

Cone Penetrometer Shear Strength Measurements of Hanford Site Sludge Waste – 15314

Jordan Follett, Joseph Meacham
Washington River Protection Solutions, LLC
Richland, Washington 99352

ABSTRACT

In response to research examining the effect of gas production on the storage capacity of artificial sludge depots [1], a new mechanism was proposed for a spontaneous deep sludge gas release event (DSGRE) that had not been described in the Hanford Site Tank Farm safety basis [2]. Implementation of a new safety basis for Hanford Site sludge waste to address the DSGRE concern required 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, safety basis development involved determining the in situ shear strength of the sludge waste in C-Farm sludge accumulation Tanks 241-AN-101 (AN-101) and 241-AN-106 (AN-106). In situ measurements were taken in the sludge waste using a cone penetrometer with a 3-inch (76-mm) diameter ball attachment.

Full-flow cone penetrometer measurements were taken in Tank AN-101 sludge waste in January 2014 and in Tank AN-106 in November 2013. Measurements in both AN-101 and AN-106 sludge demonstrated roughly uniform increasing undrained shear strength with increased depth, which was expected based on similar testing performed in soft, normally consolidated clays at test sites globally [3]. 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, which supported revision of the safety basis to allow continuation of retrieval from C-Farm tanks.

INTRODUCTION

Tanks AN-101 and AN-106 are double-shell tanks (DSTs) that serve as receivers for radioactive waste retrieved from C-Farm single-shell tanks. Waste is retrieved from C-Farm tanks using a variety of techniques and is deposited in AN-101 and AN-106 through a slurry distributor, which is an adjustable height downcomer with four nozzles at 90 degree angles from one another. Waste is pumped through the slurry distributor into the receiver tank below the liquid waste level and above the existing settled solids layer. At the time of cone penetrometer deployment, AN-101 contained waste retrieved from three single-shell tanks and AN-106 contained waste retrieved from ten tanks. The liquid (supernatant) waste temperature in AN-101 was 75 °F and the settled solids waste (sludge) was at 97 °F. Tank AN-106 contains greater radioactive source term resulting in a higher supernatant temperature of 90 °F and sludge temperature of 134 °F.

A safety basis revision was required to address concerns regarding the potential for sludge waste to retain elevated quantities of gas when stored at large depths and to spontaneously release the gas in a large enough volume to reach the flammability limit. This safety basis development involved 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 HYSON¹ 200kN “full-flow” penetrometer with a 3-inch (76-mm) diameter ball attachment. In situ resistance measurements are equated to shear strength using an empirical value called the *N* Factor, resulting in a full-depth shear strength profile of the sludge waste currently residing in each tank. While cone penetrometers have been used in soil applications for decades, this technology had never been deployed into a waste tank to measure in situ sludge properties at the Hanford

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

Site. As such, radiation resistance testing had to be performed to qualify the electronics for in-tank use and equipment had to be designed and built to provide contamination control when removing the system from the tank.

DESCRIPTION

Cone Penetrometer System

Cone Penetrometer Technology (CPT) 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 as it undergoes non-localized turbulent shearing. The full-flow penetrometer essentially provides a measure of the pressure differential necessary to induce the material to flow around the probe.

Since Hanford sludge waste was expected to be soft in comparison to soils typically measured in cone penetrometer testing, a 3-inch (76-mm) diameter full-flow ball penetrometer tip was used as a replacement to the conventional conical tip. Cone penetrometer measurements were collected in AN-101 and AN-106 using a HYSON 200kN full-flow penetrometer system. Resistance on the tip was measured using a load cell device, termed the Icone², and was equated to shear strength using empirical relationships. One meter long extending rods were 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 were installed and operated on a platform placed over a tank riser with the hydraulic power pack located on the ground nearby. Fig. 1 shows an example of the system installed for off-site testing.

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.



Fig. 1. Cone Penetrometer Test Platform

The data collection system consists of a digital “cone” called the Icone and a digital data acquisition box called the Icontrol³. 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

² Icone is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.

³ Icontrol is a registered trademark of A.P. van den Berg, Heerenveen, Netherlands.

connects to the Icontrol through the control panel. A proprietary software called *GOnsite!*⁴ was installed on the computer to record data and present results on the screen in real-time. Data analysis was performed using Microsoft Excel⁵ by importing the *GOnsite!* files.

