25	28	28.125
2.5	28	28	28
3.0	28	28	28
3.5	28	28	28
4.0	28.25	27.25	27.75
4.5	22.25	21.5	21.875
5.0	22	23	22.5
5.5	21.5	21.25	21.375
6.0	21.5	20.75	21.125
6.5	21.5	21	21.25
7.0	22	21	21.5
7.5	22.5	22	22.25
8.0	22.25	22.5	22.375
8.5	22.25	22.5	22.375
9.0	22	21.75	21.875
9.5	22.25	22	22.125
10.0	22	21.5	21.75
10.5	21.5	21.5	21.5
11.0	21.5	22	21.75
11.5	21.5	21.5	21.5
12.0	22.25	22	22.125
12.5	22	22	22
13.0	21.75	21.5	21.625
13.5	21.25	22	21.625
14.0	21.5	21.75	21.625
14.5	21.75	22	21.875
14.7	19	19	19

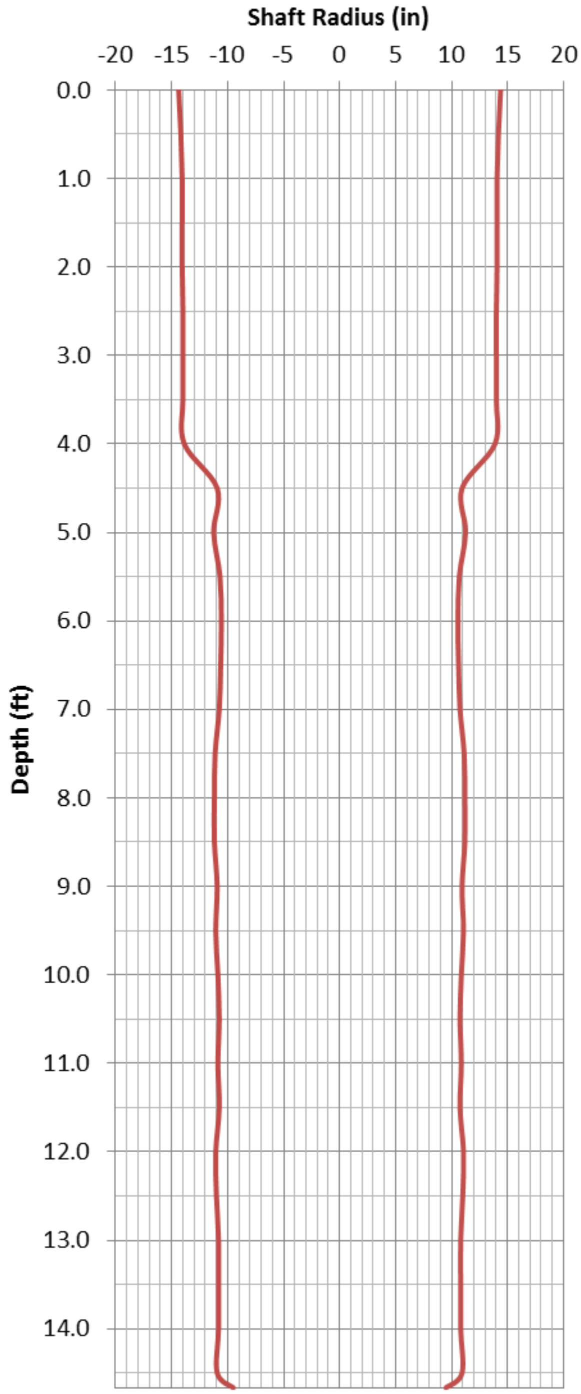


Figure H.2 Shaft B-3 caliper measurements and graphical representation of shaft shape.

Shaft P-1

Measured Length: 15’ 5”

Depth (ft)	Diameter (in)		
	D1	D2	AVG
0.0	37	27	32
0.5	28.25	28.5	28.375
1.0	28	28.5	28.25
1.5	28.5	28.25	28.375
2.0	28.25	28	28.125
2.5	28	28	28
3.0	28	28.5	28.25
3.5	27.75	27.5	27.625
4.0	27.75	28.75	28.25
4.5	30.5	29.5	30
5.0	34.25	31	32.625
5.5	22.5	23.5	23
6.0	22	22.5	22.25
6.5	21	21.25	21.125
7.0	21	21.5	21.25
7.5	20	21.5	20.75
8.0	20.75	22	21.375
8.5	20.5	21.25	20.875
9.0	21	21.5	21.25
9.5	21	21	21
10.0	21	21.5	21.25
10.5	21.25	21	21.125
11.0	21	21	21
11.5	22.25	21.5	21.875
12.0	23.5	23.5	23.5
12.5	22	22	22
13.0	21.5	21.75	21.625
13.5	21.75	22	21.875
14.0	21	22	21.5
14.5	21	21.75	21.375
15.0	21.25	21	21.125
15.4	18.5	18.5	18.5

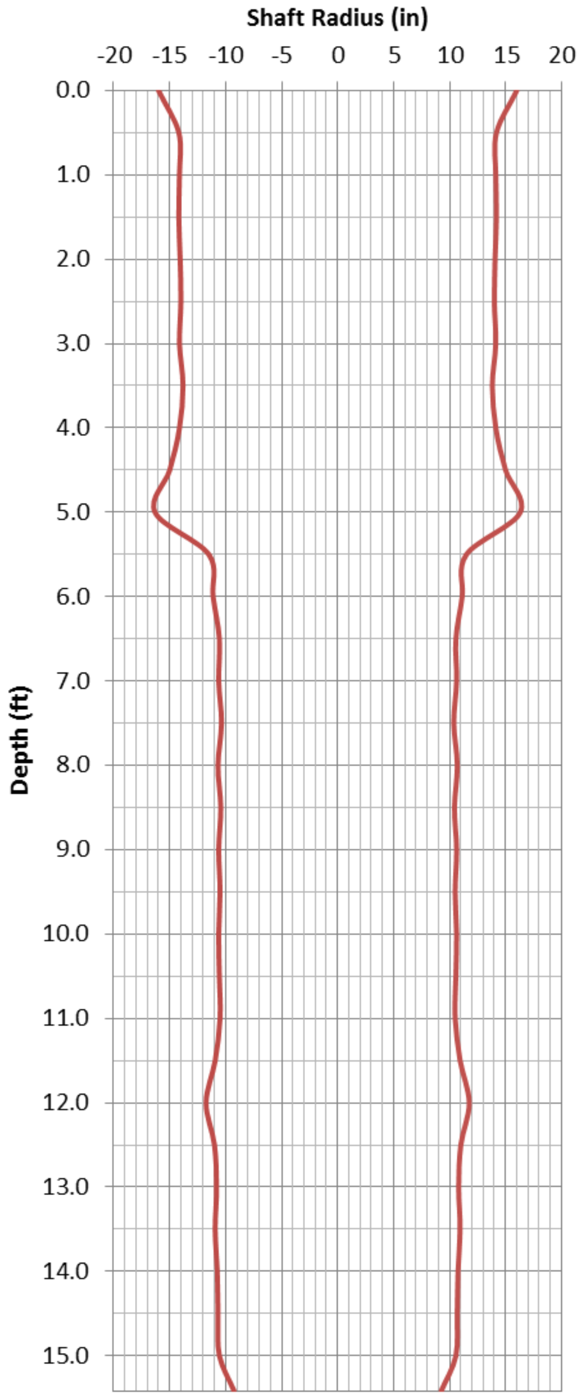


Figure H.3 Shaft P-1 caliper measurements and graphical representation of shaft shape.

