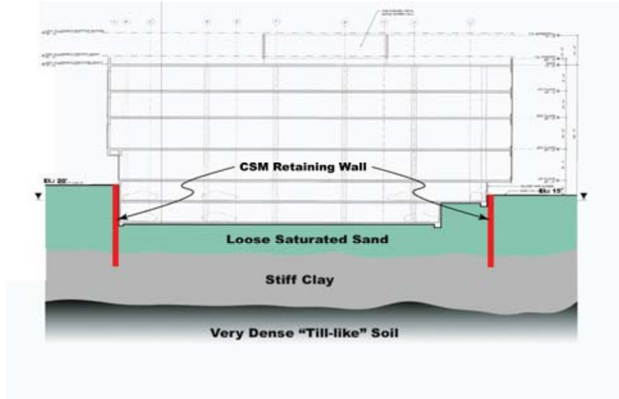
CUTTER SOIL MIXED WALL
SHORING AND SEEPAGE CUT OFF
OFFICE BUILDING NEAR WATERFRONT

By
John Kvinsland – Malcolm Drilling Company, Kent, Washington
Bob Plum – ASCE, P.E., Principal Kleinfelder Consultants, Seattle

ABSTRACT:
This paper will present several aspects of the soil mixed CSM wall installed as part of an office building project completed in 2009 near the Seattle waterfront in an area underlain by fill and loose beach deposits with a shallow groundwater. The project involved construction of a 5-story office building with below grade parking that extends below the groundwater table. Constraints included an adjacent dry cleaner with a groundwater contamination plume, an adjacent railroad track, adjacent main arterial, loose liquefiable soils, and significant long term costs associated with discharging groundwater into the City storm drain system. A perimeter Cutter Soil Mixed Wall (CSM) was proposed by the contractor and selected. The CSM wall acted as a temporary shoring wall, a temporary seepage cutoff wall and a permanent seepage cutoff wall. The paper presents the basis for the wall design, and a description of various construction aspects including the CSM wall installation, tiebacks and dewatering. Field testing, instrumentation and laboratory testing results are described that provided critical data on wall permeability, dewatering effectiveness, wall deformation, and other aspects of the performance.

INTRODUCTION
The project area was at one time near the general location of the old Elliott Bay shoreline with much of the site originally below water. Over the years the area had been filled in such that the shoreline is now located 90 to 120 m (300 to 400 feet) to the west of the project site. At one time the site included a saw mill such that encountering wood debris was a potential issue. The project includes two five-story commercial office buildings, a plaza area, and two levels of below grade parking underlying the entire complex. The lowest parking level slab is at elevation +0.6 m (+2 feet) or some 3.3 to 6 m (11 to 19 feet) below the pre-construction site grades. During construction, deeper temporary excavations were required to install pile caps. Main line RR tracks are located just to the west of the site, a main City street arterial is located just to the east with a Dry Cleaners located to the north of the site.

The site is underlain by about 6 to 11 m (20 to 35 feet) of fill and loose beach deposits over a stiff, glacially over-consolidated clay unit as shown on the idealized cross-section in Figure 1. The fill was variable but generally consisted of loose to medium dense silty sands with wood debris. The beach deposits ranged from loose clean sands to loose sandy silt. The underlying stiff clay thickness generally ranges from about 4.6 to 7.6 m (15 to 25 feet). An older glacial sequence underlies the clay consisting of a very dense till-like deposit and very dense sandy silt overlying a very dense sand and gravel that extended beyond the depth of the borings at about 90 feet. Pre-construction groundwater was measured at an elevation of about 3.7 m (12 feet). Thus, the lowest parking garage level at an elevation of +0.6 m (+2 feet) was about 3 m (10 feet) below the original pre-construction groundwater levels. The Dry Cleaners located just to the north of the site has a known groundwater contamination plume of Chlorinated Hydrocarbons that is spreading generally to the west. The Chlorinated Hydrocarbons was known to occur in the northern third of the site. In addition, petroleum based hydrocarbons were located in the north east corner. These contaminates were a concern since they could interfere with the ability for soilcrete to develop the required strength and permeability properties.



