Site Characterization for Cutter Soil Mixing of a Vertical Barrier Wall

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ABSTRACT Golder Construction recently completed a vertical hydraulic barrier wall surrounding contaminated soil and groundwater at a former manufactured gas plant site in New Jersey. The project performance specifications consisted of a barrier wall with a minimum 91 cm (36") in thickness, a maximum hydraulic conductivity of $1.0x10^{-6}$ cm/s, and a minimum Unconfined Compressive Strength (UCS) of 1,378 kPa (200 psi). The wall alignment was constructed through clean sand and gravel soil around the contamination zone. The base of the wall was keyed into an underlying clay aquitard with a termination depth of between 25 and 27 meters below surface. Cutter Soil Mixing (CSM) was identified as the preferred construction method for the barrier wall construction. Golder developed the installation work plan following a detailed review of the available geotechnical information for the site. This paper presents the methodology utilized for assessing CSM viability, identifying a suitable soil-cement mix design, and discusses unique constructability aspects associated with CSM technology. The project was subject to rigorous quality control (QC) measures, requiring strict controls on mixing energy, wall verticality/alignment, visual inspection of panel overlaps, in-situ hydraulic conductivity testing and soil-cement mix sampling. This paper also summarizes the QC verification process developed during the field mix trial required prior to full scale production.

Project Overview

A contaminated plume of soil and groundwater within a sand and gravel aquifer was identified at a former manufactured gas plant site at a confidential site in New Jersey. The extent of the plume was determined by drilling boreholes along the periphery of the former manufacturing facility and characterizing the boreholes as either in clean or contaminated soil. A line connecting clean boreholes was drawn to mark the approximate extents of contamination. The perimeter encircled a flat field with an area of approximately 5.5 acres.

Contaminated sites in the state of New Jersey had previously only gained regulatory approval as remediated following 100% soil replacement/treatment, however due to the size and depth of the aquifer 100% soil replacement was not feasible for this site. A vertical barrier wall was proposed to isolate and contain the flow of groundwater through the contamination zone. The base of the wall was designed to key into an underlying clay aquitard with a termination depth of 25 to 27m below surface. The designer selected deep soil mixing (DSM) as the methodology for construction due to the ground conditions and required depth of the wall. Golder was selected to install the soil mixed vertical barrier wall through a competitive bid process. Golder's preferred method of DSM for this project site was Cutter Soil Mixing (CSM).

Project Design Specifications

The vertical barrier wall specifications defined the DSM wall as a continuous groundwater cut-off wall with a minimum effective thickness of 91 cm, a maximum horizontal permeability of $1.0x10^{-6}$ cm/s, and a minimum Unconfined Compressive Strength (UCS) of 1,378 kPa (200 psi). The wall was to be fully mixed with "no holes, gaps, or zones that exhibit a greater permeability as demonstrated by implementing the DSM Quality Control Program." "No unmixed soil clods greater than two (2) inches in any dimension" were permitted as determined by visual inspection of drill core sampling or DSM down hole bulk samples. The wall was to be keyed a minimum of 3 feet into the underlying clay formation.

Specifics of the mix design were left to the contractor to establish through a staged process consisting of conceptual mix identification, laboratory bench scale testing using soil samples collected from site, a field verification mix program, and ultimately full production with verification through an approved Quality Control Plan. Prescriptions for injection rates, cutting speed, mixing energy, panel overlap, sampling procedure and grout mix quality control were to be developed during the field mix trials and implemented during full scale production.

Site Characterization

Boreholes were completed over several years, and the site characterization was primarily carried out through SPT sampling. Shelby tubes were collected in the underlying clay material.

Site stratigraphy consisted of the Bridgeton Formation – a medium to coarse grained sand, underlain by the Cohansey Formation – interbedded medium to coarse grained sands, clays and gravel beds. The contact between these formations was difficult to determine precisely, however the Cohansey was underlain by the Kirkwood Formation, a distinct dark grey silty clay stratum that acted as the aquitard. The Kirkwood formation was identified at a depth of 21 to 23m below ground surface.

Groundwater level fluctuated, with the seasonal high-water table between 1.5 and 3m below ground surface.

