Cone Penetrometer Shear Strength Measurements of Sludge Waste in Tanks 241-AN-101 and 241-AN-106

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Abstract: This document presents the resulting shear strength profiles for sludge waste in Tanks 241-AN-101 and 241-AN-106, as determined with a full-flow cone penetrometer. Full-flow penetrometer measurements indicate shear strength profiles that increase roughly uniformly with depth. For Tank 241-AN-101, the undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 3,300 Pa at 15 inches above the tank bottom. For Tank 241-AN-106, the undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 5,000 Pa at 15 inches above the tank bottom.

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EXECUTIVE SUMMARY

In response to research examining the effect of gas production on the storage capacity of artificial sludge depots ("Gas Production and Transport in Artificial Sludge Depots," [van Kessel and van Kesteren, 2002]), a new mechanism was proposed for a spontaneous deep sludge gas release event (DSGRE) that is not currently described in the safety basis. Implementation of a new safety basis for Hanford Site sludge waste requires showing that the waste maintains low gas fractions as settled solids depth is increased, which is directly related to the shear strength of the waste. Therefore, further safety basis development involves determining the in situ shear strength of the sludge waste in 241-AN-101 (AN-101) and 241-AN-106 (AN-106). This was accomplished by taking resistance measurements using a HYSON[1] 200kN "full-flow" penetrometer with a 3-inch diameter ball attachment. The recorded in situ resistance measurements are equated to shear strength using an empirical value, called the *N* Factor (which is specific to both the device and the material being measured), resulting in a full-depth shear strength profile of the sludge waste in each tank. This document presents the resulting shear strength profiles for AN-101 and AN-106 sludge waste.

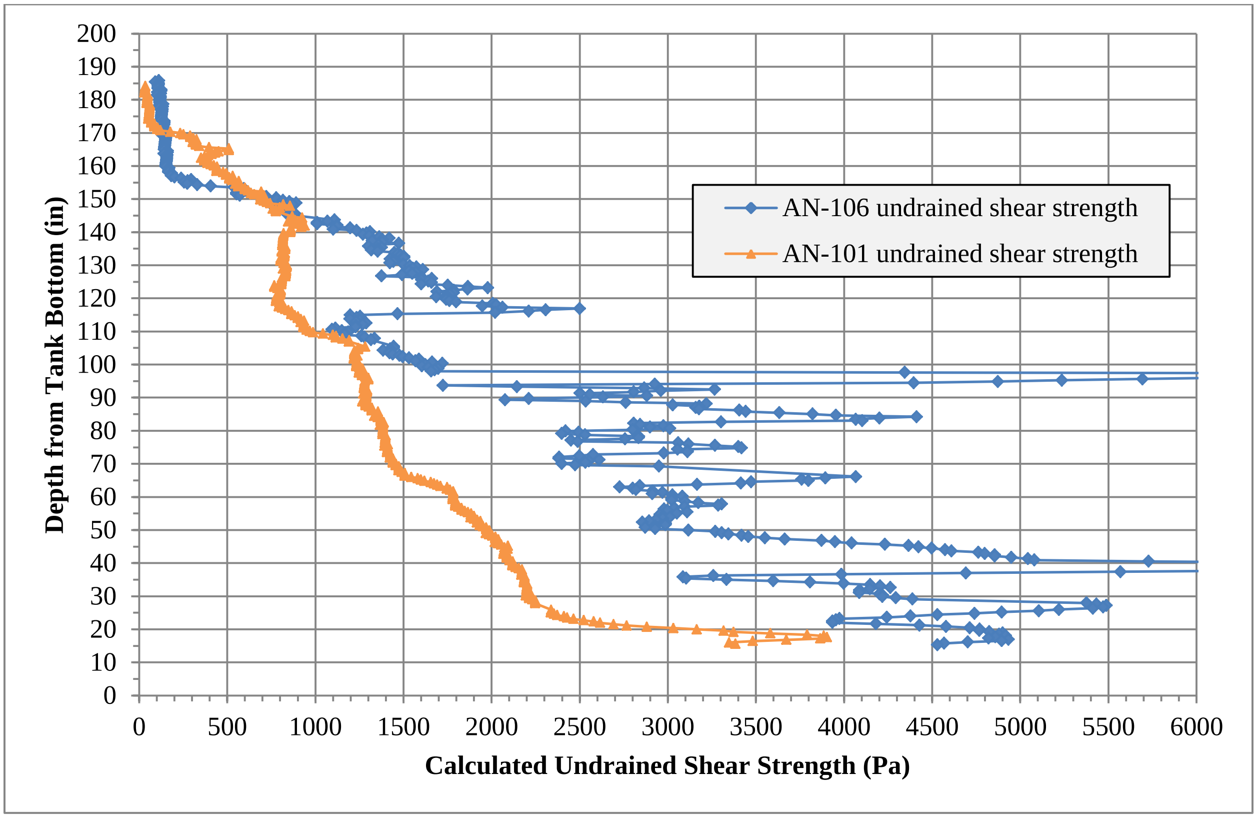
Full-flow cone penetrometer measurements taken in Tank AN-101 sludge waste on January 10, 2014 indicated a shear strength profile that increases roughly uniformly with depth. The undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 3,300 Pa at 15 inches above the tank bottom, for a standard undrained *N* Factor of 11.5. Tank AN-101 sludge measured within the region ranging from 15 inches to 64 inches above the tank bottom was found to have a sensitivity of 3.6, which is very similar to kaolin clay/water simulants used in previous *N* Factor determination testing (RPP-RPT-56006, *Cone Penetrometer N Factor Determination Testing Results*). The remolded shear strength was found to vary between 500 Pa and 800 Pa in the region from 15 inches to 64 inches above the tank bottom.

Penetrometer measurements taken in Tank AN-106 sludge waste on November 19, 2013 indicated a shear strength profile that also increases roughly uniformly with depth. The undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 5,000 Pa at 15 inches above the tank bottom, for a standard undrained *N* Factor of 11.5. Tank AN-106 sludge measured within the region ranging from 15 inches to 64 inches above the tank bottom was found to have a sensitivity of 11.8, which differs significantly from AN-101 sludge and kaolin clay/water simulants used in testing (RPP-RPT-56006). The remolded shear strength was found to vary between 200 Pa and 800 Pa in the region ranging from 15 inches to 64 inches above the tank bottom.

Testing indicates the overall strength of AN-106 sludge waste is significantly greater than AN-101, as shown in Figure ES-1. This may be attributed to the time component of sludge consolidation since the majority of sludge waste has been compacting in AN-106 for at least five years, versus the more recent retrievals into AN-101. As additional sludge is retrieved into these two tanks, the shear strength would also be expected to rise in each due to the increased overburden stress.

[1] HYSON is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.

Figure ES-1. AN-101 and AN-106 Sludge Shear Strength



The higher sensitivity observed in AN-106 sludge may indicate the calculation of undrained shear strengths using a standard *N* Factor of 11.5 is not appropriate. Industry testing of full-flow ball penetrometers in soft clay has shown sensitivity is the property primarily influencing both the undrained and remolded *N* Factors ("Recommended Practice for Full-Flow Penetrometer Testing and Analysis," [DeJong, et. al., 2010]). If an empirically calculated *N* Factor of 8.9 is applied across all depths of AN-106 sludge, the shear strength is shown to increase by about 100 Pa for the upper portion of sludge, about 1,000 Pa for the middle portion of sludge, and around 1,300 Pa for the lowest depth of sludge. The shear strength profile is presented with both an *N* Factor of 11.5 and with the empirically determined *N* Factor of 8.9. Both profiles should be considered when evaluating physical properties of AN-106 sludge waste.

Cone penetrometer measurements in both AN-101 and AN-106 sludge indicate the undrained shear strength increases roughly uniformly with depth. This behavior is expected based on similar testing performed in soft, normally consolidated clays at test sites globally ("Evaluation of Remolded Shear Strength and Sensitivity of Soft Clay Using Full-Flow Penetrometers," [Yafrate, et. al., 2009]). For a normally consolidated clay deposit, uniform increase in overburden stress is typically associated with a decrease in moisture content, resulting in a uniform increase in shear strength, which means the ratio of shear strength to overburden stress between depths is constant ("Shearing Strength of Soils," [Raymond, 1997]). Comparison of in situ data to other soft-clay sites investigated with full-flow penetrometers suggests AN-101 and AN-106 sludge wastes do not behave differently, in this regard, than other normally consolidated clay or soil deposits.

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Abbreviations and Acronyms

CPT	Cone Penetrometer Testing
DSA	Documented Safety Analysis
DSGRE	Deep Sludge Gas Release Event
DQO	Data Quality Objectives
HISI	Hanford Information Systems Inventory
JCO	Justification for Continued Operation
ORP	U.S. Department of Energy Office of River Protection
PCSACS	Personal Computer Surveillance Analysis Computer System
PNNL	Pacific Northwest National Laboratory
SVF	Spreadsheet Verification Form
TWINS	Tank Waste Inventory Network System
USB	Universal Serial Bus
USQ	Unreviewed Safety Question
WRPS	Washington River Protections Solutions, LLC

Units

cm	centimeter
°F	Degrees Fahrenheit
gal	gallon
in	inch
kg	kilogram
kN	Kilo-Newton
kPa	Kilo-Pascal
N	Newton
m	meter
mm	millimeter
Pa	Pascal
s	Second

Variables

a	Load cell area ratio, dimensionless
A_{ball}	Cross-sectional area of ball attachment, m^2
A_{shaft}	Cross-sectional area of shaft connecting to the ball attachment, m^2
d	Depth at cone penetrometer measurement, m
F_p	Pushing force, N
g	Acceleration due to gravity, 9.81 m/s^2
N_k	Undrained *N* Factor (cone factor) found in RPP-RPT-56006, dimensionless
$N_{k,calc}$	Undrained *N* Factor calculated using Equation 1-9, dimensionless
N_{rem}	Remolded *N* Factor found using Equation 1-9 with only cone penetrometer measurements, dimensionless
q_c	Correction for measured penetration resistance, Pa
q_{ext}	Corrected net penetration resistance for extraction, Pa
q_i	Corrected net penetration resistance for the i^{th} penetration or extraction where i is in increments of 0.5, Pa
q_{in}	Corrected net penetration resistance for the initial push, Pa
$q_{in,i}$	Corrected net penetration resistance for the i^{th} penetration where i is in increments of 1, starting at 0.5, Pa
q_m	Measured penetration resistance, Pa
q_{net}	Net (corrected) penetration resistance, Pa
q_{rem}	Corrected net penetration resistance for the remolded state, Pa
s_u	Undrained shear strength, Pa
s_{ur}	Remolded shear strength, Pa
S_T	Sensitivity, dimensionless
ρ_{sl}	Density of sludge waste, kg/m^3
ρ_{sup}	Density of supernatant waste, kg/m^3
u_0	Hydrostatic head pressure, Pa
σ_{v0}	Total overburden stress, Pa

1.0 INTRODUCTION

1.1 Background

In response to research examining the effect of gas production on the storage capacity of artificial sludge depots ("Gas Production and Transport in Artificial Sludge Depots," [van Kessel and van Kesteren, 2002]), a new mechanism was proposed for a spontaneous deep sludge gas release event (DSGRE) that is not currently described in RPP-13033, *Tank Farms Documented Safety Analysis* (DSA). This resulted in a positive Unreviewed Safety Question (USQ) and subsequent approval of Justification for Continued Operation (JCO) TF-13-01 to allow sludge levels in tanks 241-AN-101 (AN-101) and 241-AN-106 (AN-106) to accumulate up to 192 inches and 195 inches, respectively. However, in order to complete waste retrievals from the 241-C farm tanks, accumulation of additional sludge depth is needed.

To address concerns over the potential for a DSGRE and to support the technical justification for continued retrieval of operations into tanks AN-101 and AN-106, in situ sludge waste shear strength data were needed. Implementation of a new safety basis for deep sludge storage requires showing that Hanford Site sludge waste maintains low gas fractions as settled solids depth is increased, which is also directly related to the shear strength of the waste. Therefore, further safety basis development involves determining the in situ shear strength of the sludge in tanks AN-101 and AN-106. This was accomplished by taking resistance measurements using a HYSON[2] 200kN "full-flow" penetrometer with a 3-inch diameter ball attachment (see Section 2.1). In situ resistance measurements are equated to shear strength using an empirical value, called the *N* Factor (which is specific to both the device and the material being measured), resulting in a full-depth shear strength profile of the sludge waste currently residing in each tank. The penetrometer project was managed and implemented per RPP-PLAN-55836, *T1P38, Cone Penetrometer Field Deployment Project Execution Plan*.

