UNDERPINNING A CRANE FOUNDATION

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This paper presents a unique case history that documents the use of a braced secant pile wall to underpin a heavily loaded footing inside of a manufacturing plant. Construction of a pit for a new manufacturing process directly next to the footing necessitated the underpinning. The footing supports an overhead crane that needed to remain operational throughout construction of the pit and therefore, settlement of the footing could not be tolerated. The base of the footing was about 7.7 feet above the base of the 17-foot deep excavation.

The footing bears on a silty clay deposit that grades from a stiff consistency beneath the footing to a soft/medium consistency near the base of the pit excavation. This paper describes the design and construction of the secant pile wall and bracing to control wall deformations, ground movements and settlement of the footing. The footing was monitored for settlement throughout construction of the pit and no measurable movement was observed.

INTRODUCTION

A manufacturing plant in Buffalo, New York planned to construct a pit for a new hot strip mill inside one of its buildings as part of a plant improvement project. Construction plans for the pit showed it having reinforced concrete walls and floor with interior dimensions of 32 feet wide by 27 feet long. The floor of the pit has two levels, one requiring a 12-foot deep excavation and the other requiring a 17-foot deep excavation. The part of the pit with the 17–foot depth is directly next to a spread footing that supports the building roof, building wall and a 40-ton overhead crane. The footing has plan dimensions of 7 feet along the edge of the pit by 9 feet. Project drawings show the edge of the footing 24 inches from the outside wall of the pit. The excavation for the pit was planned to extend to 7.7 feet below the base of the footing, which is 9.3 feet below the plant floor. The excavation included a precut to the top of the footing and the remainder of the pit excavation needed shoring to underpin the footing.

Figure 1 shows the location of the pit in relation to the spread footing and Figure 2 shows a section view of the pit next to the footing. The plant required the use of the overhead crane throughout the pit construction. The estimated footing contact pressure is 3000 pounds per square foot. The project required the contractor to design and install shoring for the excavation.

