DEEP SOIL MIXED WALL AND JET GROUTING FOR AN EXCAVATION SUPPORT SYSTEM AT THE MUSEUM OF FINE ARTS IN BOSTON, MASSACHUSETTS

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A 6200 m² cement deep soil mixed (CDSM) wall was constructed for an addition to the Museum of Fine Arts in Boston, Massachusetts. The addition was located along the east side of the existing museum within an existing courtyard and in the area of a recently demolished structure. The basement for the new addition extended up to 9.1 m below the floor slabs of the adjacent buildings. The adjacent buildings are supported on a variety of foundations including; shallow spread footings on alluvial sand deposits, low capacity piles bearing in the alluvial sands and Boston blue clay, and caissons bearing on the alluvial sands and clay. Groundwater was less than one meter below the top of the CDSM wall. The new addition was founded on shallow foundations in the desiccated crust of the Boston Blue Clay. The CDSM wall was selected as the most economical means to control deep seated ground movements, limit movements of adjacent structures, and inhibit groundwater flow into the excavation. Braces and a continuous wale were used to support the CDSM wall where it was located adjacent to structures. Tiebacks were used where there were no structures.

Other geotechnical construction at the site included:

- Jet grouting (JG) to improve the ground and provide an impervious subgrade layer at the west end of the addition,
- Concrete pier underpinning was used to support an existing structure on the west end of the site, and
- A secant pile wall using alternating drilled shafts and jet grout columns was used for earth support and a barrier to groundwater flow to allow for the installation of a storage tank at the south end of the site.

Inclinometers, total station surveying, vibrating wire strain gauges on the braces and wales and load cells on the tiebacks were used to monitor performance of the excavation support system. The excavation support system performed better than required limiting lateral movements of the adjacent structures to less than 13 mm and vertical settlement to less than 8 mm. No settlements or movement were detected during the construction of the wall. Lateral movement of the CDSM wall was typically below 15 mm with the maximum movement occurring near subgrade.

PROJECT DESCRIPTION

To increase exhibit and storage space, an addition was constructed at the Museum of Fine Arts located on Boylston Street in Boston, Massachusetts. The original museum structure was built in 1909. A number of additions to the original structure were constructed between 1915 and 1969. The original structure and additions are supported on a variety of foundations including spread footings, concrete caissons, and piles (Table 1).

Building	Year Built	Foundation Type	Bearing El
Original Museum Structure	1909	Footings and Belled Caissons	-1 m
Evans Wing Picture & Connecting Gallery	1915	Footings and Belled Caissons	1 m
Decorative Arts Wing	1928	Concrete Piles	Not Known
Textile Gallery	1967	Concrete Piles	Not Known
Archive Addition (Demolished)	1969	Caissons	0 to 2 m

Table 1 - Existing Foundations

Subsurface conditions at the site consisted of 3.3 to 6.2 m of granular fill and organics over 2.6 to 3.3 m of alluvial sand over Boston blue clay. A glaciolacustrine deposit lies beneath the clay at depths of 48 to 52 m. The top of the clay varies between elevation 0 and -4 m sloping downward from west to east. There is also a silty fine sand layer in the clay between at a depth of 13.4 and 18.1 m, which acts as a confined aquifer. The silty fine sand layer was up to 5 m thick with a bottom between elevation -9.2 and -12.8 m. Groundwater elevations varied between elevation 1.7 and 2.9 m. A typical soil profile is shown in Figure 1.