Method of Analysis

This section provides the empirical equations used to analyze the data collected using the full-flow ball penetrometer. 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 an empirically determined undrained N Factor (N_k), as shown in Equation 1 [4].

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

Where:

$$\begin{aligned} s_u &= \text{Undrained shear strength, Pa} \\ q_{net} &= \text{Net penetration resistance (or } q_{in}), \text{ Pa} \\ N_k &= \text{Undrained } N \text{ Factor (cone factor), dimensionless} \end{aligned}$$

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 used for all measured penetration resistance values recorded using the cone penetrometer (i.e., both penetration and extraction) [5]. The equation is shown in a simplified and expanded form to equate to the intermediate calculation performed during data analysis.

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

Where:

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

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 [6]. For the equipment used in testing, the manufacturer provided a numerical value of 0.75.

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

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

⁵ Microsoft Excel is a registered trademark of Microsoft Corporation, Redmond, WA.

overburden stress acting above and below the penetrometer [4]. 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 was originally designed to fit through a 4-inch diameter riser and involved a 20-mm diameter tapered shaft connected to the 3-inch (76-mm) diameter ball. 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.

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 did not contain pore water sensors. However, research has shown the hydrostatic pressure can be substituted with relatively small error [4]. Hydrostatic pressure is found using Equation 3.

$$u_0 = \rho_{\text{sup}} \cdot g \cdot d \quad (3)$$

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. Overburden stress was calculated using Equation 4.

$$\sigma_{v0} = \rho_{\text{sl}} \cdot g \cdot d \quad (4)$$

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 was used to calculate penetration resistance of the full-flow penetrometer, as shown in Equation 5.

$$q_m = \frac{F_p}{A_{\text{ball}}} \quad (5)$$

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 [7]. 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 [4].

The most favorable method for determining the N Factor is to take 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 due to access limitations and radiation concerns. Instead, test measurements were taken in kaolin clay simulants with strengths encompassing the approximate anticipated conditions of AN-101 and AN-106. 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.

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

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 [6]. 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.

$$S_T = \frac{s_u}{s_{ur}} \quad (7)$$

Previous full-flow ball penetrometer tests in soft clay has shown sensitivity is the property that primarily influences both the undrained and remolded N Factors [4]. 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 [3]. 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 [4]. 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 kaolin clay testing is appropriate for in situ investigations.

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

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 [4]. The calculated N Factor can be substituted into Equation 6 to calculate shear strength based solely on in situ CPT measurements.

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

Remolded shear strength can be determined with the cone penetrometer using the remolded penetration resistance and the remolded N Factor by Equation 10 [3]. The remolded N Factor differs from the undrained N Factor and therefore must also be determined from site specific data [8].

$$s_{ur} = \frac{q_{rem}}{N_{rem}} \quad (10)$$

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 is calculated using sensitivity as a primary input to the empirical correlation shown in Equation 11 [3].

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

Tank Farm Deployment Strategy

The penetrometer was deployed in a single location in both AN-101 and AN-106 due to resource limitations and a lack of available access risers large enough to accommodate the equipment. However, because a slurry distributor is used in the DST receiver tanks to distribute solids from single-shell tank retrieval, solids transferred into the DST receiver tanks are expected to settle in horizontal layers. Therefore, shear strength within each layer is expected to vary minimally in the radial direction and by taking shear strength measurements through the vertical profile of the sludge, the ranges of shear strengths in all tank waste layers are expected to be captured.

The HYSON was used to push rods into the sludge waste at a constant rate of 2 cm/s and the system was setup to collect data points at intervals of 1 cm. The penetrometer was pushed to minimum elevation of approximately 15 inches (0.4 m) above the tank bottom. Following the initial push, the penetrometer was extracted 1.24 m and was cycled at least 10 times at a rate of 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 because the cycles were performed back-to-back.

Supporting test activities with the penetrometer indicated the Icone needed to equilibrate to the in situ temperature prior to recording data because the change in temperature causes a shift in the load cell resistance readings. To avoid potential bias in the measurements as the Icone equilibrated from the ambient to the in situ waste temperature, the Icone was held in the waste for a period of time prior recording data. This was particularly important for use in AN-106 where the sludge waste temperature was significantly higher than the ambient temperatures at the time of deployment.