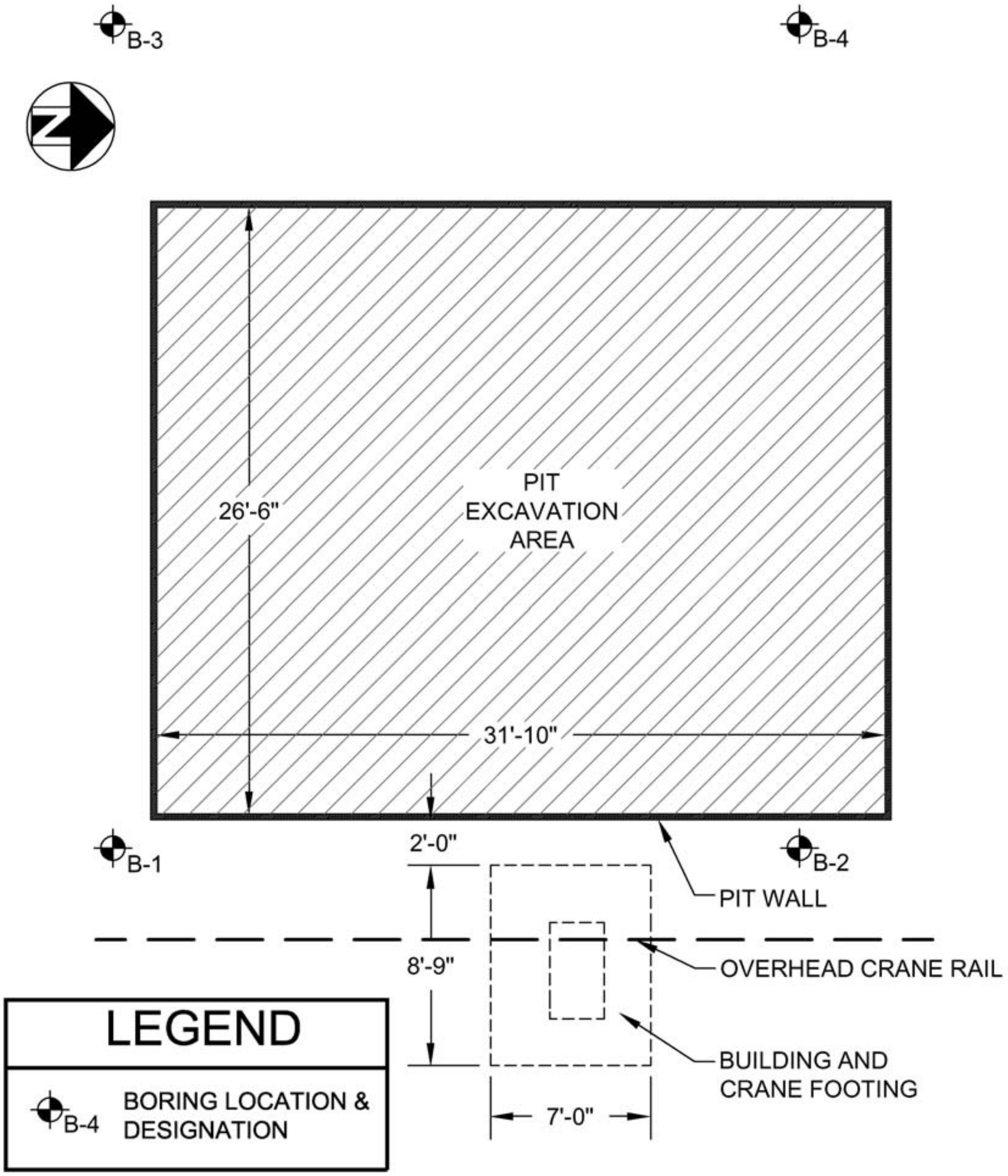


Figure 1: Plan view showing the footing, crane rail and pit

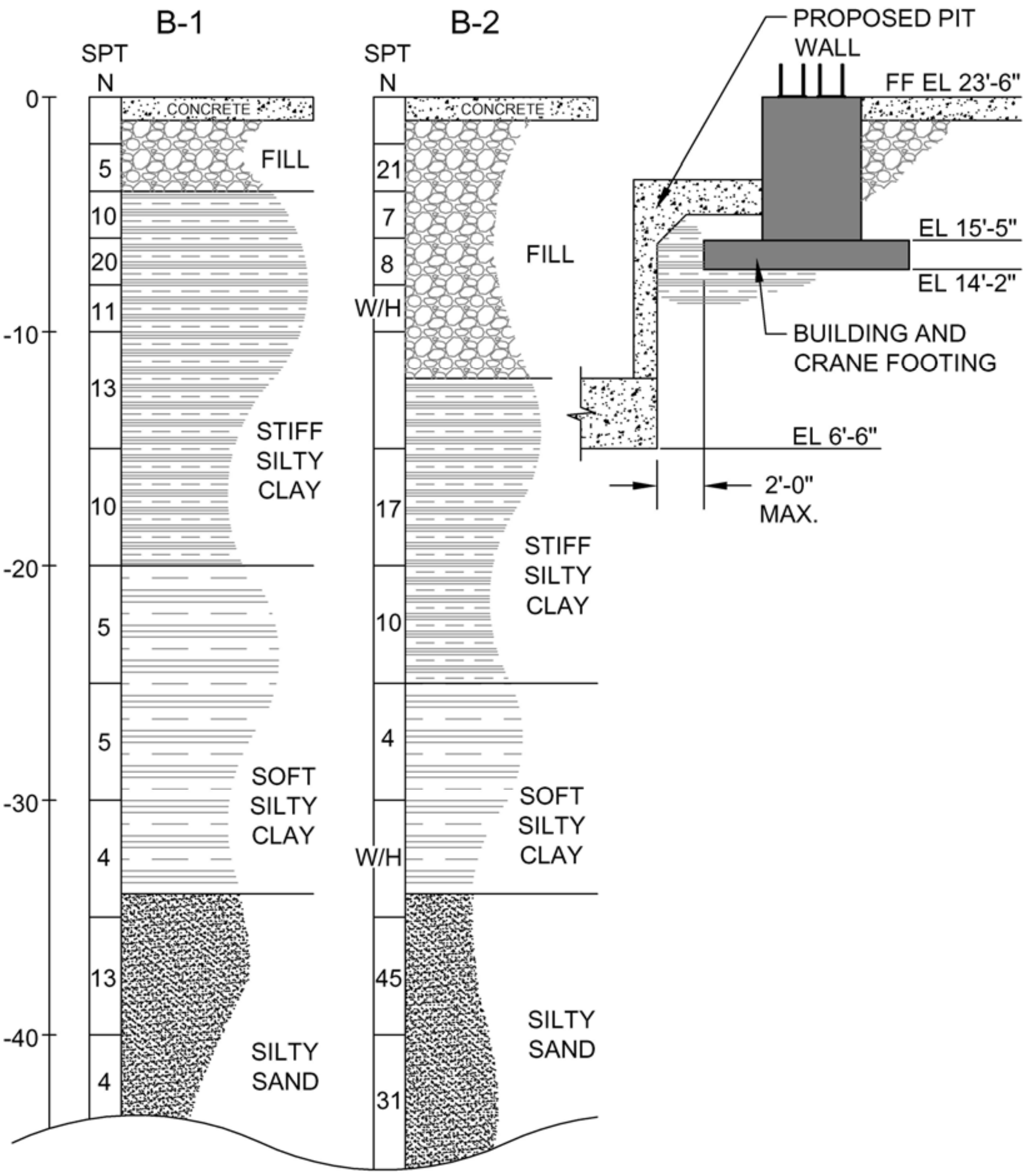


Figure 2: Section through footing and pit wall with subsurface conditions

This paper describes the planning, design and construction of a braced secant pile wall that was used for underpinning the footing and supporting the pit excavation. The wall and bracing were designed and constructed to restrict settlement of the footing because settlement of the footing would have hindered operation of the overhead crane and disrupted plant operations.

The paper reviews issues associated with ground deformations resulting from deep supported excavations. The height of excavation for this project was small compared to many described in the literature but this project had a heavily loaded footing directly behind the wall. The active thrust from the soil and footing loads is comparable to that acting on a wall supporting a deep excavation. Therefore, techniques used for limiting ground deformations in deep excavations were applied to this project.

SUBSURFACE CONDITIONS

The plant is located in a former glacial lakebed. The results of four borings made near the pit corners show a silty clay deposit underlying a thin layer of recently placed fill. The consistency of the silty clay ranges from stiff near its surface to soft to medium near the base of the pit excavation. A loose to dense silty sand layer underlies the silty clay, about 34 feet below the plant floor. The ground water level was estimated to be near the transition from the stiff clay to the medium clay about 20 feet below the plant floor. Figure 2 shows the soil sequence from borings drilled near the footing.

DESIGN CONSIDERATIONS

The project required the contractor to develop a design and construction sequence to build the pit without disturbing the crane operation. Settlement of the footing supporting the crane would disturb plant operations and was not acceptable.

The contractor favored building a retaining wall to support the footing since the remainder of the pit excavation also required shoring. The design of the wall needed to consider the loads applied to the wall, the wall deflection and constructability issues since the limited overhead clearance restricted installation of some common wall types, such as sheet piles and soldier piles.