Shaft P-2

Measured Length: 14’ 10”

Depth (ft)	Diameter (in)		
	D1	D2	AVG
0.0	26	26	26
0.5	27.75	28.5	28.125
1.0	28	28.75	28.375
1.5	28	28.5	28.25
2.0	28	28.5	28.25
2.5	28	28.75	28.375
3.0	28	28.25	28.125
3.5	27.75	28	27.875
4.0	31	31	31
4.5	33.5	36	34.75
5.0	35	45	40
5.5	33	34	33.5
6.0	34	32.75	33.375
6.5	37	33.75	35.375
7.0	37	25	31
7.5	36.5	24	30.25
8.0	21	23.5	22.25
8.5	21.5	24.25	22.875
9.0	24.25	23.5	23.875
9.5	23.5	22	22.75
10.0	22.25	22	22.125
10.5	22.5	22.5	22.5
11.0	22.5	22.75	22.625
11.5	23	23	23
12.0	22.75	23.25	23
12.5	23	23.5	23.25
13.0	22.25	23.25	22.75
13.5	22.75	23	22.875
14.0	22.75	22.5	22.625
14.5	23	21.75	22.375
14.8	20	18.5	19.25

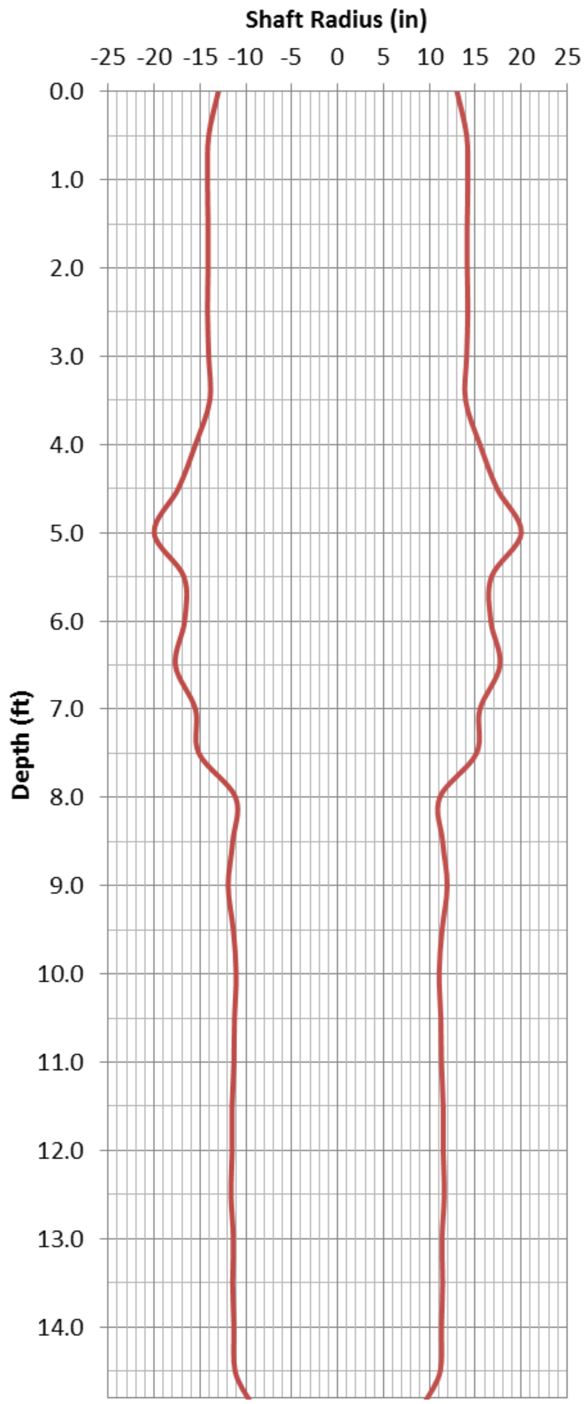


Figure H.4 Shaft P-2 caliper measurements and graphical representation of shaft shape.

Shaft P-3

Measured Length: 15’ 6”

Depth (ft)	Diameter (in)		
	D1	D2	AVG
0.0	32	35.5	33.75
0.5	28.5	28.25	28.375
1.0	28.25	28.25	28.25
1.5	28.5	28	28.25
2.0	28.5	28.75	28.625
2.5	28.25	28.75	28.5
3.0	28.5	28.5	28.5
3.5	28.5	28.5	28.5
4.0	28.5	28.5	28.5
4.5	28.5	28.5	28.5
5.0	25.25	25.25	25.25
5.5	24.5	22	23.25
6.0	23	21.25	22.125
6.5	23	22	22.5
7.0	22.25	22	22.125
7.5	22.5	22	22.25
8.0	22.25	21.5	21.875
8.5	22.5	21.5	22
9.0	21.75	21.5	21.625
9.5	21.5	21.5	21.5
10.0	21.5	22	21.75
10.5	21.25	21	21.125
11.0	21.25	21	21.125
11.5	22	21.5	21.75
12.0	22.5	22	22.25
12.5	21.5	20.75	21.125
13.0	23	21	22
13.5	22.5	21	21.75
14.0	21.75	21	21.375
14.5	21.25	21	21.125
15.0	21.25	20.5	20.875
15.5	17.5	18.5	18

