Title: Effects of Cone Penetrometer Testing on Shallow Hydrogeology at a Contaminated Site

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Abstract

Penetration testing is a popular and instantaneous technique for subsurface mapping, contaminant tracking, and the determination of soil characteristics. While the small footprint and reproducibly of cone penetrometer testing makes it an ideal method for in-situ subsurface investigations at contaminated sites, the effects to local shallow groundwater wells and measurable influence on monitoring networks common at contaminated sites is unknown. Physical and geochemical parameters associated with cone penetrometer testing were measured from a transect of shallow groundwater monitoring wells upgradient and down-gradient of CPT activity. The physical act of advancing and retracting a piezocone had a significant effect on specific conductivity and water level but no effect on dissolved oxygen or pH. While cone penetrometer effects were significant and detectable, the variability induced by CPT activity was only a fraction of the natural variation caused by precipitation events. Therefore, we concluded that CPT effects are less than those of natural event-driven variation in clayey and silty unconsolidated residuum.

Acknowledgement

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1. Introduction

Soil core recovery and penetration testing methods are essential in obtaining soil compaction, stratigraphy, depth, porosity, and hydraulic conductivity for a variety of geotechnical and engineering applications. While soil core recovery requires subsequent processing and compaction corrections, penetration testing provides instant continuous data in-situ with a lower relative cost, lower risk of cross contamination, and high accuracy. The reproducibility, speed, and reliability of penetrometer testing in saturated material makes it a widely used and highly standardized method for subsurface investigations[1, 2].

Cone Penetrometer Testing (CPT) is completed by advancing a cone-tipped pressure sensor downward through unconsolidated material at a constant rate[1, 2]. The CPT sensors are designed to account for the eccentricity of push resistance such that the cone only measures the resistivity imposed by the axial force of the soil layer which the cone is advancing through. Meaning that the cones are optimized for variably compacted sediments particularly the fine grained residuum which overlies the valley bedrock of the valley ridge formations common in the eastern conterminous United States[3]. CPT probes can further incorporate additional sensors for subsurface measurements including the monitoring of contaminants like hydrocarbons, volatile organics, toxic metals, explosives/energetics, and radioactive wastes[4, 5]. The CPT piezocone of Figure 1 provides measures of soil friction f_s, resistance q_c, and pore pressure u_2 which are used to interpret soil traits. Specifically soil type, which can be determined based on a relationship between friction ratio, R_f [$R_f = (f_s/q_c) \times 100$] and cone resistance, q_c[6, 7] with modern piezocones providing corrected cone resistance q_t to account for pore water pressure in relation to net contact area a_n [$q_t = q_c + u_2 (1 - a_n)$][8].

While the effectiveness of CPT is well documented, little is known of the immediate and residual impacts of CPT activity on local hydrogeology and groundwater monitoring wells. The effects of CPT were monitored during a CPT study completed at the contaminated Oak Ridge Integrated Field Research Challenge Site within the Y-12 National Security Complex in Oak Ridge, Tennessee, USA. A 2,600 square meter study site immediately down-gradient of the former clay-lined S3 transuranic and nitric acid waste ponds was selected for study[9]. The site and former S3 ponds are located in Bear Creek Valley, a valley and ridge province in Eastern Tennessee, USA consisting primarily of clay and silt residuum deposited from the erosion of local ridges (Figure S1). The unconsolidated sediments of Bear Creek valley overlie the Maynardville Limestone which dips 45° to the southeast with a geologic strike of N55E[9-11]. The modern topography of the unconsolidated material is largely influenced by historical activities which included grading, stream relocation, and the burial of debris recovered up to 4.1 meters below ground surface[9, 12].

2. Methods

2.1. Cone Penetrometer Testing

Over 16 days in October of 2020, a 131-push cone penetrometer grid was completed across a 2,600 square meter site (Figure 2) with pushes advancing up to 11m below ground surface. A 255 square meter study site with pre-existing groundwater wells was the focus of studies regarding CPT impacts on groundwater. Pushes North West of the 255 square meter subsite region shown in Figure 3, were completed from October 13 through 18, 2020. The South Eastern CPT boreholes including those in the study subsite (Table 2) were completed on October 18 through October 27, 2020. To collect subsurface data, a 25-ton CPT rig was driven to the bore location and leveled. Then a 35.7 mm diameter piezocone was advanced through the subsurface at a rate of 2 cm/sec with the use of a truck-mounted hydraulic ram. The piezocone advanced below ground surface to collect soil behavior data in feet which were converted to meters by dividing the depths by 3.281. The piezocone was advanced at a constant rate until the axial force of the underlying material resulted in refusal after which the piezocone was retracted and the resulting bore hole was left open until all bores had been completed for the day. After the completion of daily CPT activities, the boreholes were sealed by gravity-feeding a saturated sodium bentonite slurry until the bentonite was level with the ground surface.

2.2. Water levels

Three continuous-monitoring LevelTROLL® 400 depth to water units (In-situ, Fort Collins, CO) were deployed in FW103, FW024, and FW112 at a depth of 12.2 -to- 15.2 m below ground surface. Water level measurements were collected from the deployed units in ten minute intervals for three months before the CPT, during the 16-days of CPT, and one-week post-CPT.

2.3. Hydraulic Conductivity

A subset of 5 groundwater wells screened from 6.1 -to- 15.2 m below ground surface and identified in Table 2 were selected for hydraulic conductivity measurements (Figure 3). Two methods of aquifer recharge were used to determine the groundwater flow rate using the Hvorslev slug test method for unconfined aquifers[13-15].

$$k = \frac{r^2 ln(L/R)}{2Lt_{0.37}}$$

k = hydraulic conductivity

r = standpipe radius

L = screen length

R = sandpack radius

$t_{0.37}$ = time of 37% well recovery

Equation 1. Hvorslev equation for hydraulic conductivity in unconfined aquifers [13-15]

