Case Study: Cement-Bentonite Pre-Trenching and Cutter Soil Mixing (CSM) for Temporary Shoring and Groundwater Cutoff

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ABSTRACT: A multi-story office building in Seattle with four levels of underground parking was sited adjacent to the existing Alaska Way Viaduct in an area which had previously been occupied by turn of the century sawmills before being developed for commercial uses in more recent history. The soils at the site consist of approximately 30-ft of fill and wood debris over estuary deposits and glacial soils. The ground water regime at the site consists of an upper and lower aquifer separated by an aquitard. An upward gradient exists between the two aquifers. The upper aquifer has a piezometric head approximately 9-ft below existing grade.

The proposed excavation was 43-ft deep with a requirement that the shoring system extend an additional 25-ft below the bottom of excavation to limit seepage from the upper aquifer beneath the cutoff and into the excavation. Although initially tendered for construction with an owner designed secant wall or freeze wall system, the successful shoring contractor offered a design-build cutter soil mixed (CSM) shoring system which included pre-trenching the wall alignment under a cement-bentonite (C-B) slurry to remove the identified wood debris prior to installing the shoring system. This paper addresses the stability analysis and excavation of the C-B trench for removal of obstructions along with the design, construction, and performance of the CSM shoring system and associated depressurization of the deep aquifer.

INTRODUCTION

The Sodo district in Seattle is comprised of commercial and industrial properties which are constructed on reclaimed ground which was previously covered by the waters of Elliot Bay. The 505 1st Avenue site is two blocks from the current water front on approximately 30-ft of fill placed in the early 1900's. The presence of a high water table and permeable fill, which is susceptible to consolidation from dewatering, have previously limited the depths of excavations in this area to less than one level below grade. The 505 1st Ave building is the first structure in the Sodo District of Seattle to tackle the challenges associated with a deep excavation below the water table for the construction of multiple levels of below grade parking.

FIG. 1. Proposed 505 1st Ave Building Location and Completed Excavation

The 505 1st Ave building site is a triangular parcel located between two city streets and two existing buildings. An on-ramp to the Alaska Way Viaduct, which was damaged during the 2001 Nisqually Earthquake, is also located directly to the west of the project site. The existing building to the south of the site is a two story historic building which is thought to have a shallow foundation. The existing building to the north is an eight story building on driven timber piles; the new building will have cross passages into the old office building. Figure 1 looking north shows the completed excavation and adjacent structures.

Soil and Groundwater Conditions

A total of nine borings have been advanced at the site to assess the soil profile and properties. Four deep wells and numerous shallow monitoring wells have been installed to assess the ground water regime in the area. The stratigraphy at the site consists of 6-ft to 10-ft of fill sand overlying another 20-ft to 25-ft of fill material which consisted of both wood debris and sand. Below the fill is a thin layer of sandy-silt which was deposited by the waters of Elliot Bay prior to the land reclamation in the area. Beneath these estuary deposits, there is a very dense glacially overridden till which is classified as a sandy-silt with some sand lenses. The borings also indicated the presence of a substantial glacial outwash layer of clean gravelly-sands below the sandy-silt till. In the borings where this gravelly-sand layer was encountered, it occurred at depths of 70-ft to 80-ft and typically extended to the maximum depth of the 100-ft borings.

The ground water conditions at the site consist of an upper and lower aquifer which are separated by the sandy-silt till layer. The upper aquifer is in the fill material which extends from the ground surface to a depth of approximately 30-ft. The lower aquifer is in the glacial outwash sand which was encountered beneath the till in most of the borings. Because of the potential for dewatering of the fill material to result in settlement of adjacent historic buildings and increased down drag on the piling for the adjacent Alaska Way Viaduct, the water level in the upper aquifer could not be lowered. Two separate pump tests were performed in the deep aquifer. These tests verified the ability of the glacial till to act as an aquitard and prevent draw down of the upper aquifer during pumping of the lower aquifer. Based on the pump test results, it was estimated that an extraction rate of 20 to 40 gpm would be required to draw down the deep aquifer and prevent base heave in a deep excavation.