Engineers designing retaining walls generally estimate soil, water and surcharge loads and design the wall and bracing structures to resist these loads with an appropriate factor of safety applied. Rarely, does the analysis directly consider the amount of deflection that the wall will experience resulting from the loads applied. However, in this case, the retaining wall needed to resist the soil, water and surcharge loads without moving because horizontal deformation of the wall would allow the ground behind the wall and the footing both to settle.

Peck (1969), O'Rourke (1989), and others describe ground deformations next to deep excavations from empirical measurements. Using the Peck estimates for ground deformations with good workmanship in soft to hard clay, a vertical movement (settlement) of the footing of up to about 1 percent of the excavation height might be expected since the footing lies directly next to the retaining wall. This results in about 1 inch of estimated settlement in this case, which would be unacceptable for this project. This settlement estimate does not consider the surcharge effect of the heavily loaded footing.

Estimating the amount of deformation that a particular wall design might experience can be done using a finite element analysis, provided the load-deformation properties of the soil have been measured. However, the subsurface exploration data available for this project were insufficient for this analysis. Schedule and budget constraints also prevented use of a rigorous numerical analysis. Therefore, empirical correlations were relied upon to estimate the amount of deflection that might be expected.

The design of any retaining wall where deflection is a design criterion needs to consider potential deflection modes of the wall. Goldberg et al. (1976) presents modes of deflection for two wall types, a rigid wall and a flexible wall. A rigid wall can rotate about the top, rotate about the tip or translate, as shown in Figure 3. A flexible wall also experiences these deformation modes, but also can bulge in the mid-span, as shown in Figure 4.