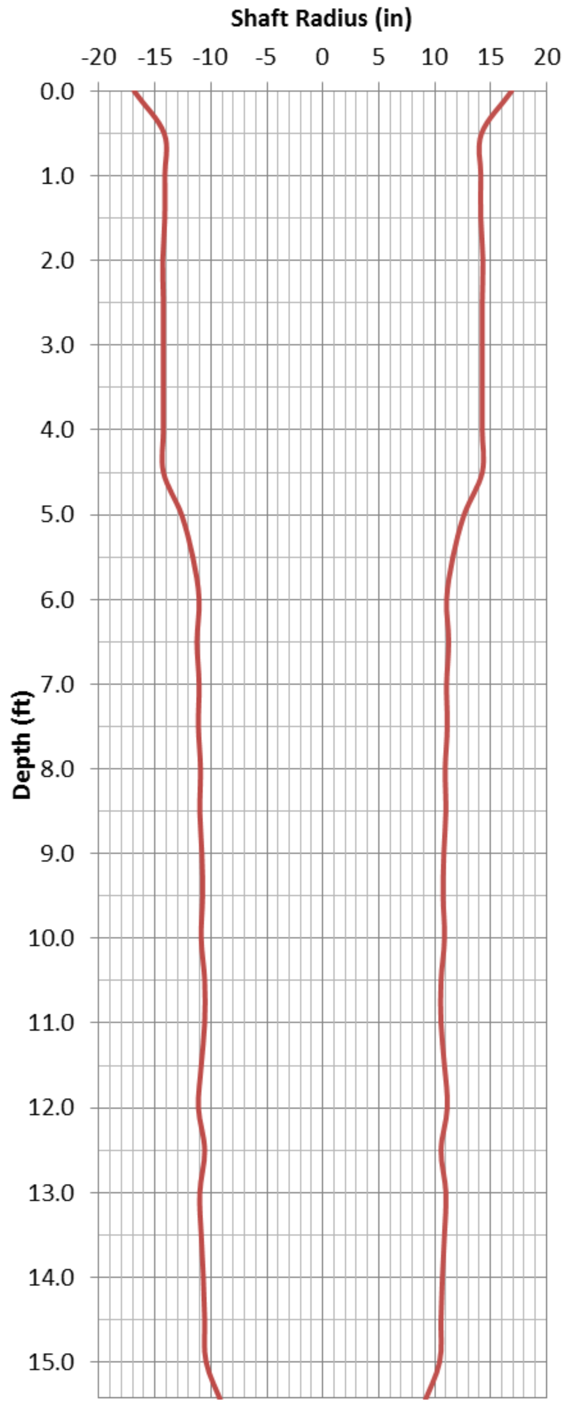


Figure H.5 Shaft P-3 caliper measurements and graphical representation of shaft shape.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	29.4	28.5	7.73	14.475	14.76321
0.5	28.75	28.3	7.55	14.2625	14.41944
0.75	28.6	28.3	7.52	14.225	14.36214
1	28.8	28.1	7.51	14.225	14.34304
1.25	28.4	28	7.49	14.1	14.30485
1.5	28.6	28	7.44	14.15	14.20935
1.75	28.65	27.9	7.42	14.1375	14.17116
2	29	27.85	7.43	14.2125	14.19025
2.25	29	27.2	7.24	14.05	13.82738
2.5	26.2	24.1	6.5	12.575	12.41409
2.75	24.9	23.9	6.42	12.2	12.2613
3	24.8	23.9	6.38	12.175	12.1849
3.25	24.6	23.7	6.39	12.075	12.204
3.5	24.9	23.8	6.38	12.175	12.1849
3.75	25	23.9	6.38	12.225	12.1849
4	25	23.9	6.38	12.225	12.1849
4.25	25	23.7	6.37	12.175	12.1658
4.5	24.8	23.25	6.38	12.0125	12.1849
4.75	24.5	23.1	6.38	11.9	12.1849
5	24.9	23.1	6.35	12	12.12761
5.25	24.5	22.8	6.28	11.825	11.99392
5.5	24.1	22.6	6.22	11.675	11.87932
5.75	23.9	22.4	6.12	11.575	11.68834
6	23	22.4	6.1	11.35	11.65014
6.25	22.9	22.6	6.05	11.375	11.55465
6.5	22.9	22.2	6.06	11.275	11.57375
6.75	22.7	22	6.09	11.175	11.63104
7	22.8	22.4	6.08	11.3	11.61194
7.25	22.9	22.5	6.14	11.35	11.72654
7.5	23	22.5	6.1	11.375	11.65014
7.75	22.7	22.4	6.09	11.275	11.63104
8	22.7	22.6	6.1	11.325	11.65014
8.25	22.6	22.5	6.11	11.275	11.66924
8.5	22.4	22.3	6.09	11.175	11.63104
8.75	22.5	22.2	6.08	11.175	11.61194
9	22.5	22.4	6.11	11.225	11.66924
9.25	22.7	22.4	6.09	11.275	11.63104
9.5	22.3	22	6.06	11.075	11.57375
9.75	22	22	6.07	11	11.59285
10	22	21.9	6.03	10.975	11.51645
10.25	22.6	22.05	6.03	11.1625	11.51645
10.5	22.2	22	5.98	11.05	11.42096
10.75	22.15	21.8	5.98	10.9875	11.42096
11	22.15	21.65	5.97	10.95	11.40186
11.25	22.1	21.5	5.95	10.9	11.36366
11.5	22.1	21.7	6.01	10.95	11.47825
11.75	22	21.85	5.94	10.9625	11.34456
12	22	22	5.95	11	11.36366
12.25	22.7	22.3	6.11	11.25	11.66924
12.5	22.7	22.7	6.14	11.35	11.72654
12.75	22.9	22.2	6.1	11.275	11.65014
13	22	22	6	11	11.45916
13.25	21.95	21	5.87	10.7375	11.21087
13.5	21.5	20.5	5.77	10.5	11.01989
13.75	21.1	20.5	5.7	10.4	10.8862
14	21.2	20.6	5.77	10.45	11.01989
14.25	21	20.6	5.7	10.4	10.8862
14.5	21.6	20.6	5.7	10.55	10.8862
14.75	21.2	20	5.65	10.3	10.79071
15	20.6	20	5.02	10.15	9.587494
15.25	20	17.5	4.45	9.375	8.498874