1.2 Purpose

This document presents the sludge shear strength profiles in tanks AN-101 and AN-106 resulting from cone penetrometer testing (CPT). The primary objective of cone penetrometer deployment to tanks AN-101 and AN-106 was established by a data quality objective (DQO) team consisting of subject matter experts from Washington River Protection Solutions (WRPS), the Washington State Department of Ecology, and the U.S. Department of Energy Office of River Protection (ORP). The primary objective was to obtain in situ shear strength measurements to determine whether the actual sludge shear strength is within the range over which modeling based on simulant testing is applicable, as stated in RPP-55919, *Cone Penetrometer Data Quality Objectives*. A number of tests are being performed by experts at the Pacific Northwest National Laboratories (PNNL) to investigate the DSGRE theories proposed by van Kessel and van Kesteren, 2002. These testing activities have been designed based on expected tank waste conditions. As a parallel path activity, the cone penetrometer was used to evaluate actual in situ conditions and verify the applicability of the PNNL tests.

[2] HYSON is a trademark of A.P. van den Berg, Heerenveen, Netherlands.

2.0 CONE PENETROMETER TECHNOLOGY

The CPT technology has been used to investigate soil mechanics in a variety of industries for many years and is performed by pushing an instrumented cone tip down into the ground at a controlled rate. The resistance on the cone tip is measured and equated to shear strength. In soft sediments the “cone” penetrometer tip may not provide enough resistance to obtain accurate measurements, thus “full-flow” penetrometers with t-bar or ball probes have been developed to increase resistance. Penetration of full-flow penetrometers in soft clay-like mediums forces material to flow around the penetrometer in a viscous, fluid-like manner. The penetrometer geometry and surface roughness influence material flow during penetration as it undergoes non-localized turbulent shearing. Thus, full-flow penetrometers essentially provide a measure of the pressure differential necessary to induce the material to flow around a symmetric, geometric probe.

Since the sludge waste in the tanks was expected to be soft in comparison to soils typically measured in cone penetrometer testing, a 3-inch diameter full-flow ball penetrometer tip was used as a replacement to the conventional conical tip. Figure 2-1 shows a photograph of the ball penetrometer attachment design that was used to collect in situ data in tanks AN-101 and AN-106.

Figure 2-1. Full-Flow Ball Penetrometer

2.1 HYSON 200kN System Overview

Cone penetrometer measurements were collected in AN-101 and AN-106 using a HYSON 200kN full-flow penetrometer system, which operates by pushing an instrumented ball tip (Figure 2-1) down into the tank sludge at a controlled rate. Resistance on the tip is measured using a load cell and can be equated to shear strength using the empirical relationships shown in Section 2.2. The load cell device, termed the Icone[3], also includes a sleeve to measure local friction. One meter long extending rods are attached one at a time and fed through a hydraulic ram in order to allow the ball to penetrate to the desired depth. The control panel, hydraulic ram, and rod rack are installed and operated on a platform with the hydraulic power pack located on the ground nearby. Figure 2-2 shows the system installed for testing at HiLine Engineering and Fabrication.

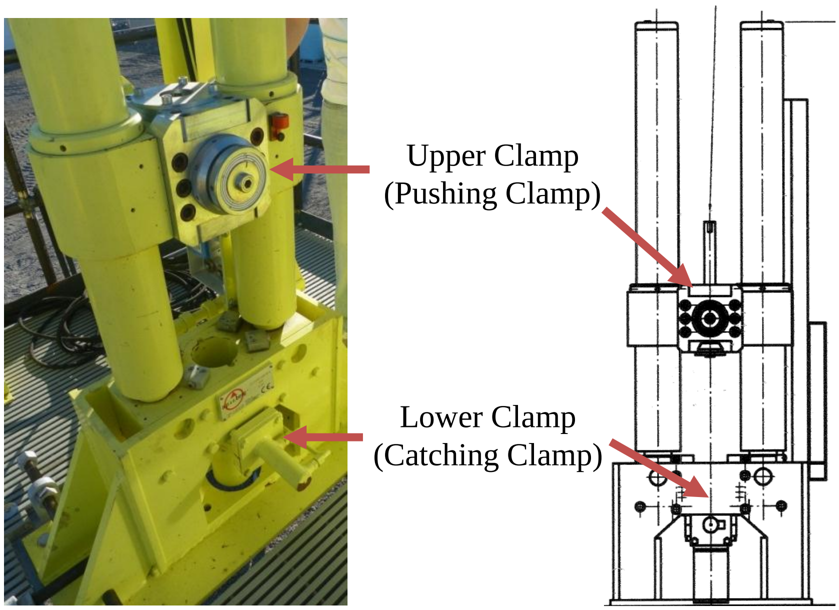
Figure 2-2. Cone Penetrometer Equipment on the Test Platform

For deployment operations, the rods were pre-strung with a data cable that connected the Icone device to the data collection system. Each rod was numbered, where rod number 1 connected directly to the Icone as the first attached rod.

[3] Icone is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.

The HYSON 200kN ram includes two hydraulically driven clamps. The upper clamp is termed the "pushing clamp" because it attaches to the rod by rising one meter from the lowest starting position and drives the unit down into the sludge in one meter increments. The lower clamp is termed the "catching clamp" because it is engaged after the rods have been pushed and functions to hold the rods and Icone in place while the ram is raised and the next rod is attached to the string. A front view photograph and schematic of the HYSON 200kN are shown in Figure 2-3.

Figure 2-3. HYSON 200kN Hydraulic Ram



The data collection system consists of a digital "cone" called the Icone and a digital data acquisition box called the Icontrol[4]. The Icone contains the load cell device and has a built-in analog-digital-conversion with a micro-controller, which provides a digital pathway to the Icontrol. The Icontrol is connected to the computer on which the data is to be recorded using a universal serial bus (USB) connection. The Icontrol combines depth, which is determined using a depth encoder that measures how far the unit has traversed by counting cycles of the hydraulic ram, with the obtained cone penetrometer resistance data and provides power to the Icone. The depth encoder connects to the Icontrol through the control panel.

A proprietary software called *GOnsite!*[5] was installed on the computer to record data and present results on the screen in real-time. The software is approved for use as Grade D - Acquired software and is registered in the Hanford Information Systems Inventory (HISI) under HISI identification number 3455. The software is managed through RPP-PLAN-55276, *Cone Penetrometer System Software Management Plan*, and was determined to be operational in RPP-RPT-56123, *Cone Penetrometer Software Acceptance Test Report*.

[4] Icontrol is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.
[5] *GOnsite!* is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.

2.2 Full-Flow Penetrometer Data Analysis Methodology

This section provides the empirical equations used to analyze the data collected using the full-flow ball penetrometer. Analysis was performed in the supporting Microsoft Excel[6] spreadsheet, *RPP-RPT-56585_R0.xlsx*, as verified in spreadsheet verification form (SVF) SVF-2887, using the equations provided here. The entire cone penetrometer data set can be found in the supporting spreadsheet.

Measurements of tip resistance are obtained continuously during penetration of the ball. This penetration resistance is used to determine the shear strength of the waste. Undrained shear strength (s_u) can be estimated as the ratio of net initial penetration resistance to the empirically determined undrained *N* Factor (N_k), as shown in Equation 1 ("Recommended Practice for Full-Flow Penetrometer Testing and Analysis," [DeJong, et. al., 2010]).

$$s_u = \frac{q_{net}}{N_k} \quad (1)$$

Where:

s_u	=	Undrained shear strength, Pa
q_{net}	=	Net penetration resistance (or q_{in}), Pa
N_k	=	Undrained *N* Factor (cone factor), dimensionless

However, the net penetration resistance is not directly measured by the full-flow penetrometer. There is an imbalance of forces above and below a full-flow probe due to overburden stress acting on the ball attachment and pore water pressure acting on the load cell. The measured penetration resistance can be corrected using Equation 2. This correction is appropriate for all measured penetration resistance values recorded using the cone penetrometer (i.e., both penetration and extraction) ("Use of Full Flow Penetrometers in Soft Clay," [Yafrate, 2008]). The equation is shown in a simplified and expanded form to equate to the intermediate calculation performed during data analysis.

$$\begin{aligned} q_{net} &= q_m - q_c \\ q_c &= \left[\sigma_{v0} - u_0(1-a)\right]\frac{A_{shaft}}{A_{ball}} \\ q_{net} &= q_m - \left[\sigma_{v0} - u_0(1-a)\right]\frac{A_{shaft}}{A_{ball}} \end{aligned} \quad (2)$$

Where:

q_m	=	Measured, uncorrected penetration resistance, Pa
q_c	=	Correction for measured penetration resistance, Pa
σ_{v0}	=	Total overburden stress, Pa
u_0	=	Hydrostatic pore pressure, Pa
a	=	Load cell area ratio, dimensionless
A_{shaft}	=	Cross-sectional area of shaft connecting to the ball attachment, m^2
A_{ball}	=	Cross-sectional area of ball attachment, m^2

[6] Microsoft Excel is a registered trademark of Microsoft Corporation, Redmond, WA.

The load cell area ratio (*a*) can be determined experimentally using a calibration vessel that allows water pressure to be applied. This value accounts for the internal pressure acting on the back of the Icone load cell (*Cone Penetration Testing in Geotechnical Practice*, [Lunne, et. al., 1997]). For the equipment used in testing, the manufacturer provided a numerical value of 0.75.

In many full-flow penetrometers, pore water pressure is measured directly through porous membranes located on the probe. Because of inherent constraints with operation in a radioactive waste environment and potential waste holdup, this system does not contain pore water sensors. However, research has shown the hydrostatic pressure can be substituted with relatively small error (DeJong, et. al., 2010). Hydrostatic pressure is found using Equation 3.

$$u_0 = \rho_{sup} \cdot g \cdot d \tag{3}$$

Where:

u_0	=	Hydrostatic head pressure, Pa
ρ_{sup}	=	Density of supernatant, kg/m^3
g	=	Acceleration due to gravity, m/s^2
d	=	Measurement depth, m

Overburden stress is included in the correction of measured penetration resistance to correct for an imbalance of forces above and below the ball attachment due to the shaft connecting to the top of the ball. The ball experiences downward force due to overburden stress as it is pushed through the sludge, but is prevented from experiencing that force on the very top edge of the ball due to the connecting shaft. This can be calculated using Equation 4.

$$\sigma_{v0} = \rho_{sl} \cdot g \cdot d \tag{4}$$

Where:

σ_{v0}	=	Overburden stress, Pa
ρ_{sl}	=	Density of the sludge, kg/m^3
g	=	Acceleration due to gravity, m/s^2
d	=	Measurement depth, m

The "measured penetration resistance" is not directly provided by the penetrometer software. Because various ball attachment sizes could potentially be used in penetrometer operations, the data logging system records the pushing force measured by the penetrometer load cell as it moves through the sludge. The cross-sectional area of the ball attachment is used to calculate penetration resistance of the full-flow penetrometer, as shown in Equation 5.

$$q_m = \frac{F_p}{A_{ball}} \tag{5}$$

Where:

F_p	=	Measured pushing force, N
A_{ball}	=	Cross-sectional area of ball attachment, m^2

The final component to determining shear strength from cone penetrometer measurements is the *N* Factor. The *N* Factor is an empirical value that is material dependent and also varies based on the roughness of the penetrometer. Direct tests of shear strength, such as shear vane measurements, occur under different strain rates and shear modes than penetrometer tests. The empirical *N* Factor is designed to account for that inherent difference ("Evaluation of Undrained Shear Strength of Busan Clay using CPT," [Hong, et. al, 2010]). For this reason, site specific empirical relationships calibrated against appropriate references are necessary to develop confidence in the undrained *N* Factors used in conjunction with full-flow penetrometer data (DeJong, et. al., 2010).

