Mar 8th - Mar 15th

Shoring Analysis, Design and Construction at the Seattle Symphony's Benaroya Hall

Carole L.B. Mitchell
Shannon & Wilson, Inc., Seattle, Washington

Monique A. Nykamp
Shannon & Wilson, Seattle, Washington

Proceedings: Fourth International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, March 9–12, 1998.

SHORING ANALYSIS, DESIGN AND CONSTRUCTION AT THE SEATTLE SYMPHONY'S BENAROYA HALL

Carole L.B. Mitchell, P.E.
Shannon & Wilson, Inc.
Seattle, Washington-USA-98103

Monique A. Nykamp, P.E.
Shannon & Wilson, Inc.
Seattle, Washington-USA-98103

Paper No. 5.08

ABSTRACT

Complex loading and geometry conditions controlled the design of the shoring wall system at Benaroya Hall, the new home of the Seattle Symphony. A combined system, including three soldier pile and tieback walls and one soil nail wall, was used to shore an excavation that ranged from 15 to 50 feet deep. A 25-foot-wide block of soil remained between the soil nail wall face and an existing, underground bus station. Prior to designing the soil nail wall, a finite difference analysis was performed to determine potential movements of the station due to the excavation. The deflection estimates from the finite difference analysis closely approximated the actual field measurements obtained from inclinometer readings and optical surveys during construction.

KEYWORDS

Shoring Wall
Soldier Pile
Tieback
Soil Nail
Finite Difference Analysis
Inclinometer
Rakers

INTRODUCTION

Benaroya Hall, the new home to the Seattle Symphony, is located at a site in downtown Seattle that posed difficult shoring design and construction challenges. When completed, the building will have an approximate area of 187,000 square feet, and the main auditorium will have a seating capacity of 2,500. There will also be two levels of underground parking. The excavation for the basement of the concert hall abuts the twin transit tunnels and the underground University Street Station of the Seattle Downtown Metro Transit (Metro), as shown in Fig. 1. Construction of the concert hall removed soil within 25 feet of the transit tunnels and station, raising concern regarding potential movements of these structures. Several buildings surround the site and are founded on relatively shallow foundations that might also have been affected by the concert hall excavation. The hall is located in downtown Seattle and is bounded by Second and Third Avenues and

The Metro station, Metro tunnels, street traffic, utilities, and the surrounding buildings had to be maintained and protected from the concert hall excavation and construction. A combination of soil nail and soldier pile and tieback walls was used to shore the excavation. A finite difference analysis of the Metro station and soil nail wall was performed. Figure 1 shows the locations of the various shoring systems. The complex excavation adjacent to the Metro station varied in height, and the configuration included an existing building basement and the station's existing and proposed pedestrian access tunnels. The analyses included the influence of rakers, grade beams, footings, and cut slopes at the top of the excavation. The soil nail wall included four design sections. A second finite difference analysis was performed for the new pedestrian access to the Metro station. Performance of the shoring walls was monitored during construction through the use of crack gauges in existing buildings, video in the Metro station, an inclinometer behind the soil nail wall, and optical