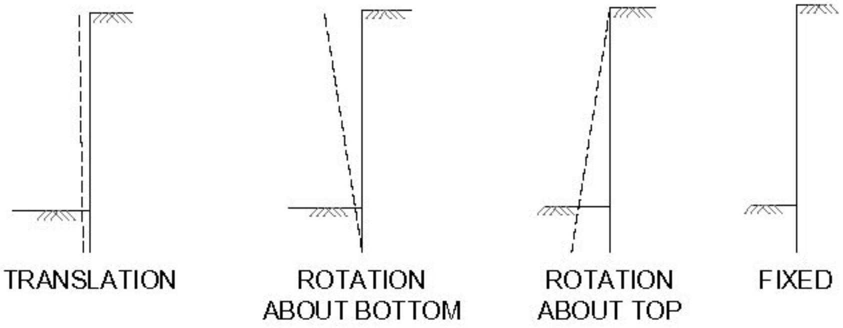


Figure 3: Deformation modes for a rigid wall, Goldberg et al. (1976)

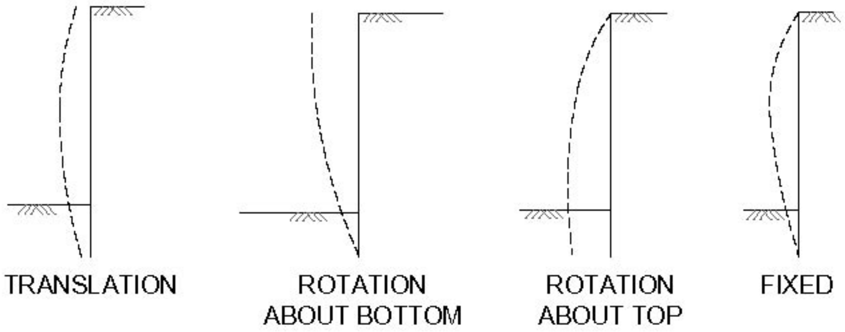


Figure 4: Deformation modes for a flexible wall, Goldberg et al, (1976)

Figure 3 shows the deformation mode of a cantilever wall, i.e., the rotation about the toe. This was expected to contribute unacceptable deformations and therefore the top of the wall needed to be supported by either an internal brace or a tieback extended beneath the footing.

A deformation mode for a wall supported at the top is rotation of the wall about the top of the wall. This could be addressed by identifying a location in the soil profile that could provide a point of fixity to create a “fixed end” condition. The soft to medium clay was considered to be unreliable and therefore the wall would need to extend into the silty sand deposit that underlies the clay. This depth was also required for moment equilibrium.

The last deformation mode to be addressed is bulging, see Figure 4. This could occur if the wall was too flexible for the loads applied. Goldberg et al. (1976) quantify the stiffness of a retaining wall using the expression EI/L^4, where E represents the modulus of elasticity of the wall material, I represents the wall moment of inertia and the L represents the vertical distance between supports. The expression EI/L^4 is large for stiff walls and small for flexible walls. Sheet pile and soldier pile walls can be considered flexible (depending on the distance between supports, L) compared to a concrete diaphragm wall because EI is less. These flexible wall types would require additional lateral support to restrict deformations as effectively as a rigid (diaphragm) wall. Goldberg et al. (1976) present empirical correlations between wall stiffness, soil strength and wall deflections. Obviously, the stiffer the wall for a given soil strength, the smaller the deflection.

Clough et al. (1989) present case history data and the results of numerical analyses to estimate lateral wall movements. The movements are related to wall stiffness and the factor of safety against basal heave. Using Clough's estimates and the estimated factor of safety against basal heave for this project of approximately 1.2 (which considers removing the fill over the top of the footing, as discussed later and placing the tip of the wall near the base of the excavation) the estimated lateral movement might range from approximately 0.7 inches for a stiff wall (such as a slurry wall) to 1.6 inches for a flexible wall (such as a sheet pile wall). Since the footing is directly behind the wall, the estimated vertical and horizontal deformations are nearly the same.