It is also 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, the penetrometer was not extracted through the entire sludge layer using the HYSON system due to contamination concerns, meaning 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.

RESULTS AND ANALYSIS

Kaolin Clay Simulant Testing

Testing was performed to determine an appropriate N Factor for the cone penetrometer system using three kaolin clay simulants with shear strengths ranging from about 2,200 Pa to 6,000 Pa. Kaolin clay has been used in a number of testing activities to model Hanford site sludge. The N Factor was found by taking reference strength measurements in the clay with a handheld shear vane. The resulting 95% confidence interval for the undrained N Factor was found to be 11.5 ± 0.1 . An undrained N Factor of 11.5 is used to calculate the undrained shear strength profiles for AN-101 and AN-106 sludge presented below. Additionally, undrained and remolded N Factors are calculated based on cyclic measurements using Equations 9 and 11 for comparison.

Tank 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 a 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 170.4 inches (4.3 m) above the tank bottom (inches are typically used as the unit for Hanford tank waste depths because based on the tank dimensions, 1 inch of waste nominally equates to 2750 gallons).

The calculated undrained sludge waste shear strength profile, determined using Equation 6 and an N Factor of 11.5, is shown in Fig. 2. The orange triangles making up the profile show continuous measurements of the sludge waste undrained shear strength down to roughly 15 inches (0.4 m) above the tank bottom. The estimated depths of retrieved C Farm sludge currently residing in Tank AN-101 are overlaid on the plot. The sludge profile shows shear strength increasing roughly uniformly with depth, which is a typical trend observed in soil and clay studies presented in literature [6]. 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 (2.8-m) elevation and increasing to about 3,300 Pa at the lowest measurement elevation.

Fig. 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.