One month-prior to the CPT, 5L of groundwater water was pumped from FW134-2, FW128, and FW127 to clean the well screens and ensure no blockages were present. One-month post-CPT, hydraulic conductivity slug tests were completed in FW127 and FW128 using a 1L polypropylene slug to remove groundwater and measure recharge rate using an electric conductivity water level tape with hydraulic conductivity calculated using the Hvorslev method (equation 1). This method was also repeated for FW134-2 and FW115-3 using a 0.5L slug. Steady-state drawdown was additionally achieved by pumping at a rate of <0.65 mL/sec in FW115-3 on October 27th following the local CPT activity on October 24th and 25th. To measure recovery, the pump was de-activated, and an electric water level tape was used to measure the rate of recharge with hydraulic conductivity calculated using the Hvorslev method (equation 1). In FW127, a colloidal borescope (Geotech, Denver, CO) was deployed to measure vector and velocity of the 12.1 -to- 14.9 m screen interval. Prior to deployment a manual systems check was performed including calibration of changing particle vector and velocity and optical calibration tests. Particle tracking was measured using AquaVision software (Geotech, Denver, CO) and the tracking parameters were adjusted to fit the clarity and conditions of the groundwater with capture set to 100 milliseconds, the particle sensitivity filter set to 2000, a minimum particle size set to 3 µm, maximum velocity capped at 5000 µm/sec, and a minimum threshold of two particle matches for tracking. Flow was measured in a fracture 12.16 m below ground surface where particle movement was observed over a 15-minute period.

2.4. Continuous Geochemistry Monitoring below CPT pushes

Continuous geochemistry was measured using an AquaTROLL® 600 multiparameter sonde measuring groundwater in well FW 106, screened from 12.2 -to- 14.9 m below ground surface. The AquaTROLL® 600 collected temperature (°C), specific conductivity (µS/cm), dissolved oxygen (mg/L), salinity (ppm), pH, and total suspended solids (ppt) every ten minutes.

All probes were calibrated prior to deployment on October 17th. Binomial-classified CPT activity data were analyzed using an ANOVA test of variance with continuous geochemistry data from FW106 and continuous water levels data from FW112.

2.4.1. Geochemistry Monitoring at Depth of CPT

On October 24th, geochemistry was measured from FW115-3 screened from 8.53 -to-9.66 m below ground surface. Measurements were collected on an AquaTROLL® 9600 (In-situ, Fort Collins, Co) treaded onto a flow cell. The unit was calibrated 4 hours before use and measured temperature (°C), specific conductivity (µS/cm), dissolved oxygen (mg/L), and pH of groundwater pumped peristaltically at a rate of 0.67 mL/sec. Three-times the volume of the screen pack was pumped to establish a geochemistry baseline prior to the start of local CPT activity, and a non-CPT measurement of the well was completed using the same method and re-calibrated unit on October 27th.

3. Results and Discussion

3.1. Geochemistry effects of CPT

3.1.1. Geochemistry at Depth of CPT pushes

Prior to piezocone advancement and retraction, peristaltic pumping at an average rate of 0.67 mL/sec in FW115-3 established a geochemistry baselines for pH, dissolved oxygen, specific conductivity, and temperature in groundwater. Stable parameter averages and standard deviations before CPT activity showed a pH of 3.82 ± 0.01, dissolved oxygen concentration of 0.12 ± 0.01 mg/L, a temperature of 22.11 ± 0.08 °C and specific conductivity of 3680 ± 15 µs/cm. Figure 4 shows the geochemistry data collected from FW115-3 during the CPT activity (excluding temperature) with the mean during the October 24th CPT activity in teal, and the background non-CPT mean from October 27th in gray. The means of pH and Oxygen during CPT activity were equal to means from non-CPT measurements on October 27th. Specific conductivity however was higher during CPT activity and peaked at 3799 µs/cm during the development of CPT47, the closest CPT borehole. The specific conductivity decrease was exponential (Figure 5) and fit by the following second-order polynomial regression, $y = 1E\text{-}05x^2 - 0.0906x + 3691.4$ with an R-squared value of 0.98 where x = volume pumped (mL) at a rate of 0.67 mL/minute post-CPT and y = specific conductivity (µs/cm at 25°C).

3.1.2. Geochemistry Below CPT pushes

Continuous monitoring in FW106 indicated that specific conductivity and water level were significantly affected during CPT activity (Table 3). Figure 6 shows that despite some local and minimal variation in the underlying well, specific conductivity had a daily downward trend preceding the CPT and during the CPT with daily highs recorded each morning and daily lows recorded each night until a rain event on October 28th and 29th. The daily variation during the CPT activity on October 24th and 25th was measured at 17µs/cm and 34 µs/cm respectively. While daily ranges in specific conductivity following 5.2 cm of rain of October 28th and 2.5 cm of rain of October 29th demonstrated that the influence of precipitation on daily variability was up to five-times that of the CPT (Figure 7). Overall, no influence to dissolved oxygen, or pH was measured during or following the CPT activity in FW106.

3.2. Borehole stability and the effects of Bentonite

As the CPT piezocone advances, it displaces subsurface material and is capable of collapsing open space between sediment grains and smearing fine grained clays along the edge of the advancing piezocone. This smearing and compaction effect of the fine grained saprolite clay material was demonstrated by cores collected using the same hydraulic press in the unconsolidated residuum (Figure 8). The smearing effect and pore deformation was visually limited to the outer 2 mm of the cores. The unconsolidated residuum materials tended to collapse, back-filling the borehole and leading to possible sediment mixing across zones[16]. An unknown number of boreholes did collapse during or immediately following the retraction of the piezocone directly influencing the final depth of the sodium bentonite slurry. Sodium Bentonite ($l_2H_2Na_2O_{13}Si_4$) has a pH of 8.5-10 and a high cation exchange capacity in groundwater measurable by increases in pH and diversion from an existing trend in specific conductivity[17, 18]. However, the mean pH remained unaltered during the application of the sodium bentonite slurry. The specific conductivity continued its downward trend in FW115-3 during the application of the sodium bentonite slurry, and daily trends in FW106 had no detectable response.