Figure H.6 Shaft B-4 caliper measurements.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	29	28.8	7.7	14.45	14.70592
0.5	28.35	28.7	7.63	14.2625	14.57223
0.75	27.9	28.8	7.57	14.175	14.45764
1	28	28.6	7.57	14.15	14.45764
1.25	27.95	28.65	7.53	14.15	14.38124
1.5	27.7	29	7.44	14.175	14.20935
1.75	28.05	28.5	7.44	14.1375	14.20935
2	28	28.55	7.44	14.1375	14.20935
2.25	27.1	28.6	7.36	13.925	14.05656
2.5	27.2	28.55	7.33	13.9375	13.99927
2.75	27.5	28.4	7.35	13.975	14.03747
3	23.9	25.9	6.6	12.45	12.60507
3.25	23.5	25.2	6.45	12.175	12.31859
3.5	23.2	24.2	6.3	11.85	12.03211
3.75	22.7	23.9	6.15	11.65	11.74563
4	22.8	22.9	6.13	11.425	11.70744
4.25	22.7	22.9	6.13	11.4	11.70744
4.5	22.8	22.9	6.14	11.425	11.72654
4.75	22.7	23.05	6.1	11.4375	11.65014
5	23.1	23.15	6.15	11.5625	11.74563
5.25	23.3	23.2	6.17	11.625	11.78383
5.5	23.05	23.1	6.14	11.5375	11.72654
5.75	22.8	22.95	6.14	11.4375	11.72654
6	22.7	22.8	6.12	11.375	11.68834
6.25	22.9	22.8	6.08	11.425	11.61194
6.5	22.8	22.85	6.05	11.4125	11.55465
6.75	22.6	22.5	6	11.275	11.45916
7	22.9	22.7	6.01	11.4	11.47825
7.25	23	22.4	6.04	11.35	11.53555
7.5	23	22.2	6.04	11.3	11.53555
7.75	23.1	22.15	6.07	11.3125	11.59285
8	23	22.4	6.08	11.35	11.61194
8.25	22.1	22.4	6.03	11.125	11.51645
8.5	22.3	22	5.94	11.075	11.34456
8.75	22.3	21.9	5.96	11.05	11.38276
9	22.5	21.8	5.96	11.075	11.38276
9.25	22.4	21.2	5.93	10.9	11.32547
9.5	22.2	21.9	5.95	11.025	11.36366
9.75	22.2	21.8	5.96	11	11.38276
10	22.2	21.9	5.94	11.025	11.34456
10.25	22.3	21.9	5.93	11.05	11.32547
10.5	22.6	21.9	5.84	11.125	11.15358
10.75	22	21.4	5.71	10.85	10.9053
11	21.8	21.4	5.65	10.8	10.79071
11.25	21.5	21.4	5.61	10.725	10.71431
11.5	21.4	21.2	5.62	10.65	10.73341
11.75	21.5	21.2	5.64	10.675	10.77161
12	21.3	21.5	5.63	10.7	10.75251
12.25	21.3	21.83	5.66	10.7825	10.8098
12.5	21.6	21.7	5.69	10.825	10.8671
12.75	21.9	21.9	5.72	10.95	10.9244
13	21.99	22	5.76	10.9975	11.00079
13.25	22	21.6	5.77	10.9	11.01989
13.5	22.4	21.3	5.78	10.925	11.03899
13.75	22.5	22	5.89	11.125	11.24907
14	22.4	21.5	5.92	10.975	11.30637
14.25	23	21.5	5.93	11.125	11.32547
14.5	23.1	23.9	6.21	11.75	11.86023
14.75	23.2	24	6.39	11.8	12.204
15	23.2	24.5	6.41	11.925	12.2422
15.25	23	22.6		11.4	
15.5	23.4	22		11.35	
15.75	23	22.2		11.3	
16	21.9			10.95	
16.25	20.5			10.25	
16.5	20.1			10.05	

Figure H.7 Shaft B-5 caliper measurements.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	29.2	28.2	7.55	14.35	14.41944
0.5	29	28.2	7.63	14.3	14.57223
0.75	29.85	28.1	7.7	14.4875	14.70592
1	28.9	27.85	7.59	14.1875	14.49583
1.25	28.6	27.6	7.45	14.05	14.22845
1.5	28.5	27.8	7.42	14.075	14.17116
1.75	28.55	28	7.4	14.1375	14.13296
2	26.6	25.95	6.84	13.1375	13.06344
2.25	25	24.6	6.52	12.4	12.45228
2.5	23.95	24	6.39	11.9875	12.204
2.75	23.7	23.4	6.28	11.775	11.99392
3	23.5	23	6.18	11.625	11.80293
3.25	23.25	22.9	6.18	11.5375	11.80293
3.5	22.9	22.9	6.16	11.45	11.76473
3.75	22.9	22.9	6.17	11.45	11.78383
4	22.75	22.8	6.18	11.3875	11.80293
4.25	23.1	22.9	6.17	11.5	11.78383
4.5	2285	22.9	6.19	576.975	11.82203
4.75	22.9	22.7	6.15	11.4	11.74563
5	23	22.5	6.11	11.375	11.66924
5.25	22.95	22.3	6.09	11.3125	11.63104
5.5	22.7	22.3	6.07	11.25	11.59285
5.75	22.7	22	6.02	11.175	11.49735
6	22.8	22.3	6.02	11.275	11.49735
6.25	22.7	21.95	6.01	11.1625	11.47825
6.5	22.9	22	6.03	11.225	11.51645
6.75	22.95	21.95	6.08	11.225	11.61194
7	22.8	22	6.08	11.2	11.61194
7.25	22.6	21.9	6.08	11.125	11.61194
7.5	22.4	21.9	6	11.075	11.45916
7.75	22.5	22	5.96	11.125	11.38276
8	22.5	21.95	5.95	11.1125	11.36366
8.25	22.74	22.4	5.96	11.285	11.38276
8.5	22.4	22.4	5.95	11.2	11.36366
8.75	22.5	22.5	5.96	11.25	11.38276
9	22.3	22.3	5.94	11.15	11.34456
9.25	22.1	22.1	5.97	11.05	11.40186
9.5	22	22	6	11	11.45916
9.75	22	22	5.98	11	11.42096
10	22.05	22.05	5.96	11.025	11.38276
10.25	21.9	21.9	5.91	10.95	11.28727
10.5	22.1	22.1	5.91	11.05	11.28727
10.75	21.85	21.85	5.91	10.925	11.28727
11	21.9	21.9	5.91	10.95	11.28727
11.25	21.9	21.9	5.93	10.95	11.32547
11.5	21.9	21.9	5.91	10.95	11.28727
11.75	21.9	21.9	5.91	10.95	11.28727
12	21.75	21.75	5.9	10.875	11.26817
12.25	21	21	5.92	10.5	11.30637
12.5	21.5	21.5	5.98	10.75	11.42096
12.75	22.4	22.4	6.11	11.2	11.66924
13	23.1	23.1	6.15	11.55	11.74563
13.25	23.3	23.3	6.3	11.65	12.03211
13.5	23.15	23.15		11.575	
13.75	23.3	23.3		11.65	
14	23.8	23.8		11.9	
14.25	22.7	22.7		11.35	