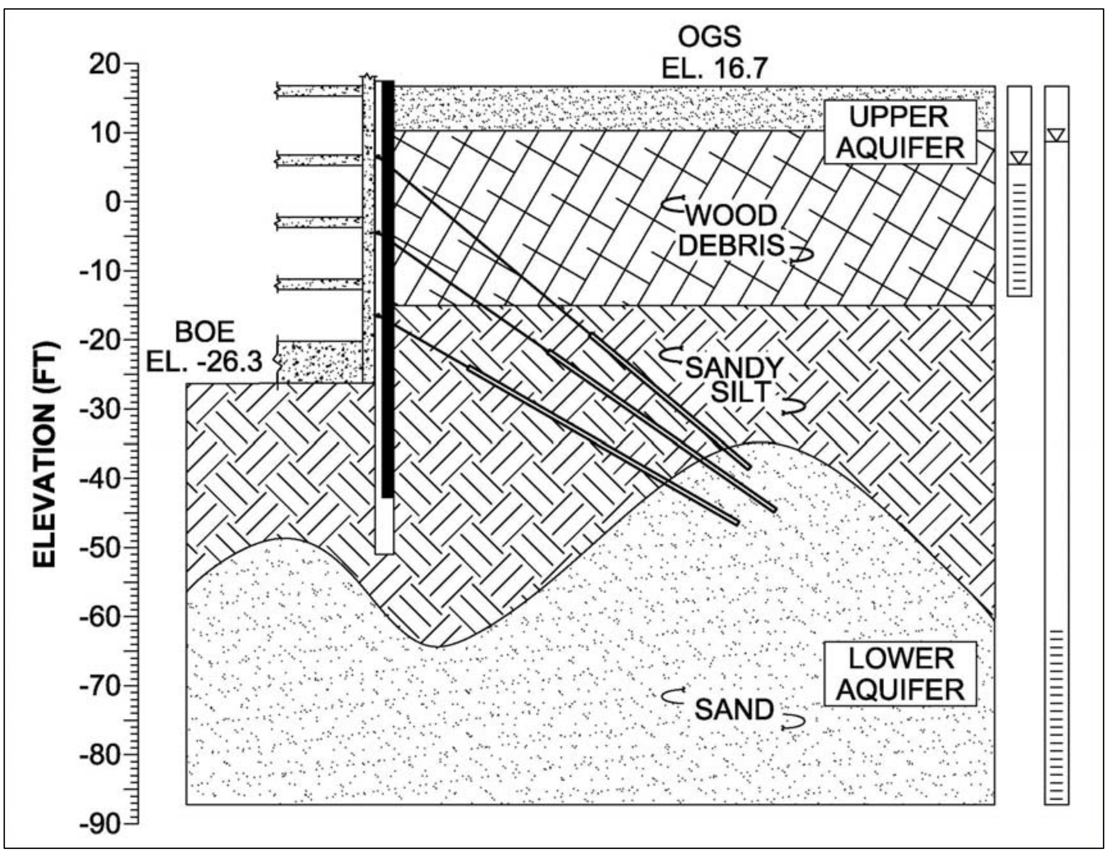

FIG. 2. Idealized Soil Profile and Shoring System

Original Shoring Design

Once the soil and ground water conditions were determined, the owner's design team established the lateral earth pressures and cutoff requirements based on the building size and site restraints. The temporary excavation would extend to a depth of 43-ft below grade. The excavation support system would have to incorporate underpinning of the adjacent eight story building, and it would have to isolate the excavation from the upper aquifer to prevent lowering of the water level in the loose fill material. The deep aquifer would need to be depressurized so that the excavation could be made safely without bottom heave of the glacial till on which the building will be founded. Based on seepage analyses, the owner's design team stipulated that the shoring extend 25-ft below the final excavation depth of 43-ft to limit in flow of water from the upper aquifer around the cutoff system. Preliminary designs for a secant pile system and a freeze wall system with four rows of tiebacks were provided for pricing by shoring contractors.