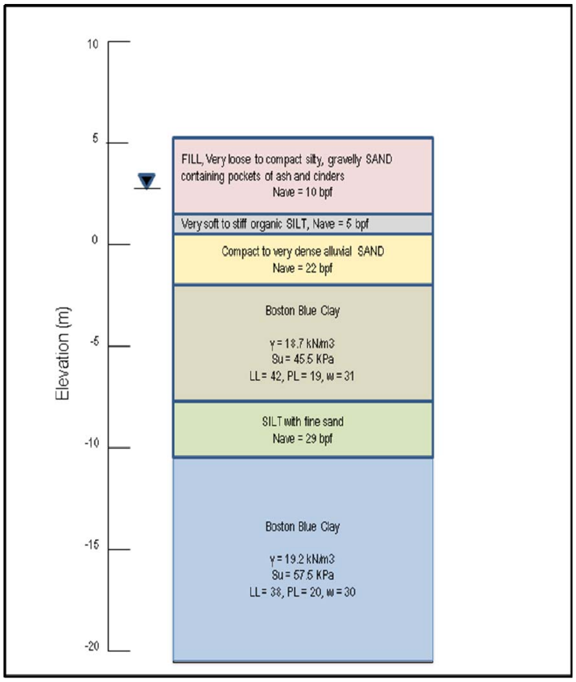

Figure 1 – Typical Soil Profile

The new addition was constructed in the shape of a "T". The stem portion of the "T", called the spine, and the two ends at the top of the "T", called the north and south pavilions, were located in an existing courtyard and within the footprint of a recently demolished structure. Existing site grades varied from elevation 5 to 6 m. The site was pre-excavated to elevation 3.3 m prior to construction to reduce the overall height of the excavation support system.

The new addition is supported on shallow foundations bearing in the desiccated clay. The bottom of footing elevation for the new structure varies between elevations -5 and -6 m. The new addition and surrounding existing structures are shown in Figure 2.

PERIMETER CUT-OFF WALL (CDSM)

Construction of the new addition required cuts of up to 9.1 m below the floor slabs of the adjacent existing structures. In some cases, the edge of excavation for the addition was within 1 m of the existing structures. A CDSM wall was chosen as the method of earth retention around the majority of the building perimeter as it is relatively stiff and impermeable which facilitates control of deep seated ground movements, limits movements of adjacent structures, and provides a relatively impermeable barrier to groundwater flow.

Other earth support systems considered included sheet piles, secant pile walls, and slurry panel walls. The Owner/Engineer selected a CDSM wall over sheet piles because of the risks associated with the vibrations caused by sheet pile installation and a CDSM wall is less permeable than sheet piles. The CDSM wall was selected over a secant pile wall and slurry panel wall because it was more economical and would take less time to construct.

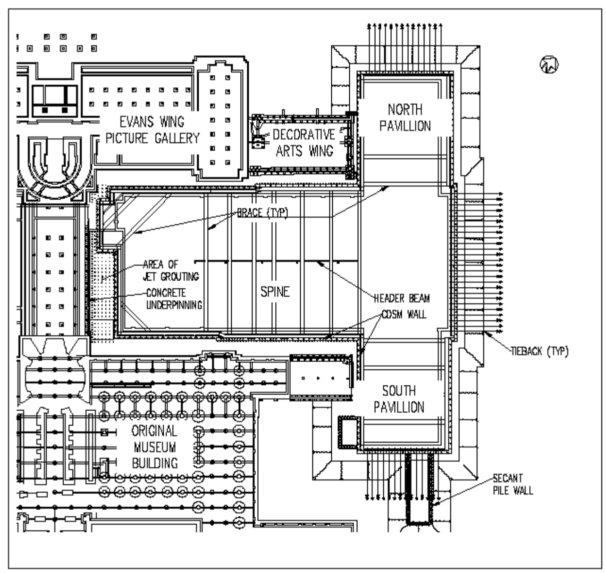

Figure 2 - Museum of Fine Arts Plan View

The CDSM wall consists of overlapping 914 mm CDSM columns drilled at 686 mm on center. Steel soldier beams, typically placed in every other column (1.37 m on center), were used to reinforce the CDSM wall. The soldier beams varied in size from a W460X74 to a W610X217. The soldier pile spacing was decreased to a pile in every hole, 0.686 m on center, in areas close to adjacent structures where a stiffer wall was required. The soldier beams typically had a tip elevation of -10.7 m. The CDSM wall extended below the bottom of the soldier beams to about 1.5 m below the bottom of the confined sand seam aquifer. The soil-cement was designed to span between the soldier beams and have an unconfined compressive strength of 760 KPa.