Figure H.8 Shaft B-6 caliper measurements.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	27	28.8		13.95	0
0.5	27.25	28.5		13.9375	0
0.75	27	28.6	7.54	13.9	14.40034
1	26.8	28.5	7.54	13.825	14.40034
1.25	26.8	28.4	7.55	13.8	14.41944
1.5	26.8	28.7	7.51	13.875	14.34304
1.75	26.7	28.4	7.41	13.775	14.15206
2	25.2	25.9	7.11	12.775	13.5791
2.25	24.5	25.1	6.7	12.4	12.79606
2.5	24	24.25	6.64	12.0625	12.68147
2.75	24	24.1	6.58	12.025	12.56687
3	24.7	24.1	6.47	12.2	12.35679
3.25	24.9	24	6.39	12.225	12.204
3.5	24.2	23.9	6.39	12.025	12.204
3.75	24	23.7	6.28	11.925	11.99392
4	24	23.5	6.26	11.875	11.95572
4.25	23.9	23.4	6.25	11.825	11.93662
4.5	23.9	23.6	6.23	11.875	11.89842
4.75	23.8	23.7	6.23	11.875	11.89842
5	23.8	23.75	6.24	11.8875	11.91752
5.25	23.8	23.6	6.25	11.85	11.93662
5.5	23.8	24.1	6.27	11.975	11.97482
5.75	23.8	24.7	6.27	12.125	11.97482
6	23.5	24.1	6.25	11.9	11.93662
6.25	23.05	23.9	6.23	11.7375	11.89842
6.5	23	24.05	6.22	11.7625	11.87932
6.75	23	24.2	6.21	11.8	11.86023
7	23.3	24	6.22	11.825	11.87932
7.25	23.25	23.9	6.19	11.7875	11.82203
7.5	23.3	24.05	6.22	11.8375	11.87932
7.75	23.2	23.99	6.18	11.7975	11.80293
8	23.8	23.99	6.14	11.9475	11.72654
8.25	23.4	23.7	6.14	11.775	11.72654
8.5	23.2	23.05	6.1	11.5625	11.65014
8.75	23	23	6.1	11.5	11.65014
9	23	23.05	6.06	11.5125	11.57375
9.25	23.2	23	6.06	11.55	11.57375
9.5	23.8	23.5	6.09	11.825	11.63104
9.75	23.2	23.75	6.17	11.7375	11.78383
10	23.8	23.7		11.875	
10.25	23.7	23		11.675	
10.5	21	23		11	
10.75	20.8	23		10.95	
11	21.2	23.4	5.95	11.15	11.36366
11.25	22	23.65	5.96	11.4125	11.38276
11.5	23	23.4	6	11.6	11.45916
11.75	23	23.5	6.05	11.625	11.55465
12	21	23.7	6.04	11.175	11.53555
12.25	20	23.5	6.04	10.875	11.53555
12.5	20.4	23	5.9	10.85	11.26817
12.75	20.9	23.25	5.86	11.0375	11.19178
13	21	23.4	5.85	11.1	11.17268
13.25	20.8	23.5	5.86	11.075	11.19178
13.5	20	24.4	5.89	11.1	11.24907
13.75	19.9	25	5.99	11.225	11.44006
14	20.95	26	6.09	11.7375	11.63104
14.25		26	6.17	13	11.78383
14.5		25.9	6.3	12.95	12.03211
14.75		25	6.33	12.5	12.08941
15			6.55		12.50958

Figure H.9 Shaft P-4 caliper measurements.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	28	29.05	7.7	14.2625	14.70592
0.5	28.5	28.95	7.6	14.3625	14.51493
0.75	28.4	28.85	7.55	14.3125	14.41944
1	28.4	28.9	7.54	14.25	14.40034
1.25	28.6	28.6	7.54	14.25	14.40034
1.5	28.5	28.4	7.5	14.1875	14.32394
1.75	28.1	28.25	7.45	14.15	14.22845
2	28.15	28.5	7.45	14.1625	14.22845
2.25	28.15	28.35	7.47	14.125	14.26665
2.5	28	28.4	7.48	14.1	14.28575
2.75	28.4	28.3	7.48	14.175	14.28575
3	28.5	29.2	7.8	14.425	14.8969
3.25	27	24.7	6.6	12.925	12.60507
3.5	24.65	24	6.6	12.1625	12.60507
3.75	25.5		7.7	12.75	14.70592
4	32.9		7.72	16.45	14.74411
4.25	35.6		8	17.8	15.27887
4.5	34.1		7.75	17.05	14.80141
4.75	33.9		7.68	16.95	14.66772
5	33.5	23.9	7.6	14.35	14.51493
5.25	33.41	23.9	7.54	14.3275	14.40034
5.5	33.3	24	7.5	14.325	14.32394
5.75	32	24	7.2	14	13.75099
6	25.5	24	6.35	12.375	12.12761
6.25	24	24	6.28	12	11.99392
6.5	23.5	24	6.24	11.875	11.91752
6.75	23	24	6.24	11.75	11.91752
7	22.9	24	6.23	11.725	11.89842
7.25	22.7	24	6.21	11.675	11.86023
7.5	22.1	24	6.21	11.525	11.86023
7.75	21.8	23.9	6.19	11.425	11.82203
8	21.65	24	6.19	11.4125	11.82203
8.25	21.4	24.4	6.26	11.45	11.95572
8.5	21.3	24.3	6.22	11.4	11.87932
8.75	21.1	23.95	6.2	11.2625	11.84113
9	21.15	23.95	6.2	11.275	11.84113
9.25	21.3	24.5	6.25	11.45	11.93662
9.5	21.95	27.8	6.85	12.4375	13.08254
9.75	21.75	27.35	7.5	12.275	14.32394
10	21.8	23.5	6.78	11.325	12.94885
10.25	22	22.4	6.6	11.1	12.60507
10.5	21.8	22.2	6.5	11	12.41409
10.75	21.2	21.05	6.33	10.5625	12.08941
11	21.05	21.1	6.24	10.5375	11.91752
11.25	21.1	21.1	6.18	10.55	11.80293
11.5	21.1	20	6.03	10.275	11.51645
11.75	21.6	19.9	6.1	10.375	11.65014
12	21.6	20.9	6.09	10.625	11.63104
12.25	21.6	20.5	6.11	10.525	11.66924
12.5	21	21	6.1	10.5	11.65014
12.75	20.9	21.2	6.1	10.525	11.65014
13	22.2	21.1	6.2	10.825	11.84113
13.25	21.8	22.1	6.42	10.975	12.2613
13.5	22.9	22.5		11.35	
13.75	23.5	24.7		12.05	
14	23.15	25		12.0375	
14.25	22.6	25.9	6.5	12.125	12.41409
14.5	22.4	25.8	6.47	12.05	12.35679
14.75	21	25.75	6.38	11.6875	12.1849
15	20.5	23.9	6.33	11.1	12.08941
15.25	20.5	23.85	5.9	11.0875	11.26817
15.5	19.9	21.5	5.63	10.35	10.75251
15.75	18.7	20.5	5.51	9.8	10.52332
16	18.5	20.2	5.28	9.675	10.08406
16.25		19	4.89	9.5	9.339212
16.5		18.2	4.62	9.1	8.82355
16.75			4.123		7.87435
17			3.65		6.970987

Figure H.10 Shaft P-5 caliper measurements.