Based on the engineering and cost evaluations, the project design included an auger cast pile foundation; a perimeter Cutter Soil Mixed Wall (CSM) which functioned as temporary shoring and a temporary\permanent groundwater cut-off wall; vertical steel H beams and tiebacks installed as part of the CSM wall providing structural integrity; and a permanent underdrain system inside the CSM wall and below the slab. Liquefaction risks were considered in the overall design. Although the perimeter CSM walls were designed for hydrostatic pressures, the slab was not since it was isolated from the outside water pressures by the CSM wall penetrating into the underlying clays. The CSM wall isolated the effects of the excavation on the groundwater and the adjacent Dry Cleaner's contamination plume. To improve construction conditions, it was decided to install a temporary dewatering system consisting of wells and well points inside the excavation. The intent was to dewater the soils to a depth of about 4 feet below the construction excavation levels. The dewatering system was installed and operated before the excavation reached the original groundwater levels.

WALL SELECTION AND DESIGN

There were numerous issues relating to the selection of the perimeter foundation wall type including impacts on the adjacent Dry Cleaner's contamination plume, long term underdrain flow rates, hydrostatic pressures on the walls and slab, construction risks, and cost. The owner's strong preference was a system which would have minimal impacts on the Dry Cleaner's contamination plume. The City of Seattle charges a substantial fee for disposing of underdrain flows into the City sewer system which would be imposed over the entire life of the building. Thus the owner had a strong desire to limit the flows, both during and following construction. Due to the size of the building, designing the lower slab to resist hydrostatic uplift would have added significant costs to the project. Based on these and other considerations, the design decision was to take advantage of the site geology which allowed the below grade perimeter wall to penetrate into the underlying clay unit to form an effective seepage cut-off. This significantly reduced both construction and long term groundwater inflows and allowed the lower slab to be designed with underdrains to eliminate any uplift pressures. Both a drilled concrete secant pile wall and a CSM wall were initially considered with the CSM wall selected due to costs and schedule. It is estimated that using the CSM wall saved two months and a million dollars compared with the more conventional secant pile wall. The main disadvantages of the CSM wall were the risks of encountering major obstructions and the risk of encountering contamination that would adversely impact the soilcrete strengths. Neither concern was a major issue during construction. The permanent below grade earthpressures were supported with the permanent wall poured up against the CSM wall and braced with the building floors.

Unlike conventional slurry walls and diaphragm walls that utilize concrete, soil mixing relies on mixing the soils in situ with a cement and bentonite slurry to create a soil-cement wall. Cutter Soil Mixing technology utilizes two sets of vertically mounted cutting wheels rotating about a horizontal axis to produce rectangular panels of treated soil as shown on Figure 2. By overlapping the soil mix panels, a continuous rectangular wall is constructed, as opposed to circular columns created with conventional single-axis or multiple axes deep soil mixing systems. Upon completion of an individual panel, two 460 mm (18 inch) wide flange beams are inserted into the wet "concrete like" soil cement material to provide structural strength to the non-permeable mix. Later, following excavation of the interior of the foundation, tieback anchors can be installed to further increase the shoring capacity of the CSM cutoff wall.