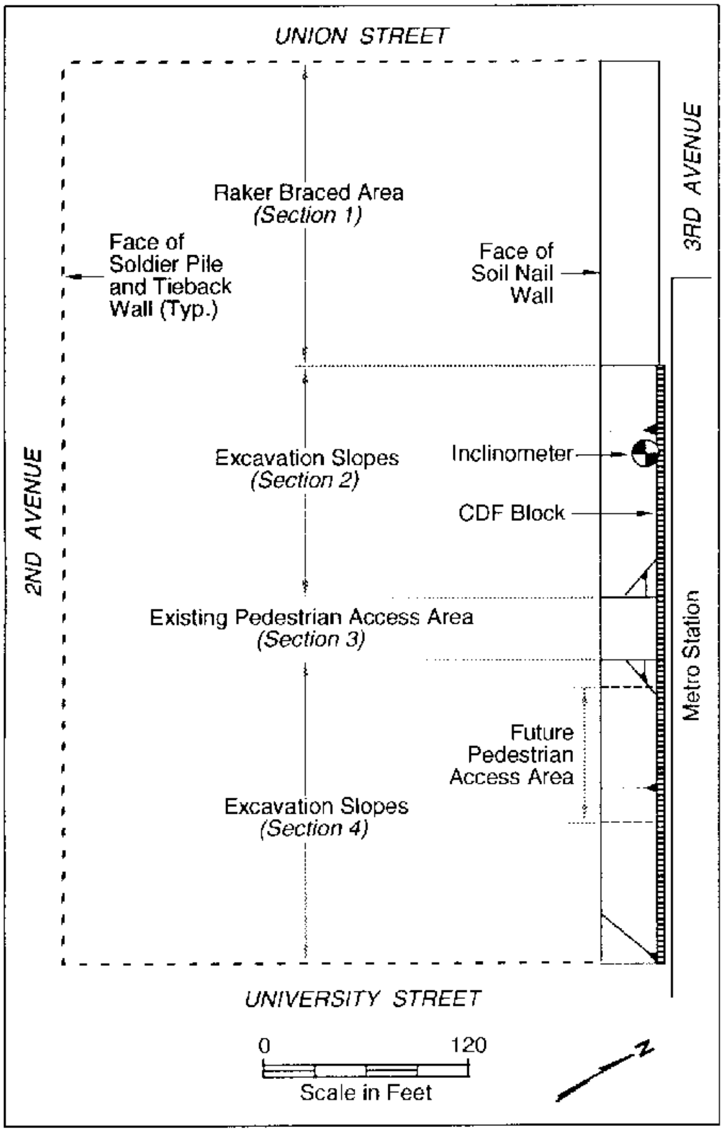

Fig. 1 Shoring Plan

The University Street Station was constructed by Metro in the late 1980s and stretches for approximately two blocks beneath Third Avenue between Seneca and Union Streets. The total length of the station is about 575 feet with a width of about 72 feet. The northern terminus of the station, where the station transitions into twin tubes for the transit vehicles, is located about 80 feet south of the concert hall's north property line. The finished floor elevation of the station is about elevation 55 feet, and the top of the station is at elevation 99 feet (or approximately 15 feet below Third Avenue). In relation to the station floor elevation, the concert hall excavation extended to elevations between 60 and 65 feet. After the station was constructed, the top of the station was filled with CDF to the pavement subgrade elevation.

The Metro station was constructed using cut-and-cover techniques that employed both internally and externally braced shoring systems, including both tangent piles and soldier piles. During excavation, lateral support to these walls was provided by internal bracing within about 15 feet of the street level. Tiebacks were used extensively along the east wall of the station to support adjacent buildings. The first row of tiebacks installed along the east wall of the station was destressed following construction. The other tieback rows remained stressed to provide support for the adjacent buildings. Tiebacks were used along the western wall of the station as well; these tiebacks were encountered during the concert hall's shoring installation and excavation. During the Metro station construction, settlements of approximately 0.5 inch occurred at some adjacent building foundations to the east, which subsequently required localized underpinning. Therefore, prior to starting any construction at the symphony site, a thorough crack survey was completed in all of the surrounding buildings. Crack gauges were installed and several existing crack gauges (installed during the station construction) were measured again to obtain a zero reading for the new construction.

SUBSURFACE CONDITIONS AND TOPOGRAPHY

Several exploratory borings had been made in the streets surrounding the symphony site for earlier studies in the vicinity. The subsurface conditions encountered in these borings indicated variable soil conditions. The materials encountered were very dense, clean to silty sand with varying percentages of gravel and hard, clayey silt to silty clay overlying glacial till or till-like soils. The glacial till or till-like soils consisted of very dense, clayey, silty sand with varying percentages of gravel. Most of the soils encountered in the borings were native materials and essentially had Standard Penetration Test (SPT) resistance values greater than 100 blows per foot. Some surficial fill was encountered, usually less than 15 feet thick.

From observations made during drilling and from measurements taken in observation wells installed in two borings, it appeared that perched groundwater existed at the contact of the sand and the relatively impervious layers of clay and till-like material. Sand layers within the underlying glacial till might also be water bearing. During construction, the site was relatively dry with the exception of portions of the north shoring wall. Seepage was observed from behind the shoring wall at various locations, and a temporary sump was installed at the northeast corner to collect the water.