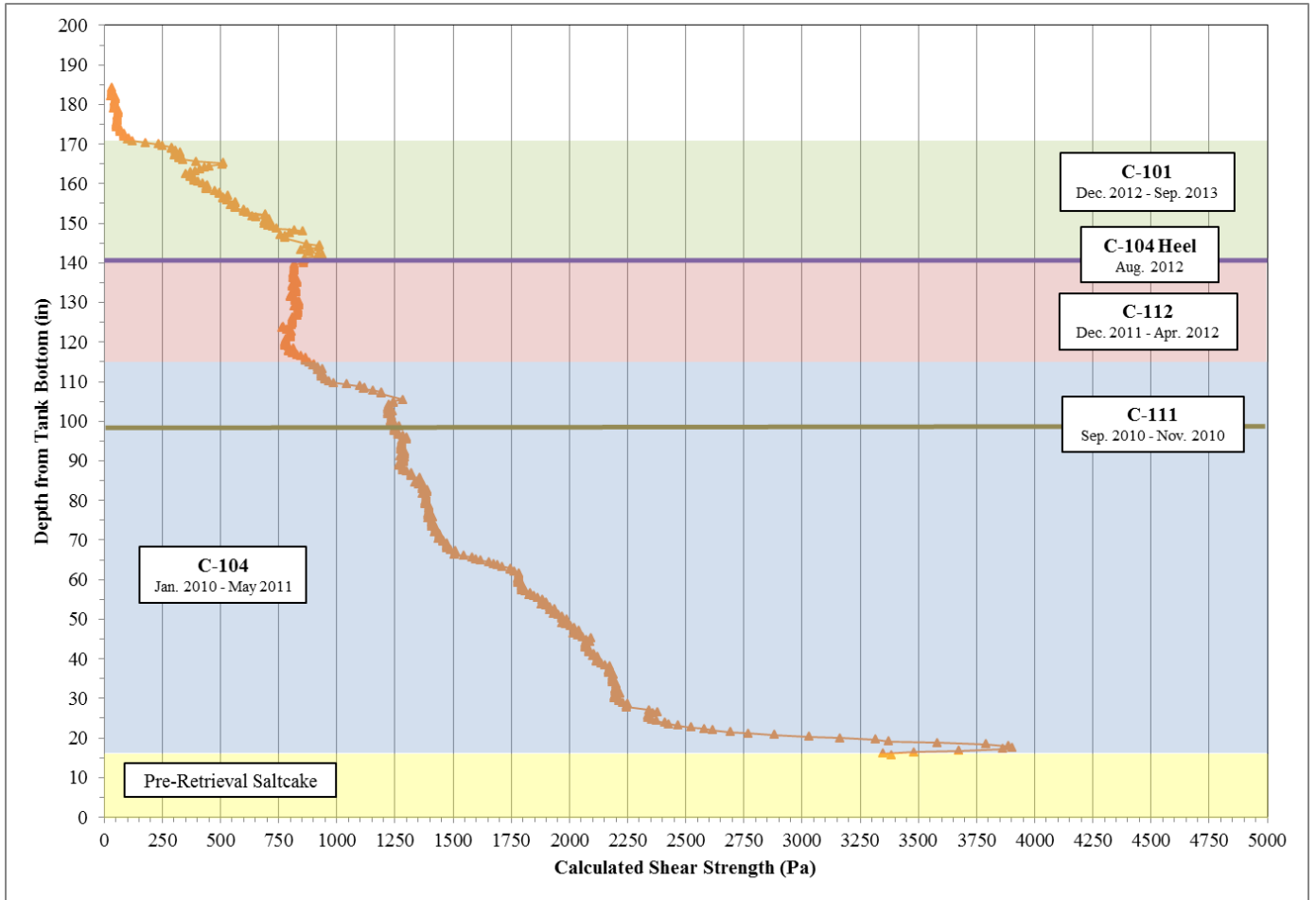


Fig. 2. AN-101 Sludge Waste Undrained Shear Strength Profile

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 ranging from about 15 inches (0.4 m) to 64 inches (1.6 m) 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 I.

TABLE I. AN-101 Strength Parameter Confidence Intervals

S_T	N_{rem}	$N_{k,calc}$
3.6 ± 0.1	13.9 ± 0.1	12.8 ± 0.1

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 I to the entire profile, is shown with orange triangles in