The most favorable method for determining the *N* Factor is by taking reference strength measurements in the same material as the cone penetrometer to relate the CPT data directly to shear strength. Unfortunately, measurements with a shear vane could not be made in situ for AN-101 and AN-106 sludge. Instead, measurements were performed in kaolin clay with strengths encompassing the approximate anticipated conditions of AN-101 and AN-106, as documented in RPP-RPT-56006, *Cone Penetrometer N Factor Determination Testing Results*. For kaolin clay ranging from about 2,200 Pa to 6,000 Pa, the undrained *N* Factor was found to be 11.5. Therefore, if the *N* Factor is known with confidence for the site at which the cone penetrometer is to be deployed, Equations 1 through 5 can be combined and rearranged to provide the undrained shear strength as a function of CPT resistance measurements and the undrained *N* Factor, as shown in Equation 6.

$$s_u = \frac{F_p - \left[(\rho_k \cdot g \cdot d) - (\rho_w \cdot g \cdot d)(1 - a)\right] A_{shaft}}{N_k \cdot A_{ball}} \tag{6}$$

However, as mentioned previously, the *N* Factor is highly material dependent. In the absence of site specific reference strength data to relate resistance to shear strength, the next best method for analyzing cone penetrometer measurements is to determine the *N* Factor using empirical models that are based on sensitivity. Sensitivity (S_T) is defined as the ratio of undisturbed undrained shear strength to totally remolded shear strength, as shown in Equation 7 (Lunne, et. al., 1997). Remolded shear strength (s_{ur}) typically provides important data for geotechnical applications as it represents the reformed strength a material returns to after it has been disturbed, but it also provides the necessary input to determine sensitivity.

$$S_T = \frac{s_u}{s_{ur}} \tag{7}$$

Previous full-flow ball penetrometer testing in soft clay has shown sensitivity is the property that primarily influences both the undrained and remolded *N* Factors (DeJong, et. al., 2010). In the absence of the site-specific data indicating the undrained and remolded shear strengths required for Equation 7, sensitivity can be determined empirically using Equation 8 ("Evaluation of Remolded Shear Strength and Sensitivity of Soft Clay Using Full-Flow Penetrometers," [Yafrate, et. al., 2009]). This equation requires cycling the cone penetrometer up and down through the sludge to reach a remolded state. Remolded penetration resistance (q_{rem}) is measured by cycling the penetrometer at a certain depth at least ten times, or until penetration resistance stabilizes to the point where additional cycling would result in a minimal reduction in strength, across a depth of at least three ball diameters (DeJong, et. al., 2010). Sensitivity calculated by this method can be compared to tests in kaolin clay to determine the similarities between the clay simulants and sludge waste, which will indicate whether the *N* Factor determined in RPP-RPT-56006 is appropriate for in situ investigations.

$$S_T = \left(\frac{q_{in}}{q_{rem}}\right)^{1.4} \tag{8}$$

Where:

S_T = Sensitivity, dimensionless
q_{in} = Corrected net penetration resistance for the initial push, Pa
q_{rem} = Corrected net penetration resistance in remolded state, dimensionless

If sensitivity is known, either from Equation 7 with site specific data or Equation 8 with cone penetrometer measurements, the undrained *N* Factor can be determined using Equation 9 (DeJong, et. al., 2010). The calculated *N* Factor can be substituted into Equation 6 to calculate shear strength based solely on in situ CPT measurements. This method will be used for comparison to the undrained *N* Factor determined in RPP-RPT-56006.

$$N_{k,calc} = 13.2 - \frac{7.5}{1 + \left(\frac{S_T}{10}\right)^{-3}} \tag{9}$$

Remolded shear strength can be determined with the cone penetrometer using the remolded penetration resistance and the remolded *N* Factor by Equation 10 (Yafrate, et. al., 2009). The remolded *N* Factor differs from the undrained *N* Factor and therefore must also be determined from site specific data ("Interpretation of Sensitivity and Remolded Undrained Shear Strength with Full Flow Penetrometers," [Yafrate and DeJong, 2006]).

$$s_{ur} = \frac{q_{rem}}{N_{rem}} \tag{10}$$

Where:

s_{ur} = Remolded shear strength, Pa
q_{rem} = Corrected net penetration resistance in remolded state, dimensionless
N_{rem} = Remolded *N* Factor, dimensionless

Similar to Equation 9, the remolded *N* Factor used to determine remolded shear strength in Equation 10 can be calculated using sensitivity as a primary input to the empirical correlation shown in Equation 11 (Yafrate, et. al., 2009).

$$N_{rem} = 13.2 + \frac{7.5}{1 + \left(\frac{S_T}{8}\right)^{-3}} \tag{11}$$

3.0 TEST DESIGN

The strategy for collecting in situ sludge waste measurements in AN-101 and AN-106 was documented in RPP-PLAN-56088, *Cone Penetrometer Tank Deployment Strategy*, which captured the important testing requirements. However, it should be noted that some of the requirements were slightly altered, per engineering guidance, between the AN-106 and AN-101 deployments based on operating experience. The specific strategy used for each tank is outlined in Sections 3.1 and 3.2.

The area ratio is defined as the ratio of the projected cross-sectional area of the penetrometer to the cross-sectional area of the shaft. Area ratio is a key component often cited when comparing test sites to one another and is a primary factor that can influence penetration resistance due to the difference in overburden stress acting above and below the penetrometer (DeJong, et. al., 2010). A penetrometer area ratio of 10:1 is recommended, although less than 10% variation in penetration resistance was observed between penetrometers with 10:1 and 5:1 area ratios.

The penetrometer used for in-tank data collection, originally designed to fit through a 4-inch diameter riser, involves a 20-mm diameter tapered shaft connecting to the 3-inch diameter ball, as shown in Figure 2-1. Therefore, the area ratio of the penetrometer used in this testing activity is 14.5:1. This provides context for comparing in-tank measurements to those taken in soft sediments at various test sites around the world using the same technology. Also, note the ratio of the ball to the 36-mm diameter Icone/connecting rods is 4.5:1.

It is recommended to obtain baseline “zero load” measurements before and after each sounding taken with a cone penetrometer in order to check changes due to malfunction or damage of the Icone. However, since the penetrometer was not extracted through the entire sludge layer using the HYSON system due to contamination concerns, the Icone could not be zeroed at the end of the test under the same conditions as the beginning of the test. Therefore, a proper system check could not be performed after completion of each CPT and subsequent data analysis required use of offsets to account for the difference in initial and final penetration resistance.

3.1 AN-101 Deployment Strategy

The CPT evaluation in AN-101 took place in Riser 009 on January 10, 2014, following AN-106 deployment on November 19, 2013. As a result, a few exceptions were made to the original strategy to allow for more efficient data collection.

Prior to any pushing with the HYSON, the ball attachment, Icone, and rods 1 and 2 were pre-installed in the upper spray ring and held in place with a manual clamp. Icone number 101024T was used in AN-101 operations (tested in RPP-RPT-56006 as “Unit 2”). Rod 3 was then attached to the string, the HYSON was raised 0.44 m, and the pushing clamp was engaged two inches below the top of the rod. At this time, data collection was initiated using the *GOnsite!* software in a file titled “AN-101 Testing 1” (shown as worksheet “AN1-T1” in *RPP-RPT-56585.xlsx*). Therefore the initial starting depth of the ball attachment was offset 3.23 m from the measured elevation of the pushing clamp at its lowest position.

The HYSON was used to attach and push rods 4 through 15 into the tank at the higher speed of roughly 5.5 cm/s. After attaching and pushing rod 15, the ball and Icone were submerged in the supernatant waste at an elevation of roughly 183 inches above the tank bottom, which was approximately 13 inches above the anticipated solids level.

Because the Icone was installed prior to the day of measurement, the unit was at ambient temperature at the start of testing. Previous testing and analysis, documented in RPP-RPT-55741, *Cone Penetrometer Load Cell Temperature and Radiation Testing Results*, indicated the Icone needs to equilibrate to the in situ temperature prior to recording data because the change in temperature will cause a shift in resistance readings. The AN-101 supernatant temperature was approximately 75 °F at the time of deployment (Personal Computer Surveillance Analysis Computer System [PCSACS], 2014). To avoid potential bias in the measurements as the Icone equilibrated from the ambient to in situ temperature, the unit was held at the 183-inch elevation for 90 minutes.

The *GOnsite!* software only records data over given depth intervals, so when the Icone is held at a constant depth, data is not recorded. A manual log was used to record the shift in resistance measurements as the Icone equilibrated to the supernatant waste temperature and the completed data sheet is shown in Appendix A. It was noted that after the 90-minute holding period the resistance values were still decreasing slightly, but testing was continued due to time constraints. Based on testing documented in RPP-RPT-55741, minimal additional shift is expected to have occurred.

Data collection was again initiated in a *GOnsite!* file titled “AN-101 Testing 2” (shown as worksheet “AN1-T2” in *RPP-RPT-56585.xlsx*). The HYSON was then used to push rods 16 through 20 into the sludge at a constant rate of 2 cm/s. Resistance force data from penetrating the sludge was recorded and later used to calculate the undrained shear strength profile. Data points were collected every 1 cm of depth traveled in order to provide a full sludge profile.

When the ball reached an elevation of approximately 67 inches above the tank bottom, the HYSON was extracted 1.24 m at 2 cm/s to a ball elevation of about 115 inches above the tank bottom. The HYSON was then lowered again and measurements of the sludge profile continued regularly. This operation was performed per engineering direction to acquire additional extraction data beyond the cycling at the lowest sludge depth. Some correlations found in literature use initial penetration and extraction data to empirically determine the *N* Factor, similar to Equation 8 (Yafrate, et. al., 2009). However, this extraction data was not used in analyzing the sludge because it is not a preferable replacement to using the remolded penetration resistance in Equation 8. Since remolded resistance was determined to be adequate, this data was not considered for calculating undrained and remolded *N* Factors.

At the conclusion of the initial push to approximately 15 inches above the tank bottom, RPP-PLAN-56088 recommended the HYSON be extracted 1.24 m and a new test be initiated for collecting cyclic data. Prior to cycling the penetrometer, another temperature equilibration period was planned due to the increased temperature between the supernatant and the sludge. However, during AN-106 deployment it was discovered the operation of collecting data occurred fast enough to where significant heating of the Icone would not be expected during cycling at the in situ sludge temperature of AN-101, which was approximately 97 °F at the time of deployment (PCSACS, 2014). Therefore, a second temperature equilibration in the sludge was not performed for AN-101 deployment.

Following the initial push and 1.24 m extraction, the penetrometer was cycled 10 times at 2 cm/s, with a cycle defined as both penetration and extraction of 1.24 m, to collect resistance measurements necessary for calculating remolded shear strength and sensitivity. The time between cycles was negligible and not recorded because the cycles were performed back-to-back.

3.2 AN-106 Deployment Strategy

The CPT evaluation in AN-106 took place in Riser 010 on November 19, 2013. Prior to any pushing with the HYSON, the ball attachment, Icone, and rods 1 and 2 were pre-installed in the upper spray ring and held in place with a manual clamp. Icone number 101023T was used in AN-106 operations (tested in RPP-RPT-56006 as "Unit 1"). Rod 3 was then attached to the string, the HYSON was raised 0.40 m, and the pushing clamp was engaged two inches below the top of the rod. At this time, data collection was initiated using the *GOnsite!* software in a file titled
"AN-106Testing 1a" (shown as worksheet "AN6-T1a" in *RPP-RPT-56585.xlsx*). Therefore the initial starting depth of the ball attachment was offset 3.27 m from the measured elevation of the pushing clamp at its lowest position.

The HYSON was used to attach and push rods 4 through 15 into the tank at the higher speed of roughly 5.5 cm/s. Operations were briefly stopped after pushing rod 10, per engineering direction, because the tip resistance was observed to have increased significantly from the starting point. A new test was initiated using *GOnsite!* in a file titled "AN-106Testing 11" (shown as worksheet "AN6-T1b" in *RPP-RPT-56585.xlsx*) to determine if the readings would persist. Rods 11 through 15 were subsequently deployed with the HYSON and elevated tip resistance measurements were no longer observed. The cause of the anomalous readings is unknown, but it is possible that the ball was contacting the guide sleeve as it was being deployed into the tank, producing positive force readings despite being well above the waste surface level. While it is not fully understood why the anomalous readings were observed, it is expected to have no impact on the sludge data collected from AN-106.