The pre-construction ground surface across the site sloped gently downward to the southwest from Third to Second Avenue. Elevations across the site ranged from approximately 115 feet along Third Avenue to about 80 feet at the intersection of Second Avenue and University Street. City records indicated that relatively minor cuts and fills had been completed at the site for street construction.

SOIL NAIL WALL - EAST SHORING WALL

The existence of the Metro station, Metro tunnels, Jones Building basement wall and rakers, and temporary pedestrian access staircase impacted the design and construction of the eastern shoring wall system. The major concerns involving the Metro station and transit tunnels were providing lateral support to the station and tunnels during basement excavation of the concert hall. The outer wall of the Metro station was approximately 25 feet from the face of the concert hall excavation. Therefore, because of the proximity of the station wall, soil nails were used to reinforce the soil block within the 25-foot-wide zone.

Finite Difference Analysis

During the design process, a soil structure interaction analysis was performed to evaluate the expected deflections, shears, and moments that may be experienced within the Metro Station as a result of the excavation for the concert hall. This analysis was also used to evaluate the expected lateral deformations of the proposed soil nail wall. A two-dimensional, plane strain, soil-structure interaction program called FLAC (Fast Lagrangian Analysis of Continua, version 3.22) was used to perform the numerical analyses. This program uses a finite difference method to compute deformations and stresses in continuous media such as soil. The FLAC program uses beam, cable, and support elements that interact with the continuous media to represent structural components such as walls, tiebacks or soil nails, and bracing struts.

Based on project information provided by the structural engineers at Skilling Ward Magnusson Barkshire, a FLAC model was developed for an average cross section of the excavation in the vicinity of the Metro Station. The model was developed as a two-dimensional, rectangular grid of nodes and elements and is shown on Fig. 2. The actual analysis boundaries extend horizontally from those shown on Fig. 2. A temporary soil nail wall with a shotcrete facing was used to support the excavation wall. A horizontal and vertical soil nail spacing of 5 feet was used in the analyses.

Since the soils in the vicinity of the excavation are very dense or hard, one soil type was assumed for the FLAC model. Groundwater was not included in the analysis. A soil with a Young's Modulus of about 50 kips per square inch (ksi), a friction angle of about 43 degrees, and a cohesion of about 200 pounds per square foot (psf) were estimated. These soil parameters are based on our experience with similar soils in the vicinity of the project site.

Several analyses were performed to test the effect of different soil models and mesh configurations. Both elastic and Mohr-Coulomb models were used with small and large mesh configurations. The cases were also bracketed to evaluate the effects of the presence of the mezzanine level in the Metro station and the effects of soil loading on the east side of the station.

The results of the FLAC analyses indicated lateral movements of the top of the excavation shoring wall of about 0.3 inch or less. A plot of the deflected mesh is shown on Fig. 3. Since the estimated movements were reasonable and less than one-half inch, the soil stress-strain characteristics are still in the elastic range; therefore, the elastic model was selected as acceptable for use in other design variations.