Figure 2. CSM Cutting Head

The CSM wall had to provide two critical functions: 1) be an effective temporary/permanent cut-off wall; and, 2) support the temporary excavation earthpressures. This is unusual since the CSM wall can normally be optimized for either strength or low permeability depending on its function. For this project, the soilcrete properties had to meet both criteria. The cut-off wall function was satisfied by extending the wall at least 2.3 m (7.5 feet) into the underlying clay, constructing tight joints between the CSM panels, and developing a soilcrete mix that had a low permeability. The achievable 28-day soilcrete strength at this site was in the range of 690 to 2,000 kPa (100 to 300 psi). At this relatively low strength, the soilcrete could not provide the necessary structural integrity to support the earthpressures. Thus, the wall design included vertical H beams installed in the CSM wall at about 1.07 m (3.5 foot) centers as shown on Figure 3. Due to easement constraints, the west side excavation next to the RR included a lower cut slope section to reduce the wall height such that the wall functioned as a cantilever wall. On the other sides of the building footprint, the excavations were deeper and one row of tiebacks was installed to provide lateral support. Structurally, the loads were resisted by the steel beams and tiebacks with the soilcrete functioning as the lagging. In some areas, the hole drilled through the wall to install the tieback was below the groundwater table. Installing the tiebacks below the water table turned out not to be a significant issue as there was minimal loss of ground and seepage during installation and after installation, the holes were effectively plugged by Non Shrink Grout. In a handful of cases, minor leakage occurred which was sealed by injecting semi ridged injection grout.

Figure 3. Completed CSM Wall

The nominal minimal acceptable long term leakage for the entire below grade area was selected by the owner and design team as 64 liters/minute (17 gpm). A series of calculations were made to estimate the required clay and wall permeability to meet the 64 liters/minute (17 gpm) criteria. The calculations indicated that the majority of the inflow would be through the wall with the wall needing to have a gross overall average permeability less than about 5 x 10^{-6} cm/sec with an assumed maximum permeability of the underlying clay of 10^{-6} cm/sec. It was felt that much of the flow through the wall might be due to leaks at joints, cracks and/or areas of poor quality soilcrete. Accordingly, it was required that the soilcrete samples obtain a laboratory permeability less than 10^{-6} cm/sec and all identified leaks in the wall had to be sealed, even if the flows were small.

The owner did not want any actual seepage, wet areas or wall seepage discoloration within the below grade space. Even with the low expected seepage rates, it was felt that the owner's requirement would likely not be met by the CSM and permanent walls alone. Thus, a geosynthetic drainage mat was installed between the CSM wall and the adjacent permanent wall. Any drainage mat flow will drain down the mat into a perimeter underdrain pipe. Even though the flows are low, a watertight slab will eventually develop full hydrostatic uplift pressures. Accordingly, a full slab underdrain system consisting of a drainage layer with perforated pipes was installed below the slab. This collects the long term seepage flowing up through the clay and eliminates any seepage pressures on the slab. All of the underdrains flow into sumps under the slab with the water pumped out of the building into the City's sewer system after treatment.

CSM WALL DESIGN AND INSTALLATION ISSUES

Cutter Soil Mixing (CSM) was selected as the method of choice based on price and schedule relative to a Secant Pile wall. The decision was also based on the CSM's ability to construct a permanent, high quality soil-cement wall even in the gravels and stiff plastic clays, its capacity to key into the glacial till, and its ability to produce a soil-cement material with a minimum strength of 690 kPa ((100 psi) and a maximum permeability of 5 x 10^{-6} cm/sec.

Initial concerns related to several issues. It was known and anticipated that Chlorinated Hydrocarbons existed throughout the northern third of the site. In addition, petroleum based hydrocarbons were located in the north east corner. It was uncertain how the injected grout recipe would react with these contaminates and how it would impact permeability and compressive strengths. Another concern was the ability to develop a mix design that was able to meet the performance specifications in three completely different soil conditions. Lastly, it was uncertain how the cutter head would perform when encountering buried obstructions such as driven wooden piles which were prevalent in this area of Seattle at the turn of the century.