Conceptual Mix Design

A drilling and sampling plan was developed to obtain sufficient quantities of soil representing each distinct soil type present on site. Three soil blends were created by combining like samples collected from several different boreholes. The three sample blends are described as follows:

- Soil Type 1 (Bridgeton Formation): Gravelly Sand, pH tested at 7.1, average natural moisture content 13.0%
- Soil Type 2 (Lower Cohansey): Sandy Silt, pH tested at 5.8, average natural moisture content 34.3%
- Soil Type 3 (Kirkwood Formation): Fat Clay, pH tested at 5.1, average moisture content 47.9% - Liquid Limit of 66% - Plasticity Index of 46%.

Factors affecting soil cement performance include grain size distribution, moisture content, and groundwater characteristics. In addition to the soil samples, water samples were collected and sent to the lab for dissolved chemicals and pH testing. Water was to be taken from a city waterline for batching so water with similar properties was used when mixing in the lab.

The project performance specifications, grain size analysis results, pH and moisture content of the in-situ soils were reviewed and compared to mixes tested on previous job sites. An initial estimate of quantities of cement and bentonite that would likely be required to meet the project specifications in terms of strength and hydraulic conductivity were established through this review. A blend of Portland Cement and Ground Granulated Blast Slag (GGBS) blend was chosen as a binding agent.

The intent of the bench scale tests was to bracket the performance criteria by designing a lean mix that will provide lower bound results with respect to the specifications, a second upper bound mix that exceeds the specifications, and a third average mix with results close to the target values. The project required every panel to meet the specifications; due to inherent variability in the soil and installation procedures, conservative estimates of suitable mixes were used during construction.

In practice, it is necessary to fully fluidize the soil during the cutting phase of mixing using CSM equipment. Due to the target depths, it was decided to install the CSM panels using a two-stage cutting and filling approach to mitigate the risk of the cement setting during panel construction. The first cutting stage was completed by injecting bentonite slurry or water only, therefore a minimum volume of bentonite slurry was required. During the second stage, cement was incorporated after reaching the target depth, so the panels was built from the bottom up.

Trial mixes were defined by mixing parameters for soil type, water to cement ratio, addition of bentonite slurry or water (cutting fluid), or quantity of added slag cement slurry (filling fluid). Generally, panel strengths decrease with increased moisture content. Efficient two-phase mix design requires a sufficient volume of injected cutting fluid to fluidize the panel, but not an excessive amount that will negatively impact panel strength. Likewise, filling fluid needs to be thin enough to flow through slurry pipes while not so thin as to unnecessarily increase the water to cement ratio of the soil cement panel.

Bench Trial Mix Design

Nine different mixes were prepared during the mix trials. The soil types were chosen in order to determine the worst-case condition for both the permeability and UCS performance requirements. The three soil types were blended with varying quantities of bentonite slurry, cement slag slurry, and potable water and cast into 3” x 6” cylinders.

In-situ density for each soil type was estimated based on index testing, SPT results and literature review. These values were required when determining volumes of additives. The density of Soil Type 1, 2 and 3 were estimated at 2,130 kg/m^3, 2,010 kg/m^3, and 1,970 kg/m^3, respectively. Volumes of additives were calculated as L/m of panel. Installed panel dimensions were dictated by the size of the CSM cutter head, which is 1m wide x 2.8m long. The specific re-agents used in the Pilot Test and Bench Scale test were identified as the following:

- Baroid Aquagel Gold Seal Premium Sodium Bentonite
- LaFarge NewCem Ground Granulated Blast Slag from the Sparrow’s Point, Maryland
- LaFarge Portland Cement Type 1 from Whitehall, Pennsylvania
- Mix Water from the site location, Glassboro New Jersey

Table 1 identifies the grout mixes evaluated in the mix design:

Table 1 Bench Trial Mixes

Mix #	Soil Material	Bentonite content	Bentonite or Water Slurry Volume	Binder Content (Cement-Slag)
1.1	Soil Type 1	med	med	low
1.2		Medium	Medium	Medium
1.3		None	Low (water only)	Medium
2.1	Soil Type 2	Medium	Medium	Low
2.2		Medium	Medium	Medium
2.3		None	Medium (water only)	Medium
3.1	Soil Type 3	High	Medium	Med-low
3.2		High	Medium	High
3.3		None	Medium (water only)	High

Soil Type 1 (Bridgeton Gravelly Sand) consisted of the coarsest material found in the samples. It was identified as the "worst" case scenario for permeability and the "best" case scenario for strength. Soil Type 2 was identified as representative of the Cohansey Sandy to Silt to Silty Sand unit. Soil Type 3 (Kirkwood Clay) consisted of the finest-grained material found in the samples. It was identified as the "best" case scenario for permeability and "worst" case scenario for strength.