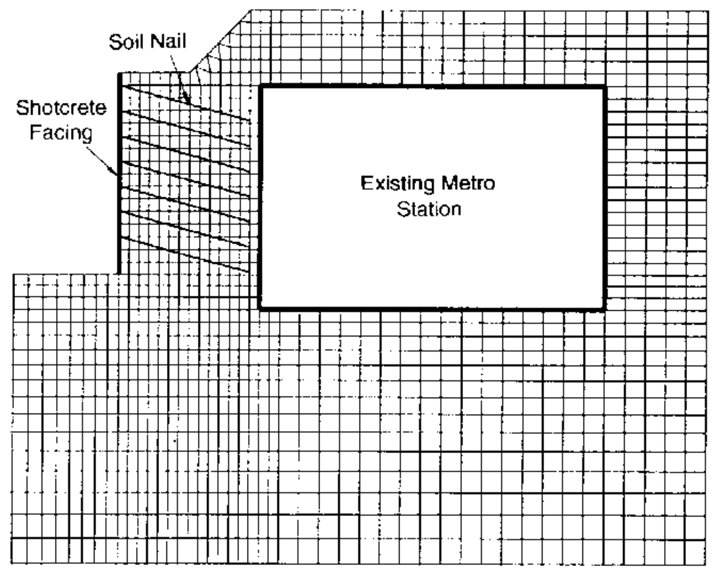

Fig. 2 FLAC Model for Soil Nail Excavation

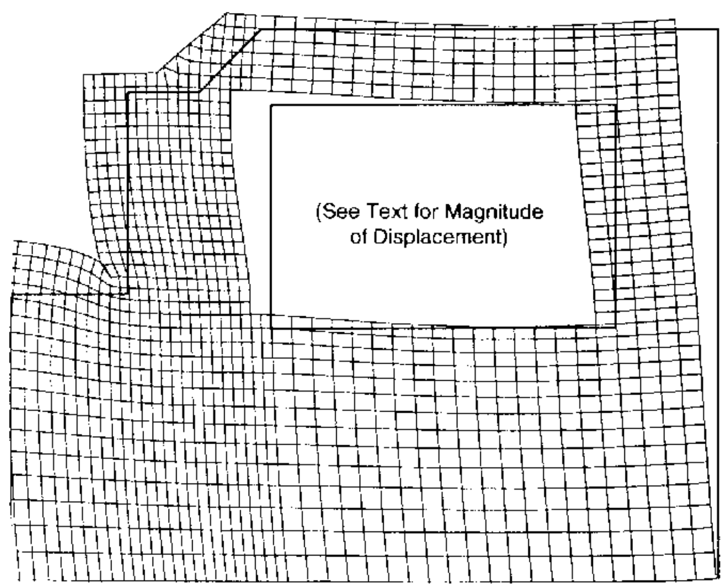

Fig. 3 Deflected Mesh for Soil Nail Excavation

Other information that was provided by the FLAC analyses included deflection, shear, and moment diagrams for the Metro station tunnel and movements in the excavation. The finite difference analyses found that adequate support to the Metro Station could be provided by constructing a soil nail wall within a distance of about 25 feet from the face of the station and maintaining movements of the station to about 0.3 inch or less.

Soil Nail Wall Design

Based on the results of the finite difference study, a soil nail wall was designed for the eastern shoring wall. The total length of the soil nail wall was approximately 358 feet. The height of the wall ranged from about 16.5 feet to 34 feet. The wall was split into four sections based on the geometry and loading conditions. The plan locations of the sections are shown on Fig. 1.

Section 1 includes the northern 120 feet of the eastern shoring wall and is shown on Fig. 4. During the initial construction phase, an old, six-story, brick-faced building called the Jones Building, was demolished on the northeast corner of the site. The Third Avenue side of the Jones Building basement wall was used in conjunction with steel tube rakers as the upper portion of the northeast shoring wall.