CDSM WALL CONSTRUCTION

The CDSM wall was constructed using multi-auger mixing equipment designed to mix an element of 4 soil-cement shafts in one stroke. Separate positive displacement pumps delivered the grout slurry through the center of the augers to the bottom of each shaft. Mixing paddles counter rotated and blended the cement grout slurry with the soil as the augers were inserted and extracted. The mixing shafts rotated at 12 RPMs on the down stroke and 24 RPMs on the upstroke and during re-stroking of the element. The mixing shafts were advanced at around 0.46 m per minute during the down stroke and 0.91 m per minute during the up stroke. Soldier beams were set in the semi-fluid soil-cement mix prior to initial set.

Work proceeded in a continuous manner with around 15 m of wall completed on a typical day. In all, around 6,200 m^2 of CDSM wall was installed. Figure 3 shows the equipment used to construct the CDSM wall. The mixing paddles on the four auger shafts are evident in this Figure. This figure also shows the protective plastic sheet and plywood cover over the windows installed by the Construction Manager to protect the existing building from splatter caused by soil/cement falling off the augers. Figure 4 shows the cutting heads at the end of the augers.

Figure 3 – Installation of Soil Mix Wall

Figure 4 - Detail of Soil Mixing Cutter Heads

No movement of the nearby structures was measured during the CDSM wall installation.

Extensive sampling and testing of the soil mix was performed during construction of the CDSM wall as part of a QA/QC program. Unconfined compression tests were conducted on wet grab samples at 3, 7, and 28-days. The results of these tests are shown in Figure 5 and show that the minimum strength at 28 days exceeded the required design strength of 760 KPa.

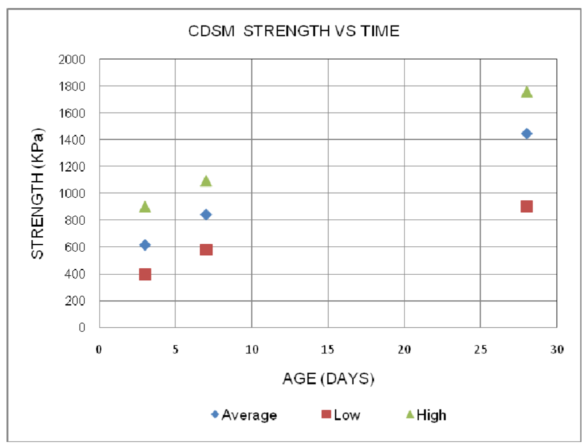

Figure 5 – CDSM Strength vs Time

Lateral support for the CDSM wall was provided by two levels of internal cross lot braces, corner braces, and/or tiebacks. Internal bracing was used where the CDSM wall was adjacent to buildings as installation of tiebacks under buildings was not allowed by the Owner due to potential conflicts with existing foundations. The elevation and location of the braces was selected by the Owner to avoid penetrations in the new structure. The load from the CDSM wall was transferred to the braces using a continuous steel wale designed to resist both bending and thrust loads. The braces were pre-loaded to 50 percent of their design load after installation. The pre-load was locked into the braces using steel wedges. Support piles connected to a header beam were used to support the braces at mid-span. A section through the braced portion of the excavation support system (ESS) at the spine is shown in Figure 6. The completed excavation showing the braces and support piles is shown in Figure 7.