3.3. Local hydrologic effects

Water levels are naturally attuned to precipitation events, as demonstrated by Figure 9. Seasonal and event-driven water table fluctuations prior to the CPT result in regularly oscillating water levels. However, unique variation events in FW112 resulted in deviations from the daily trend during the CPT activity on October 18th, 24th, and 25th with water levels in flow-adjacent FW103 and FW024 not showing any fluctuations associated with local CPT activities. FW112 is local to the CPT activity and roughly upgradient of the CPT activity based on groundwater vector measured in FW127 and FW106. Figure 10 shows however, that the localized and short-term fluctuations in FW112 water levels occurred during CPT activities in the overlying residuum on October 24th. During piezocone advancement, the process displaced sediment and groundwater increasing the local water level in FW112, and generated a void spaces estimated at 0.0112 m^3, 0.0107 m^3, and 0.0111 m^3 for CPT49, CPT 47, and CPT 43 respectively. As the piezocone was retracted, the void was filled by water from a recharging unit causing an observed decrease in local water level. The water table elevation of FW112 in Figure 10 ranged from 304.40 -to-304.47 m above mean sea level with a maximum water table fluctuation of 0.07 m during CPT activities and water elevations stabilizing immediately following the CPT activity. On October 30th, following the rain event of October 28th and 29th, the total daily water level range in FW112 was 0.085 m indicating that the CPT water level variation is less than that of a precipitation event. An ANOVA test of variance (Table 3) determined that water level in FW112 was significantly influenced by physical advancement and retraction of a CPT piezocone. This highly fractured material was very responsive to the CPT activity and recovered quickly, but rates of recovery and radius of influence will vary based on local storativity, transmissivity, and hydraulic conductivity. Across the saturated subsurface, hydraulic conductivity and permeability at the site have been well-defined over several decades and have been determined to be between 10^{-6} -to- 10^{-7} m/sec in the shallow material 1-12 m below ground surface with underlying fractures providing flow up to 10^{-2} m/sec[9]. Three days post-CPT, hydraulic conductivity in FW115-3 was determined to be 1.22×10^{-7} m/sec and 6.60×10^{-7} m/sec one month later. One-month following the CPT, hydraulic conductivities of the shallow unconsolidated residuum were remeasured and ranges were all within the expected for the material (Table 2) indicating that any impacts of subsurface cavities, or compaction were not present or negligible on overall hydraulic conductivity. While physical disruptions to subsurface structures and grain-to-grain relationships can alter flow paths, tortuosity, and Reynolds numbers for the material, the CPT did not have a measurable impact on local hydraulic conductivity[16].

3.4. Overall Assessment of CPT Effects

The process of advancing and retracting the CPT probe significantly affected water level, specific conductivity, salinity, and oxidative reductive potential in underlying wells. At depth of the CPT, specific conductivity increased above background as CPT activity neared the monitoring well reaching a local maxima of 3799 µs/cm. However, a rain event at the site resulted in a peak specific conductivity of 3979 µs/cm in FW106. The CPT daily variation in specific conductivity in FW106 was a fifth of the daily variation measured following a rainfall event at the site. The rainfall also resulted in a maximum daily water level variation of 0.08 m while the CPT resulted in only a daily variation of 0.07 m. Means for pH and dissolved oxygen did not vary from background and sealing of the boreholes with the sodium bentonite slurry had no measurable effect on groundwater geochemistry. This suggests that the effects of the CPT advancement and retraction have a limited impact on the local hydrogeology, but that the effects and influence on each measured geochemical and physical parameter was less than that of a rainfall event.