Depth (ft)	D1 (in)	D2 (in)	C (ft)	R (avg of D)	R (from C)
0.25	29.5	28.7	7.79	14.55	14.8778
0.5	29	28.6	7.75	14.4	14.80141
0.75	28.75	28.5	7.67	14.3125	14.64862
1	28.75	28.4	7.63	14.2875	14.57223
1.25	28.75	28.4	7.6	14.2875	14.51493
1.5	28.7	28.3	7.63	14.25	14.57223
1.75	28.9	28.5	7.65	14.35	14.61042
2	29.2	28.6	7.73	14.45	14.76321
2.25	29.2	28.5	7.81	14.425	14.916
2.5	25.7	24.7	6.81	12.6	13.00614
2.75	24.6	24.2	6.73	12.2	12.85335
3	26.7	28.4		13.775	0
3.25	25.5	31.2		14.175	0
3.5	26.7	31.6		14.575	0
3.75	27.3	31.99		14.8225	0
4	27.6	32		14.9	0
4.25	27.1	31.9		14.75	0
4.5	24.5	25.2		12.425	0
4.75	23.45	24		11.8625	0
5	23.37	23.4	7.11	11.6925	13.5791
5.25	23.8	24.1	6.79	11.975	12.96794
5.5	23.4	23.9	6.66	11.825	12.71966
5.75	23.9	24.1	6.47	12	12.35679
6	23.9	24.2	6.45	12.025	12.31859
6.25	23.89	23.99	6.45	11.97	12.31859
6.5	23.8	24.2	6.45	12	12.31859
6.75	23.9	24.2	6.53	12.025	12.47138
7	23.8	24.3	6.54	12.025	12.49048
7.25	24.2	24.2	6.52	12.1	12.45228
7.5	24.2	24	6.44	12.05	12.29949
7.75	23.9	23.4	6.39	11.825	12.204
8	23.3	23.2	6.31	11.625	12.05121
8.25	23.1	23	6.29	11.525	12.01302
8.5	23	22	6.26	11.25	11.95572
8.75	22.9	23	6.27	11.475	11.97482
9	23.2	22.6	6.28	11.45	11.99392
9.25	22.6	22.6	6.24	11.3	11.91752
9.5	22.4	22.8	6.22	11.3	11.87932
9.75	22.5	22	6.15	11.125	11.74563
10	21.7	21.5	6.14	10.8	11.72654
10.25	21.3	21.5	6.09	10.7	11.63104
10.5	21.75	21.5	6.07	10.8125	11.59285
10.75	21.48	21.4	6.04	10.72	11.53555
11	21	20.85	6.01	10.4625	11.47825
11.25	21	20.65	5.96	10.4125	11.38276
11.5	21.2	20.7	5.97	10.475	11.40186
11.75	21	21.5	6.04	10.625	11.53555
12	21.4	21.4		10.7	
12.25	21.4	21		10.6	
12.5	21	20.3		10.325	
12.75	20.8	20.2		10.25	
13	20	20		10	
13.25	21	20.7		10.425	
13.5	21.3	20.86		10.54	
13.75	21	21.1		10.525	
14	21.2	21.04		10.56	
14.25	21.2	21.55		10.6875	
14.5	21.3	21.4		10.675	

Figure H.11 Shaft P-6 caliper measurements.