Bentonite slurry had a specific gravity of 1.05 and a Marsh Viscosity of 50 seconds at 22.0° C in the lab. The slurry mix selected based on experience and practical considerations. Too thin a bentonite slurry will not support the trench walls and lubricate the cutter sufficiently and too thick a bentonite slurry will clog the supply lines.

Cement slag grout was mixed at a water/binder ratio picked to produce a slurry thick enough to reach the correct cement content that is still pumpable using a slurry delivery pump and relatively easy to clean out at the end of the day. Cement Slag grout used in the mix design had a specific gravity of 1.69 and a Marsh Viscosity of 1 minute 27 seconds at 27.0° C.

The wet soil mixes assessed in the mix design had specific gravities measured between 1.25 and 1.95 using a mud balance. It was found that a change in specific gravity correlated with the soil type of the wet mixes, but not with variations in cement content. A minimum specific gravity tolerance of 1.20 was set for results in the field.

UCS testing was completed in accordance with ASTM D1633, and permeability testing was completed in accordance with ASTM D5084. The following table presents the lab testing results for the nine mixes.

Table 2 Bench Trial Results

Mix #	Specific Gravity	Slump (inch)	Strength (kPa)		Permeability (cm/sec)
			14-day	28-day	28- day
1.1	1.9	9.5"	2,660	2,976	7.6E-08
1.2	1.95	9.75"	4,430	5,264	7.3E-08
1.3	1.95	11.75"	5,195	5,960	8.7E-08
2.1	1.71	6.0"	1,006	1,047	2.0E-08
2.2	1.68	5.5"	331*	1,826	1.8E-08
2.3	1.66	5.0"	1,261	1,681	2.0E-08
3.1	1.42	0"	255*	441*	6.5E-08
3.2	1.25	0"	861*	937*	2.0E-08
3.3	1.47	0"	620*	1,282*	3.1E-08

Note: Test results with a * next to them contained air voids and are significantly lower in strength than a representative sample of material mixed and cured in-situ.

Slump tests were conducted on all nine wet soil mixes during the mix design. Results varied from 0" to approximately 11.75". Slump measurement correlated with the soil type of the wet mixes, but not with variations in cement content. It was proposed that no slump tolerance be used since the variation of soil plasticity between the Kirkwood Clay and overlying sands and gravels varied widely. Instead it was proposed that strength and permeability be confirmed through lab testing since slump testing was shown to not necessarily be indicative of performance with soil cement samples. Mix 1.3 showed that a wet soil cement sample with a slump of 11.75" can meet the strength and permeability performance requirements.

Samples from all nine mixes tested in the lab met the maximum horizontal permeability performance requirement of 1.0×10^{-6} cm/s. Mixes 1.3, 2.3 and 3.3 demonstrated that the permeability requirement could be met using a water only cutting fluid. Bentonite slurry was selected as a cutting fluid in the Bridgeton and Cohansey units, as it improved cutting performance, promoted trench stability by forming a filter cake against the loose permeable soils, and reduced wear and tear due to abrasion by lubricating equipment during cutting. Water was selected as a cutting fluid in the Kirkwood clays, as it was observed to be a more effective fluidizing agent of the stiff clays and the low permeability of the soil unit presented little risk of losing cutting fluid into the formation.

As expected, UCS testing results were found to be highly dependent on the soil type. Mix 1.1 in Soil Type 1 exceeded the 1,378 kPa strength requirement with a low [l] cement content while Mix 2.1 in Soil Type 2 did not meet the design requirements. Kirkwood Clay Soil Type 3 Mix 3.1, 3.2 and 3.3 did not meet the 1,378 kPa UCS performance requirement, even with the high cement content in Mix 3.3.

It was noted that Soil Type 3 mixes resulted in very stiff samples that were difficult to cast into the 3" x 6" sample cylinders without leaving air voids. It was concluded that while Mix 3.3 did not reach the 1,378 kPa requirement at 28 day curing time, the samples would likely meet the performance requirements if mixed in-situ and cast in a representative manner.