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Figures

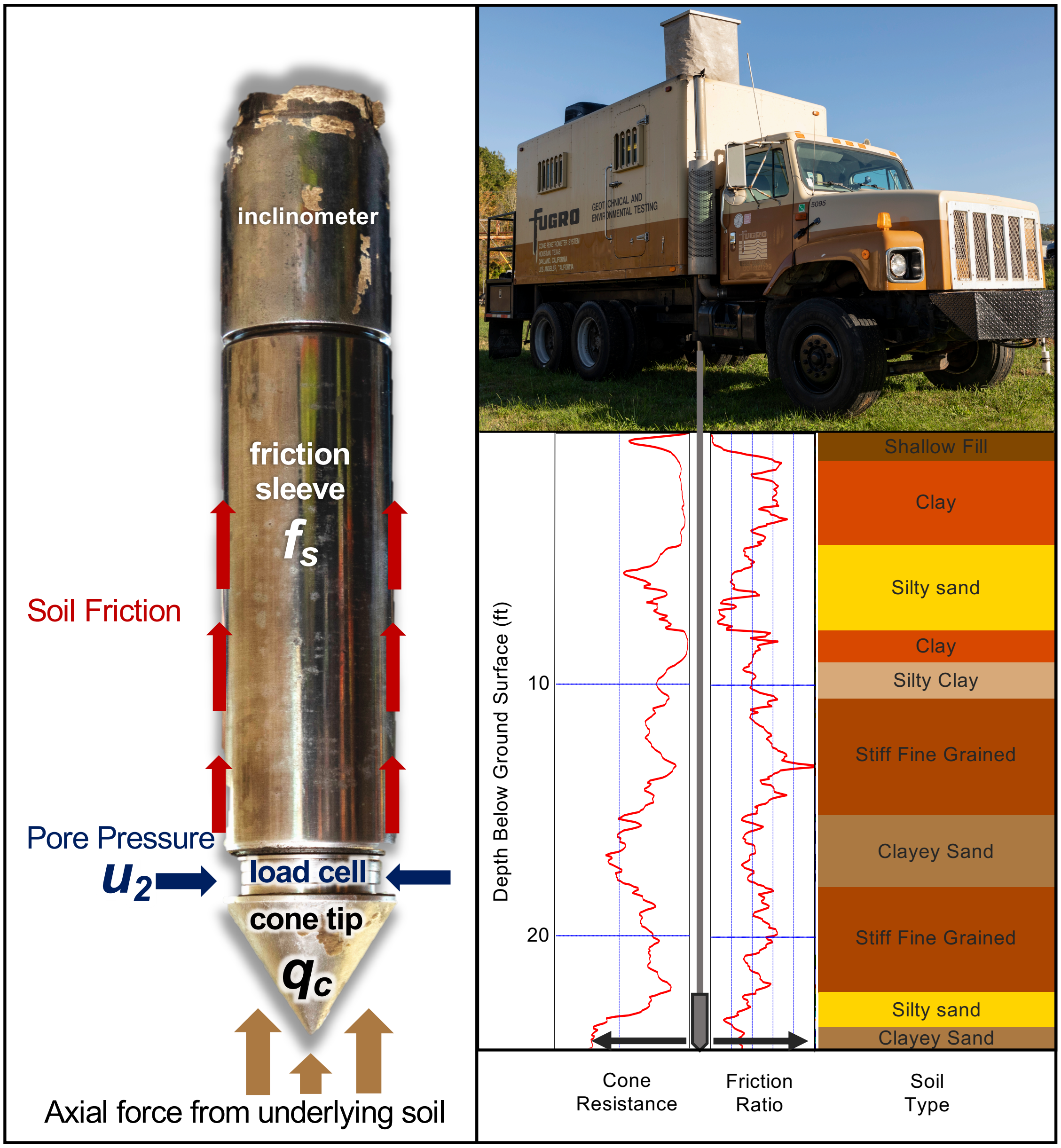


Figure 1. Piezocone sensors (left) measure the axial force on the cone, the upward bore wall friction, and the inward pore pressure to determine soil behavior which is interpreted during subsurface piezocone advancement (right).

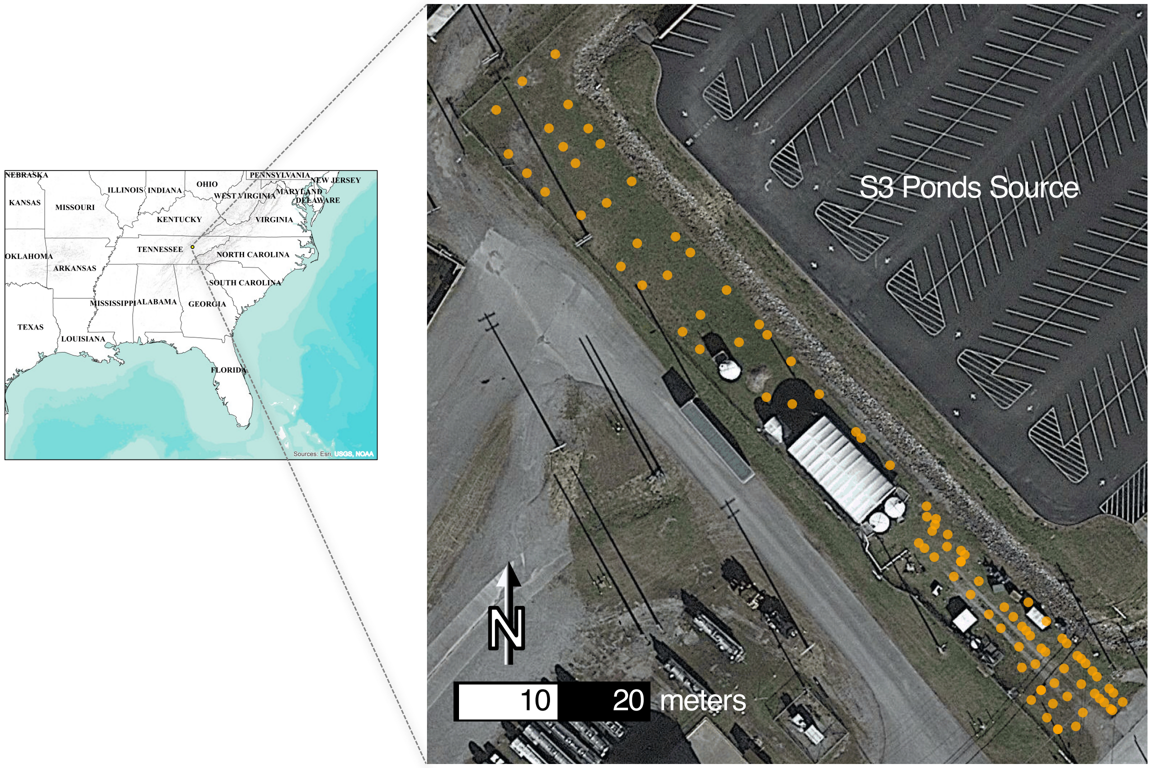
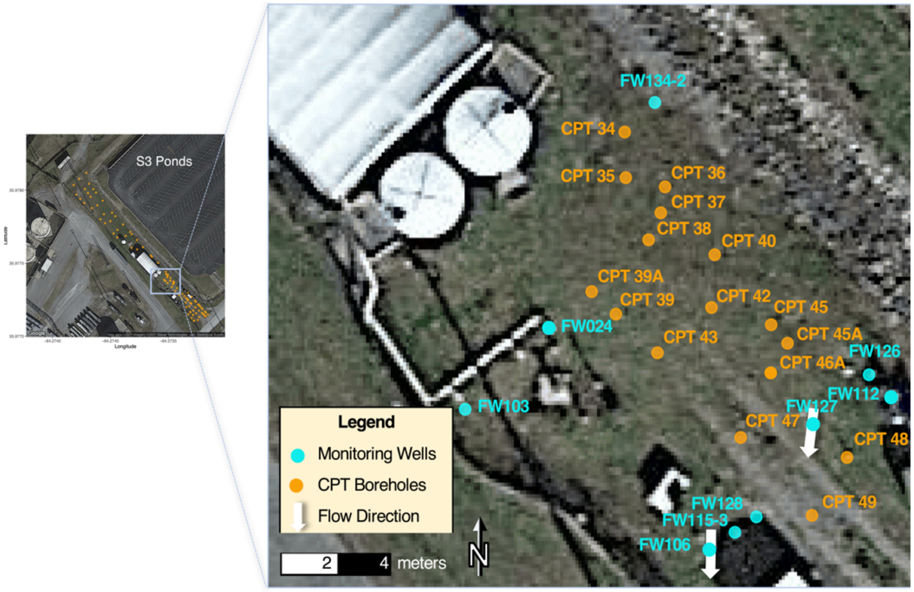


Figure 2. The cone penetrometer study was conducted in the 2,600 square meter Area 3 site at the Y-12 complex in Oak Ridge, TN, USA. Boreholes shown in orange form parallel transects downgradient of the former S3 waste ponds contaminant source.