After attaching and pushing rod 15, the ball and Icone were submerged in the supernatant waste at an elevation of roughly 186 inches above the tank bottom, which was approximately 18 inches above the anticipated solids level.

Because the Icone was installed prior to the day of deployment, the unit was at ambient temperature at the start of testing. Previous testing and analysis, documented in RPP-RPT-55741, indicated the Icone needs to equilibrate to the in situ temperature prior to recording data because the change in temperature will cause a shift in resistance readings. The AN-106 supernatant temperature was approximately 90 °F at the time of deployment (PCSACS, 2014). To avoid potential bias in the measurements as the Icone equilibrated from the ambient to in situ temperature, the unit was held at the 186-inch elevation for 30 minutes. Note that the ambient temperature for AN-106 deployment was much warmer than for AN-101, which impacted the equilibration time.

The *GOnsite!* software only records data over given depth intervals, so when the Icone is held at a constant depth, data is not recorded. A manual log was used to record the shift in resistance measurements as the Icone equilibrated to the supernatant waste temperature and the completed data sheet is shown in Appendix A.

Data collection was again initiated in a *GOnsite!* file titled “AN-106Testing 2” (shown as worksheet “AN6-T2” in *RPP-RPT-56585.xlsx*). The HYSON was then used to push rods 16 through 20 into the sludge at a constant rate of 2 cm/s. Resistance force data from penetrating the sludge was recorded and later used to calculate the undrained shear strength profile. Data points were collected every 1 cm of depth traveled in order to provide a full sludge profile.

At the conclusion of the initial push to approximately 15 inches above the tank bottom the HYSON was extracted 1.24 m and a new test, “AN-106Testing 13,” was initiated for observing a potential shift in resistance values during sludge temperature equilibration. While temperature equilibration was not performed in AN-101 sludge, it was determined necessary in AN-106 because the in situ sludge temperature of AN-106 was approximately 134 °F at the time of deployment (PCSACS, 2014). The Icone was held in the sludge for 2 hours and 45 minutes prior to the start of cyclic testing. A manual log was used to record the shift in resistance measurements and the completed data sheet is shown in Appendix A.

After it was determined the Icone had equilibrated to the in situ sludge temperature, a new test was initiated in a *GOnsite!* file titled “AN-106Testing 3” for cyclic testing (shown as worksheet “AN6-T3” in *RPP-RPT-56585.xlsx*). The penetrometer was cycled 10 times at 2 cm/s, with a cycle defined as both penetration and extraction of 1.24 m, to collect resistance measurements necessary for calculating remolded shear strength and sensitivity. The time between cycles was negligible and not recorded because the cycles were performed back-to-back. However, it should be noted that the time between the initial push and the subsequent second cycle was 2 hours and 45 minutes due to temperature equilibration.

4.0 RESULTS AND ANALYSIS

Analysis was performed in a supporting Microsoft Excel spreadsheet, *RPP-RPT-56585_R0.xlsx*, as verified in SVF-2887. The entire cone penetrometer data set can be found in the spreadsheet.

Data analysis to determine the *N* Factor for using the cone penetrometer in three kaolin clay simulants ranging from about 2,200 Pa to 6,000 Pa was performed in the Microsoft Excel spreadsheet, *RPP-RPT-56006_R0.xlsx*, as verified in SVF-2863. The *N* Factor was determined by taking reference strength measurements with a handheld shear vane. The resulting 95% confidence interval for the undrained *N* Factor found in that analysis is shown in Table 4-1.

Table 4-1. Undrained *N* Factor Confidence Interval

Tanks 1, 2, & 3 Combined	
N_k Average	11.5
Standard Deviation	1.2
Number of Data Points	880
Z value	1.96
±	0.1
Lower Bound	11.4
Upper Bound	11.6

Note: Data taken from RPP-RPT-56006.

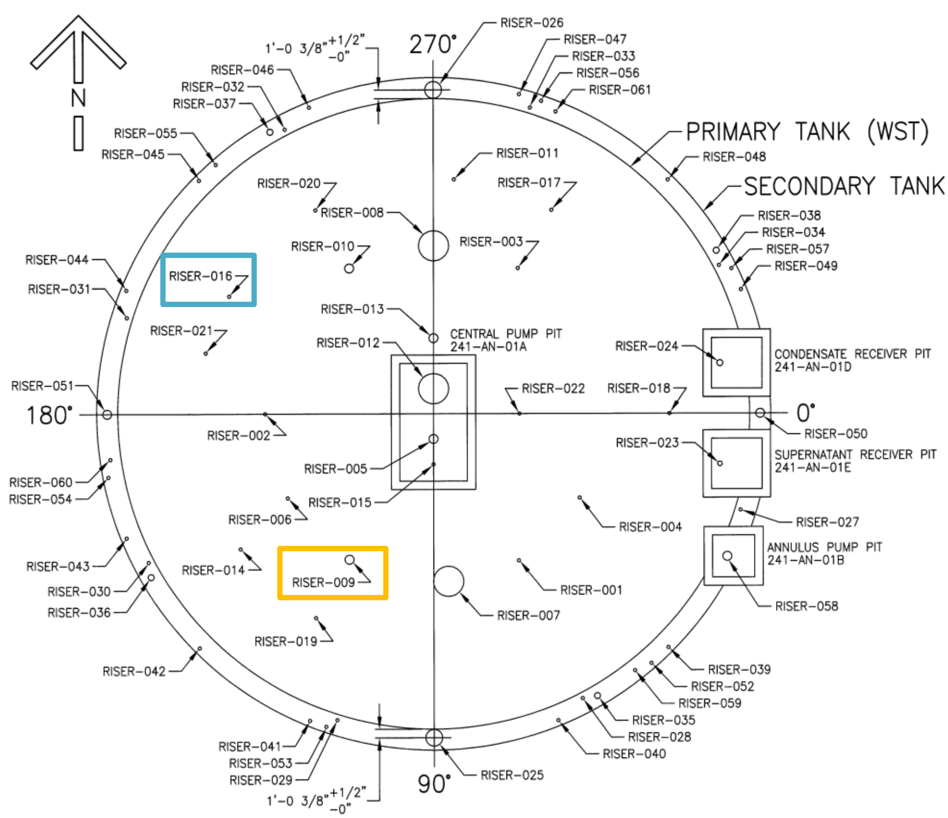
An undrained *N* Factor of 11.5 is used to calculate the undrained shear strength profiles for AN-101 and AN-106 sludge. Additionally, undrained and remolded *N* Factors are calculated based on cyclic measurements using Equations 9 and 11 for comparison. The comparison of AN-101 and AN-106 sludge waste to the kaolin clay test simulants is presented in Section 4.3.

4.1 AN-101 Results

Undrained shear strength was calculated with cone penetrometer measurements and an undrained *N* Factor of 11.5 using Equation 6. It was assumed that calculated shear strength of 200 Pa indicates initial contact of sludge waste (i.e., the supernatant and sludge interface). A threshold of 200 Pa was chosen because it provides a clear point of increase in force measurements from the Icone and once the 200 Pa level was surpassed, the shear strength did not drop below that value again for the remainder of the push. Based on this assumption, the cone penetrometer first contacted sludge waste at an elevation of 170.35 inches above the tank bottom.

Figure 4-1 shows the dome penetrations for AN-101. The cone penetrometer was deployed in Riser 009 (orange box), which is located 20 feet from the tank center at 120 degrees from zero (H-14-010501, Sh.1, R.22). A sludge weight measurement was taken in AN-101 on November 12, 2013 using Riser 016 (blue box), which indicated a sludge surface elevation of 169.88 inches above the tank bottom (TFC-WO-13-5586). Riser 016 is located 28 feet from the tank center at 210 degrees from zero. Based on the distances from the tank center, the sludge weight and cone penetrometer were deployed approximately 34 feet apart from one another.

Figure 4-1. Tank AN-101 Riser Location (H-14-010501, Sh.1, R.22)



The sludge weight and cone penetrometer provide independent measurements of the supernatant/sludge interface less than an inch apart from one another, despite being located in a different quadrant of the tank and on a different radial distance from the tank center, where the slurry distributor is located. It should be noted that no retrieval activities into AN-101 occurred between the sludge weight measurement and cone penetrometer deployment, but roughly two months passed between these activities, which may have allowed for some settling of previously retrieved solids to occur.

4.1.1 AN-101 Undrained Shear Strength

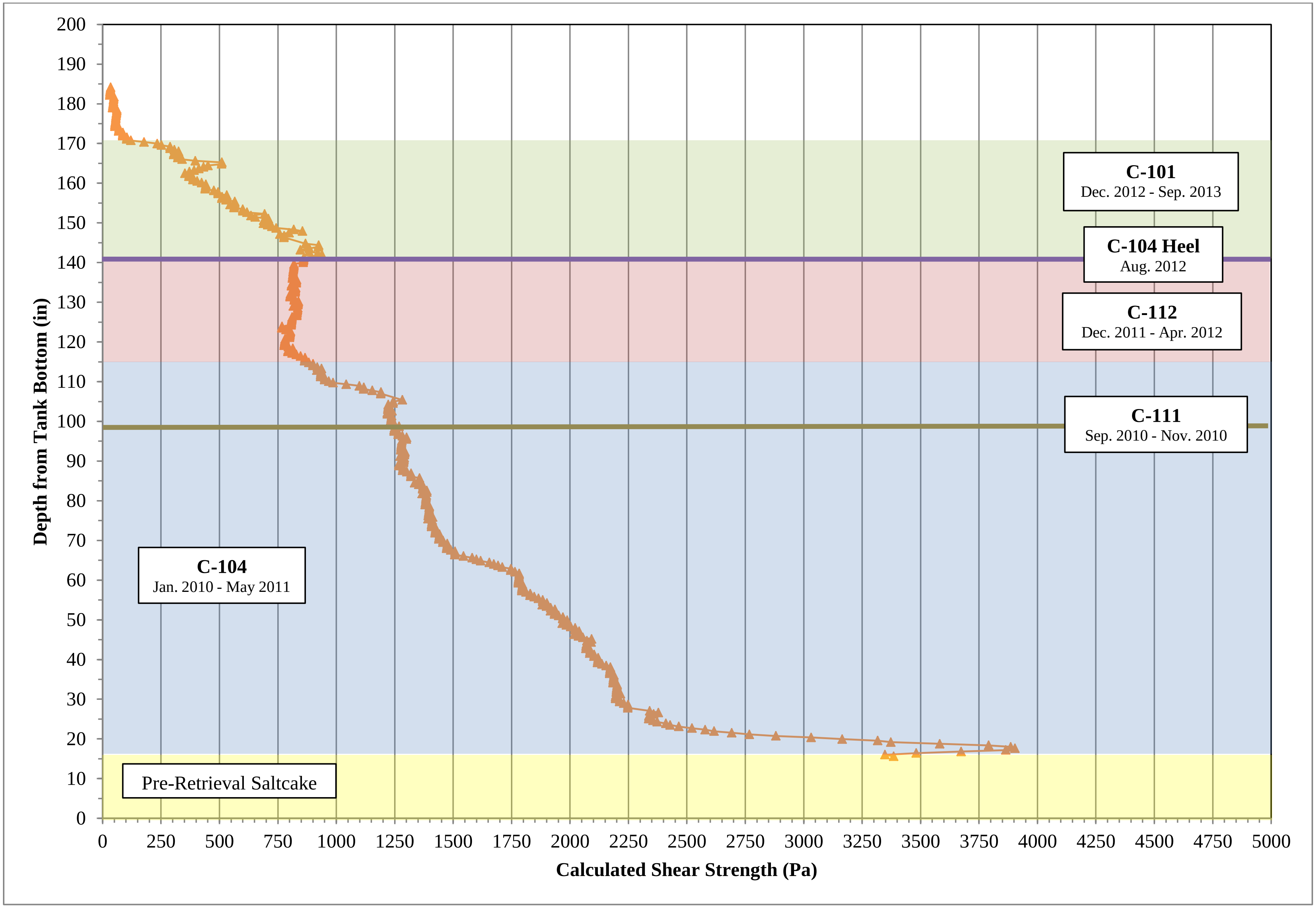
The calculated undrained sludge waste shear strength profile, determined using Equation 6 and an *N* Factor of 11.5, is shown in Figure 4-2. The orange triangles making up the profile show continuous measurements of the sludge waste undrained shear strength down to roughly 15 inches above the tank bottom.