The following two mixes were selected for field mix trials based on the bench scale trial results. It was recognized that cutting fluid volumes may vary in the field with soil conditions so cutting volumes were set as a target, not a hard value.

Table 3 Field Trial Mix Designs

Mix #	Cut from Ground to 2m above Kirkwood Clay	Cut from 2m above Kirkwood Clay to bottom depth	Fill from bottom depth to 2m above Kirkwood Clay	Fill from 2m above Kirkwood Clay to Surface
1	Medium (bentonite)	High (water only)	High	Medium
2	Medium (bentonite)	High (water only)	High	Low

Field Mix Program

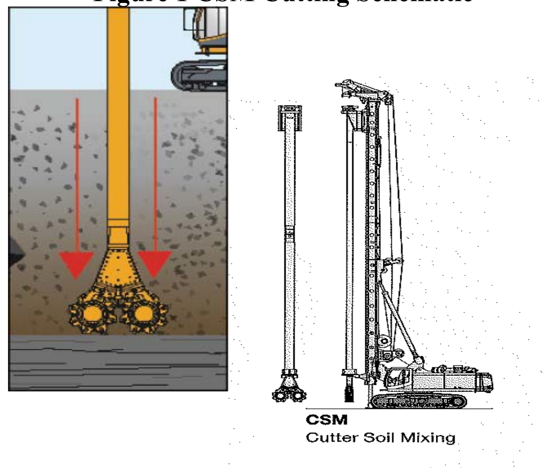
The two mixes identified in the bench scale testing were completed on sets of three panels; two primary panels were installed with a secondary panel installed between them. Panels were completed in sets of three to quantify any impact of excess bleed water originating from primary panels as well as boundary condition changes along the ends of secondary panels as a result of adjacent primary panel construction. Secondary panels were installed at least 12 hours after completion of the adjacent primary panels.

The CSM cutter was positioned over the panel and Phase 1 cutting began using bentonite slurry with a target maximum injection rate in accordance with the mix designs presented in Table 3. Additional fluid was required to fluidize the Kirkwood Clay in the lab, so cutting was completed using a higher maximum water injection rate for Mix 1 and Mix 2 in the bottom 3m of the panel.

Filling was completed in accordance with the field mix trial injection rates described in Table 3. A re-stroke was performed in the bottom 3 m of the panel, where the stiff Kirkwood clay was located, to increase the mixing energy while pumping cement slag slurry. The cutter-head was retracted at a maximum rate of 40 cm/min throughout the filling phase, and the CSM wheels were kept running at the maximum practical RPM. This was done to maximize the mixing energy within the panel and create a more homogenous soil-cement panel.

Figure 1 shows a schematic of the CSM equipment and cutting process.

Figure 1 CSM Cutting Schematic



Samples were collected from each panel at depths selected by the owner's engineer. These samples were slump tested in the field, cast into cylinders and tested in the lab for UCS and permeability at 28-day cure times. Results from these lab tests are presented in Table 4. Panels P002, P006 and P014 were constructed as secondary panels. The rest were primary panels.

Table 4 Field Mix Trial Lab Results

Mix #	Panel ID	Soil Type Based on Sample Depth	UCS (kPa)	Permeability (cm/sec)
			28-day	28-day
1	P001	1	8,523	0
		2	5,484	2.5×10^{-08}
	P002	2	6,456	2.5×10^{-08}
		2/3	9,226	8.4×10^{-09}
	P003	1/2	6,483	6.9×10^{-09}
		3	3,920	7.3×10^{-09}
2	P005	2/3	4,747	2.2×10^{-09}
		3	2,542	6.6×10^{-09}
	P006	1	10,376	2.6×10^{-08}
		2/3	9,756	8.7×10^{-09}
	P007	1/2	10,280	2.5×10^{-08}
		2	10,535	2.5×10^{-08}