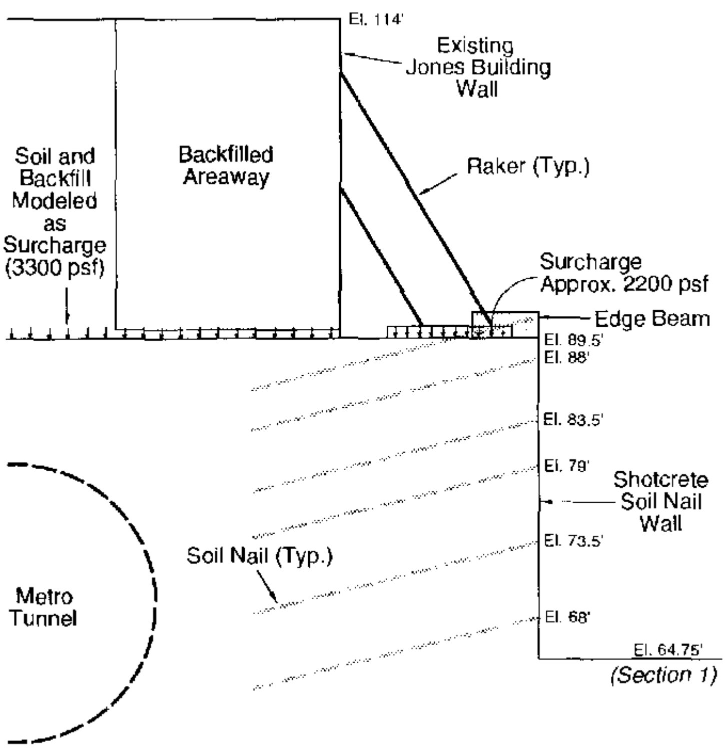

Fig. 4 Soil Nail Wall Section 1 at Jones Building

Sections 2 and 3 are south of the raker system and represent two different excavation depths as shown on Fig. 5. In these sections control density fill (CDF) was poured in a 5-foot-wide by 5-foot-deep trench adjacent to the sidewalk prior to shoring installation. This CDF block was used to keep the sidewalk and utilities in place during construction. During excavation, material was removed at a 1 Vertical to 1.5 Horizontal (1V:1.5H) slope from the base of the CDF block down to the top of the soil nail wall. This cut slope was 15 feet high.

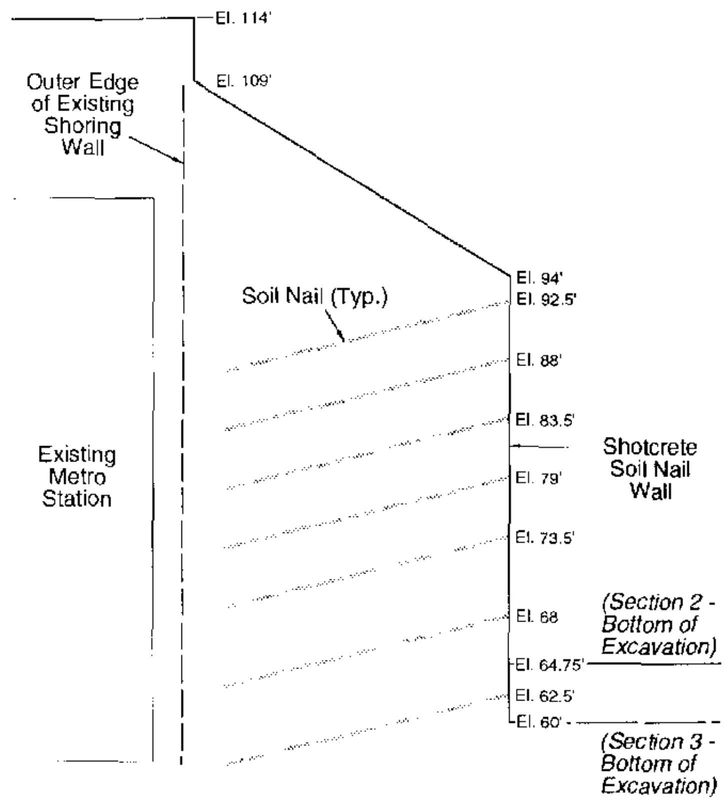

Fig. 5 Soil Nail Wall Sections 2 and 3 for Shallow and Deep Excavations at Station

Section 4 is between Sections 2 and 3 (see Fig. 6). The pre-construction site had a pedestrian access tunnel leading into the Metro station (location is shown on Fig. 1). As a part of the symphony project, the pedestrian access was removed and a temporary, emergency, stair exit was built from the Metro station up to the Third Avenue sidewalk. Design Section 4 includes stair footing loads at the top of the soil nail wall.

Each of these sections was analyzed and design recommendations were developed using the computer program SNAIL (version 2.11), which was developed by the California Department of Transportation (CALTRANS). This program uses a bi-linear wedge analysis to evaluate the stability of soil nail reinforced cut slopes. The program computes a factor of safety (FS) against slope failure for a specified soil nail spacing, length, and load transfer capacity. The analyses were conducted to develop a design that would provide a minimum FS of 1.3 for static loading. Because the wall was temporary, dynamic loading conditions were not analyzed. Analyses were also conducted to develop a design that would provide an FS of at least 1.25 for intermediate stages of construction (that is, after excavation of a lower level is completed and before the nails are installed). The length of the soil nails was limited to 22 feet in order to avoid the Metro station and its existing soldier pile and tieback shoring wall. In addition to achieving the FS requirements above, the design included a uniform nail spacing, inclination, and length for ease of construction. The final design included a horizontal nail spacing of 4.5 feet and a vertical spacing that varied from 4.5 to 5.5 feet.