The estimated depths of retrieved C Farm sludge currently residing in Tank AN-101 are overlaid on the plot. These sludge depths were determined using assumed retrieval waste volumes presented in the Microsoft Excel spreadsheet *SVF-2889, Rev. 0 – AN-101 and AN-106 Sludge Levels.xlsx*, verified in SVF-2889. The sludge depths presented in SVF-2889 indicate the sludge surface level to be located at approximately 163 inches from the tank bottom. Since the estimated sludge level was different from the measured sludge level based on the sludge weight and cone penetrometer measurements, the sludge volumes from each C Farm tank were increased by 3% to match up with the actual detected sludge surface level.

The sludge profile in Figure 4-2 shows shear strength increasing roughly uniformly with depth, which is a typical trend observed in soil and clay studies presented in literature (Lunne, et. al., 1997). When the penetrometer ball is submerged in the sludge to a depth of at least three diameters, undrained shear strength is measured at 400 Pa or greater. Shear strength increases with depth, reaching 1,000 Pa at the 110 inch elevation and increasing to about 3,300 Pa at the lowest measurement elevation.

Figure 4-2 shows a complete sludge profile with measurements recorded for every 1 cm of depth traveled. However, it should be noted that a few isolated data points were excluded from the plot due to measured penetration speeds below the required 2 cm/s. During deployment, rods are connected in one meter increments, requiring the HYSON system to start and stop pushing after every one meter of depth traveled. The resulting data shows the HYSON often requires at least 2 cm of travel depth before a steady measurement speed of 2 cm/s is achieved. Thus, individual data points recorded at the start or end of each rod push in the sludge were excluded from the plot because they produced anomalous results that are not representative of the actual in situ shear strength.

Figure 4-2. AN-101 Sludge Waste Undrained Shear Strength Profile



4.1.2 AN-101 Remolded Shear Strength

Remolded strength parameters were found after the initial full-depth push by cycling the penetrometer up and down ten times in 1.24-m increments at the lowest measured depth (from about 15 inches to 64 inches above the tank bottom). The resulting resistance measurements were corrected using Equation 2.

Sensitivity was calculated with Equation 8 using the resistance data from the initial push and the final push. The calculated sensitivity was then used to determine a remolded *N* Factor using Equation 11 and undrained *N* Factor using Equation 9. Resulting 95% confidence intervals for the three parameters are shown in Table 4-2.

Table 4-2. AN-101 Strength Parameter Confidence Intervals

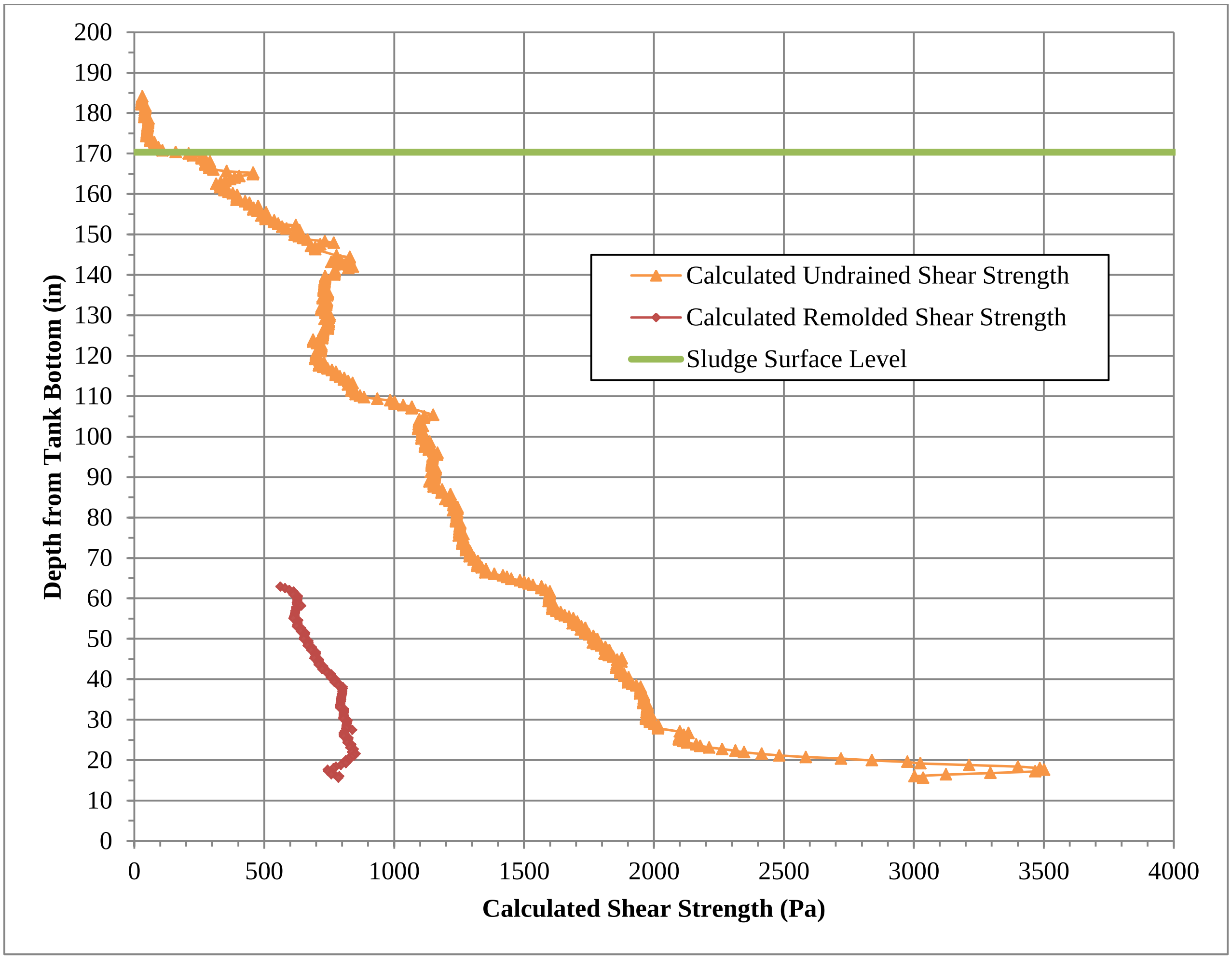
	S_T	N_{rem}	$N_{k,calc}$
Average	3.6	13.9	12.8
Standard Deviation	0.7	0.5	0.3
Number of Data Points	121	121	121
Z value	1.98	1.98	1.98
±	0.1	0.1	0.1
Lower Bound	3.5	13.8	12.7
Upper Bound	3.8	14.0	12.9

Using the undrained *N* Factor of 12.8, calculated with Equation 9, results in a shear strength profile with slightly lower strengths versus using the standard *N* Factor of 11.5 found during kaolin clay simulant testing. The calculated undrained shear strength profile, determined by applying $N_{k,calc}$ from Table 4-2 to the entire profile, is shown with orange triangles in Figure 4-3.

It should be noted that the calculated undrained *N* Factor from Table 4-2 was found using data collected only in the lower 1.24 m of sludge, but the profile presented in Figure 4-3 shows the calculated *N* Factor applied to the entire depth of sludge waste. This may introduce additional error in the shear strength measurements calculated at higher tank elevations.

The calculated remolded shear strength profile, determined by applying N_{rem} from Table 4-2 to the resistance measurements taken on the final 1.24-m cyclic push, is shown with red diamonds in Figure 4-3.

Figure 4-3. AN-101 Sludge Waste Remolded Shear Strength Profile



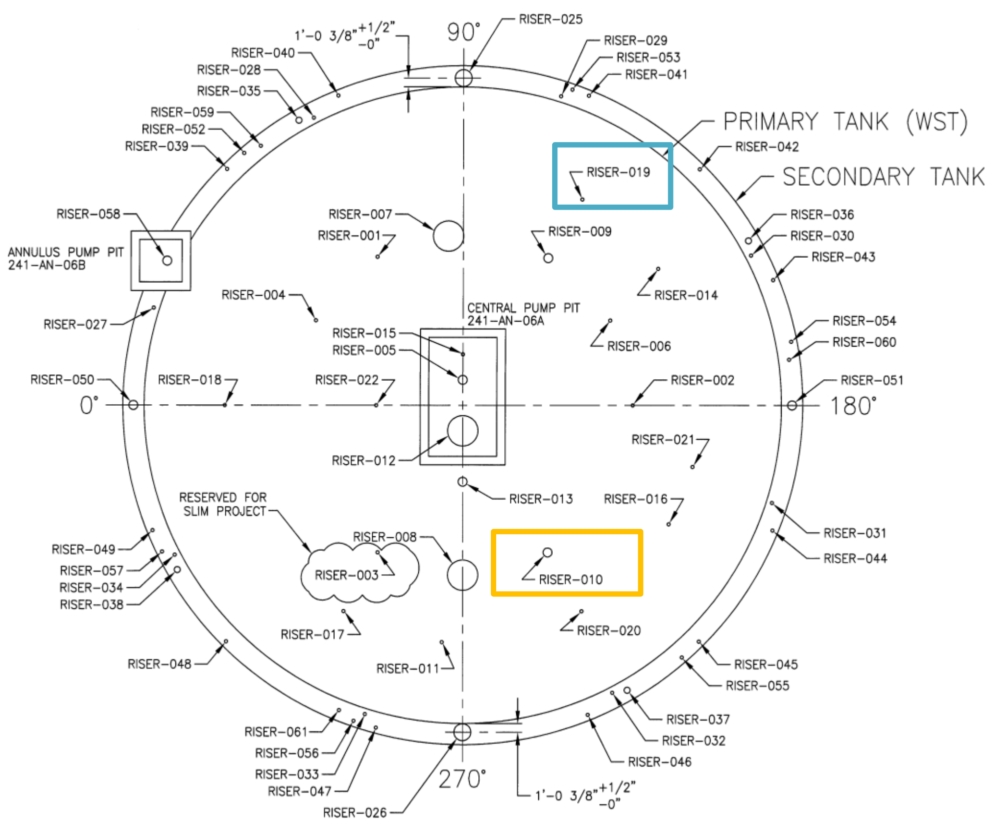
Since the standard *N* Factor is not significantly different from the empirically calculated undrained *N* Factor, the undrained shear strength profile does not change significantly. When applying a calculated undrained *N* Factor of 12.8, versus the nominal 11.5 value determined in kaolin clay simulant testing, the calculated undrained shear strength decreases by about 40 Pa in the upper portion of the sludge and about 120 Pa in the lower portion of sludge.

4.2 AN-106 Results

Undrained shear strength was calculated with Equation 6 using cone penetrometer measurements and an undrained *N* Factor of 11.5. It was assumed that calculated shear strength of 200 Pa indicates initial contact of sludge waste (i.e., the supernatant and sludge interface). A threshold of 200 Pa was chosen because it provides a clear point of increase in force measurements from the Icone and once the 200 Pa level was surpassed, the shear strength did not drop below that value again for the remainder of the push. Based on this assumption, the cone penetrometer first contacted sludge waste at an elevation of 157.07 inches above the tank bottom.

The cone penetrometer was deployed in Riser 010, which is located 20 feet from the tank center at 120 degrees from zero. A sludge weight measurement was taken in AN-106 on October 31, 2013 using Riser 019, which indicated a sludge surface elevation of 153.125 inches above the tank bottom (TO-040-560, "200 East/West Tank Farms Sludge Level Readings"). Riser 019 is located 28 feet from the tank center at 240 degrees from zero. Figure 4-4 shows the dome penetrations for AN-106. Based on the measurements from the tank center, the sludge weight and cone penetrometer were deployed approximately 42 feet apart from one another.

Figure 4-4. Tank AN-106 Riser Location (H-14-010501, Sh.6, R.18)



The sludge weight and cone penetrometer provide independent measurements of the supernatant/sludge interface less than three inches apart from one another, despite being located in a different quadrant of the tank and on a different radial distance from the tank center, where the slurry distributor is located. It should be noted that no retrieval activities into AN-106 occurred between the sludge weight measurement and cone penetrometer deployment.