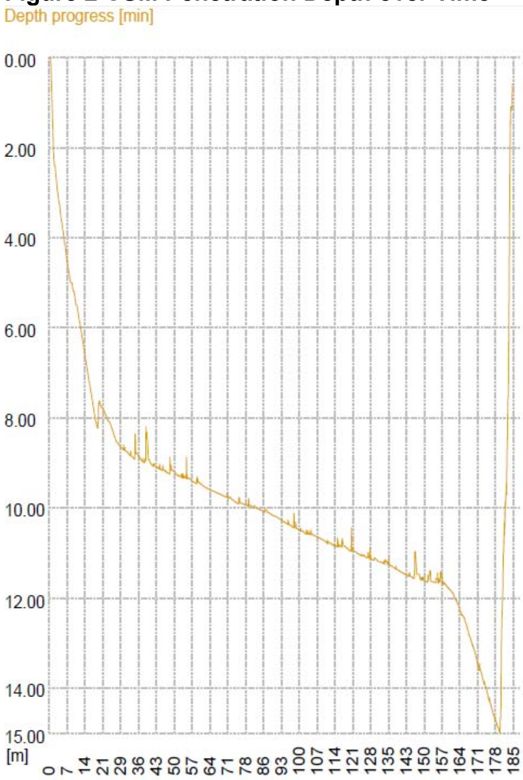
Samples were collected and tested in pairs. UCS results represent the average of two tests.

Permeability results from samples collected in-situ were similar or better than those obtained in the bench trial for both mixes. The UCS testing results were all significantly better than those obtained in the bench scale tests. No significant variations in sample results were noted between primary and secondary panels.

Soil Pre-Treatment

A significant decrease in cutting penetration rate was noted at a depth of 9 to 12m below ground while installing the field trial panels. This was recorded on the onboard CSM rig computer and is shown for one of the panels on Figure 2.

Figure 2 CSM Penetration Depth over Time



The reduction in penetration rate shown on Figure 2 equated to an increase in cutting time of over two hours and is representative of a generally denser soil horizon. This layer was not identified during the site characterization process and appeared on every subsequent panel installed. It was noted that the penetration rate within this layer was significantly faster during secondary panel installation. This unexpected reduction in production rate led to the consideration of soil pre-treatment options.

A large diameter continuous flight auger drill was used to drill into and loosen up the existing dense soil prior to CSM cutting. The auger drill showed no difficulty drilling through the hard layer encountered by the CSM rig and no impact to drilling rates were noted. Auger drilling was performed on a large section of the barrier wall alignment, but ultimately did not measurably improve the rate of CSM cutting. No other methods of soil pre-treatment were completed over the course of the project.

In-situ Drilling and Verification

The panels completed during the field trial were left to cure for three weeks. A drilling contractor was mobilized to site to complete in-situ field testing and sample recovery on the completed panels following this curing period. Drilling and field verification were completed to obtain continuous core samples from surface to bottom depth of the soil cement panels. The samples were collected for visual inspection and laboratory testing.

Mud Rotary drilling was completed using a standard PQ drill bit with outside diameter of 122.6mm and a triple tube sampler setup.

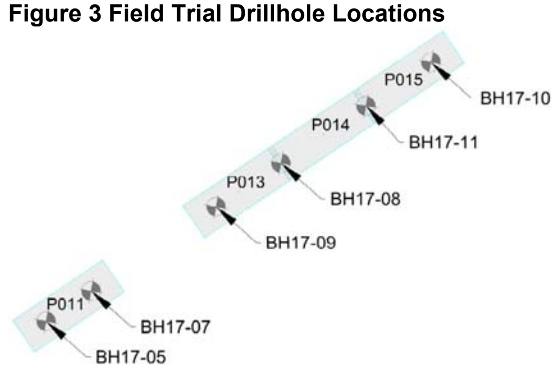
While the lab testing for both mixes met the performance requirements, the Owner’s Representative rejected Mix 1 upon visual inspection of the drill core after identifying “unmixed soil clods greater than two (2) inches” in diameter. The lower cement content Mix 2 was identified as the mix to be tested going forward. The maximum rate that the cutter-head could be retracted was reduced from 40 cm/min to 25 cm/min throughout the filling phase in order to increase the total mixing energy in the panel. A method for verifying the total number of wheel rotations per meter of panel that was integrated into the Quality Management Plan.

Initially falling head tests were performed on the open boreholes following borehole completion. Non-conforming in-situ permeability results were recorded. A down hole borehole camera was deployed to inspect the sidewalls of the drill holes. It was recognized that a single small crack or void in the panel would act as a water conduit with a permeability orders of magnitude higher than that of the intact soil-cement panel. Voids were identified in the sidewalls that likely caused the initial lower-than-expected results.