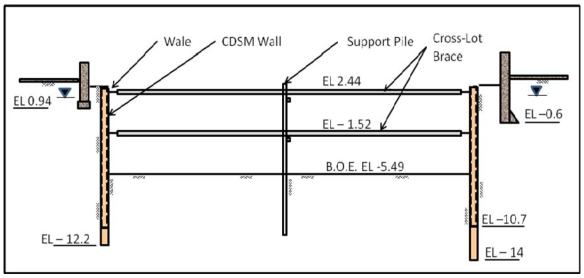

Figure 6 - Section Through ESS at Spine

Figure 7 - Completed CDSM Wall and Bracing

The tiebacks were installed using concentric rotary duplex drilling methods with water flushing. Each tieback was re-grouted at least once after initial grouting. The tiebacks were tested and locked off against a continuous wale.

The initial design of the wall was conducted using conventional methods. The wall was designed to resist combinations of earth and water pressures, construction surcharges and building surcharges. The principal concern in the design was to limit movement of the CDSM wall and surrounding structures. Wall movements were estimated using a plane strain finite element simulation using PLAXIS. This simulation relied on elements of the conventional design, such as brace loads and wall stiffness, for input.

Three numerical models were developed to estimate the movements of the braced wall system. Both a Mohr-Coulomb (MC) and Hardening Soil (HS) model were used in the simulations for various structural entities, with initial soil parameters primarily from Shawkat's (1993) PhD dissertation on the properties of Boston Blue clay and MFA geotechnical reports (Haley and Aldrich, 2003; McPhail Associates, 2006).

The hardening soil model with small strain stiffness (HSsmall) was not available in the PLAXIS versions utilized in these studies. The movements were estimated for a number of construction stages including the initial stage, excavation for the top strut, installation of the top strut, excavation for the second strut, installation of the second strut, excavation to subgrade, and removal of the bottom strut after the new foundations were complete.

FEM estimates performed prior to availability of any measured deflections showed deep-seated movements of up to 18 mm below elevation -3 m. After completion of the project and when measured data was made available, a model was developed (Katkhuda, 2008) that continued to show larger than measured deep seated movements of greater than 25 mm at elevations below -9 m. Katkhuda concluded that the effects of non-linear small-strain stiffness must be taken into account to appropriately model the deflections.

SFC continued to develop the model, concluding that the following were important aspects for modeling the deflections: (1) The undrained modulus should be used for the Boston blue clay for the project and measurement time-periods involved, (2) A small-strain stiffness must be utilized, particularly for the deeper soil regions that are undergoing smaller strains, and (3) Appropriate K_0 values must be utilized in the over-consolidated Boston blue clay layers. SFC varied the parameters to achieve a relatively good fit, including adjusting the small-strain moduli of the layers based on the average strain in the layer. The results of the SFC finite element simulation at the end of excavation are compared with inclinometer measurements near the Evans Wing Picture Gallery in Figure 8.