Fig. 3. It should be noted that the calculated undrained N Factor from TABLE I was found using data collected only in the lower 1.24 m of sludge, but the profile presented in Fig. 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 I to the resistance measurements taken on the final 1.24-m cyclic push, is shown with red diamonds in Fig. 3.

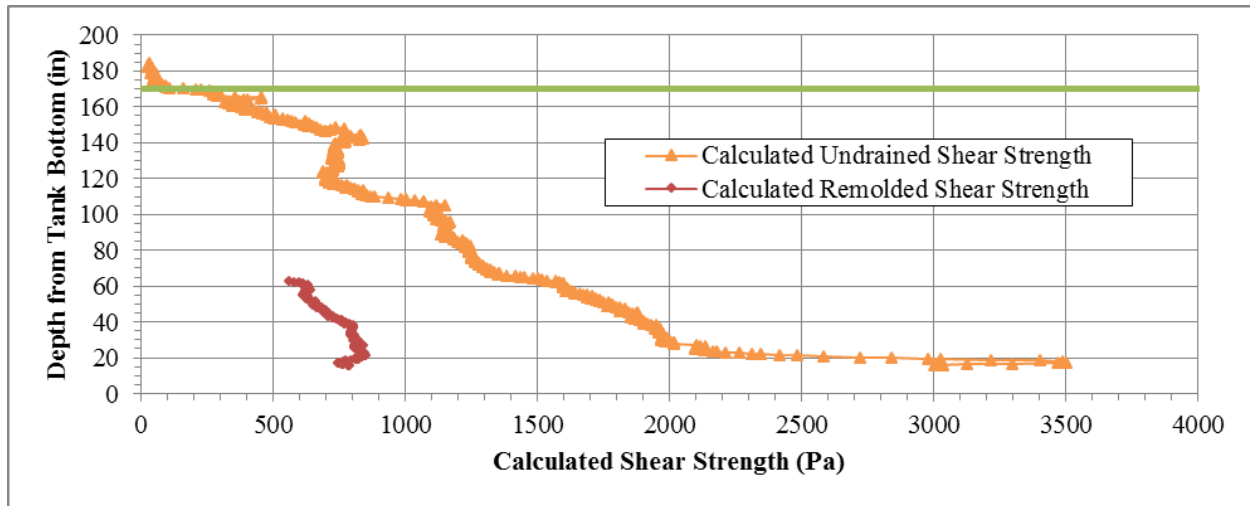


Fig. 3. AN-101 Sludge Waste Remolded Shear Strength Profile

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.