CONTRACTOR DESIGNED EXCAVATION SYSTEM ALTERNATIVE

The successful shoring contractor provided an alternate design-build excavation support system which relied on pre-trenching through the wood debris to remove known obstructions in the fill before installing a 68-ft deep soil mixed cutoff with three rows of tiebacks to support the excavation. The deep soil mix wall system would be installed using Cutter Soil Mixing (CSM) technology. After evaluating the potential cost and schedule risks of the three competing systems, the owner selected the design build CSM system for two reasons. First, the proposed C-B slurry pre-trenching eliminated impacts to the shoring installation process by removing the known debris in the fill. Second, the real-time verticality controls of the CSM equipment provide an assurance of panel overlap and a continuous water cutoff which neither soil freezing nor secant piles are able to provide.

Cement-Bentonite (C-B) Slurry Pre-Trenching

The use of C-B slurry to stabilize a trench up to 35-ft deep for the removal of wood debris was a key aspect of the proposed excavation support system. Although the true extent of the wood debris would not be known until excavation began, it was never considered feasible to construct a structural soil-cement wall through a fill containing significant zones of wood debris, sawdust, and timber piles. The pre-trenching was intended to remove potential obstructions and wood material which is not conducive to achieving a homogeneous soil-cement product. For this same reason, the shoring subcontractor elected to backfill the open slurry trench with sand as the trench was being advanced to provide a more suitable material for the subsequent soil mixing.

A C-B slurry was initially proposed over conventional bentonite slurry for the pre-trenching for two reasons. First, the C-B slurry is self hardening to a compressive strength on the order of the 20 to 50 psi. Second, the C-B slurry is better able to maintain trench stability because the fresh C-B has a higher density and a higher viscosity compared to bentonite slurry. The increased density increases trench stability. The increased viscosity maintains more spoil material in suspension, thereby increasing the density of the slurry in the active trench. The increased viscosity also reduces potential slurry loss into open gravel or debris along the trench.

While stability analyses are seldom done for slurry wall excavations, the City of Seattle Department of Transportation (SDOT) required the submission of a trench stability factor of safety for the C-B slurry pre-trenching prior to production work beginning adjacent to the city streets. Utilizing the soil parameters outlined in the original geotechnical report for a loose sand fill and the C-B slurry properties recorded in previous bench testing, a factor of safety against trench failure was calculated using the closed form solution proposed by Filz et. al. (2002). Table 1 outlines the parameters used to calculate the factor of safety. The soil strength and density parameters were varied to assess the potential impact of the wood debris on the trench stability.

Table 1 – Slurry Trench Stability Parameters and Resulting Factors of Safety

Trench Depth	Slurry Depth	GW Depth	Surcharge Loading	Slurry Density	Soil Total Unit Wt.	Phi Angle	FS Against Global Slide
(ft)	(ft)	(ft)	(psf)	(pcf)	(pcf)		
10	1	7	100	74	114	30	1.30
20	1	7	100	74	114	30	1.25
30	1	7	100	74	114	30	1.15

During the first day of C-B slurry pre-trenching, it became obvious that the fill below the upper sand fill was almost entirely wood debris which consisted mainly of mill ends and slab wood laced together with pockets of sawdust and the occasional timber pile coming out in the excavator bucket. There was very little sand in the wood debris. While the actual amount of wood was more substantial than initially anticipated, the interlacing of the wood debris had the desirable effect reinforcing the sidewalls of the pre-trench excavation.

During the pre-trenching, the density of the slurry in the active trench was measured. It confirmed that the slurry density of 74 pcf used in the stability analysis was actually being achieved. There were no significant slurry loses and no observed sidewall stability problems. The excavation monitoring points along the east side of the excavation were set in the curb and experienced a maximum lateral movement of 1.5-in. This movement was likely the result of the weight of the 180,000 lb excavator which had one track on the sidewalk during trench excavation. The monitoring points on the west side of the project were located in the street and did not experience any lateral movement in excess of 0.5-in. Aside from the damage to the sidewalk, the pre-trenching was successfully completed to an average depth of 34-ft without any unacceptable movements of structures or utilities.

