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DESIGN AND CONSTRUCTION OF THE SEATTLE SYMPHONY'S BENAROYA HALL ABOVE AN OLD RAILROAD TUNNEL

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ABSTRACT

Benaroya Hall, the new home of the Seattle Symphony, is located directly over an old railroad tunnel in downtown Seattle. The railroad tunnel was hand excavated in the early 1900s; the tunnel excavation caused considerable settlement of the buildings and streets above. The tunneling disturbance and subsequent rotting of timber supports resulted in numerous voids in the vicinity of the tunnel. Excavation for the Benaroya Hall removed up to 55 feet of soil overburden and came to within 12 feet of the tunnel crown. The foundations for the symphony hall were required to protect the railroad tunnel from carrying symphony hall building loads as well as preventing the hall from settling because of tunnel void collapse. A combination of drilled shafts and a foundation mat was used to support the symphony hall in the vicinity of the tunnel. A series of tape extensometers and optical surveys within the tunnel confirmed the success of the combination foundation system.

KEYWORDS

Drilled Shafts
Tape Extensometers
Railroad Tunnel
Foundation Mat

INTRODUCTION

Benaroya Hall, the new home to the Seattle Symphony, is located at a site that posed difficult foundation design and construction challenges. Located within the downtown Seattle block bounded by Second and Third Avenues and Union and University Streets, the project is directly over the Burlington Northern Santa Fe Railroad (BNSF) tunnel, which carries frequent train traffic beneath downtown Seattle. Once complete, the 187,000-square-foot concert hall will have main auditorium seating for about 2,500 patrons and a two-story, underground parking facility.

The two major factors affecting the foundation selection in the immediate vicinity of the BNSF tunnel were the potential existence of disturbed soils above the tunnel that may cause building foundation settlement and the potential building foundation interaction effects on the underlying tunnel. Foundation design took into account that construction of the concert hall removed up to 55 feet of soil overburden and came to within 12 feet of the tunnel crown. To maintain the integrity of the tunnel and provide building support, a combination of deep drilled shafts and a foundation mat was used in the immediate vicinity of the BNSF tunnel. A layout of the foundation types and locations is shown on Fig. 1. The drilled shafts were founded below the BNSF tunnel invert, thereby transferring the building loads below the tunnel. The foundation mat spans over the tunnel, transferring building loads to the drilled shafts. A generalized cross section of this area of the foundation support is shown on Fig. 2. Beyond the tunnel's influence, shallow spread footings were used to found the structure. In addition to continuous drilled shaft installation monitoring, tunnel movements and conditions were monitored using 12 sets of tape extensometers and an optical survey.

The condition of the BNSF tunnel and the soil above it were critical to the design and performance of the concert hall foundations because the tunnel crosses diagonally under the center of the site. The double-track railroad tunnel was constructed by hand excavation between mid-1903 and early 1905. Although there are no available construction records for the BNSF tunnel, we understand that it was constructed by a
multiple drift method in which several smaller drifts were constructed around the perimeter of the tunnel prior to the mass excavation for the tunnel and the installation of the tunnel lining. The drifts ranged from about 10 to 15 feet on a side. The entire tunnel excavation was a horseshoe-shape, with outside dimensions of about 38 feet wide by 38 feet high. The tunnel crown is at approximately elevation 48 feet with an invert elevation of about 10 feet. The tunnel was initially supported with up to 12-inch-square timber sets spaced up to 6 feet apart, with the intervening soils supported with 3-inch-thick wooden lagging. A concrete lining was cast against these wooden supports to form a final lining about 3.5 to 4.5 feet thick. The finished inside diameter is 30 feet wide by 28 feet high. The wall footings of the tunnel are 2.5 feet thick. There are some indications that different excavation methods or sequences may have been used at various times.

The tunnel was constructed by hand excavation without the use of a shield. Apparently no dewatering was used along the alignment, and the alignment was not driven under compressed air. There are some reports of large inflows of water; however, quantities were not documented. The tunnel was constructed primarily in hard or dense glacial soil, including sand and gravel, blue clay, and "hardpan" (till). In the vicinity of Third Avenue and University Street, sand and gravel were encountered and continued to the vicinity of Pike Street and First Avenue (a few blocks north), where a heavy inflow of groundwater was encountered.

Following construction of the tunnel, ground surface settlements were observed along various portions of the alignment. The settlements resulted in damage to buildings along the alignment as well as settlement of streets and curbs, tilting of light posts, and general fracturing and degradation of the soils overlying the tunnel. For example, settlements on the order of 1 to 2 inches were recorded for a building located over the tunnel near the intersection of Third Avenue and University Street. In general, settlements during construction ranged from an initial 0.1 to 2 feet with an average of about 0.5 foot. Long-term settlements over the next eight to nine years added another 0.5 to 2 feet of settlement. Much of this additional settlement was attributed to rotting of the timber supports and collapse of wood cribbing. Between 1912 and 1914, a crown drift above the tunnel was excavated from shafts...
and along adits, and the timber over the crown was removed and replaced with an additional thickness of lean concrete. Consequently, in some areas the concrete arch of the tunnel may be 6 to 8 feet thick.