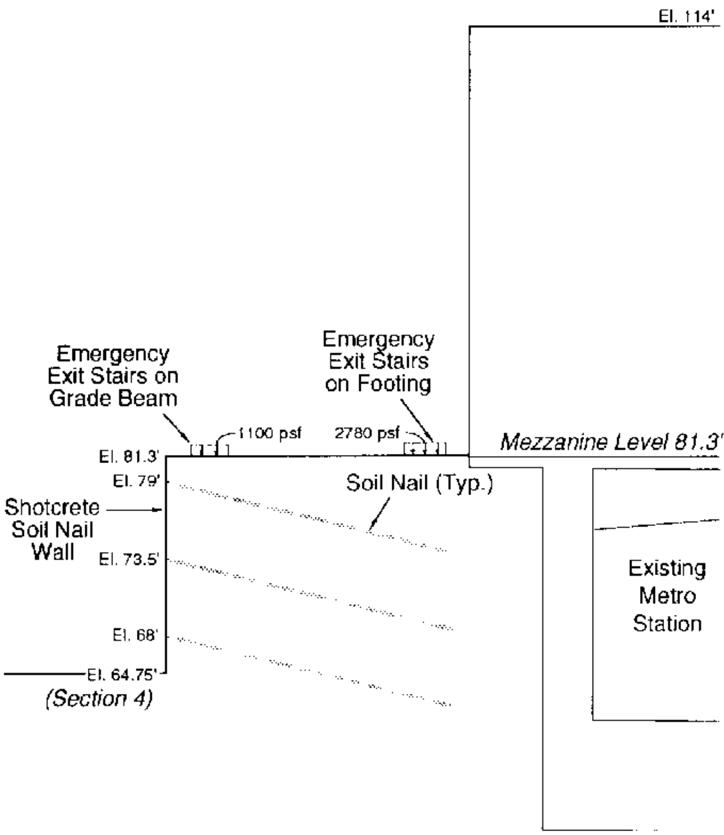

Fig. 6 Soil Nail Wall Section 4 at Station Entrance

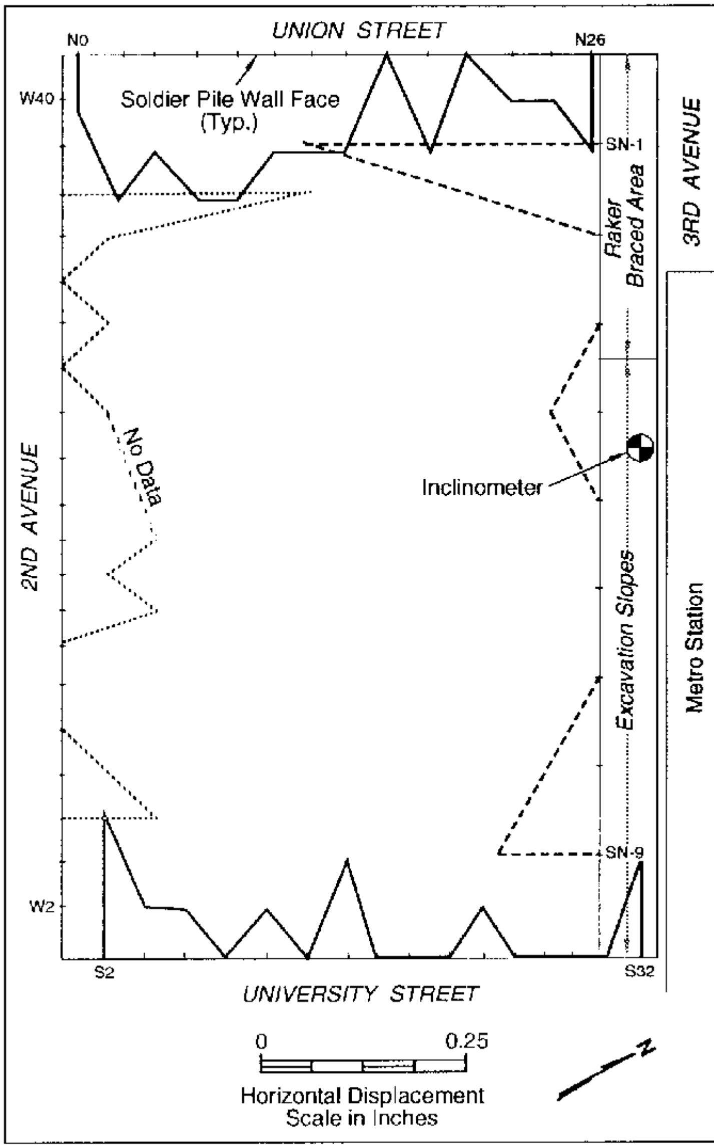

Fig. 7 Surveyed Horizontal Shoring Movement at Maximum Excavation Depth

Soil Nail Wall Performance

Performance of the soil nail wall was monitored through measurements of an inclinometer installed between the station and the shoring wall face (location is shown on Fig. 1), and through weekly optical surveys of nine angle irons attached to the top of the wall. According to the optical surveys, the angle irons moved between 0.0 to 0.36 inch at the maximum excavation depth, as shown on Fig. 7. The average movement was less than a tenth of an inch. The maximum survey reading was taken in the vicinity of the transit tunnels away from the station. The inclinometer measured a maximum soil movement of 0.1 inch at the maximum excavation depth. This maximum movement was recorded at the top of the inclinometer tubing, which was within the cut slope above the soil nails. When compared to the measurements taken during the excavation, the results of the FLAC analyses were generally higher in magnitude than the actual measurements.

Pedestrian Access Soil Nail Wall

During construction, a new pedestrian access point into the Metro station was opened by cutting through the station wall south of the pre-construction access point (see Fig. 1). To obtain this new access point, additional soldier piles were installed perpendicular to the eastern soil nail wall and the area was excavated next to the station wall. An existing soldier pile shoring wall that was installed for the construction of the station was re-used as shoring for the new pedestrian access excavation. To model potential movements of the station due to the pedestrian access excavation, an additional finite difference analysis was completed.

The model was developed as a two-dimensional, rectangular grid of nodes and elements and is shown on Fig. 8. The actual analysis boundaries extend horizontally from those shown on

Fig. 8. The input soil values were the same as for the previous analyses. Again, the effects of the presence of the mezzanine level in the Metro station were analyzed. The results of the FLAC analyses indicated lateral movements of the station wall of less than 0.3 inch. A plot of the deflected mesh is shown on Fig. 9.