Cutter Soil Mixing (CSM) Excavation Support System

CSM Method

The CSM equipment was developed by Soletanche-Bachy and Bauer utilizing the cutter head technology from hydro fraises, which are used to excavate diaphragm walls. The CSM equipment has two hydraulically driven motors mounted horizontally at the bottom of a single element kelly bar as shown in Figure 3. As the cutters rotate, the soil is broken down and mixed with the slurry being injected just above the cutter wheels. Depending on soil conditions and depth, bentonite slurry or cement slurry is injected during penetration. When the CSM reaches the maximum depth, cement slurry is injected as cutter head is retracted in a series of steps. The rate of slurry injection and the withdraw speed of the cutter head are pre-determined to insure that each 20-in step of the panel receives the target amount of cement and the minimum number of wheel rotations for adequate mixing. Once the panel is completed, any steel reinforcing is then inserted into the wet soil-cement mixture.

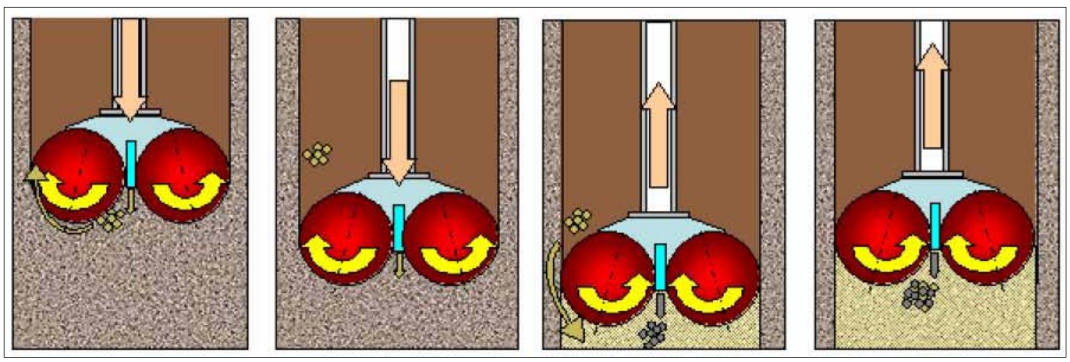

FIG. 3. Continuous Soil Mixing (CSM) Equipment and Process

Although the CSM method of soil mixing is able to treat a wider range of soils than conventional multi-axis soil mixing, the CSM's greatest advantage for cutoff applications is its verticality monitoring and control system. The operator of the CSM has a display of the location of the cutter head in the ground relative to the plan location of the panel. The operator can adjust the left and right location of the cutter head by changing the rotation speed and direction of one or both of the cutter wheels. The fore and aft location of the head is changed by manipulating the boom angle.

CSM Excavation Support Design

With the depth of the CSM excavation support system stipulated to be 25-ft below the bottom of the 43-ft deep excavation to limit seepage, the shoring contractor's design had to determine the pile sizes and spacing, tieback locations, and compressive strength of the soil-cement. The CSM unit used for this project creates a panel with plan dimensions of 2.6-ft x 9.2-ft By utilizing a primary-secondary sequence of panel installation and inserting one pile in the primary panels and two piles in the secondary panels as shown in Figure 4, the resulting pile spacing is 5.5-ft on center.