Tank AN-106 Results

As with AN-101, the undrained shear strength was calculated with cone penetrometer measurements and an undrained N Factor of 11.5 using Equation 6. Assuming a threshold of 200 Pa indicates sludge waste, the cone penetrometer first contacted sludge waste at an elevation of 157.1 inches (4.0 m) above the tank bottom.

The calculated undrained sludge waste shear strength profile, determined using Equation 6 and an N Factor of 11.5, is shown in Fig. 4. The blue diamonds making up the profile show continuous measurements of the sludge waste undrained shear strength down to roughly 15 inches (0.4 m) above the tank bottom. Again, the estimated depths of retrieved C Farm sludge currently residing in Tank AN-106 are overlaid on the plot.

The sludge profile in Fig. 4 shows shear strength increasing roughly uniformly with depth, which is a typical trend observed in soil and clay studies presented in literature [6]. 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 (3.0-m) elevation and increasing to about 4,000 to 5,000 Pa at the lowest measurement elevation.

Two large increases are shown in Fig. 4; one at a depth of 97 inches (2.5 m) above the tank bottom and another at 39 inches (1.0 m) above the tank bottom. When looking at these increases, it is important to note that the individual 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 (76-mm) 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 at 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 may 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.

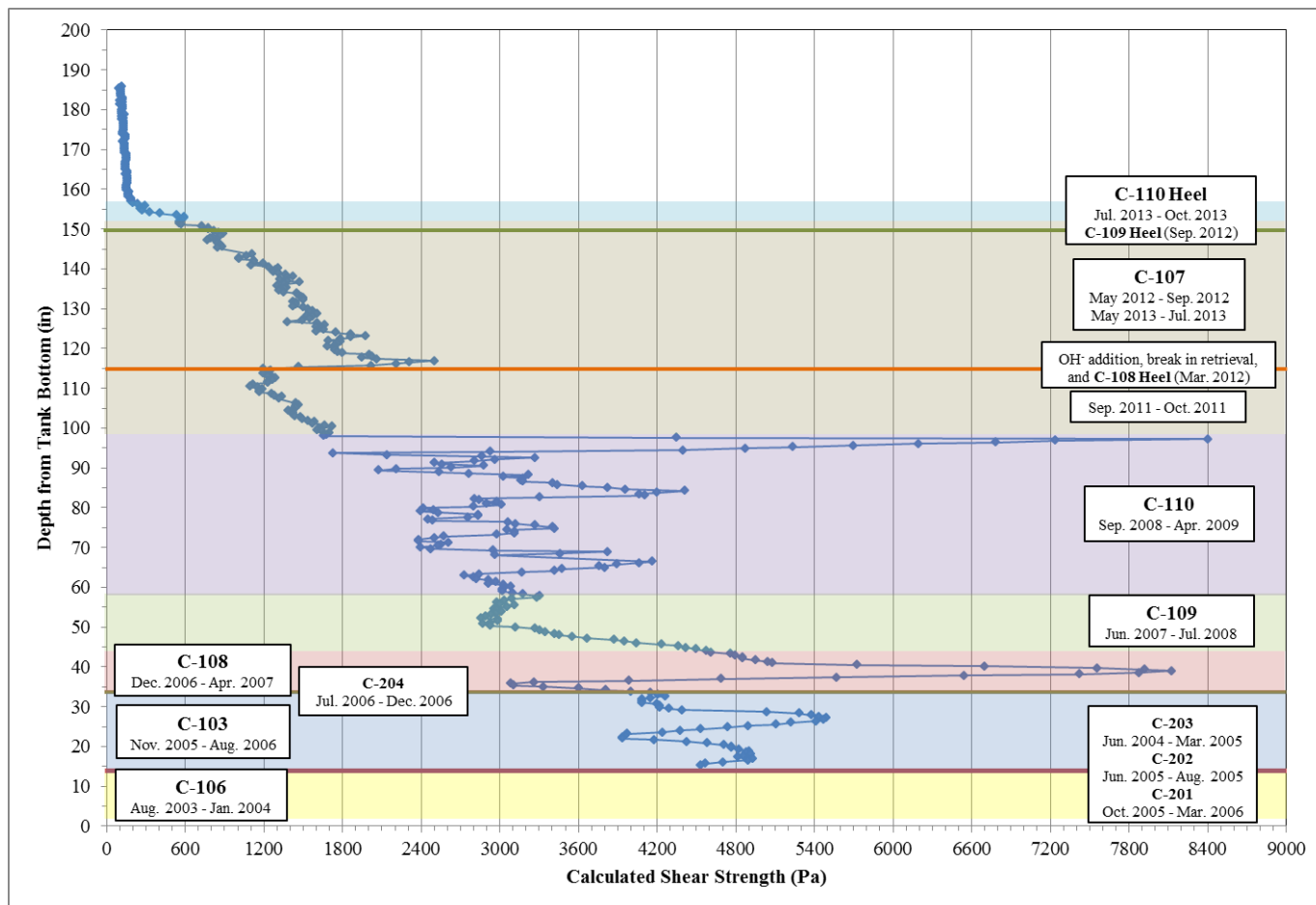


Fig. 4. AN-106 Sludge Waste Undrained Shear Strength Profile

Fig. 4 shows a clear decrease in shear strength at the 115-inch (2.9-m) 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 64,350 L of 50 weight percent sodium hydroxide were added to AN-106 for corrosion control purposes. Since the trending decrease in strength persisted for roughly 15 inches (0.4 m), 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 more 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. 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 the same method of modified sluicing [9]. 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 notable that the upward trend in shear strength with depth remains relatively constant when looking at the AN-106 profile as a whole.

Remolded strength parameters were found after the initial full-depth push by cycling the penetrometer up and down twelve times in 1.24-m increments at the lowest measured depth ranging from about 15 inches (0.4 m) to 64 inches (1.6 m) 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 II.

TABLE II. AN-106 Strength Parameter Confidence Intervals

S_T	N_{rem}	$N_{k,calc}$
11.8 ± 0.7	18.6 ± 0.2	8.9 ± 0.2

TABLE II 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. 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. 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 II to the entire profile, is shown with blue diamonds in Fig. 5. It should be noted the calculated undrained N Factor from TABLE II was found using data collected only in the lower 1.24 m of sludge, but the profile presented in Fig. 5 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 II to the resistance measurements taken on the final 1.24-m cyclic push, is shown with green triangles in Fig. 5.