Bore	Depth (m)	Date
CPT 34	7.559	18-Oct
CPT 35	6.898	22-Oct
CPT 36	8.278	21-Oct
CPT 37	8.019	21-Oct
CPT 38	8.358	21-Oct
CPT 39	1.78	24-Oct
CPT 39A	1.64	24-Oct
CPT 40	9.796	21-Oct
CPT 42	9.778	21-Oct
CPT 43	11.156	24-Oct
CPTB 45	1.759	21-Oct
CPT 45A	9.418	21-Oct
CPT 46A	8.458	21-Oct
CPT 47	10.756	24-Oct
CPT 48	7.958	20-Oct
CPT 49	11.198	24-Oct

Figure 3. Map of cone penetrometer bore holes and monitoring wells used to investigate the localized effects of the CPT in Area 3. Flow direction arrows were drawn from vectors collected using colloidal borescope and indicate a southerly groundwater flow in the residuum.

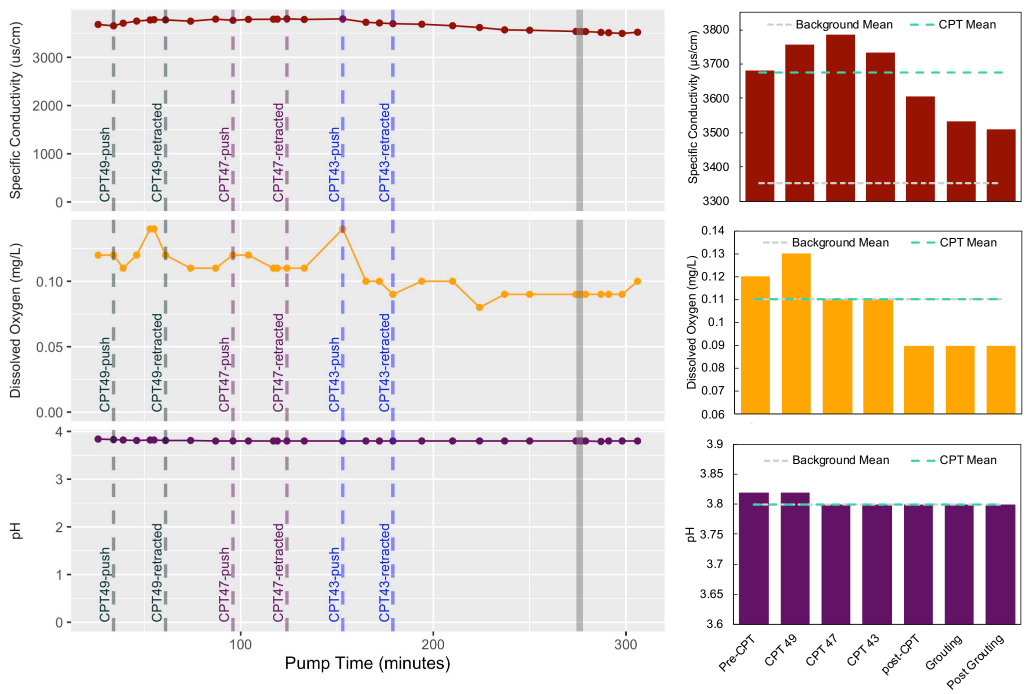


Figure 4. Geochemistry measured in FW115-3 throughout local cone penetrometer activities are shown on the right with boreholes grouted around 270 minutes (charcoal). Mean values for CPT activity are plotted in the bar charts on the right with mean during CPT activity in teal and mean non-CPT geochemistry background in ash.

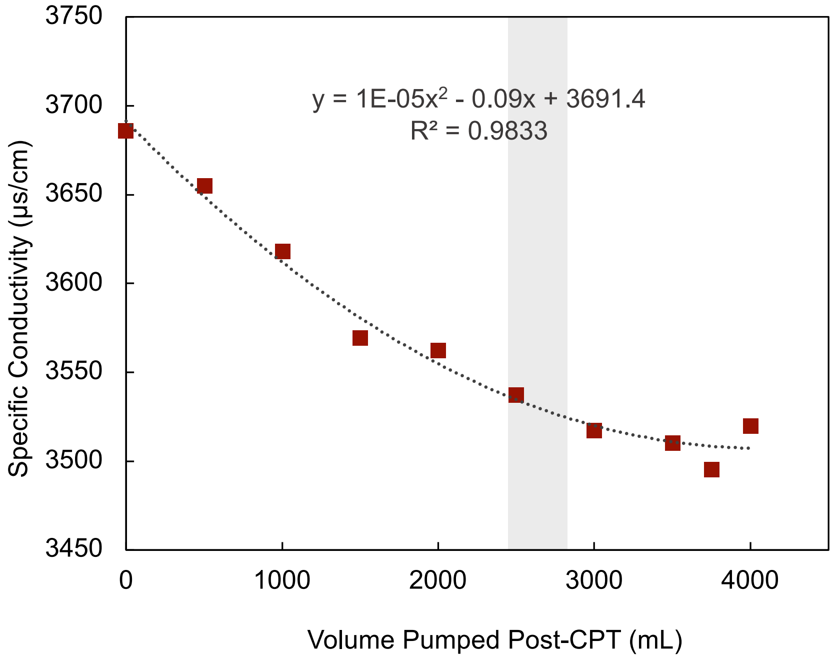


Figure 5. Specific conductivity decrease following the localized cone penetrometer activity including during the addition of a bentonite slurry (charcoal) in CPT 43, 47, and 49.

