ACTIVE SOIL NAIL WALL UNDERPINNING SOLUTION FOR THE BRUCE MUSEUM PROJECT

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ABSTRACT

The Bruce Museum, located in Greenwich, Connecticut, is home to an extensive display of art and natural history exhibitions. A large addition was designed to be constructed adjacent to the museum requiring new spread footings to be installed up to 16.5 feet below the existing foundations. The soil conditions at the site consist of highly variable sand and gravel overlying weathered rock and sound bedrock.

The Contract Documents called for traditional foundation underpinning. Traditional underpinning techniques, however, presented two major challenges on this Project; (1) deep underpinning pits would be required involving multiple levels and staging with tieback support and (2) the highly variable soil and bedrock composition and elevations presented uncertainty in the design and construction of the pits. In lieu of traditional underpinning, Geosciences Testing and Research, Inc. (GTR) proposed an "active" soil nail underpinning system. A major reason that the soil nail underpinning option was feasible, related to the fact that the soil nails and facing could be installed slightly in front of the existing footings rather than directly underneath the existing footings. The soil nail wall design involved one to four rows of soil nails with nail positions and wall depth able to be adjusted "on the fly" as excavation progressed depending on the field conditions encountered. To create the "active system," the soil nails were pre-loaded to mitigate wall deformations that would be associated with a standard passive soil nail wall design.

To evaluate the performance of the active soil nail wall and confirm design assumptions, an extensive automated monitoring, on-site testing and inspection program was proposed and executed by GTR to monitor deformations of the wall and the museum in real-time, evaluate and confirm bedrock and soil bond stresses and ensure that each soil nail was pre-loaded and locked off. Careful analysis, planning, and use of the observational method illustrates the importance of collaboration between design and construction personnel and applying engineering judgement throughout construction. The use of the observational method includes the potential for modifying design based on conditions observed. This paper presents a unique case study of the "active" soil nail underpinning system to support and protect sensitive structures, close collaboration between design and construction facilitated by real-time deformation monitoring, and its successful application as a safe and cost-effective alternative to traditional underpinning.

SITE/BUILDING HISTORY AND PROJECT BACKGROUND

The Bruce Museum is an art science and natural history museum that features natural science located in Greenwich, Connecticut. The museum was originally built as a private residence in 1853, and has undergone several renovations, including a 1992 renovation being the most recent prior to the current construction. The current renovation is part of a $60 million capital expansion plan for the "New Bruce". The renovation includes the installation of a 43,000-square-foot, three-story addition that will more than double the size of the museum, adding space for new exhibitions, education and community spaces. The proposed foundations for the renovation sit up to ±16 feet below the Bruce Museum's existing shallow foundations.

PROJECT/GEOTECHNICAL CHALLENGES

To excavate and install the proposed foundations up to 16 feet below the existing foundations, traditional underpinning was proposed by the Geotechnical Engineer of Record. Eastern Excavation, Inc. of Elmsford, New York, was retained by the Owner to perform the required earthwork and excavation support. Geoscience Testing and Research, Inc. (GTR) of North Chelmsford, MA was retained by Eastern Excavation, Inc., to design the temporary underpinning system. Based on the underpinning height, GTR considered the feasibility of traditional underpinning and considered it unnecessarily hazardous and too complex to construct at the site. Several options were discussed with the Eastern Excavation and the Project Engineers and Architects for an alternative to traditional underpinning. Based on the "Soils and Foundation Investigation Report, 2015" (Beattie, 2015) and results from drill probes performed, the depth to competent bedrock was variable across the site, ranging from approximately ±3 feet (1m) to ±16 feet (5m) below existing grade. In addition to the bedrock variability, sloping bedrock was anticipated beneath the traditional underpinning, posing issues with sliding. Excavation would require removal of bedrock beneath the upper underpinning tier and the existing foundations, whereby excessive vibrations due to excavation activities could cause movement and instability.