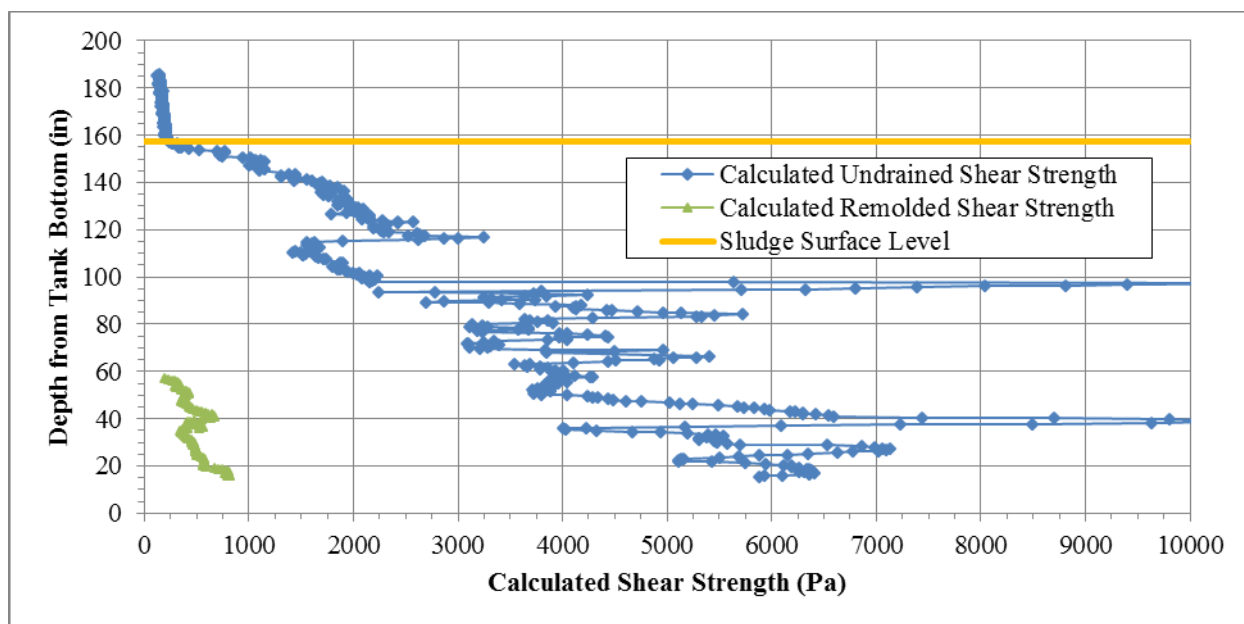


Fig. 5. AN-106 Sludge Waste Remolded Shear Strength Profile

Fig. 5 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.

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. The simulant testing was performed in three 1,900-L polyethylene tanks, referred to here as Tank 1, Tank 2, and Tank 3. The kaolin clay was mixed in batches and added to the 1,900-L test tanks. The simulants for Tanks 1, 2, and 3 were created with average weight percent kaolin concentrations of 60.4%, 64.0%, and 66.0%, respectively. A handheld shear vane device was used to measure the shear strength in each of the three simulants. The shear strength was measured at 2,200, 4,000, and 6,000 Pa for Tanks 1, 2, and 3, respectively.

Remolded and undrained shear strengths were also determined from the cyclic penetrometer measurements taken in each kaolin simulant using the empirical equations presented previously. The resulting calculated 95% confidence interval strengths are shown in TABLE III. 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 Fig. 2 and Fig. 4, the kaolin clay simulants adequately encompassed the in situ undrained shear strengths for the bulk of AN-101 and AN-106 sludge.

TABLE III. 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)
810 ± 60	2090 ± 40	1470 ± 40	3340 ± 110	2090 ± 150	5110 ± 170

The sensitivity and remolded N Factor were also empirically calculated for the kaolin clay simulants using the equations presented previously. The 95% confidence interval for sensitivity was calculated as 3.4 ± 0.3 and the remolded shear strength was calculated as 13.8 ± 0.1 .

From the tank sludge cyclic penetrometer measurements taken between 15 inches (0.4 m) and 64 inches (1.6 m) 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 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 [4]. 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 Fig. 4 and Fig. 5 was considered when reporting undrained shear strength for AN-106 sludge.

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 [10]. This trend is typical of highly characterized clay sites worldwide presented in literature [5]. 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 [5].

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 [3].

Cyclic degradation plots were developed using the penetrometer data from AN-101, AN-106, and kaolin clay simulants. However, the extraction data (q_{ext}) were 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 were not included, a cyclic offset also was not applied for the AN-101 and AN-106 data. The cyclic degradation curves are shown in Fig. 6.