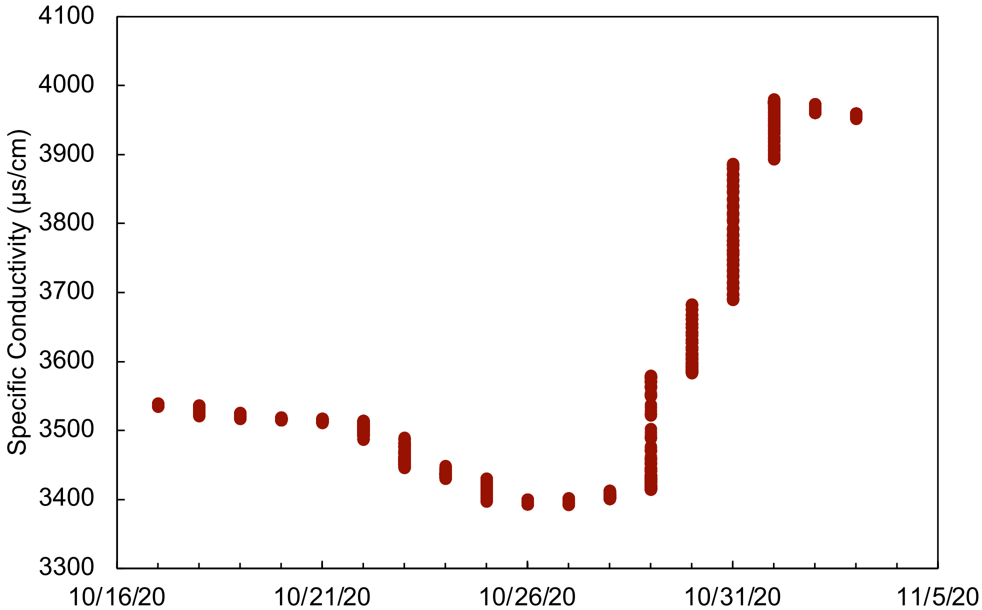


Figure 6. Groundwater specific conductivity continuous monitoring of underlying groundwater well FW106. Measurements collected every 10 minutes are plotted as daily ranges with dates recorded in month/day/year. CPT activities localized to FW106 took place on 10/18/20, 10/20/20 – 10/22/20, 10/24/20 and 10/25/20. On 10/28/20 the site received 5.2 centimeters of rain and an additional 2.5 centimeters on 10/29/20 after which the specific conductivity increased daily until stabilizing on 11/02/20.

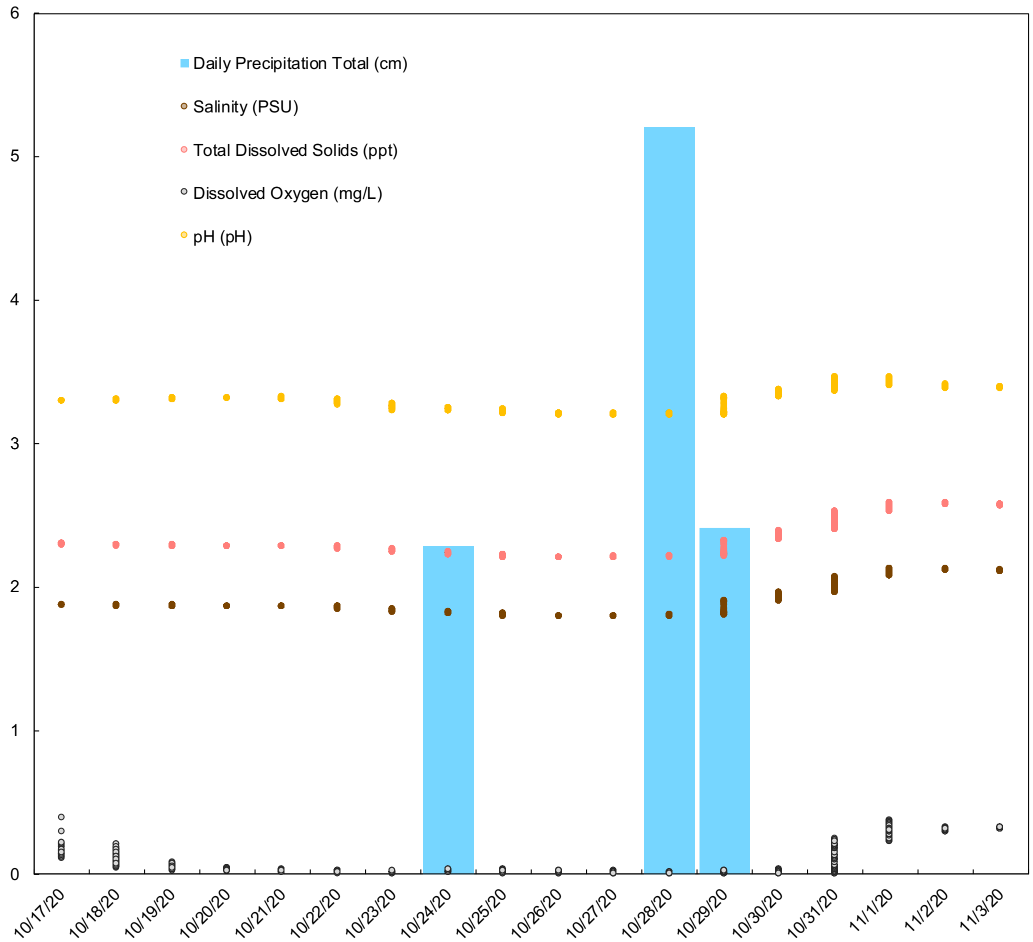


Figure 7. Continuous monitoring data collected every 10 minutes are plotted as daily ranges with dates recorded in month/day/year from FW106 for all parameters except specific conductivity. CPT activities upgradient of FW106 took place on 10/18/20, 10/20/20 – 10/22/20, 10/24/20 and 10/25/20. On 10/28/20 the site received 5.2 centimeters of rain and an additional 2.5 centimeters on 10/29/20 resulting in a higher daily variability until stability was achieved around 11/02/20.