Given the concerns mentioned above, an intensive test program was undertaken before wall production installation to help identify site hazards and at the same time develop a mix recipe that would meet the specified criteria in every potential environment. A secondary exploration program was undertaken by the contractor to identify locations of existing wood piles and the occurrence of any buried rip-rap that might have been part of an old sea wall. The sampling also obtained more information on the occurrence and composition of contaminates. Once the samples were obtained, the contractor developed three separate mix designs which were used to construct three test panels. Cement was the primary component in the mix with Bentonite making up only 7.5% of the cementicious mix. When the results for the various tests were provided by the independent testing firm, the results were better than anticipated. It was determined that the chlorinated hydro-carbons essentially burned off during the hydration of the sample due to the molecules relationship to water. Testing of soilcrete mixed with high levels of petroleum hydrocarbon contaminated soils indicated unacceptably low strengths. It was later determined that the single phase mixing process diluted the limited zones of high contamination to a point where it has minimal effect if any on the mix. With the various ground conditions at the site, a single phase system was utilized to insure a homogenous product.

Based on the experience gained on this project, it was concluded that the CSM method dealt well with obstructions. Unlike a drill that cuts in one direction such as in conventional DSM installations, the cutter wheels run on independent drives and are capable of being steered. This aspect proved invaluable, for the operator was able to adjust the speed of the cutter wheels via the variable speed controls and essentially manipulate the pressure applied on the obstruction. For the most part, underground piles were reduced to splinters which floated to the top of the mix where it was pumped to the spoils pile. Due to the size of the cutter, hard obstructions such as cobbles were able to be moved to the surface.

INSTALLATION CONTROLS

The CSM installation equipment includes a computer control and recording system. The touch screen computer system allows the rig operator to monitor and control the position of the cutter head to within tenths of an inch, independently control the cutter wheels, and monitor grout and hydraulic pressures. The data from each panel and corresponding batch of grout was stored on memory cards which were then transferred to a laptop computer allowing software to create graphical logs of each panel. These logs were submitted to the project team on a daily basis, providing real time quality control and assurance. During panel installation, the real time data enabled the operator to make on-the-fly corrections to account for obstructions and changes in soil types. In cases where obstructions caused significant positional deviations, the contractor was able to determine immediately whether re-digging the panel to achieve proper position and overlap was required since vertical tolerances were critical.

The computer installation data, which was provided to the engineers, proved to be helpful the QC/QA monitoring of the installation.

TESTING

Based on the design, the main CSM criteria were that the QC/QA testing demonstrates a minimum 28-day strength of 690 kPa (100 psi) and have a permeability less than 10^{-6} cm/sec.

QC/QA field and laboratory testing were performed throughout the wall installation process. In general, this involved taking samples of the soilcrete mix (referred to as wet samples) and completing laboratory strength and permeability testing. Initially attempts were made to obtain in-situ samples from the wall after the soilcrete had cured. These attempts were unsuccessful even though several drilling methods were tried including coring. It was concluded that the high gravel content of the soilcrete was making the in-situ sampling impractical. In general, seven wet samples were taken for material being installed when the panel was at 2.7 and 7.6 m (9 and 25 feet) for one out of every four panels which included back-up samples. Laboratory testing included unconfined compressive strength testing and flexible wall permeameter testing. The strength testing included samples tested at 5 days, 7 days, 14 days and 28 days.

Initially, the strength test results were erratic with many of the results less than the requirements. It was determined that the samples were often being transported to the laboratory with too little field curing time and the method of transportation was not protecting the samples from vibration and disturbance. It was apparent that the samples were very sensitive and easily disturbed early in the curing process. Subsequently, all samples were transported on 3 inches of soft foam only after they had cured for at least 2 to 4 days. This transportation procedure resulted in higher, more consistent results that met the strength criteria.

More than half of the permeability results were below the 10^{-6} cm/sec criteria with many of the results being below 10^{-7} cm/sec. Less than half exceeded 10^{-6} cm/sec but very few exceeded 5 10^{-6} cm/sec. The average result was below the criteria. As the excavation proceeded and the wall exposed, minor leakage was identified generally at joints and cracks. Once identified, the contractor was able to seal the leaks and essentially eliminate known leaks. Leaks that may have developed below the base of the cut could not be observed and were not repaired unless identified above the cut and "chased" below the cut level.