4.2.1 AN-106 Undrained Shear Strength

The calculated undrained sludge waste shear strength profile, determined using Equation 6 and an *N* Factor of 11.5, is shown in Figure 4-5. The orange triangles making up the profile show continuous measurements of the sludge waste undrained shear strength down to roughly 15 inches above the tank bottom.

The estimated depths of retrieved C Farm sludge wastes currently residing in tank AN-106 are overlaid on the plot. These sludge depths were determined using assumed retrieval waste volumes presented in SVF-2889. The sludge depths presented in SVF-2889 indicate the sludge surface level to be located at approximately 227 inches from the tank bottom, but do not account for solids dissolution or volume changes due to mobilization and setting in the receiver tank. The depths of retrieved solids are also based on assumed pre-retrieval waste volumes in the single-shell tank. It is known that the actual sludge level significantly differs from the retrieval tracking volumes, but these volumes provide a best estimate of the ratio of C Farm sludge wastes to one another. Since the estimated sludge level was different from the measured sludge level based on the sludge weight and cone penetrometer measurements, the sludge volumes from each C Farm tank were decreased by about 69% to match up with the actual detected sludge surface level.

The sludge profile in Figure 4-5 shows shear strength increasing roughly uniformly with depth, which is a typical trend observed in soil and clay studies presented in literature (Lunne, et. al., 1997). When the penetrometer ball is submerged in the sludge to a depth of at least three diameters, undrained shear strength is measured at 800 Pa or greater. Shear strength increases with depth, reaching 1,800 Pa at the 120-inch elevation and increasing to about 4,000 to 5,000 Pa at the lowest measurement elevation, using an *N* Factor of 11.5.

Two large increases are shown in Figure 4-5; one at a depth of 97 inches above the tank bottom and another at 39 inches above the tank bottom. When looking at these increases, it is important to note that the reported values of shear strength can be a little misleading. Equation 6 is applicable in full-flow conditions where material is flowing around the 3-inch diameter ball. Therefore, while discrete data points are used to illustrate the shear strength profile, individual isolated points may not be representative of the true shear strength of the material at that location. Data points were collected every 1 cm of depth traveled, meaning the observed increased readings represent less than one ball diameter. While these readings do indicate that something more stiff was encountered, based on the surrounding trend it would not be appropriate to classify those increases as “layers” with shear strengths around 8,000 Pa due to the method by which the data is collected and analyzed. These increases cannot be fully explained, but may be an artifact of encountering a larger, sludge waste agglomerate that was pushed aside by the penetrometer, resulting in an initial increased force over a small depth interval before returning to more consistent readings.

Figure 4-5. AN-106 Sludge Waste Undrained Shear Strength Profile

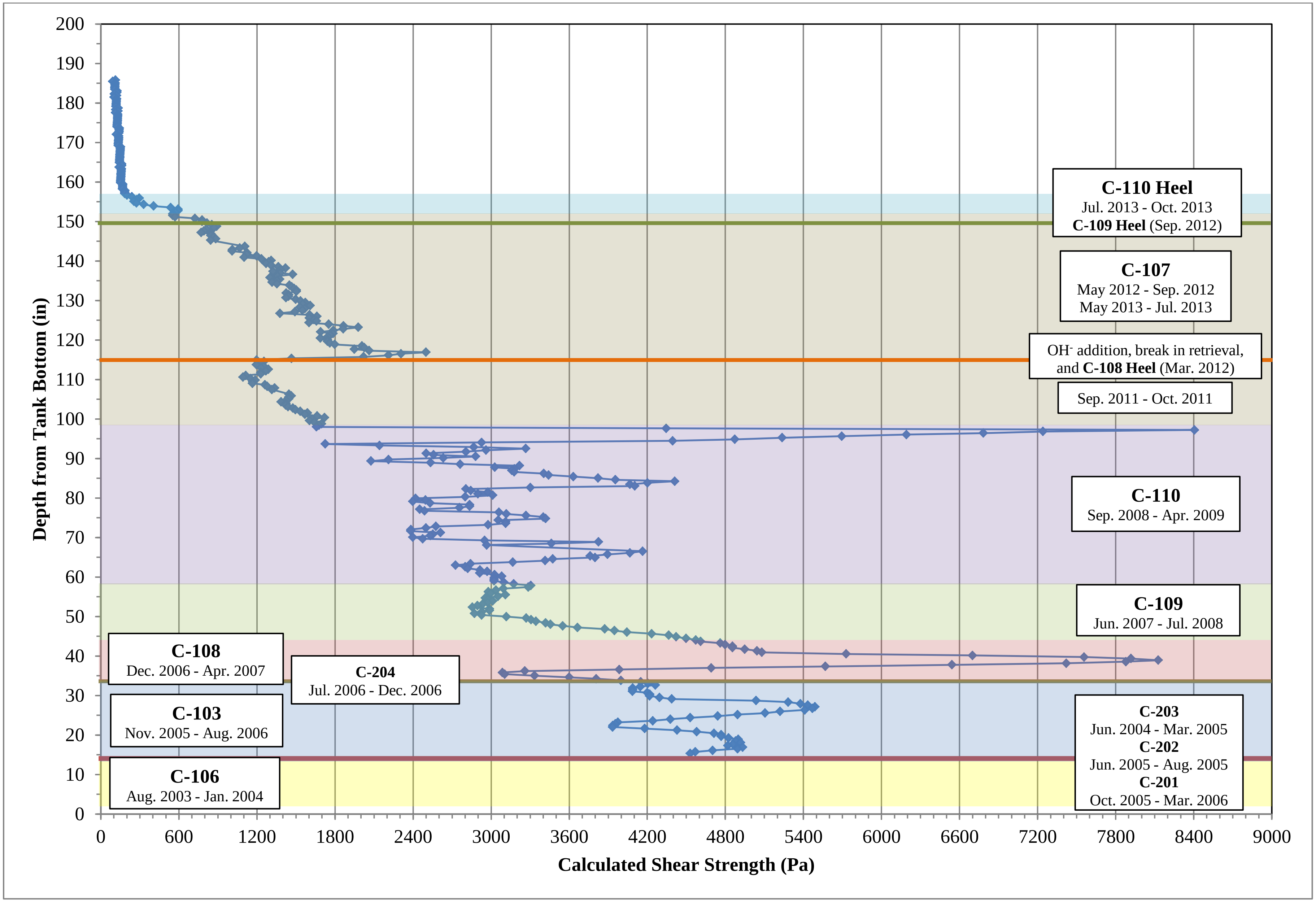


Figure 4-5 shows a complete sludge profile with measurements recorded for every 1 cm of depth traveled. However, it should be noted that a few isolated data points were excluded from the plot due to measured penetration speeds below the required 2 cm/s. During deployment, rods are connected in one meter increments, requiring the HYSON system to start and stop pushing after every one meter of depth traveled. The resulting data shows the HYSON often requires at least 2 cm of travel depth before a steady measurement speed of 2 cm/s is achieved. Thus, individual data points recorded at the start or end of each rod push in the sludge were excluded from the plot because they produced anomalous results that are not representative of the actual in situ shear strength.

Figure 4-5 shows a clear decrease in shear strength at the 115-inch depth. The decrease lines up with the assumed sludge depth in March 2012, following the small C-108 heel retrieval, after a significant break in single-shell tank retrieval took place. Tank C-108 retrieval included a sodium hydroxide addition to convert gibbsite to sodium aluminate, which was then dissolved with a water wash. Following C-108 heel retrieval, prior to continuing retrieval of C-107 sludge, approximately 17,000 gal of 50 weight percent sodium hydroxide were added to AN-106 for corrosion control purposes (Tank Waste Information Network System [TWINS], 2014). Since the trending decrease in strength persisted for roughly 15 inches, before increasing to expected strengths indicative of linear strength increases with depth, it is possible addition of the caustic-rich material resulted in a decrease in strength for the recently retrieved C-107 sludge.

There is significantly more scatter in the AN-106 cone penetrometer data versus the AN-101 data. The reason for the differences is not fully understood at this time, although based on the assumed layering of C Farm sludge, it appears to be primarily attributed to C-110 retrieved sludge waste. Tank C-110 primarily consisted of first cycle decontamination waste from the Bismuth Phosphate process (1C waste), which was expected to be very similar to the previously retrieved sludge from C-103, C-108, and C-109 (RPP-RPT-43037, *2009 Auto-TCR for Tank 241-C-110*). It should be noted that C-110 contained higher solids loading in the retrieved slurry during the initial retrieval stage than its other C Farm retrieval predecessors due to the capability of a newly installed slurry pump. Solids concentration was calculated at 25.9% solids by volume in the C-110 slurry, versus only 7 to 11% bulk volume for C-103, C-108, and C-109, which were also retrieved via modified sluicing (RPP-56214, *Retrieval Completion Certification Report for Tank 241-C-110*). The higher solids concentration may have affected the sludge settling or particle size distribution, resulting in a less physically uniform settled sludge layer. While there is no clear indication as to why C-110 sludge would behave differently from other sludge wastes retrieved into AN-106, the general upward trend of increased shear strength with depth is still consistent, despite the scatter.

It is also clear that the overall strength of AN-106 sludge waste is significantly greater than AN-101. It's possible the time component of sludge consolidation plays a role since a majority of the sludge waste has been compacting in AN-106 for at least five years, versus the more recent retrievals into AN-101. As additional sludge is retrieved into these two tanks, the shear strength would also be expected to rise in each tank due to the increased overburden stress. Despite the differences in the calculated shear strengths, it is important to note that the upward trend in shear strength with depth remains relatively constant when looking at the AN-106 profile as a whole.

4.2.2 AN-106 Remolded Shear Strength

Remolded strength parameters were found after the initial full-depth push by cycling the penetrometer up and down 1.24 m twelve times at the lowest measured depth (from about 15 inches to 64 inches above the tank bottom). The resulting resistance measurements were corrected using Equation 2. Sensitivity was calculated with Equation 8 using the resistance data from the initial push and the final cyclic push. The calculated sensitivity was then used to determine a remolded *N* Factor using Equation 11 and an undrained *N* Factor using Equation 9. Resulting 95% confidence intervals for the three parameters are shown in Table 4-6.

Table 4-3. AN-106 Strength Parameter Confidence Intervals

	S_T	N_{rem}	$N_{k,calc}$
Average	11.8	18.6	8.9
Standard Deviation	3.8	1.0	1.2
Number of Data Points	106	106	106
Z value	1.98	1.98	1.98
±	0.7	0.2	0.2
Lower Bound	11.1	18.4	8.7
Upper Bound	12.5	18.8	9.1

Table 4-3 shows that AN-106 sludge is much more sensitive than AN-101 sludge or kaolin clay simulants used in testing activities. Higher sensitivity means the shear strength in the remolded condition varies more significantly from the undrained shear strength. Previous full-flow ball penetrometer testing in soft clay has shown sensitivity as the property that primarily influences both the undrained and remolded *N* Factors (DeJong, et. al., 2010). Thus, the remolded and undrained *N* Factors calculated with Equation 11 and Equation 9, respectively, differ significantly from the values determined from testing in kaolin clay (RPP-RPT-56006). The smaller undrained *N* Factor results in an increased calculated shear strength profile with the increase more prevalent at higher strengths.

The calculated undrained shear strength profile, determined by applying $N_{k,calc}$ from Table 4-3 to the entire profile, is shown with blue diamonds in Figure 4-6. It should be noted the calculated undrained *N* Factor from Table 4-3 was found using data collected only in the lower 1.24 m of sludge, but the profile presented in Figure 4-6 shows the calculated *N* Factor applied to the entire depth of sludge waste. This may introduce additional error in the shear strength measurements calculated at higher tank elevations.

The calculated remolded shear strength profile, determined by applying N_{rem} from Table 4-3 to the resistance measurements taken on the final 1.24-m cyclic push, is shown with green triangles in Figure 4-6.