The drilling contractor drilled with a high-pressure water pump designed to blow any blockage out of the drill rods if the bit got stuck. It was theorized that this pump had periodically kicked in during drilling and this water pressure had hydraulically fractured the panel, resulting in the cracks and voids observed in the borehole sidewall. The drill was also not equipped with deviation monitoring equipment, so it was unclear if the drill bit had deviated to the edge of the panel near the bottom of the hole. The panels were only 1m wide, leaving less than 0.5m of space between the drillhole and edge of panel. Ultimately a second set of panels were installed using Mix 2 and a second drilling subcontractor, with previous experience with drilling soil cement, was brought in to complete the drilling.

For the second field mix trial drillhole locations were selected in primary and secondary panels, and along panel overlaps to get representative samples of all barrier wall characteristics. Figure 3 shows the location of drillholes completed during the second field trial.

Figure 3 Field Trial Drillhole Locations



Wells for falling head permeability testing were completed in boreholes BH17-08, BH17-09 and BH17-10 as selected by the Owner’s Representative. Two were selected within individual panels and one was selected along the overlap between two panels. Standpipe piezometers were installed at specific intervals selected by the client based on visual inspection of the drill core. They were installed as per New Jersey well install guidelines using filter sand, bentonite chips, screened 2” ID PVC, and solid 2” ID PVC.

All falling head tests were performed by lowering a Solinst Levelogger downhole and topping the well off with water. For tests done with screened intervals above the groundwater table enough water was poured down the PVC well to fully saturate the surrounding sand pack prior to starting the test. The rate of level drop, borehole and standpipe dimensions, panel dimensions, surrounding groundwater table, and test interval length were all recorded.

Results were analysed using the Hvorslev borehole variable head permeability equation for a wellpoint filter in uniform soil (Department of the Army Navy and Airforce, “Dewatering and Groundwater Control”, 1983, Page 3-7). If reached, results were taken for the 90% drawdown time. If not reached due to the test ending before 90% drawdown occurred, results were taken from the end of test.

The Hvorslev equation solves for hydraulic conductivity assuming no variation in lateral soil properties with distance from the borehole. Due to the narrow dimensions of the soil cement wall within a highly permeable sand and gravel aquifer, a correction factor was applied to the in-situ permeability results. The correction factor was derived by finite element modelling the panel geometry in the Geostudio program SEEP/W. The panel dimensions and 12.26cm borehole diameter were defined in plan view for each test location, and the flow rate was compared to a base case model with very large panel wall dimensions. The base case was modelled to approximate the Hvorslev equation, which solves for a soil cement wall of infinite lateral dimensions. A flux section was drawn to capture all flow flowing laterally from the borehole, and the flux rate was used to calculate the correction factor.

$$[1]\ \text{Correction Factor} = \frac{\text{Base Case Flux}}{\text{Geometry Specific Flux}}$$

Through multiple model runs, it was determined that as long as the material and constant head conditions were consistent between models, the ratio of flux between the base case and the specific dimensions of the panel remained the same. This ratio was unaffected by permeability and hydraulic gradient model inputs, as these terms cancel out when comparing the two geometric conditions. The models were run multiple times for numerical confirmation of this mathematical relationship.

Figure 4 and 5 show screenshots from the SEEP/W model under base case and CSM panel specific boundary conditions. Note the preferential flow paths along the shortest distance to the panel sidewalls in Figure 5.

Figure 4 Seepage Flow Model Under Hvorslev Assumptions (Plan View)