In addition to the testing and leak repair, observation wells monitoring the water levels in the granular formations above the clay were installed outside of the excavation near the wall. These were installed to demonstrate that the excavation had no measurable impact on the groundwater levels outside of the excavation. Although the monitoring would not identify minor leaks, any major leaks would have lowered the water levels next to the wall. None of the exterior wells measurements indicated wall leakage.

TIEBACK INSTALLATION ISSUES

The tiebacks were installed using air pressure which resulted in water being evacuated from the nearby observation wells during the installation process. Concurrently with the tieback installation, ground cracks and settlement were observed near the excavation which extended to the adjacent arterial street on the east side of the project. The maximum settlement of about 1 to 3 inches was measured at the curb line. Settlements occurred quickly and the area stabilized after the tiebacks were installed through an area. Fortunately, the City was about to grind and repave the road such that the settlement impacts were minimal. The City did require that the curb was replaced and any voids below the pavement filled.

It was theorized that the settlement was caused by the installation of the tiebacks, specifically the air and water pressure used to advance the tieback hole. These pressures may have induced localized liquefaction of the loose soils below the water table and above the stiff clays. Although the significance is not known, it was felt that the CSM wall, which acts as an underground dam, likely increased the impacts of the installation pressures as the pressures could not dissipate towards the inside of the excavation.

WALL PERFORMANCE

To date, the cut-off wall performance has been excellent with the actual inflows generally less than 4 liters/minute (1 gpm) once the permanent slab and underdrains were installed. This is less than the design goal of 65 liters/minute (17 gpm) and indicates that the effective wall permeability is quite low. Using the 4 liters/minute (1 gpm) as a leakage value, the likely macro permeability of the underlying clay is on the order of 10^{-7} cm/sec with an effective wall permeability on the order of 4 x 10^{-7} cm/sec. The low rates also indicate that sealing the leaks at the tieback holes and wall cracks were successful. Virtually all of the wall leaks occurred at the panel joints with the worst leakage problems occurring in the area of the one re-entrant corner along the wall. A re-entrant corner develops minimal compression or even tension loads at the corner.

The temporary wall performed well with deflections similar to a standard soldier pile and tieback wall. The main performance issue related to the tieback installation procedure using high pressure air which did cause ground cracking and settlement as discussed under Tieback Installation Issues above.

CONCLUSION

Based on the experienced gained on this project, several conclusions can be made relating to the design and use of a CSM wall for both a permanent low permeability cut-off wall and a temporary shoring wall. These include:

- GENERAL CONCLUSION: The CSM wall successfully provided both an effective seepage cut-off and temporary shoring wall. The CSM wall likely achieved an overall large scale permeability of less than 10^{-6} cm/sec. The CSM process also proved to be robust dealing with obstructions, leaks and variability in the soil conditions.
- CONSTRUCTION DEWATERING: The temporary construction dewatering of the soils above the clay inside the excavation was effective in tightening up the ground, facilitating excavation and providing an adequate subgrade for construction activities.
- LEAKAGE CRACKS: Some leakage at panel joints occurred but was effectively sealed. Other than the tieback holes, the wall leaks appeared to occur at panel joints with a re-entrant corner providing an adverse condition for joint leakage.
- SOILCRETE WET SAMPLE SENSITIVITY: It was found that the wet soilcrete samples were sensitive to movement and vibration until they had time to cure. It is important to establish a procedure for handling and transporting the samples.
- POSSIBLE WALL EFFECTS ON TIEBACK INSTALLATION: As discussed above, the CSM wall, which acts as an underground dam, may have increased the impacts of the installation pressures as the pressures could not dissipate towards the inside of the excavation as it would with a normal soldier pile installation.
- SPOILS CONTROL: On this project single phase system was utilized meaning that wall was cut with the same mix that was extracted to insure a homogenous product. If the soil conditions had been more uniform, a two phase mix which cuts with Bentonite and water might have been used to cut down on spoil removal and disposal costs by reusing the cutter mix and separating out the solids with de-sanders and de-silters.