Figure 4-6. AN-106 Sludge Waste Remolded Shear Strength Profile

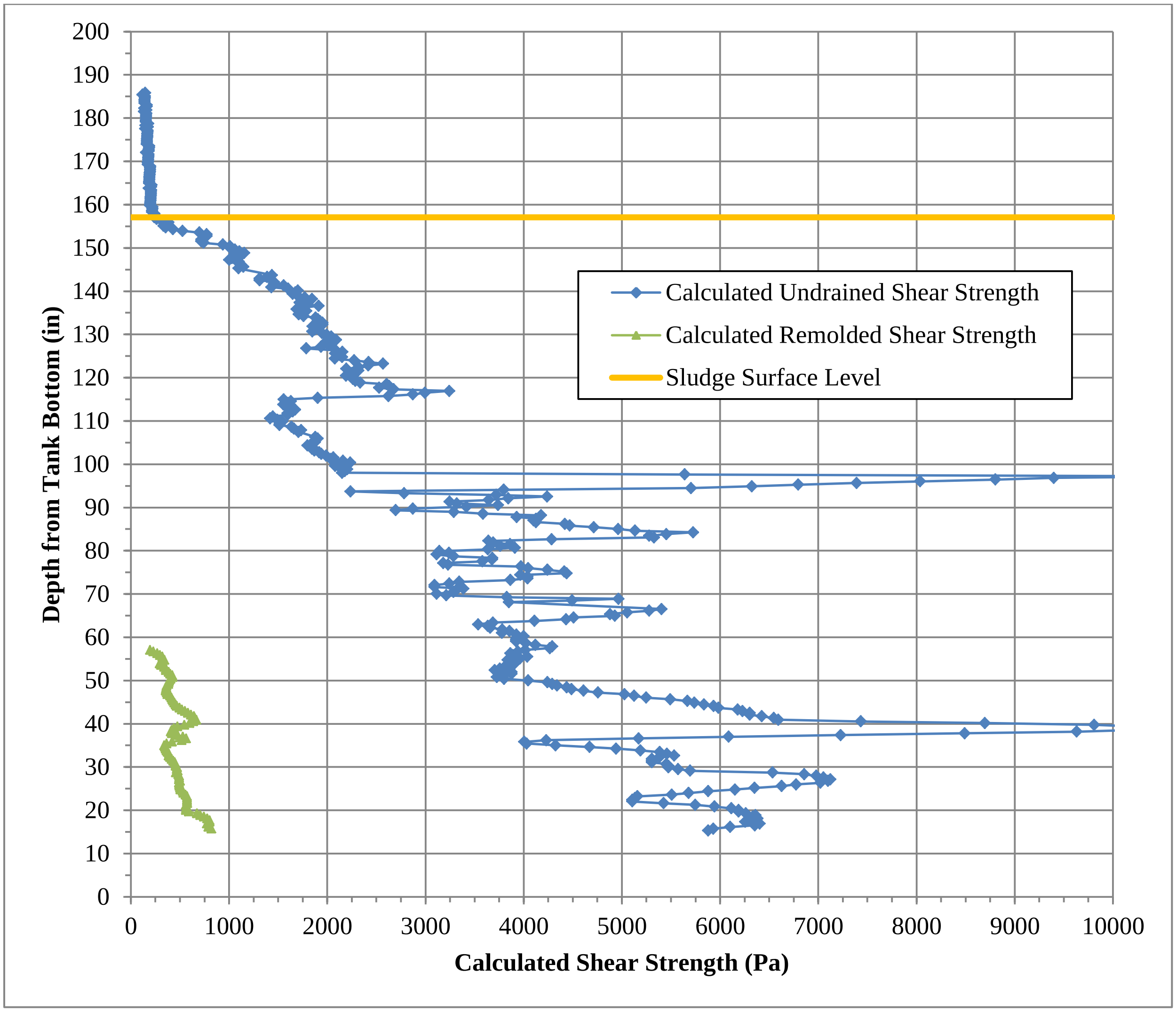


Figure 4-6 shows that when using a calculated undrained *N* Factor of 8.9, versus the nominal 11.5 value determined in kaolin clay simulant testing, the undrained shear strength increases by about 100 Pa for the upper portion of sludge, by about 1,000 Pa for the middle portion of sludge, and by about 1,300 Pa for the lowest depth of sludge.

4.3 Comparison to Kaolin Clay Test Simulants

Kaolin clay is often used to simulate the physical properties of Hanford sludge waste. The full-flow penetrometer system was tested in three kaolin clay/water simulants, designed to encompass the anticipated sludge shear strengths in AN-101 and AN-106. Testing aimed to determine the undrained *N* Factor for the 3-inch diameter ball full-flow penetrometer, as documented in RPP-RPT-56006. The compositions for the three simulants and the shear strengths, measured with a handheld shear vane device, are shown in Table 4-4.

Table 4-4. Kaolin Clay Test Simulants

	Tank 1	Tank 2	Tank 3
Average Weight % Kaolin	60.4%	64.0%	66.0%
Average Shear Strength (Pa)	2,200	4,000	6,000

Note: Data was taken from RPP-RPT-56006.

Remolded and undrained shear strengths were also determined from the cyclic penetrometer measurements taken in each kaolin simulant using the empirical equations shown in Section 2.2. The resulting calculated strengths are shown in Table 4-5. Note the vane measured shear strengths were slightly higher than the empirically determined undrained shear strengths for each tank, but were in general agreement. Based on Figure 4-2 and Figure 4-5, the kaolin clay simulant adequately encompassed the in situ undrained shear strengths for the bulk of AN-101 and AN-106 sludge.

Table 4-5. Remolded and Undrained Shear Strengths for Kaolin Clay Simulants

	Tank 1		Tank 2		Tank 3	
	s_{ur} (Pa)	s_u (Pa)	s_{ur} (Pa)	s_u (Pa)	s_{ur} (Pa)	s_u (Pa)
Average	810	2090	1470	3340	2090	5110
Standard Deviation	220	130	140	387	500	570
Number of Data Points	51	51	51	51	44	44
Z value	1.96	1.96	1.96	1.96	1.96	1.96
±	60	40	40	110	150	170
Lower Bound	750	2050	1430	3230	1940	4940
Upper Bound	870	2130	1510	3450	2240	5280

Note: Data was taken from RPP-RPT-56006.

The sensitivity and remolded *N* Factor were also empirically calculated for the kaolin clay simulants using equations shown in Section 2.2. The resulting 95% confidence intervals are shown in Table 4-6.

Table 4-6. Remolded Strength Parameters for Kaolin Clay Simulants

	S_T	N_{rem}
Average	3.4	13.8
Standard Deviation	1.6	0.7
Number of Data Points	146	146
Z value	1.96	1.96
±	0.3	0.1
Lower Bound	3.1	13.7
Upper Bound	3.7	13.9

Note: Data was taken from RPP-RPT-56006.

From the tank sludge cyclic penetrometer measurements taken between 15 inches and 64 inches above the tank bottom, the sensitivity was calculated as 3.6 ± 0.1 in AN-101 and 11.8 ± 0.7 in AN-106. Based on that in situ data, AN-101 sludge appears to behave very similarly to kaolin clay simulant when it is disturbed, but AN-106 sludge is appears to be much more sensitive than either AN-101 sludge or kaolin clay simulants. This means the AN-106 sludge reforms at a much lower strength relative to the original undisturbed, undrained shear strength than AN-101 sludge or kaolin clay mixtures.

Previous full-flow ball penetrometer testing in soft clay has shown sensitivity is the property that primarily influences both the undrained and remolded *N* Factors (DeJong, et. al., 2010). This indicates that the undrained *N* Factor of 11.5, determined through testing the penetrometer in kaolin clay, may not be appropriate to use in analyzing the AN-106 sludge. As a result, both Figure 4-5 and Figure 4-6 should be considered when reporting undrained shear strength for AN-106 sludge.

4.4 Comparison to Soft Clay Test Sites

Consistent trending of increasing shear strength with depth was observed in both AN-101 and AN-106 sludge. This behavior is anticipated based on observations in soil. In a fresh, fully consolidated soil, the effective overburden stress increases relatively uniformly with depth. For that normally consolidated soil deposit, the uniform increase in overburden stress is typically associated with a decrease in moisture content, resulting in a uniform increase in shear strength. The same relationship is true for normally consolidated clay deposits, where the ratio of shear strength to overburden stress is constant between depths ("Shearing Strength of Soils," [Raymond, 1997]). This trend is typical of highly characterized clay sites worldwide presented in literature (Yafrate, 2008). The in situ AN-101 and AN-106 measurements suggest the sludge wastes do not behave differently in this manner than normally consolidated clay or soil deposits.

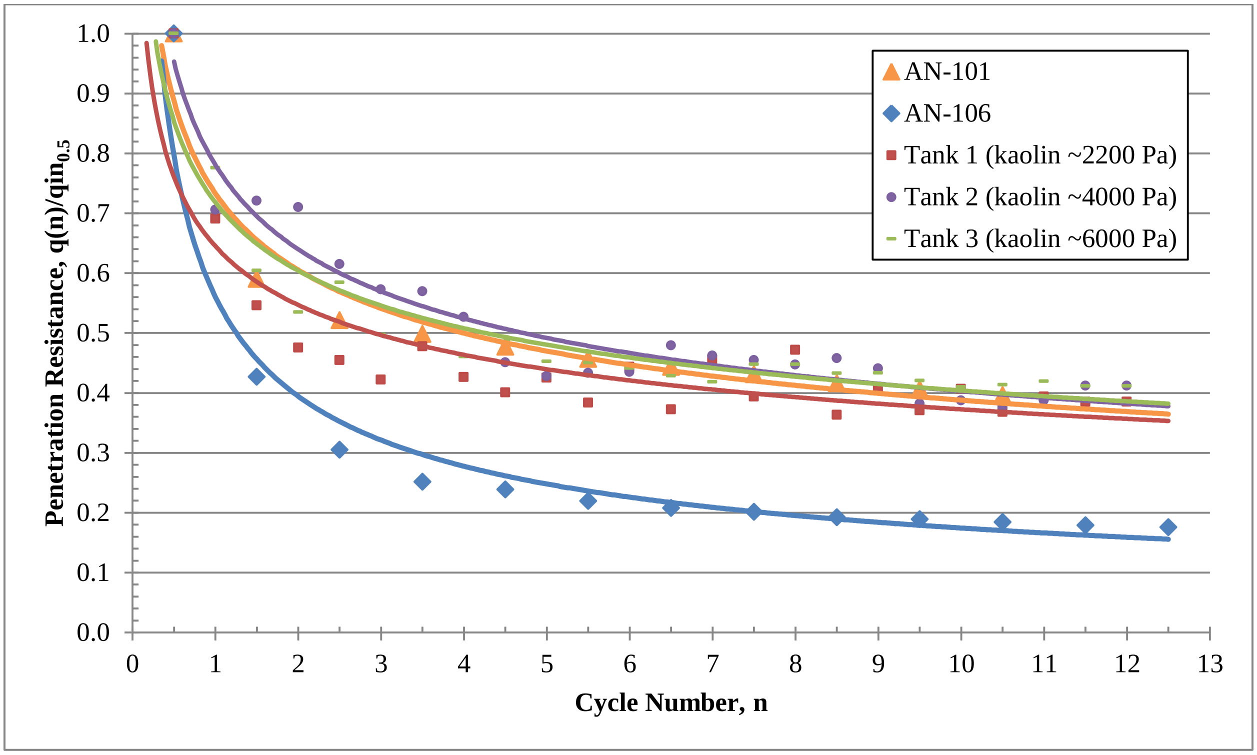
When cycling the cone penetrometer to determine remolded shear strength, data is collected for both penetration and extraction. The penetration data points are referred to as q_{in} and the extraction data points are referred to as q_{ext}. To distinguish between subsequent pushes, the variables are simplified to q_i where "i" represents the penetration or extraction cycle in increments of 0.5. For instance, typically $q_{0.5}$ represents the initial penetration, q_1 represents the initial extraction, $q_{1.5}$ represents the second penetration, etc.

Theoretically, q_{ext} data should be close in magnitude, but with an opposite sign (negative) to q_{in}, and should decrease in magnitude with subsequent pushes during cyclic testing. At the remolded condition, the extraction and penetration resistances should be equal. However, there is a cyclic offset between the penetration and extraction when using full-flow ball penetrometers, as noted in literature. The source of the offset is largely undetermined, but may be influenced by several factors, including potential changes in overburden stress or the presence of the push rod resulting in different projected areas based on the direction of movement during penetration or extraction (Yafrate, 2008).