Based on the required cut heights, the traditional underpinning approach would create the need for an anchor system. Underpinning and supporting ±16 feet of soil with surcharge load from the existing building foundations would require two (2) levels of anchored support, depending on the location of the traditional underpinning in addition to multiple levels of staging to install the underpinning.

Existing foundation elements also posed several challenges. The existing shallow foundations ranged from 3.5 to 7 foot square foundations at column locations, connected by 2.5 foot wide strip footings around the existing building exterior. The bearing pressures beneath the existing footings ranged from 3.4 to 3.7 kips per square foot (ksf). Typically, these bearing pressures would be transferred directly to the underpinning elements. With no immediate access to the backside of the footings, the underpinning contractor would have to: (a) expand underpinning pits deep into the slope to reach the back of the footings, (b) excavate below the basement level on the inside of the building to reach the back of the existing footings, or (c) account for these bearing pressures as additional lateral surcharges on the underpinning. If these foundation pressures acted upon traditional underpinning as surcharges, these loads would create the need for significant additional lateral bracing and underpinning elements. See Fig. 1 for location of required underpinning and lateral earth support layout with respect to the 1992 renovation and existing stone building structure.

Excavation heights of up to approximately 16 feet in additional to the technical challenges described above also poses significant risk to the safety of the workers. They are working directly beneath existing concrete or stone that could potentially fall or soil that could potentially cave in if the underpinning pit was not prepared properly.

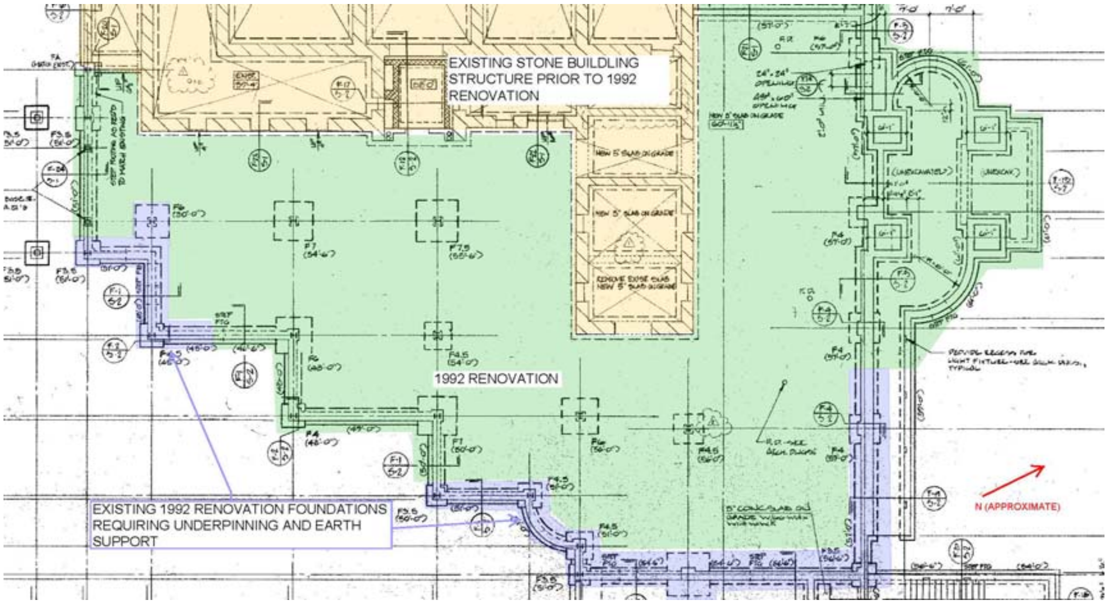

Figure 1: Required underpinning locations (blue) and existing structures (green and yellow).