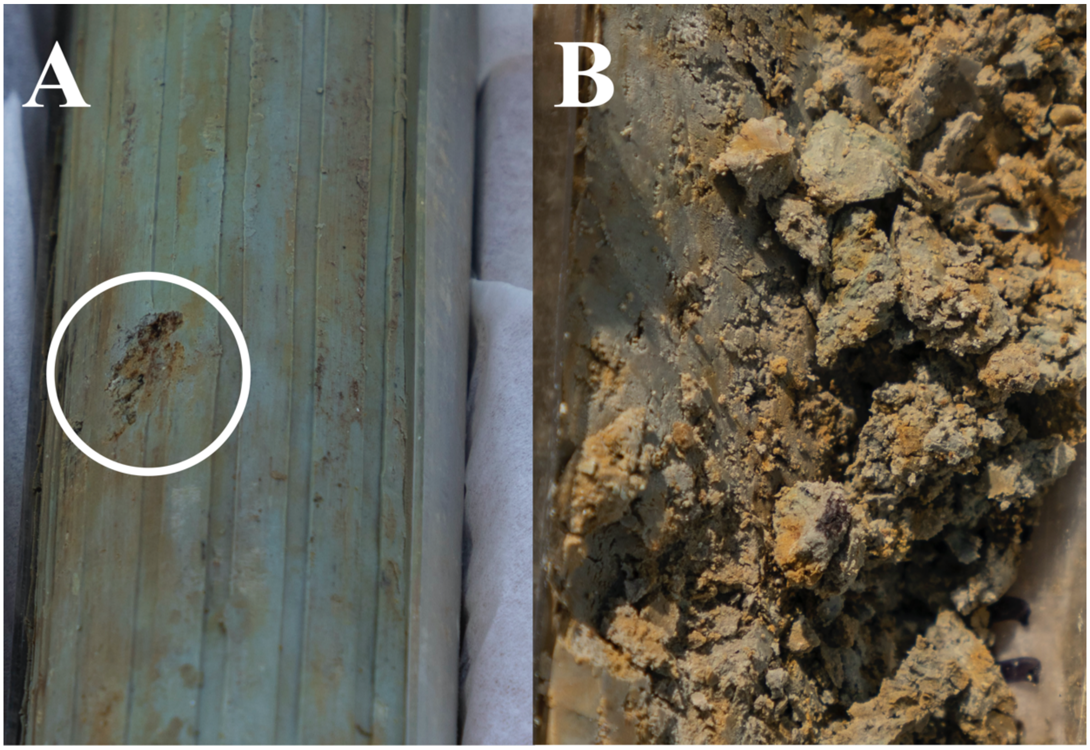


Figure 8 Sediment collected from the unconsolidated residuum where (A) pore compaction was caused by the advancement of the probe against (B) the typical material structure of the clayey residuum. The white circle shows a window into the core ~2 mm deep demonstrating the limited extent of the pore compaction and smearing.

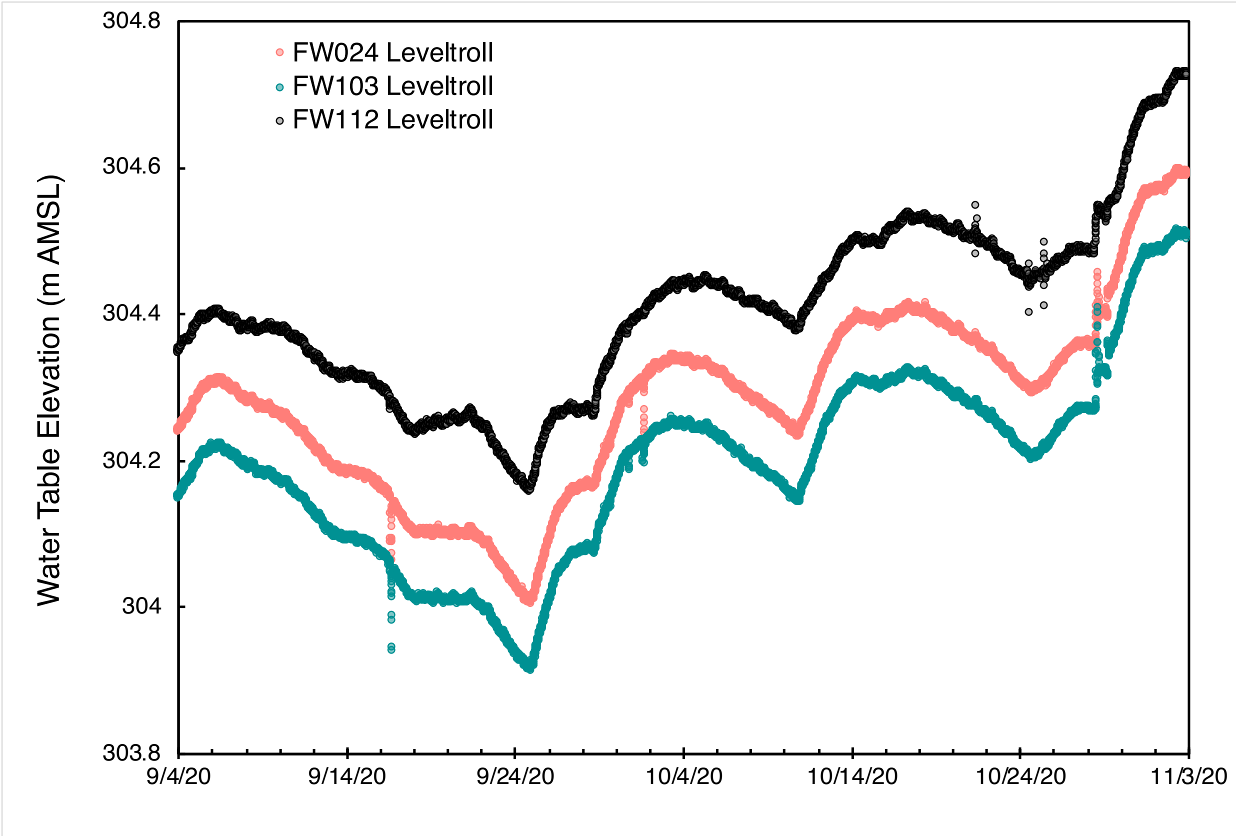


Figure 9. Continuous water level data from FW024, FW103, and FW112 collected in 10 minute intervals and recorded as month/day/year demonstrates the oscillating pattern of water level change common under ambient conditions. Local CPT activities occurred on 10/18/20, 10/20/20 – 10/22/20, 10/24/20 and 10/25/20. Observable water level variation is exhibited in FW112 from local CPT activities on 10/21/20, 10/22/20, 10/24/20 and 10/25/20. On 10/28 the site received 5.2 centimeters of rain and an additional 2.5 centimeters on 10/29 resulting in the rising water levels after 10/28/20.