In summary, the information presented in the referenced literature indicates that wall movement and corresponding ground deformations should be expected for this project if the wall design follows conventional methods. The literature also suggests that basal heave is possible. This information influenced the design in that it identified the need to fix the top of the wall and extend the wall into the underlying sand to address the basal heave potential. It also identified the need to make the wall stiff.

These deformation estimates consider good workmanship used to build the excavation support walls. However, ground deformations are sensitive to construction procedures, which are an integral part of controlling ground deformations along excavations. A wall designed to limit deflections can deform if procedures used to construct are deficient (O'Rourke, 1989). Some deficient procedures include:

- Excavating below a bracing level before installing the brace,
- Relying on berms for passive support of the retaining wall, and
- Failure to properly shim bracing against the retaining wall.

The wall design should be developed to eliminate these deficient procedures, if possible.

WALL TYPE SELECTION

Sheet piles were considered, but they would need to be spliced due to the low headroom to advance them sufficiently into the underlying sand deposit. These also are considered flexible and might need multiple levels of support to make the wall sufficiently stiff to limit the horizontal deformations to tolerable levels. Multiple internal bracing levels would have interfered with the excavation of the pit and construction of the pit foundations.

Soldier piles with wood lagging were also considered. Soldier piles would have needed to extend deeper into the sand than sheet piles to develop the required horizontal support. They also would have required splicing and likely would have required multiple bracing levels.

For these reasons, a rigid wall was preferred. A concrete diaphragm wall using bentonite slurry for temporary support of the trench was considered impractical for a wall of this magnitude. (The estimated wall length is about 15 feet.) A diaphragm wall constructed using the slurry method for temporary trench support requires room for slurry mixing devices and slurry storage containers. Restricted space inside the plant limited these ancillary activities.

A second rigid wall type, a secant pile wall, was also considered. This is a continuous wall constructed of interlocking bored piles, Tomlinson (1975). It could be constructed at this site with a low-headroom caisson drill rig by excavating alternating piles that extend to the design depth.

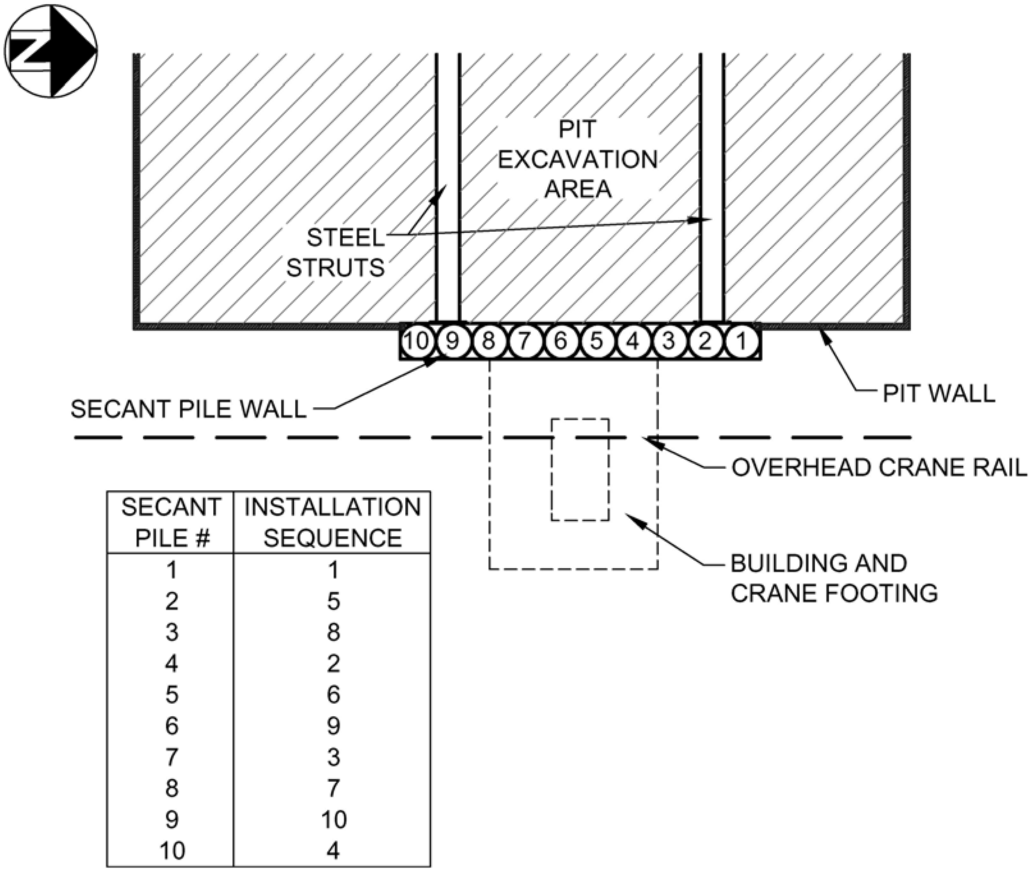
This option offered several advantages from a construction perspective. A small excavation could be made to identify the actual edge of the footing nearest the pit and define the edge of the retaining wall. The opposite side of the secant pile wall (the side facing the pit) could serve as the outside form for the pit wall.