GEOTECHNICAL BACKGROUND AND RECOMMENDATION

The "Soils and Foundation Investigation Report, 2015" (Beattie 2015) outlined the existing soils as loose to medium dense fill material consisting of sands and silty sands with varying amounts of gravel overlying medium dense to very dense silty sand with varying amounts of gravel overlying fractured gneiss/gneiss bedrock with RQD values ranging from 30 to 50 percent. Additionally, based on historical photos of the 1992 renovation, the base course used beneath the existing foundations was visually similar to roadway base course.

There was no mention of underpinning of existing foundations in the geotechnical report. This report may have been prepared before the proposed foundation elevations were discussed to be below the existing foundations. Initially, the report called for earth support to resist the lateral earth and surcharge pressures and called for the proposed walls to be designed for the lateral earth and building surcharge pressures. Based on discussions with the Project Structural Engineer, the proposed foundations and walls were only designed for lateral earth pressure, and therefore the proposed underpinning was required to be permanent to support the existing building and prevent the existing building from surcharging the proposed renovation foundation walls. Initially, due to the challenges traditional underpinning typically faces and the added permanent design requirement, GTR proposed an active soil nail wall design to be executed to support the lateral earth and existing foundation surcharge pressures. For simplicity in the design that eliminated the need to consider variable soil conditions, a soil profile consisting of only sand was conservatively assumed in the design (no rock used in design).

SOIL NAIL WALL APPLICATION AND FEASIBILITY

Based on a review of the subsurface conditions and the results of additional test pits next to the adjacent existing foundations, soil nailing posed to be a feasible option for the support of the earth and surcharge pressures. Based on the test pits performed, the material beneath the existing footings was confirmed to be a dense well-graded granular subgrade, similar to roadway base course. Below the dense fill material was dense to very dense silty sands, which had varying amounts of gravel. This soil was considered to have some apparent cohesion. These soils were a factor in the proposal of a soil nail wall and were well suited for the application. Conservatively, no cohesion was used in the design of the active soil nail system.

In addition to the favorable soils, several other advantages were considered with the use of an active soil nail wall. An active soil nail wall improves the soil stability. By transitioning the passive nature of a soil nail wall to an active state prior to excavation, the deflections typically seen with a soil nail wall due to reinforcement elongation and activating loads within the nails were mitigated. This was more significant where the location of the proposed active soil nail wall was in close proximity to the existing footings. Other advantages also include safety and minimal soil disturbance. Considering the variable nature of the soil within the building's footprint and the irregularity of the existing footings, there would have been increased risk while excavating beneath the existing footings.

Due to the nature of the construction, the soil nails would be drilled in the shotcrete facing which was placed in shallow sequenced excavated faces in front of the existing footings. Drilling would create low vibrations on the existing structure. During sequencing, the soil nail concrete facing was placed and soil nails were drilled though using casing, which further mitigated soil disturbance and soil loss resulting in limiting settlement of the existing foundations.

The depth to rock was variable across the site, and in turn, variable depths of soil nail wall were needed below the existing foundations to reach the top of rock. A soil nail wall could effectively be terminated at the top of rock, while the nail spacing was maintained (see Figure 1). Although the soil nail wall would be terminated at the top of the rock, the excavation was to continue to around ±16 feet below the bottom of existing footings. A rock shelf in front of the soil nail facing was proposed to support the soil nail facing, while the excavation continued below to the proposed footing depths. See photo in Figure 2 for an example of the soil nail excavated face at the required excavation depth. To facilitate the excavation of rock, rock below grade was line drilled by the contractor in several areas to the bottom of footing elevation just outside the proposed footing footprint. This allowed the rock to be excavated with limited disturbance to the rock beneath the existing footings and soil nail wall.

Figure 2: Photo of soil nail wall facing above excavated rock face.

ACTIVE SOIL NAIL WALL DESIGN

The need to minimize vertical and horizontal movement of the existing foundations was the primary consideration for utilization of an active soil nail wall design. Soil nail wall designs are typically passive systems that require wall deflection to activate and generate resistance along the soil nails. Although there were no performance specifications on the Project, there was a strong concern from the Project Team about the movement of the existing foundations and how it could adversely affect the existing building structure. Therefore, a conservative design approach was taken.