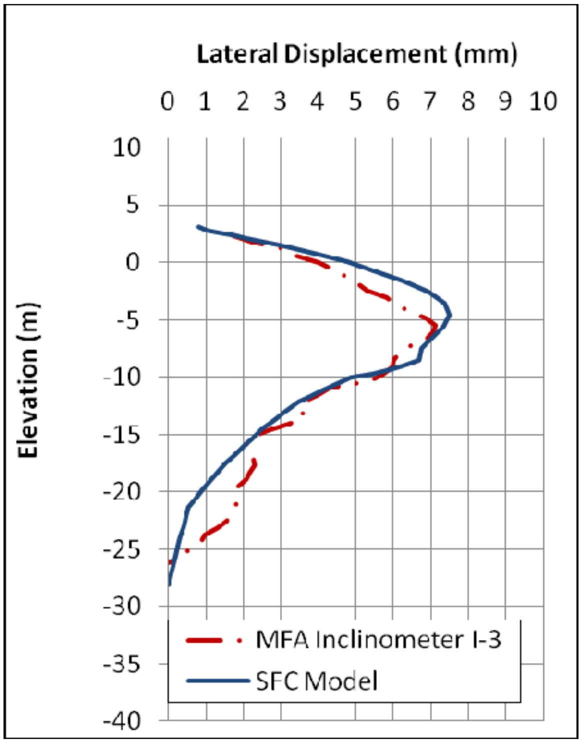

Figure 8 – Comparison of Measured Movements and FEM Model

Field monitoring of the lateral movement of the CDSM wall was accomplished using eight conventional inclinometers, three automated in place inclinometers, and robotic and manual total stations and webcam. The inclinometers were installed in drill holes located just behind the CDSM wall. The automated inclinometers gave erratic data or did not work and their data was not used. The conventional inclinometers gave consistent data and were used to measure ground movements behind the wall.

Lateral and vertical deflection of the existing structures and the tops of the piles in the CDSM wall were measured using robotic and manual total stations. The readings were taken using prisms attached to the structures and tops of piles. The vertical movement of the existing structures was confirmed by monitoring fixed points on the structure using a level.

The loads in the wales and braces were monitored using 62 vibrating wire strain gages. The strain gages were placed in groups of 3 spaced 120 degrees apart on the braces and near the center of the wales. Loads in the tiebacks were monitored using load cells.

The maximum lateral movement was expected to be around 20 mm based on the initial FEM analysis conducted prior to starting the work. The actual movement measured in the inclinometers was typically less than 15 mm with the maximum movement occurring at subgrade as predicted.

Lateral and vertical deflections at the tops of the piles, measured using the robotic webcams and a conventional total station, showed similar movement trends to that indicated in the inclinometers although the magnitudes were much greater than the movements at the tops of the piles shown in the inclinometers. Lateral movement at the tops of the piles was typically less than 12 mm with the greatest amount of movement occurring in the piles which were braced above subgrade in the north and south pavilions. A small amount of movement (<6 mm) was also measured parallel to the wall in the area of the corner braces. Measurements of the vertical (settlement or heave) and lateral movement of the existing structures was erratic but never exceeded 13 mm. In all cases the movements were less than the project requirements. Crack gages installed across pre-existing cracks in the existing structure also showed no relative movement or widening and there was no observable damage to the structure.

The strains and temperatures in the braces and wales were recorded several times per day using an automated data logger. Temperature measurements were taken to allow the loads in the braces to be corrected for thermal effects. In general, the loads measured in the strain gages, after a brief period of time, were less than the design lock off load measured in the jacks. When the lower braces were cut, around 20% to 30% of the load was transferred to the upper braces. The strain gages in the wales were installed prior to the installation and jacking of the braces. The loads measured in the wales were erratic and may have been affected by temperature.

JET GROUTING

At the west of the spine jet grouting (JG) was used to cut off the upward flow of groundwater, partially underpin an existing structure, and improve the ground for a mat foundation. In addition, hand excavated concrete pier underpinning was used to underpin the existing

Evans Wing building at the west end of the addition. The JG was performed in the fill and alluvial sand. A section through the JG and underpinning is shown in Figure 9.