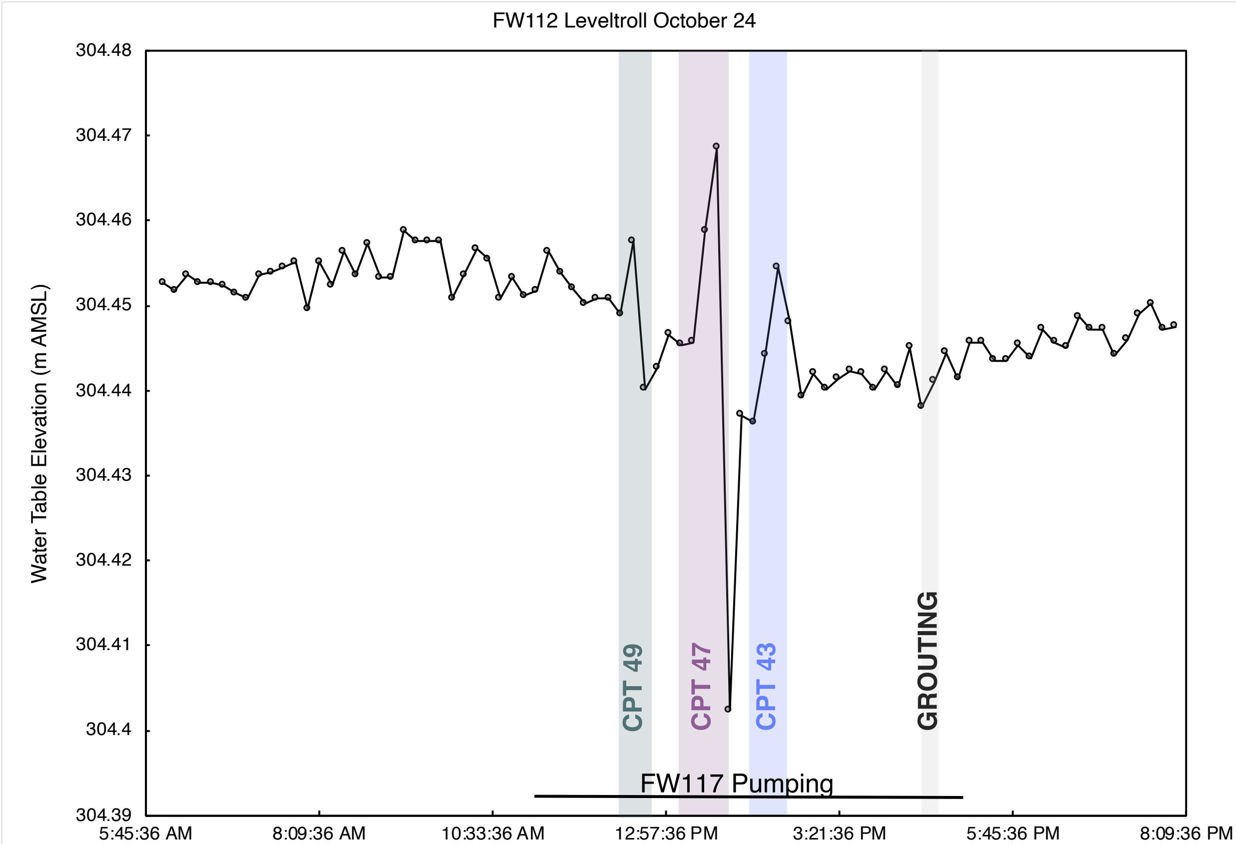


Figure 10. Continuous water level data from FW112 demonstrating the water level fluctuations of local CPT activities on 10/24/20. Each bar represents the CPT push and retraction with downward advancement occurring in the first half of each bar and retraction occurring in the later half.

Tables

Table 1. CPT subsite borehole depths and date of completion

Bore	Depth (m)	Date
CPT 34	7.559	18-Oct
CPT 35	6.898	22-Oct
CPT 36	8.278	21-Oct
CPT 37	8.019	21-Oct
CPT 38	8.358	21-Oct
CPT 39	1.78	24-Oct
CPT 39A	1.64	24-Oct
CPT 40	9.796	21-Oct
CPT 42	9.778	21-Oct
CPT 43	11.156	24-Oct
CPTB 45	1.759	21-Oct
CPT 45A	9.418	21-Oct
CPT 46A	8.458	21-Oct
CPT 47	10.756	24-Oct
CPT 48	7.958	20-Oct
CPT 49	11.198	24-Oct

Table 2. Local hydraulic conductivity

well	screen interval (m)	local CPT depth (m)	well proximity to CPT	method	*k (m/sec)*
FW134-2	6.1 – 7.6	7.6	upgradient	0.5 L Slug	2.59×10^{-6}
FW115-3	8.5 – 9.7	10.8	down-gradient	0.5 L Slug	6.60×10^{-7}
FW115-3	8.5 – 9.7	10.8	down-gradient	Pump	1.22×10^{-7}
FW128	12.4 – 15.1	10.8	down-gradient	1 L Slug	1.01×10^{-5}
FW103	11.27 – 13.7	1.8	down-gradient	1 L Slug	2.65×10^{-5}
FW127	12.16 – 15.1	9.4	down-gradient	Borescope	1.77×10^{-4}

Table 3. ANOVA test of variance results

	Sum of Squares	**F-value**	**p-value**	**Significance**
FW112 Water Level	0.743	10.36	0.002	**
Temperature	0.004	0.052	0.821	
Specific Conductivity	0.427	5.954	0.016	*
Salinity	0.355	4.957	0.028	*
Total Suspended Solids	0.026	0.357	0.551	
Resistivity	0.008	0.108	0.743	
Barometric Pressure	0.176	2.448	0.120	
pH	0.166	2.316	0.130	
Oxidative Reductive Potential	0.671	9.364	0.003	**

*$p<0.05$ **$p<0.01$