To evaluate the surcharges, the historical building plans from the 1992 renovations were provided by the Project Owner. These plans provided bearing pressures of each footing location along the area to be underpinned. Lateral surcharge pressures were calculated using the program SNAIL using Boussinesq's method, modeling the foundations as strip surcharges at distances behind the soil nail wall. After considering various options for the facing, an increased section was selected with additional reinforcement to reduce flexural deflections. Introducing an active condition was performed by prestressing each soil nail. To properly apply a prestresss load, each nail would require a free length, within the soil failure plane wedge, which in-turn ensured that the bond zone was being activated beyond the failure plane. To accommodate the free stressing length and prestresss loads, the facing was designed for a higher nail head loading, using the maximum stress found in the soil nails during analysis.

Nail spacing was also considered in the design due to the proximity of the existing building and foundations to the soil nail wall. Soil nails were spaced on a 4-foot-by-4-foot grid. Therefore, shallower lifts could be made during construction, reducing the probability of a lift sloughing.

Another aspect of design was the requirement for the wall to be permanent, which eliminated the surcharge loads from the existing building foundations on the proposed addition foundation walls. Considering the wall was to be buried, the contractor elected to use a single shotcrete facing, and install a steel end cap on each nail head with corrosion inhibiting grease. All soil nails installed were manufactured with the Post Tensioning Institutes (PTI) Class 1 Double Corrosion Protection (DCP) with all bar hardware, bearing plates and steel end baps being galvanized to resist potential corrosion. The soil nail wall was also designed for seismic conditions.

Based on the aforementioned design requirements, 4.5-inch diameter soil nails ranging from 22 to 27 feet in length utilizing a #10, Grade 75 threaded bar for reinforcement were selected for the permanent design. The soil nail design loads ranged from 36 kips to 40.5 kips depending on their location and up to four rows were considered for the cut heights anticipated. A 6-inch thick shotcrete facing (minimum f'_c = 4,000 psi) was designed using two layers of welded wire mesh for the support of the soil around the nails.

SOIL NAIL CONSTRUCTION

Typical construction of a soil nail wall consists of excavating typically in 5 foot lifts along the whole length of the proposed wall, installing soil nails, and installing the reinforcing and shotcrete facing after all nails are installed for each lift. After the lift is stabilized with the soil nails, the entire subsequent lift is excavated for the installation of each subsequent row of soil nails and the process is repeated for each level.

Considering the proximity of the existing foundation and building structure, construction sequencing was crucial to mitigate soil loss and disturbance. Shallow lifts, limited to 4 feet, were maintained during excavation with sequencing the excavations of short and precise spans of soil nail rows to limit time for soil to be open cut. The soil nail installation sequencing was more important in areas of concern where the soil nail wall beneath existing footings was in close proximity. See Figure 3 for an example of the soil nail sequencing used for each lift at one portion of the site. Additionally, in soil, the contractor used rotary duplex drilling methods (casing and drill string) to reduce ground loss. In rock, the casing was seated into rock and the rock was open hole drilled to the required depth.