WALL DESIGN

Once the secant pile wall alternative was selected, the design progressed considering that:

- It needed to be less than 24 inches wide,
- It needed to be restrained at the top and at the tip, and
- It needed to resist flexure.

Figure 5 shows the secant pile wall in plan and Figure 6 shows a section through the wall.



SECANT PILE #	INSTALLATION SEQUENCE
1	1
2	5
3	8
4	2
5	6
6	9
7	3
8	7
9	10
10	4

Figure 5: Plan of secant pile wall

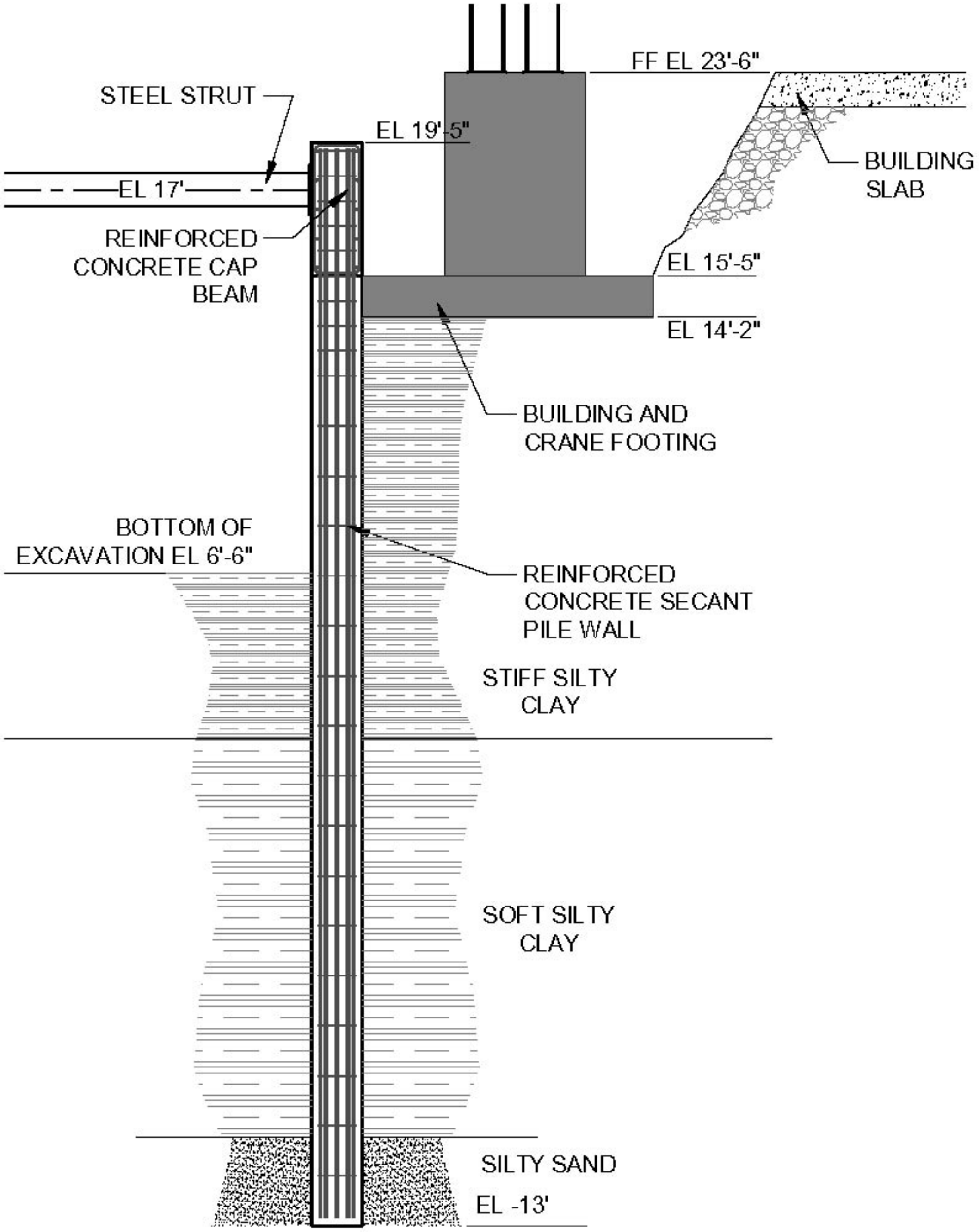


Figure 6: Section through secant pile wall

Figure 6 shows the wall extending 3 feet into the underlying silty sand deposit. This is necessary to address three design issues.

1. The factor of safety against basal heave is low and extending the wall into a firm stratum improves the factor of safety against basal heave.
2. The silty sand deposit provides resistance for moment equilibrium of the wall about the brace because resistance

contributed by the soft to medium silty clay is insufficient.

3. The silty sand provides a ”fixed end” condition for restricting wall translation and rotation about the brace.

The design considered that the top of the wall would be braced to resist rotation about the tip and translation. O’Rourke (1989) describes a “cantilever movement” condition which occurs before the uppermost brace is installed. The amount of deformation resulting at this stage in a deep excavation may be small compared to the total, but it was considered unacceptable for this project. Therefore, the design opted to set the upper bracing above the top of the footing. This would prevent the “cantilever movement” condition, and allow the contractor to complete bracing installation before advancing the excavation below the footing.

The bulging deformation mode was addressed by making the wall stiff. Reinforcing steel was specified to extend the entire length of the secant piles to resist flexure from the applied lateral soil and footing loads.

BRACING

The next challenge was to design the location and type of lateral support for the wall. The design needed to allow the contractor to excavate for the pit, form the pit floor and walls, construct the reinforcing and place the concrete.

The sides of the drilled shafts were expected to be irregular when excavated, conforming to the shape of the excavated drilled shaft. Internal bracing supporting the secant pile wall needed an even surface for setting a wale against the secant piles.