APPENDIX I: PHASE I THERMAL ANALYSIS

Shafts B-1, B-2, B-3, and P-1

Shaft B-1

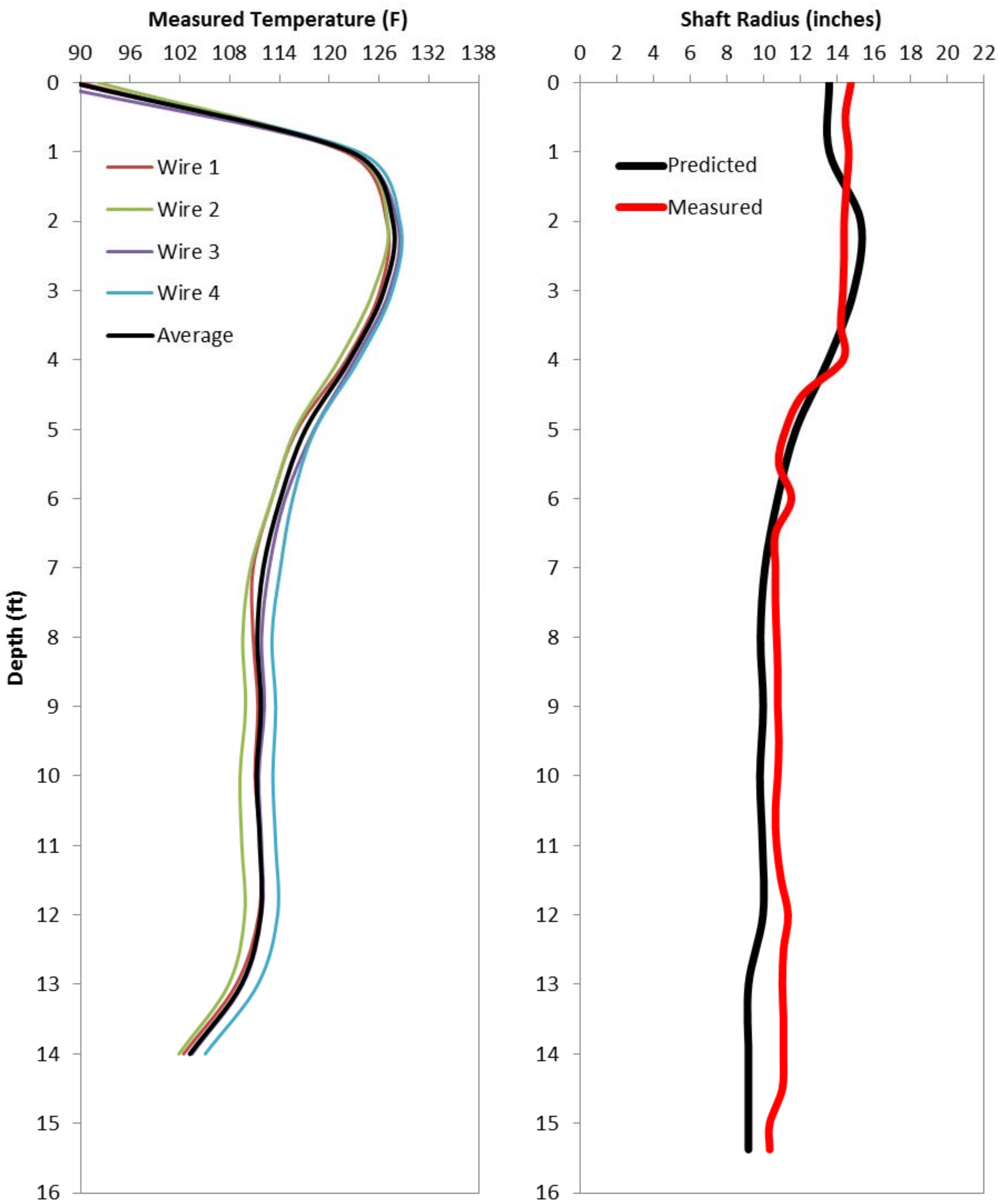


Figure 0.1 Thermal data, predicted shaft size and measured shaft size for Shaft B-1.

Shaft B-2

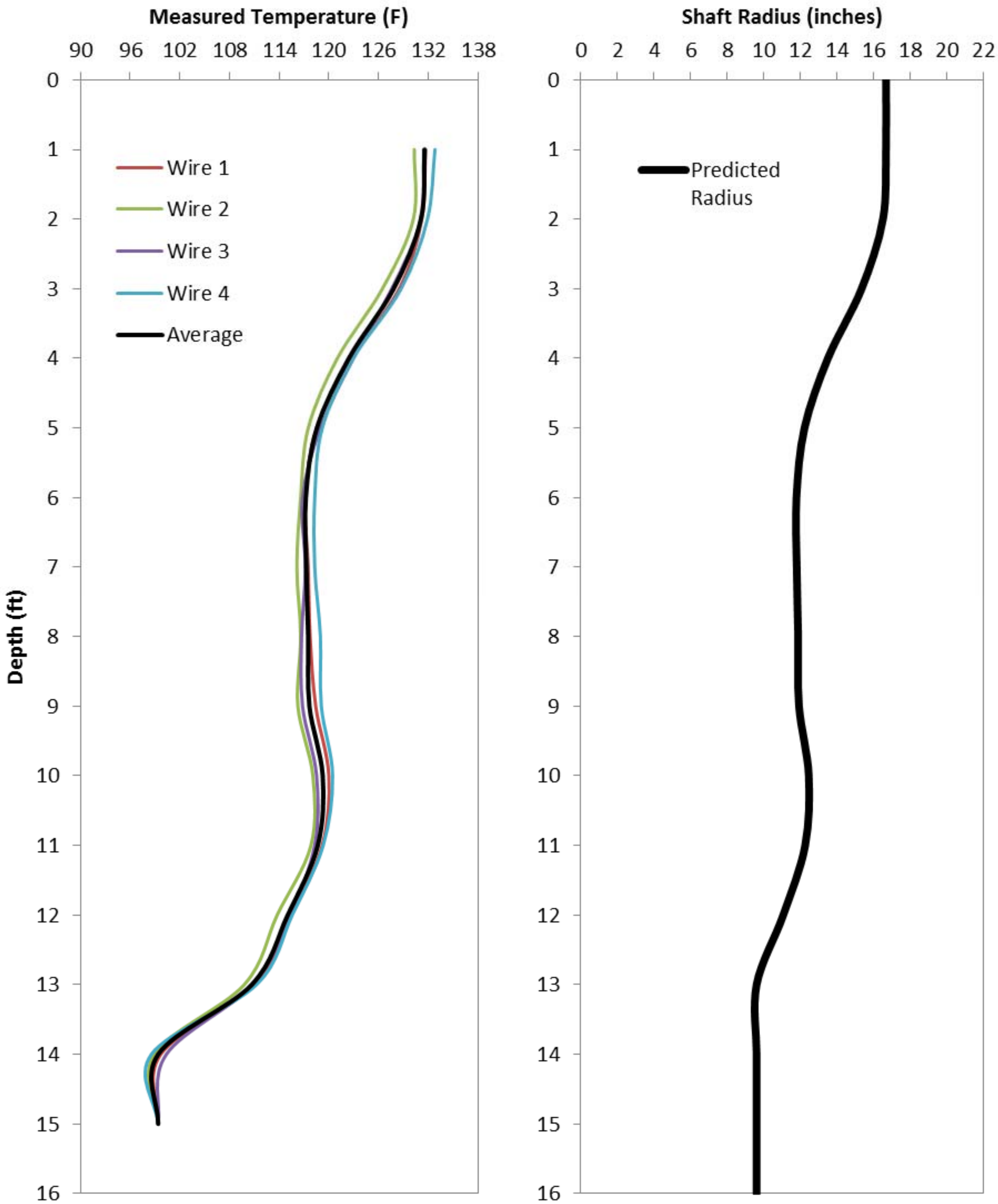


Figure 0.2 Thermal data and predicted shaft size for Shaft B-2.