**SUBSURFACE CONDITIONS AND TOPOGRAPHY**

The soils at the site were identified by several perimeter borings completed for earlier studies in the vicinity. The borings varied in depth from 48 to 150 feet, and none were completed immediately adjacent to the BNSF tunnel. 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 exhibited 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. During construction, the site was relatively dry with the exception of portions of the north wall. Seepage was observed from behind the north shoring wall at various locations, and a temporary sump was installed at the northeast excavation 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.

**DRILLED SHAFT DESIGN AND CONSTRUCTION**

In order to support Benaroya Hall on native, intact soils, drilled shafts bearing outside the potential zone of tunnel construction disturbance and at or below the tunnel invert were recommended. This zone of disturbance resulted from the tunnel construction itself or from subsequent decay and rotting of the timber support systems outside of the concrete lining of the tunnel. The zone of disturbance was estimated to extend out from the base of the tunnel at a 60 degree angle from horizontal, as shown in Fig. 3. Spread footings were not recommended within the zone of disturbance because footings might sustain undesirable differential settlements as a result of any collapse of voids that may exist between the footing and the tunnel. Also, the use of spread footings above the tunnel may add concentrated and potentially damaging loads to the tunnel lining. Spread footings were used, however, in areas outside of the tunnel disturbance zone, as shown in Fig. 1.

The drilled shaft support system provides support completely independent of the performance or the existence of the BNSF tunnel. Additionally, the use of the drilled shafts will help to isolate the symphony hall from vibrations from train traffic within the tunnel.

The drilled shafts ranged in size from 4 to 6 feet in diameter and were founded at or below the tunnel invert at elevations ranging from 10 to 11 feet. The shafts were drilled using a variety of methods, depending on the soil conditions. These methods included open hole, slurry, and water head. Temporary casing was used frequently in the upper 20 to 40 feet of the shafts. Care was taken to maintain the integrity of the drilled shafts as well as to maintain the lateral support of the tunnel by avoiding excessive caving.

During drilling, obstructions such as boulders had to be cored through and tiebacks from previous construction had to be cut out and removed. Voids and disturbed and sloughing or caving soils were encountered in many of the shafts. A water head was being maintained during drilling of one shaft when, within a few seconds, the water level dropped 15 feet. During the concrete placement in another shaft, approximately 25 cubic yards of concrete was pumped into a sidewall void about 20 to 25 feet below the ground surface. When the problem was noticed, the sidewall hole was blocked with a piece of plywood and the shaft was completed. After each of these incidents, a BNSF tunnel walkthrough was completed to determine if any damage had occurred to the tunnel. After the extra concrete was pumped into the shaft mentioned above, a watery concrete was observed in the track ballast where it apparently had blown through the weep holes into the tunnel. No other evidence of disturbance was noted.
FOUNDATION MAT DESIGN AND CONSTRUCTION

To span the building loads over the top of the tunnel, a 6.5-foot-thick, reinforced concrete mat was built connecting the shafts on either side of the tunnel, forming a bridge. The plan location of this foundation mat is shown on Fig. 1, and the general cross section is shown on Fig. 2. Prior to placing the mat, the upper 6 inches of soil was scarified, loosening the surface of the soil and allowing any initial deflection of the mat to be taken in the loosened soil rather than transferring load to the tunnel. Because the base of the mat was only 12 feet above the top of the BNSF tunnel crown, large equipment was restricted from working within the excavated foundation mat area to avoid over stressing the tunnel.

Because of the size of the foundation mat, it was poured in three sections starting with the northwest third, then the middle, and finally the southeast section. The estimated volume of concrete poured for the first, second, and third sections were 2,100 cubic yards (cy), 1,900 cy, and 2,300 cy. Each of the concrete pours was completed in one day. An estimated 250 trucks were used to pour each section; the average rate was one truck every 3 to 4 minutes. Figure 4 shows the foundation mat under construction. Vertical drilled shaft reinforcement is in the foreground of the photo.

![Fig. 4 Foundation Mat Construction](image)

BNSF TUNNEL MONITORING

To monitor the performance of the BNSF tunnel, tape extensometers were installed and monitored starting before construction, and they will continue until the majority of the building is completed. Twelve instrumentation lines, including four lines installed for previous projects, extended across the project and about 50 to 100 feet outside of the building footprint. The lines are spaced approximately 50 feet apart and consist of four measuring points in each line (as shown on the cross section on Fig. 5). The tape extensometers were measured approximately once a month during excavation and then every 2 months thereafter or when access into the heavily used tunnel was available. Most of the readings were 0.03 inch or less, with a maximum measurement of 0.05 inch.

![Fig. 5 Tape Extensometer Locations in BNSF Tunnel](image)

In addition, an optical survey of the top two measuring points within the tunnel was completed each time the tape extensometers were measured. This optical survey also indicated minimal movement.

DRILLED SHAFT INSTALLATION SCHEDULE

Although difficult subsurface conditions were encountered, 67 shafts were successfully installed in 5 weeks during the summer of 1996.

CONCLUSION

The deflections measured within the BNSF tunnel during excavation, drilled shaft installation, and during building construction, have been negligible. The drilled shaft and foundation mat combination support is successfully supporting the new symphony hall and protecting the underlying railroad tunnel.

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