Therefore, a cap beam was designed for the top of the secant pile wall. The cap beam would be formed in the field and its side (facing the pit) would be sufficiently smooth to allow steel struts to bear on it. It was also designed as a wale to resist bending considering the strut locations. The reinforcing steel in the secant piles was extended to the top of the cap beam.

INITIAL CONSTRUCTION

The contractor began this project by excavating the fill over the top of the footing, as shown on Figure 6. This reduced the lateral load applied to the wall and allowed the contractor to identify the edge of the footing along the pit. Once the edge of the footing was exposed, the contractor could establish the edge of the secant pile wall so that the wall could be constructed abutting the footing.

DEFORMATION MONITORING

The contractor developed a monitoring network to allow observation of the soil and footing response to the excavation. The contractor established two survey targets on the column and made baseline measurements of the targets in three dimensions. The contractor repeated these measurements several times daily throughout the excavation and pit construction to identify settlement and rotation of the column and footing. If the footing began to move, the contractor could stop and re-evaluate the design and procedures.

PILE CONSTRUCTION

The secant pile wall consisted of ten, 18-inch diameter drilled shaft excavations. The contractor drilled every third secant pile on the first pass to limit the potential for soil deformation beneath the footing. This allowed the concrete to develop an initial set before beginning the second pass. Figure 5 shows the construction sequence. The secant piles were excavated without casing. The contractor used a concrete mix that produced an unconfined compressive strength of 3000 pounds per square inch in three days to allow the piles to develop sufficient strength to allow drilling directly next to it.

The contractor used an 18-inch diameter caisson auger attached to an excavator boom to excavate the secant piles. Theoretically, the secant piles should be 18 inches apart (center to center) to result in adjacent piles abutting one another. However, the 18-inch auger with the drilling equipment used excavates a hole slightly larger than 18 inches. The secant pile spacing was increased to about 20 inches in the field to allow for this larger diameter excavation and still construct the piles such that they would be aligned in a straight line. The resulting wall was still continuous with the greater than theoretical spacing.