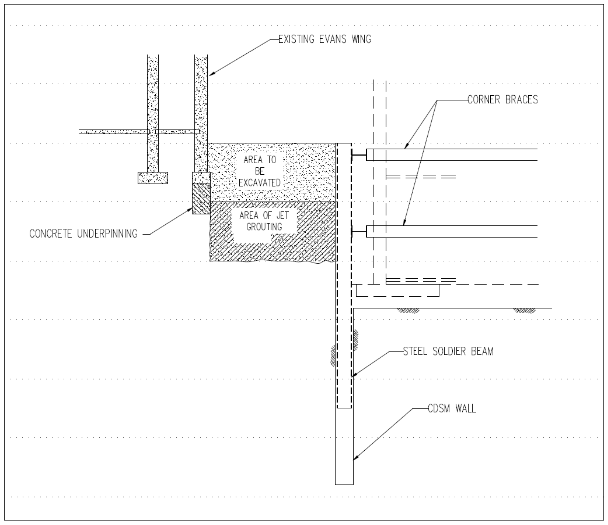

Figure 9 – Section through Jet Grout and Underpinning

Three hundred and six over-lapping columns were jetted in the 36.6 by 6.4 m area. The jet grout comprised about 2040 m of drilling and 1220 m of jetting. The average total drill length was 6.1 m and the jet length was 3.7 m. Column diameters varied between 0.8 and 0.9 m. The jet grout columns were laid out in a pattern to provide total coverage of the area to be treated. The perimeter columns along the existing Museum wall were jetted partially beneath the wall footing or underpinning pits to help support the structure. The perimeter columns were spaced at 460 mm on center to provide additional support of the existing structure and cut off vertical and horizontal groundwater flow. Interior columns were spaced on a 910 mm by 910 mm grid in order to improve the bearing capacity for the mat and inhibit upward flow of groundwater. Installation of the JG is shown in Figure 10. The location of each jet grout hole had to be carefully surveyed as significant amounts of spoil were generated which buried any previously set survey marks.

Wet samples of the jet grout spoil were taken to test the unconfined compressive strength of the jet grout. These strengths are shown in Figure 11.

Figure 10 - Installation of Jet Grouting

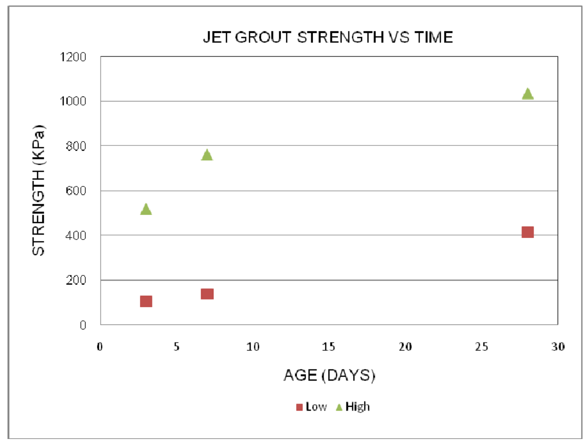

Figure 11 – Jet Grout Strength VS Time

<u>Secant Pile Wall</u>

A cantilevered secant pile wall was constructed at the south end of the south pavilion to allow for excavation of an underground storage tank. The secant pile wall consisted of overlapping drilled shafts (primary piles) and jet grout columns (secondary shafts). The primary piles, with soldier beams (W530X74), were installed in 750 mm cased drilled holes and backfilled with 20.7 MPa concrete. The primary piles were located on 1.5 m centers. The primary piles had a length of 7.7 m and supported a cut of 3.3 m. Single fluid jet grout columns were constructed between the drilled shafts to complete the secant pile wall. The jet grout columns terminated in the Boston blue clay at Elevation -1.54 m. The use of jet grout columns as the secondary shafts allowed for a savings in the construction schedule.

CONCLUSIONS

The following conclusions and observations can be gained from the design, construction, and performance of the CDSM wall, jet grouting, and secant pile wall at the Museum of Fine Arts:

- A stiff CDSM cutoff wall was successfully used for the excavation support system at the MFA. Adjacent structures experienced no significant movement or damage during either construction of the CDSM wall or subsequent excavation.
- Jet Grouting was effective at creating a groundwater cutoff, strengthening the existing soils, and underpinning an existing building at the MFA.
- A drilled shaft and jet grout secant pile wall provided excavation support and cut off the groundwater for a tank excavation.
- Monitoring of deep excavations in low strength clays should not rely on points at the tops of the piles as most of the movement may occur at subgrade.
- Total station monitoring may not be accurate enough to monitor the small movements that occur in surrounding structures.
- Finite element modeling of deflections requires using a small-strain stiffness model, undrained moduli and appropriate K_o values for the overconsolidated clays.

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