Cyclic degradation curves are used to show the change in measurements as the penetrometer is cycled and inherently contain information regarding remolded strength and sensitivity. The degradation curve is shown as a plot of normalized penetration resistance (q_i/q_{in}) versus the cycle number, where the initial push is numbered 0.5 and the initial extraction is numbered 1. Using normalized penetration resistance enables comparison to data taken from other test sites. Typically, a cyclic offset, which is calculated as half the difference between the final penetration and extraction resistance measurements at the remolded condition, is applied to the entire data set to create a smooth curve. Examples of cyclic degradation curves for a number of soft clay test sites around the world, with varying shear strengths and sensitivities, are presented in Yafrate, et. al., 2009.

Cyclic degradation plots were developed using the penetrometer data from AN-101, AN-106, and kaolin clay simulants. However, the extraction data (q_{ext}) was not utilized in developing the cyclic plots for AN-101 and AN-106 because the extracted force readings were shown to be significantly lower than the resistance measurements determined during each push ($q_{in,i}$). This may be indicative of insufficient overburden stress at the depths tested in the tanks, resulting in formation of an open cavity behind the penetrometer. Since the extraction data was not included, a cyclic offset also was not applied for the AN-101 and AN-106 data. The cyclic degradation curves are shown in Figure 4-7.

Figure 4-7. Cyclic Degradation Curves for AN-101, AN-106, and Kaolin Simulant



Comparing Figure 4-7 with testing presented in literature, the degradation curves appear to trend similarly, with decreasing penetration resistance between pushes consistent with a power function curve. The material in AN-101 and simulant test Tanks 1, 2, and 3 were each shown to have sensitivities between 3.0 and 3.8. The final normalized penetration resistance for each settled at about 0.40; consistent with the Burswood and Onsøy test sites, which had sensitivities of 3.8 and 6.0, respectively (Yafrate, et. al., 2009).

Figure 4-7 also further demonstrates the difference observed in AN-106 measurements, which show a calculated sensitivity of 11.8. The AN-106 normalized penetration resistance settled at about 0.18; consistent with the more sensitive Amherst and Louiseville test sites, which had sensitivities of 7.3 and 22, respectively (Yafrate, et. al., 2009).

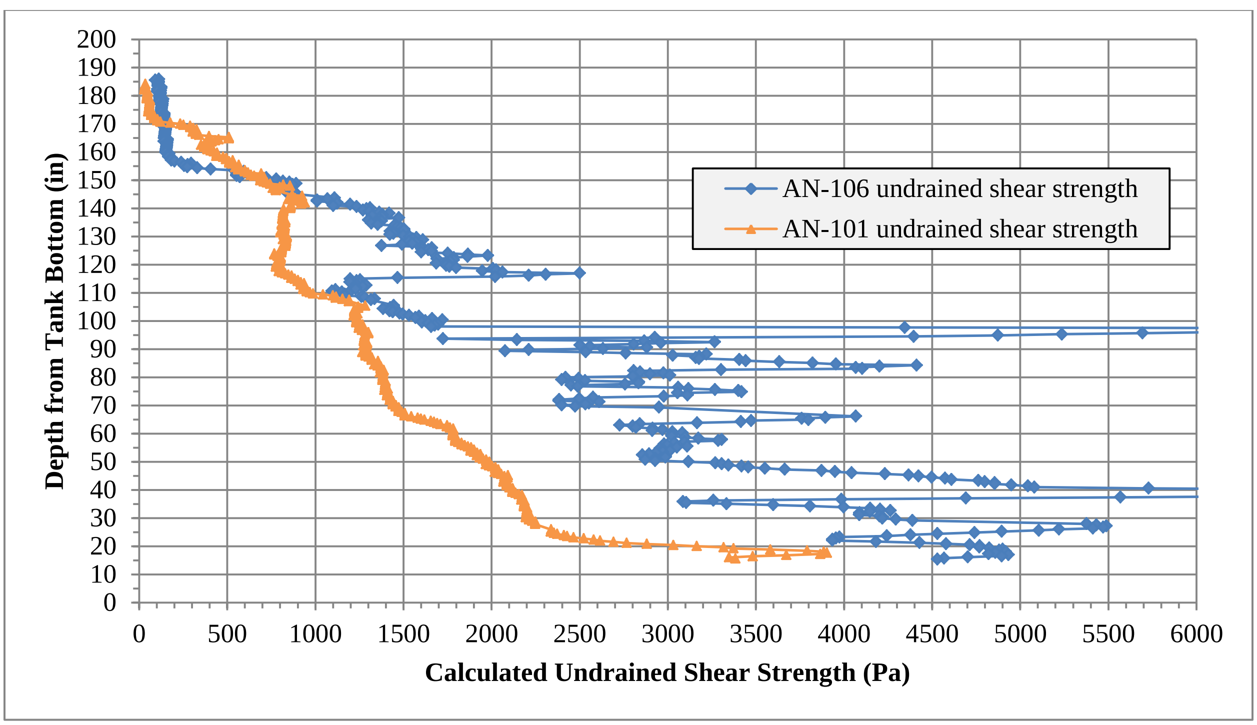
5.0 CONCLUSIONS

Full-flow cone penetrometer measurements taken in Tank AN-101 sludge waste on January 10, 2014 indicate a shear strength profile that increases roughly uniformly with depth. The undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 3,300 Pa at 15 inches above the tank bottom, for a standard undrained *N* Factor of 11.5. Tank AN-101 sludge was measured between 15 inches and 64 inches above the tank bottom and was found to have a sensitivity of 3.6, which is very similar to kaolin clay/water simulants used in *N* Factor determination testing (RPP-RPT-56006). The remolded shear strength was found to vary between 500 Pa and 800 Pa in the region 15 inches to 64 inches above the tank bottom.

The CPT measurements taken in Tank AN-106 sludge waste on November 19, 2013 indicate a shear strength profile that also increases roughly uniformly with depth. The undrained shear strength was calculated to range from 500 Pa near the sludge surface to roughly 5,000 Pa at 15 inches above the tank bottom, for a standard undrained *N* Factor of 11.5. Tank AN-106 sludge was measured between 15 inches and 64 inches above the tank bottom and was found to have a sensitivity of 11.8. The remolded shear strength was found to vary between 200 Pa and 800 Pa in the region from 15 inches to 64 inches above the tank bottom.

Plots of undrained shear strength for both AN-101 and AN-106 are shown side by side in Figure 5-1. It is clear that the overall strength of AN-106 sludge waste is significantly greater than AN-101. This may be attributed to the time component of sludge consolidation since the majority of sludge waste has been compacting in AN-106 for at least five years, versus the more recent retrievals into AN-101. As additional sludge is retrieved into these two tanks, the shear strength would also be expected to rise in each due to the increased overburden stress.

Figure 5-1. AN-101 and AN-106 Sludge Shear Strength



Both tanks showed similar remolded shear strengths, but the higher undrained shear strength found in AN-106 means the AN-106 sludge is much more sensitive than AN-101 sludge. The AN-106 sludge also appears to be much more sensitive than the kaolin clay simulant used in *N* Factor determination testing. Industry testing of full-flow ball penetrometers in soft clay has shown sensitivity is the property that primarily influences both the undrained and remolded *N* Factors (DeJong, et. al., 2010). Therefore, using the standard undrained *N* Factor of 11.5 may not be appropriate for AN-106 sludge. If an empirically calculated *N* Factor of 8.9 is applied across all depths of AN-106 sludge, the shear strength is shown to increase by about 100 Pa for the upper portion of sludge, about 1,000 Pa for the middle portion of sludge, and around 1,300 Pa for the lowest depth of sludge. The shear strength profile is shown with an *N* Factor of 11.5 in Figure 4-5 and with the empirically determined *N* Factor of 8.9 in Figure 4-6. Both profiles should be considered when evaluating physical properties of AN-106 sludge waste.

Cone penetrometer measurements in both AN-101 and AN-106 sludge indicate the undrained shear strength increases roughly uniformly with depth. This behavior is expected based on similar testing performed in soft, normally consolidated clays at test sites globally (Yafrate, et. al., 2009). For a normally consolidated clay deposit, uniform increase in overburden stress is typically associated with a decrease in moisture content, resulting in a uniform increase in shear strength, which means the ratio of shear strength to overburden stress between depths is constant (Raymond, 1997). Comparison of in situ data to other soft-clay sites investigated with full-flow penetrometers suggests AN-101 and AN-106 sludge wastes do not behave differently, in this regard, than other normally consolidated clay or soil deposits.

6.0 REFERENCES

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APPENDIX A

TANK DEPLOYMENT DATA SHEETS

AN-101 Temperature Equilibration Data Sheet

Data Collector	Date	Depth (m)	Cone ID
Jordan Follett	1/10/2014	12.45 m	101024 T

Time	Tip Resistance (kN)	Local Friction (mPa)	Inclination (°)
0:00 (1045)	0.022	-0.001	0.3
0:02	0.031	-0.001	0.1
0:04	0.037	-0.002	0.2
0:06	0.040	-0.002	0.1
0:08	0.041	-0.002	0.2
0:10	0.042	-0.002	0.2
0:15	0.041	-0.002	0.2
0:20	0.040	-0.002	0.2
0:25	0.039	-0.002	0.2
0:30	0.038	-0.002	0.2
0:40	0.037	-0.002	0.2
0:50	0.036	-0.002	0.3
1:00	0.036	-0.002	0.2
1:10	0.035	-0.002	0.4
1:20	0.034	-0.002	0.4
1:30	0.034	-0.002	0.4

Comments	
	→ started test ~2 inches from the top of Rod 3 (0.0m) → data recorded in project 'AN-101 Testing' file 'Test 1' → started equilibration recording at the end of Rod 15 push → values may be trending downward slightly, but moving ahead with measurements due to minimal shift and time constraint

AN-106 Temperature Equilibration Data Sheet (1)

Data Collector	Date	Depth (m)	Cone ID
Jordan Follett	11/19/2013	4.98 m after end of Test I	101023T

Time	Tip Resistance (kN)	Local Friction (mPa)	Inclination (°)
0:00	-0.009	0.000	0.1
0:02	-0.005	0.000	0.1
0:04	-0.001	0.000	0.2
0:06	-0.000	-0.001	0.3
0:08	-0.001	-0.001	0.3
0:10	-0.001	-0.001	0.3
0:12	-0.001	-0.001	0.4
0:14	-0.002	-0.001	0.3
0:16	-0.003	-0.001	0.4
0:18	-0.003	-0.001	0.3
0:20	-0.004	-0.001	0.4
0:22	-0.004	-0.001	0.4
0:24	-0.005	-0.001	0.4
0:26	-0.005	-0.001	0.4
0:28	-0.005	-0.001	0.4
0:30	-0.006	-0.001	0.4

Comments	
	→ Rod 15 has been pushed → Both Test I and Test II are completed

AN-106 Temperature Equilibration Data Sheet (2)

Data Collector	Date	Depth (m)	Cone ID
Jordan Follett	11/19/2013	End of Test 2 (3.1 m)	101023T

Time	Tip Resistance (kN)	Local Friction (mPa)	Inclination (°)
0:00	0.004	0.000	0.1
0:05	0.009	0.000	0.2
0:10	0.011	0.000	0.1
0:15	0.008	0.000	0.2
0:20	0.007	0.000	0.1
0:25	0.010	0.000	0.2
0:30	0.010	0.000	0.2
1:00	0.000	0.000	0.2
1:15	-0.001	0.000	0.3
1:30	-0.004	0.000	0.1
1:45	-0.008	0.000	0.2
2:00	-0.014	0.000	0.2
2:05	-0.018	0.000	0.2
2:10	-0.021	0.000	0.2
2:15	-0.022	0.000	0.2
2:20	-0.022	0.000	0.2

Comments	
	→ Temperature shift captured using Test 13 → sheet 1 of 2

AN-106 Temperature Equilibration Data Sheet (3)

Data Collector	Date	Depth (m)	Cone ID
Jordan Follett	11/19/2013	End of Test 2 (3.1 m)	101023 T

Time	Tip Resistance (kN)	Local Friction (mPa)	Inclination (°)
2:25	-0.021	0.000	0.2
2:30	-0.021	0.000	0.2
2:35	-0.019	0.000	0.2
2:40	-0.019	0.000	0.2
2:45	-0.017	0.000	0.2

Comments	→ Temperature shift captured using Test 13 → Sheet 2 of 2