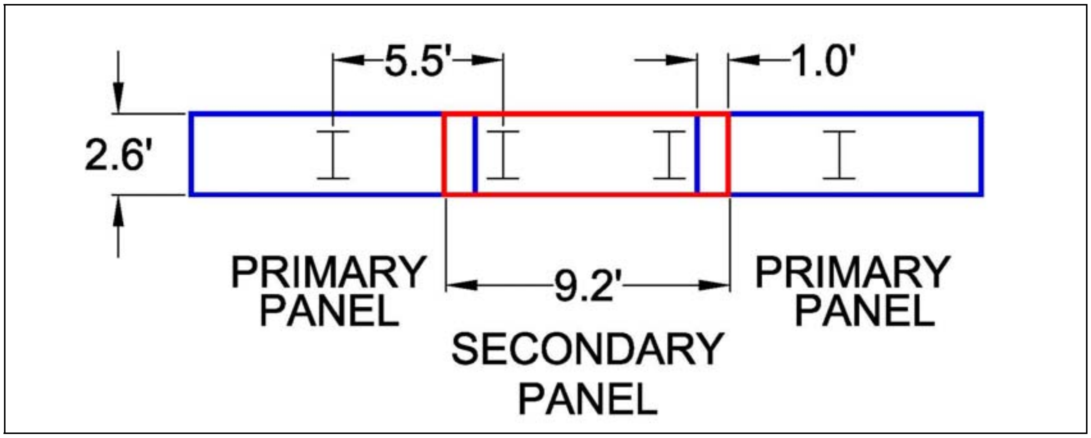

FIG. 4. Typical CSM Panel and Soldier Pile Plan View

Because of the dominance of water pressure loading versus earth pressure loading, the individual tieback design loads are controlled by the intermediate stages of construction, not the completed excavation. The total anchor design loads are approximately 25 percent higher than would be inferred from the design earth pressure diagram. The anchors are installed at steep 30 to 40 angles to develop their bond in the underlying till, resulting in axial loads of over 300 kips on each soldier pile. Punching shear stability of the pile within the soil-cement panel requires consideration of skin friction around the pile perimeter both above and below the base of excavation and end bearing of the pile within the soil-cement panel. The soil-cement panel acts as watertight lagging and transfers the water and lateral earth pressure loads to both flanges of the soldier piles by arching. The calculated compressive arch loading within the soil-cement panel is 60 psi; the specified design strength of 200 psi represents a factor of safety greater than 3.

CSM Construction

Following pre-trenching, CSM installation and soldier beam placement began. In addition to the real time monitoring and control of grout flow, grout density, cutter wheel rotations, and depth, wet soil-cement samples were taken from the fresh panels for quality assurance testing. Several sets of wet samples resulted in low breaks before the sampling tool was modified to take discrete samples which could not be contaminated by wash water at the surface of the panels being tested.

The effectiveness of the CSM system is judged by its ability to safely support the adjacent ground with minimal movement and to isolate the excavation from the ground water. Monitoring of the system indicated that the only appreciable lateral movement was out of the excavation. When the first row of tiebacks was locked off, the tops of the soldier beams moved over 1-in out of the excavation. Even with the subsequent excavation phases, very little of this outward movement has been reversed. There were no leaks in the CSM wall system although some weeping and dampness occurred; especially, in the outside corners where the combined movements of the panels out of the excavation tended to open the corner joints.

Dewatering

Since CSM excavation support and water cutoff extends 25-ft below the bottom of the excavation in the till layer, the water in the upper aquifer is prevented from flowing into the excavation. However, the water trapped inside the cutoff had to be removed to permit excavation. A series of six shallow wells were installed inside the perimeter of the excavation to a depth of 65-ft and screened full length to remove the upper aquifer water trapped by the soil mix cutoff. They were decommissioned when the bottom of the excavation was reached.

With the excavation extending to a depth of 43-ft and the lower aquifer having a piezometric head at a depth of 8-ft, the lower aquifer had to be depressurized to prevent bottom heave in the completed excavation. During the installation of the upper two rows of tiebacks, the piezometric head in the lower aquifer was lowered in stages. Since the upper and lower aquifers could be connected by the tieback drill holes, there was concern that a large differential head between the two aquifers would lead to washout of the grout. This concern had to be balanced with the fact that if the water pressure in the lower aquifer exceeded the pressure of the grout in the cased tieback drill hole the grout would be pushed out of the anchor bond zone during installation. For constructability reasons, the piezometric head of the lower aquifer was lowered to a minimum depth of 48-ft by the time the bottom of the excavation was reached. Three 100-ft deep wells are currently pumping 20 gpm out of the lower aquifer to maintain depressurization until the exterior cladding is installed.

CONCLUSIONS

The use of C-B pre-trenching to remove wood debris in the upper 30-ft of fill in an urban environment permitted the subsequent installation of a CSM excavation support and water cutoff system. By removing the wood debris and replacing it with sand, a soil mix wall with a minimum strength of 200 psi was successfully installed to a depth of 68-ft without the potential for delays and increased costs associated with the wood debris and timber piles located in the fill material. The CSM system with its real-time verticality monitoring and controls on the cutter head was used successfully for the first time to construct an excavation support and water cutoff system in the Western United States.

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