CAP BEAM

Once the drilled shafts had been completed with the reinforcing steel extending from the top of the shafts, the cap beam was formed and placed. The pit excavation had yet to extend below the top of the footing, see Figure 7.

Figure 7: Cap beam reinforcing steel

BRACING

The soldier piles for the remainder of the pit excavation were installed next and two horizontal struts were placed against the cap beam and spanned across the excavation to the wale on the opposite side of the excavation. The bracing scheme, shown on Figure 8, was completed before the contractor extended the excavation below the top of the footing. The struts were shimmed tight against the wale.

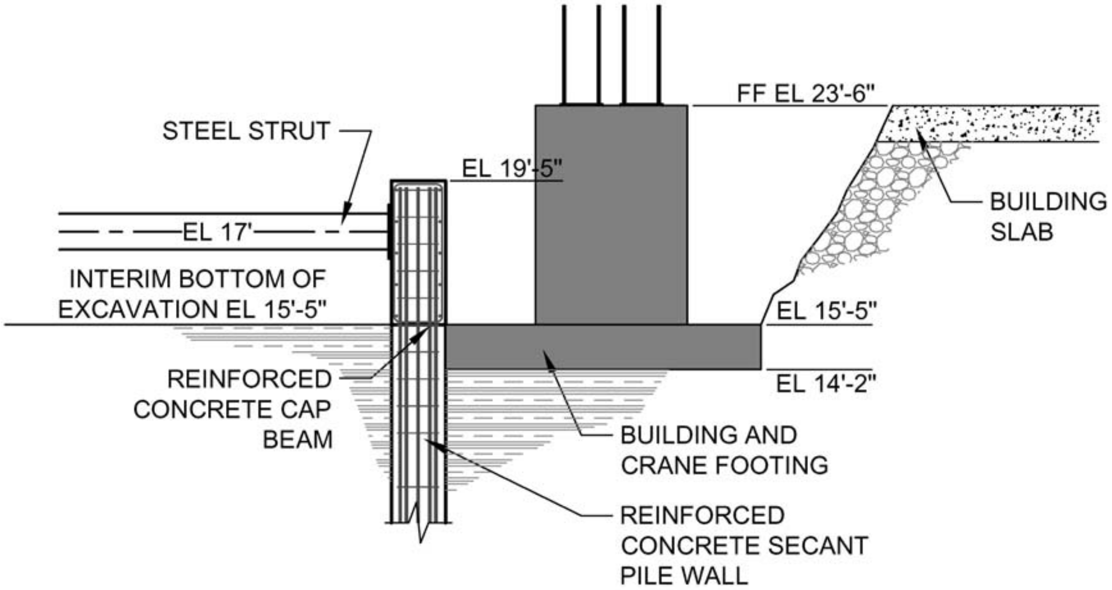


Figure 8: Section through secant pile wall prior to excavation

Figure 9 shows the completed secant pile wall with the cap beam and struts in place. Figure 10 shows a closer view of the secant pile wall surface.

Figure 9: Completed secant pile wall and bracing

Figure 10: Close up view of completed secant pile wall

MONITORING RESULTS

Measurements of the monitoring point elevations were made daily during and following excavation. The data indicated that the crane footing had not settled during the entire pit construction process.

The lack of measurable movement is likely attributed to the depth of the wall, the stiffness of the wall and the location of the brace. The brace was installed above the top of the footing, which confined the footing bearing soil. It was installed before advancing the excavation below the footing, which prevented the “cantilever movement” described by O’Rourke (1989).

SUMMARY

The case history presented in this paper illustrates the use of a retaining wall to successfully underpin a foundation that is sensitive to movements by considering the deformation modes associated with a wall supporting a deep excavation. The wall successfully prevented the foundation from moving as the adjacent excavation was advanced through a silty clay deposit for the following reasons. First, the wall design considered the applicable stiffness and modes of deformation. Second, the installation details and construction sequence of the wall were such that the installation of the wall and bracing were completed prior to any excavation below the foundation. Finally, the design considered all of the loads to estimate both depth requirements for a balanced design for moment equilibrium and strength requirement needed to resist bulging deformations.

The wall was constructed and the excavation for the pit was made without any measurable settlements.

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