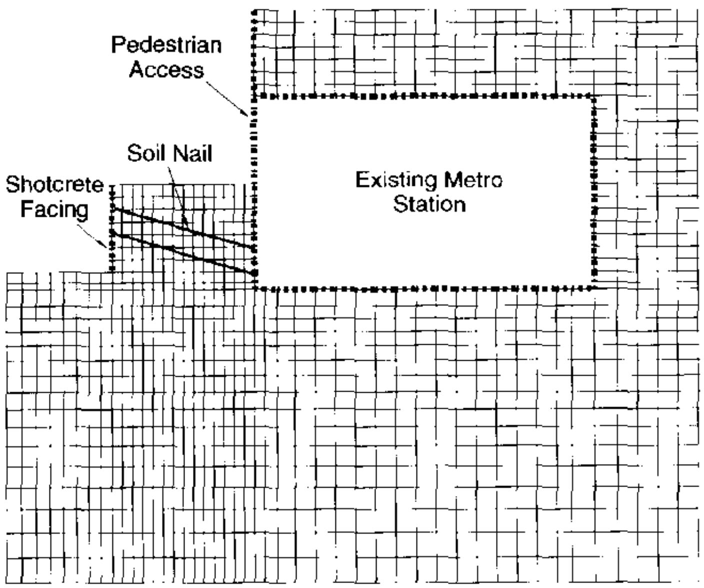

Fig. 8 FLAC Model at Pedestrian Access

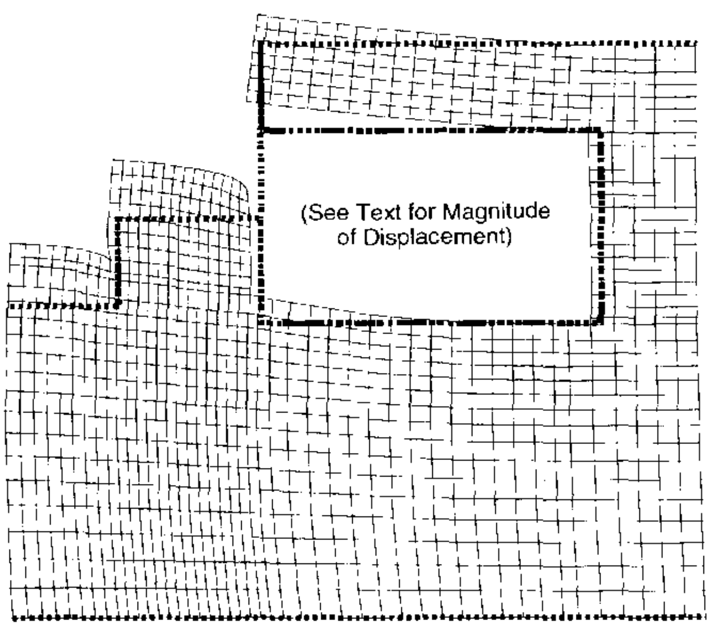

Fig. 9 Deflected Mesh at Pedestrian Access

SOLDIER PILE AND TIEBACK WALLS

The north, south, and west sides of the concert hall site were shored using soldier pile and tieback construction. Because of the change in grade along the walls, the soldier pile walls included cantilever walls and walls with up to three levels of tiebacks. The wall heights varied from 15 to 50 feet. For tieback design, an allowable skin friction value of 1 kip per square foot (ksf) was used to size the anchors. The wall design was based on a trapezoidal pressure distribution with a maximum pressure equivalent to 20H, where H represents the height of the excavation cut (in feet) below the street level. The top and bottom of the pressure distribution were truncated at 0.2H.

The soldier pile walls were also monitored using weekly optical surveys during excavation and basement level construction. The surveys were made, in general, at the top of every other soldier pile. The results of these measurements indicated that, at the maximum excavation depth, the range of deflections was between 0.0 and 0.30 inch, as shown on Fig. 7. The average deflection was less than 0.1 inch. Throughout the excavation, shoring and initial basement floor construction activities, the soldier pile and tieback walls moved an average of about 0.2 inch, with a maximum movement of 0.5 inch.

SHORING COSTS AND SCHEDULE

The cost of the soldier pile and tieback shoring walls on the north, south, and west sides of the concert hall excavation averaged approximately $42 per square foot of wall face. This cost includes drilling through and using a core barrel to get through the many on-site obstructions. These obstructions included buried footings, concrete walls, and buried tiebacks from the Metro station construction. For approximately 100 soldier piles and 170 tiebacks, the installation and tieback stressing took 11 weeks to complete.

The soil nail wall cost was about $20 per square foot of wall face. Over 450 soil nails were installed and tested in 8 weeks.

MONITORING SCHEDULE

Inclinometer readings and optical surveys were made through February 1997 when the building had approximately reached the Third Avenue street level. The final reading of the crack gauges in the surrounding buildings will be made in the late summer or early fall of 1997.

CONCLUSION

The estimated east shoring wall deflections obtained from the design analyses were, in general, slightly higher than the measured deflection values. The deflections observed on the soldier pile and tieback walls were typical values for this type and depth of construction in the Seattle downtown area. The FLAC analyses provided reasonable deflection values that closely approximated actual field measurements.

The Benaroya Hall construction began in April of 1996, and the estimated opening date is September 1998.

REFERENCES

California Department of Transportation (CALTRANS), Division of New Technology, Materials and Research, Office of Geotechnical Engineering. SNAIL Program. Version 2.11 - PC Version.

Itasca Consulting Group, Inc. FLAC--Fast Lagrangian Analysis of Continua. Version 3.22.

Shannon & Wilson, Inc. [1995]. "Geotechnical Report, Seattle Concert Hall, Seattle, Washington.

Shannon & Wilson, Inc. [1995]. "Addendum No. 1 to Geotechnical Report, Seattle Concert Hall, Seattle, Washington."