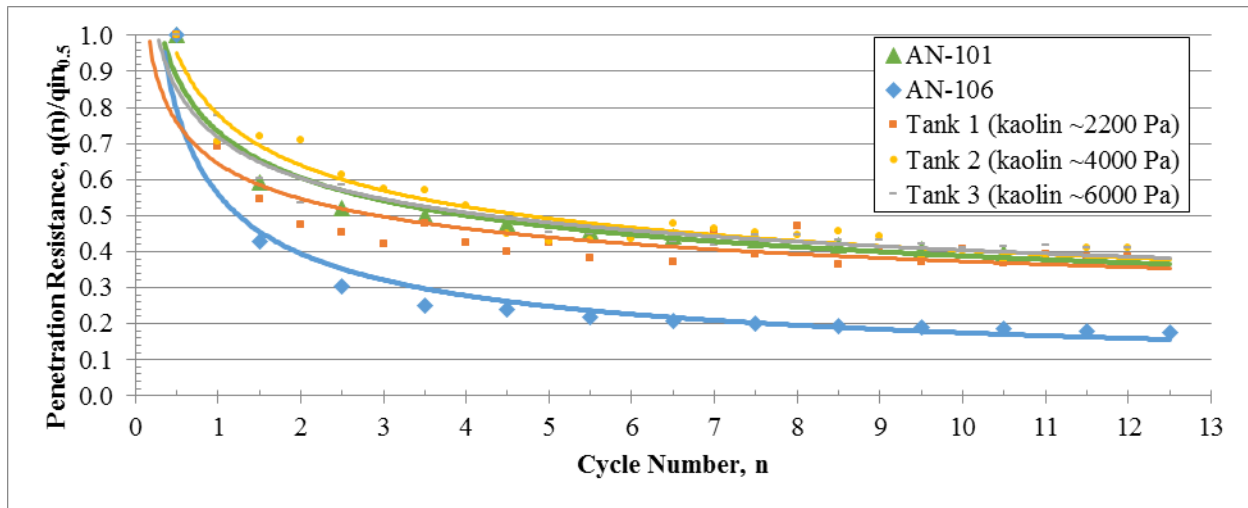


Fig. 6. Cyclic Degradation Curves for AN-101, AN-106, and Kaolin Simulant

Comparing Fig. 6 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 [3]. Fig. 6 also further demonstrates the difference observed in AN-106 measurements, which shows 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 [3].

CONCLUSIONS

Full-flow cone penetrometer measurements taken in Tank AN-101 sludge waste indicate shear strengths ranging from 500 Pa near the sludge surface to roughly 3,300 Pa at 15 inches (0.4 m) above the tank bottom, for a standard undrained N Factor of 11.5. Tank AN-101 sludge between 15 inches (0.4 m) and 64 inches (1.6 m) above the tank bottom was found to have a sensitivity of 3.6 and the remolded shear strength was found to vary between 500 Pa and 800 Pa. The CPT measurements taken in Tank AN-106 sludge waste indicate shear strengths ranging from 500 Pa near the sludge surface to roughly 5,000 Pa at 15 inches (0.4 m) above the tank bottom, for a standard undrained N Factor of 11.5. Tank AN-106 sludge between 15 inches (0.4 m) and 64 inches (1.6 m) above the tank bottom was found to have a sensitivity of 11.8 and the remolded shear strength was found to vary between 200 Pa and 800 Pa.

The overall measured shear 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. 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.

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 [3]. 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 [10]. 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. As such, these results support the predicted sludge strength and behavior, providing a basis for simulant strengths and compositions used in additional testing activities that lead to revision of the safety basis to address the DSGRE concern and allow continuation of retrieval from C-Farm tanks.

REFERENCES

1. Van Kessel, T., and W.G.M van Kesteren, 2002, "Gas Production and Transport in Artificial Sludge Depots," *Waste Management*, vol. 22, p. 19-28, Elsevier Science Ltd.
2. RPP-13033, 2013, *Tank Farms Documented Safety Analysis*, Rev. 4-T, Washington River Protection Solutions, LLC, Richland, Washington.
3. Yafrate, N. J., DeJong, J. T., and DeGroot, D. J., 2009, "Evaluation of Remolded Shear Strength and Sensitivity of Soft Clay Using Full-Flow Penetrometers," *Journal of Geotechnical and Geoenvironmental Engineering*.
4. DeJong, J. T., et. al., 2010, "Recommended Practice for Full-Flow Penetrometer Testing and Analysis," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 33, No. 2.
5. Yafrate, N. J., 2008, "Use of Full Flow Penetrometers in Soft Clay," University of California Davis, ProQuest.
6. Lunne, T., Robertson, P. K., and Powell, J. J. M, 1997, *Cone Penetration Testing in Geotechnical Practice*, Routledge Taylor and Francis Group, New York, New York.
7. Hong, S. J., Lee, M. J., Kim, J. J., & Lee, W. J., 2010, "Evaluation of undrained shear strength of Busan clay using CPT," *2nd International Symposium on Cone Penetration Testing, CPT*, (Vol. 10, pp. 2-23).
8. Yafrate, N. J., and DeJong, J. T., 2006, "Interpretation of Sensitivity and Remolded Undrained Shear Strength with Full Flow Penetrometers," p. 572-577, *ISOPE-06: Proc. International Society for Offshore and Polar Engineering*, San Francisco, California.
9. RPP-56214, 2014, *Retrieval Completion Certification Report for Tank 241-C-110*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.
10. Raymond, G. P., 1997, "Shearing Strength of Soils," *Geotechnical Engineering*.