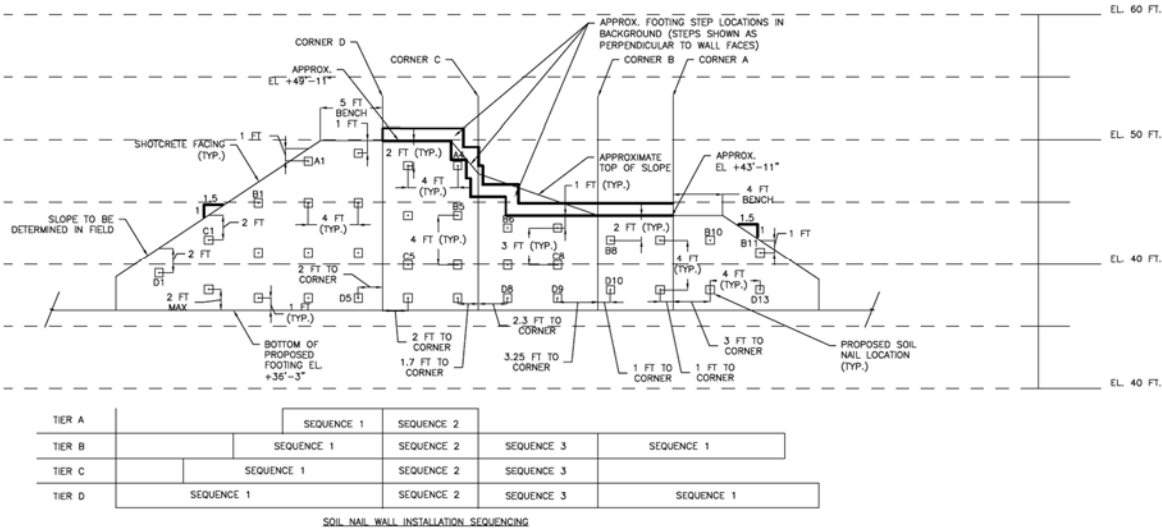

Figure 3: Soil nail lift sequencing drawing with soil nail elevation view.

Facing rebar and shotcrete was assembled and installed on the same day excavations were performed to reduce soil loss before the soil nails were installed for each lift and sequence section. After soil nails were installed, each soil nail was locked off at 50% of the design load to create an active condition. The lock off sequence also was considered a form of modified proof testing of each soil nail. See Fig 4 for facing construction (wire mesh installation and shotcrete placement).


Figure 4: Shotcrete facing – rebar installation and shotcrete placement

During construction, daily on-site inspection was performed by GTR to confirm the soil nails and shotcrete facing were installed in accordance with the design. This allowed the use of the observational method (Peck, 1969) for making field modifications to the design on an as-needed basis in real-time through communication with a representative of the design engineer present on site. The layout of the foundation and excavation heights were modified during construction due to varying rock elevations and existing site conditions not indicated on the plans. GTR observed these changes and the wall design was analyzed on a case by case basis resulting in a modified layout consisting of installing additional nails or eliminating nails where they were unnecessary.

GTR observed and documented all soil nail testing, including 4 verification tests and 7 proof tests, to confirm the soil and rock bond stresses were consistent with our design methodology. To confirm there was limited movement of the wall and the existing structure, GTR's Automated Deformation Monitoring program was implemented using two automated robotic total stations (AMTS), accurate to 1 second (vertical and horizontal) with an accuracy of 0.05 inches at 1000 feet (using optical survey prisms and total station) – see Figure 5. Deformation monitoring points installed on the existing structure showed minimal northing, easting and elevation fluctuations throughout construction and after the completion of the soil nail wall, confirming the soil nail wall was performing as intended. Figure 5 shows the elevation changes of the existing structure above the underpinning elevations throughout the monitoring program of the Project.

Figure 5: Elevation data of existing structure behind soil nail wall through the monitoring program and one of the AMTS setups at the project.

CONCLUSIONS

An efficient alternative underpinning solution that was executed through careful analysis and planning. The design was coordinated using effective communication between the Architect, Engineer, Contractor and Earth Support Designer. Through automated near real-time deformation monitoring, this active soil nail wall design proved to be an effective and safe solution given the existing and proposed foundation geometry and complex ground conditions. With GTR's on-site inspection, the use of the observational method illustrated the importance of exercising engineering judgment throughout the construction phase. The observational approach allowed for a more organized and efficient design and acknowledged potential for modifying the design during the construction process based on in-situ conditions as well as promoting a safer alternative than traditional underpinning. Given its safe application and capability to tolerate large surcharges with little deformation, an active soil nail wall is considered a viable option when underpinning existing foundations.

ACKNOWLEDGEMENTS

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