Shaft B-3

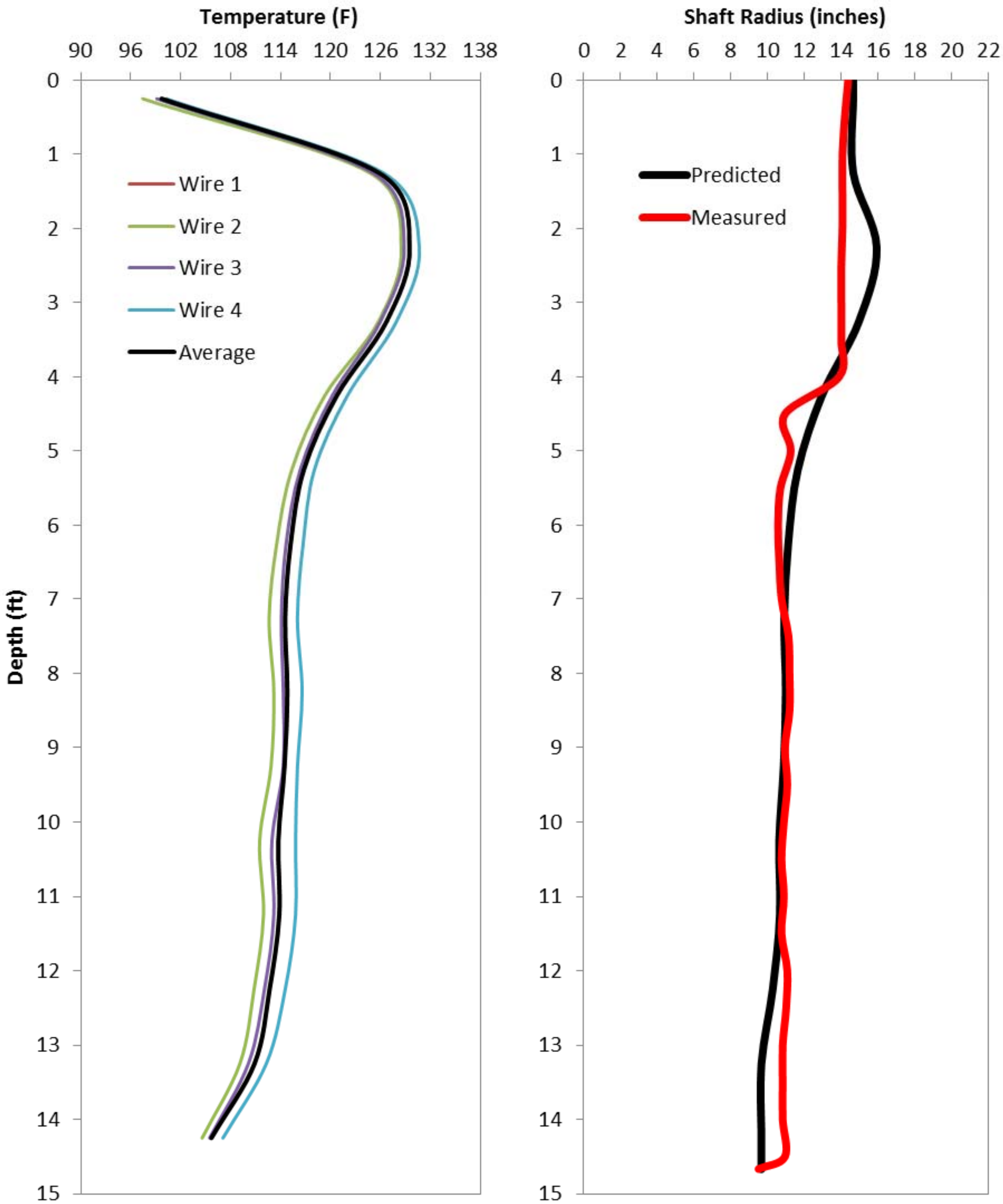


Figure 0.3 Thermal data, predicted shaft size and measured shaft size for Shaft B-3.

Shaft P-1

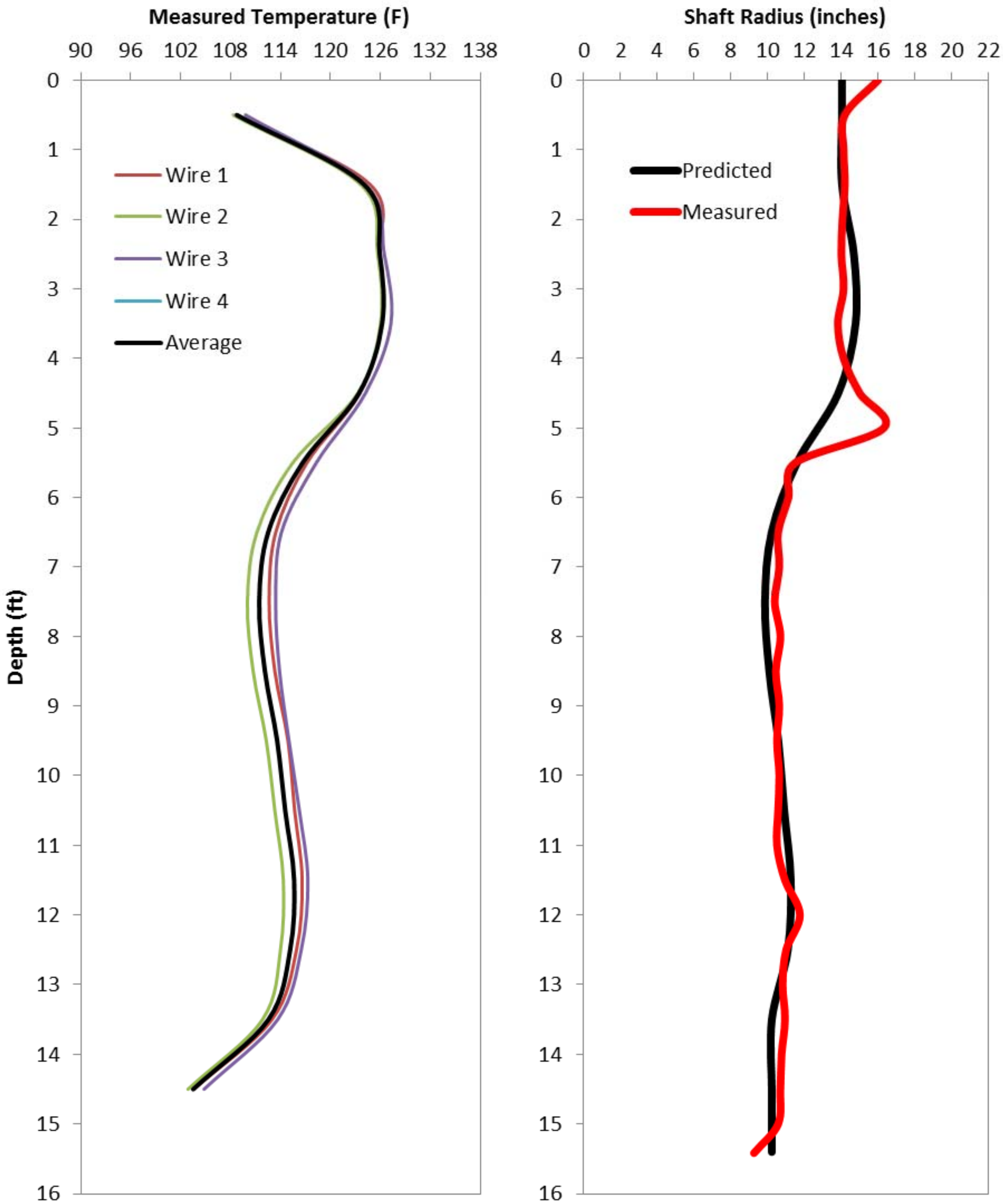


Figure 0.4 Thermal data, predicted shaft size and measured shaft size for Shaft P-1.