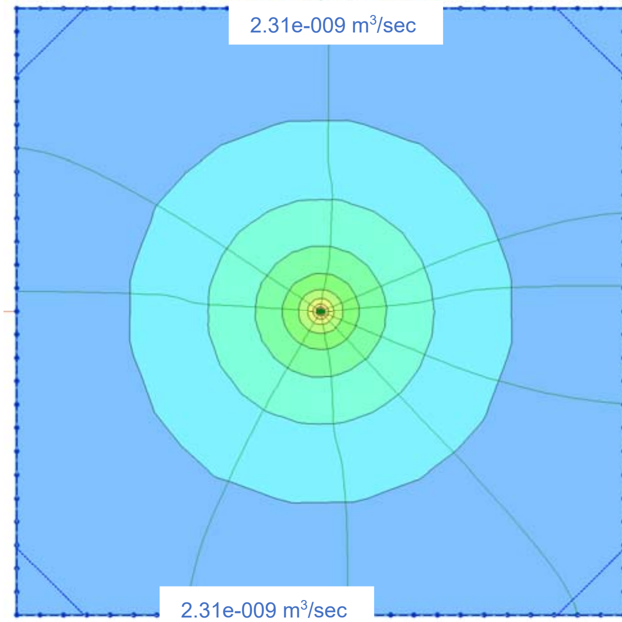
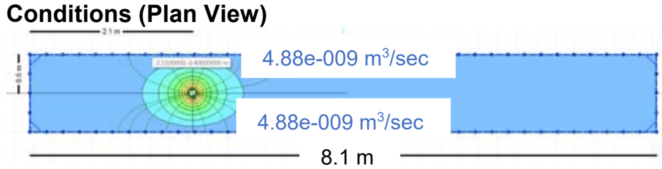


Figure 5 Seepage Flow Model for CSM Panel Boundary Conditions (Plan View)



Correction factors varied slightly based on the location of the boreholes within the three-panel set. Table 5 presents the calculated geometric shape factors and falling head permeability results for the three installed wells.

Table 5 In-situ Horizontal Permeability Results

Borehole	Test Interval (m bgs)	Geometric Shape Factor	Calculated Permeability (cm/s)
BH17-08-P013	0.9 – 21.3	2.1	4.2×10^{-7}
BH17-09-P014/P015	0.6 – 21.1	2.0	2.8×10^{-7}
BH17-10-P017	16.2 – 21.2	2.1	3.7×10^{-7}

Samples were collected from each borehole and tested for permeability and UCS. Table 6 presents the results of these tests:

Table 6 Lab Results from Borehole Samples

Borehole	Sample Depth (ft bgs)	UCS (kPa)	Permeability (cm/s)
BH17-08-P013	15.5 – 15.7	6,084	1.3×10^{-8}
BH17-09-P014/P015	7.2 – 7.4	3,376	2.8×10^{-8}

All intervals tested satisfied the maximum horizontal permeability performance requirement of 1.0×10^{-6} cm/s. These permeability results were noted to generally be an order of magnitude higher than results obtained in the lab. This was attributed to panel disturbance while drilling and possible drill bit deviation towards the edge of the panel.

Wall Continuity Verification

A section of wall was excavated and exposed following field mix trial drilling and verification testing. Joints between panels were exposed and the as-built panel width dimensions were measured. Visual inspection of the joints between primary and secondary panels was conducted. It was determined that the exposed joints were intact with no visible impact to the effective wall width. Joints were determined to not provide a preferential flow path for groundwater flow. The overall vertical barrier wall installation method was approved following this visual assessment, and the project proceeded into the full production phase of construction.

Figure 6 Exposed CSM Wall and Panel Joint

Conclusions

Site characterization for the purpose of soil-cement panel installation is a specialized process that requires taking into account both engineering (technical) and construction considerations. This lends itself to a design build approach requiring a team of experienced engineers and contractors. The product verification process is highly dependent on the project specifications and presents many unique challenges.

The project specifications, requiring hard minimum UCS and permeability results, led to the selection of a mix design with a conservative binder content. The mix design was selected to meet the requirements in the “worst” case scenario, resulting in samples that generally exceeded the 1,378 kPa UCS requirement. Probabilistic-based approaches to performance specifications have been gaining popularity among engineering practitioners but are not currently a state-of-the-practice approach. Given the inherent variability of soil-cement products, a probabilistic-based approach to performance specifications has the potential to lead to a more efficient mix design. As a result the design requirements of the final product should be carefully considered when preparing DSM construction packages.

Drilling down the center of a CSM panel for the purpose of permeability testing is extremely difficult and has the potential to damage the panels. Other options for field verification should be explored for future projects. If the drilling method presented in this paper is used, a geometric shape factor may be applied to falling head test results to account for the boundary conditions of the CSM panel.

The soil conditions that led to the decreased CSM cutting rate on this project remain unknown. This project showed that SPT results can be unreliable when assessing expected CSM cutting speed. This presents an unforeseen risk when assessing production rates and estimating project costs. Additional means of site investigation that would provide continuous data with depth, such as CPTu testing may help to reduce this uncertainty.

References

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