Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)

Conventional tunneling in urban areas

N. Munfah
AECOM, New York, New York, USA

V. Gall, W. Klary & T.M. O'Brien
Gall Zeidler Consultants, Ashburn, Virginia, USA

ABSTRACT: Conventional tunneling as defined by ITA's Working Group 19 is often referred to as New Austrian Tunneling Method (NATM); Sequential Excavation Method (SEM); or Sprayed Concrete Liner (SCL). It is being used more often in urban settings, in very soft ground, low cover, and overbuilt conditions for the creation of tunnels, station caverns and cross passages between previously TBM driven soft ground tunnels. To enable open face excavation ground improvement methods are used and include various methods of dewatering, grouting, and ground freezing. The paper examines criteria to be used for the implementation of conventional tunneling in urban areas, impact on existing facilities, ground improvement measures, and risks mitigation measures for conventional tunneling under such circumstances. The paper illustrates these aspects in two recent examples: Chinatown Metro Station in San Francisco and Sound Transit Bellevue Tunnel in Seattle, both very recently and successfully completed tunnels in urban settings in the US.

1 INTRODUCTION

Conventional tunneling has become a method of choice in urban areas to construct complex underground structures such as metro stations, multi-track metro lines, rail crossovers, short road tunnels, and underground road ramps in order to avoid cut and cover construction with its impacts on streets, utilities, traffic, businesses and the public. Under these conditions and where complex and challenging ground conditions exist, underground construction requires a flexible design that can be executed effectively and safely, while minimizing impacts to existing structures. This specifically includes tunneling in running and flowing ground, tunneling under high water pressure, encountering mixed face conditions, low ground cover, presence of sensitive building and structures within the influence zone of the excavation, presence of boulders, abandoned foundations or unchartered utilities and complex geometrical configurations. Conventional tunneling method minimizes impacts on traffic and utilities/services throughout construction, reducing disruption to everyday life. Urban settings provide a host of challenges that require a risk managed approach from the very beginning of the design process through construction. This paper evaluates the components of a risk mitigated project from design through construction in two recent examples of challenging conventional tunneling in urban settings projects: Chinatown Metro Station, San Francisco, CA and Sound Transit Bellevue Tunnel, Seattle, WA.

2 CHALLENGES OF TUNNELING IN URBAN AREAS

Conventional tunneling in a complex urban setting presents a number of unique challenges. A typical urban setting will include the presence of major roadways, potential shallow ground cover, soft ground conditions and potentially mixed ground, potentially existing or abandoned foundations and buried structures, and large intricate networks of utilities. Additionally, space constraints in urban settings magnify the challenge of implementing tunneling in such a manner as to avoid inducing displacements damaging to adjacent facilities, structures and utilities. Such challenges can be addressed with carefully designed excavation and support sequencing, including potential ground improvement and a robust instrumentation and monitoring program. With a risk mitigated approach during the design phase, conventional tunneling has proven successful in complex urban settings (Gall et al. 2016 & Gall et al. 2017).

3 GEOTECHNICAL AND HYDROLOGICAL CONSIDERATIONS

A thorough ground investigation program, including assessment of geotechnical and hydrogeological conditions is a key to the success of any conventional tunneling project. Such investigations facilitate the collection of information to assess the anticipated ground behavior during excavation. A clear understanding of the anticipated ground conditions along the tunnel alignment allows the implementation of ground improvement measures if needed, which could include dewatering, grouting or ground freezing. However, such a process needs to occur very early in a project so as to allow careful considerations with respect to tunnel design and the potential impact on existing structures and facilities along the tunnel alignment, which can limit the available techniques for ground improvement measures, such as dewatering, due to their potentially adverse impact on the structures. Identification of contaminated ground and groundwater and the presence of hazardous substances such as hydrocarbons, gases, and other hazardous materials allows for planning of special remedial/mitigation measures, or modification of the tunnel alignment if possible to avoid such ground conditions all together. Typical ground conditions that result in ground instability include: 1) fractured and decomposed rock in near surface conditions, 2) potential swelling mainly due to presence of swelling prone clay minerals, 3) mixed face conditions, 4) soft ground (cohesive and non-cohesive) and low ground cover, and 5) high ground water pressure.

4 GROUND IMPROVEMENT MEASURES

4.1 *Ground Improvement*

Ground improvement measures serve to improve strength and stiffness of the ground. With respect to conventional tunneling, ground improvement improves soil standup time during excavation and allows installation of optimized initial support while providing safe excavation (FHWA, 2009). Ground improvements also serve to control ground water, reduce ground loss and potential surface settlements and minimize the tunnel deformations during excavation. The variety of ground improvement techniques available are diverse and include dewatering, jet grouting, cementitious or chemical permeation grouting, compaction grouting, ground freezing, etc. In the scenario where settlement would potentially occurs, compensation grouting can be used as a remedial measure to overcome tunneling induced settlements. Instrumentation and monitoring are critical for detecting ground movement and implementing corrective measures.

4.2 *Pre-Support Measures*

Common methods of pre-support, which include spiling, pipe arch canopies and sub-horizontal jet grouting, act to improve the standup time of weak ground during and after excavation. In addition to minimizing risk during excavation, effective pre-support measures will minimize disturbance to in-situ ground during excavation, thereby limiting surface settlements. However, pre-support measures are only suitable for implementation when they have close contact with the ground. This is essential in order for ground and pre-support elements to work effectively as a reinforcement integrated into the ground.

5 EXCAVATION AND SUPPORT MEASURES

Conventional tunneling is an observational method that relies on the ground behavior and its interaction with the installed support system. Design of an effective excavation and support sequence is predicated on a comprehensive understanding of the anticipated ground conditions and behavior along the alignment, particularly with respect to weak soils/ground and local groundwater. Classification of the ground into different ground support classes provides flexibility during construction to implement pre-support, staged excavation and initial support measures consistent with the encountered ground conditions. The number of drifts, round length and sequencing of the excavation are based on the cross sectional size of the excavation, ground condition, and available cover; and they are critical for a successful tunneling in urban areas.

6 INSTRUMENTATION AND MONITORING

Instrumentation and monitoring is an integral part of conventional tunneling, allowing verification of design assumptions and the interaction between the ground and the support system during excavation (FHWA, 2009). The primary purpose of instrumentation in conventional tunneling is to monitor the initial lining deformation systematically as excavation progresses in comparison with anticipated deformations and to measure ground settlement at various depths above the excavation and at the surface. Displacement that exceeds critical threshold values triggers implementation of contingency measures such as the use of additional support, reduction of round length, or implementation of ground improvement. An extensive instrumentation program will also assess potential impacts on existing facilities, structures, and utilities during construction. This will permit the implementation of remedial measures in a timely manner if needed. Instrumentation usually includes internal extensometers, strain gages, total stationing, surface settlement markers, inclinometers, multiple point borehole extensometers, piezometers and shallow and deep settlement indicators.

7 IMPACT ON EXISTING FACILITIES

A robust design and a suitably designed staged excavation and support system for conventional tunneling serves to minimize the impact of construction on existing facilities by limiting settlement of the ground. Implementation of ground improvement measures and/or pre-support in the worst ground in conjunction with a compensation grouting program and a robust instrumentation and monitoring program will limit the impact of excavation on existing structures, while also having measures in place to immediately remediate and mitigate in the event of settlements in excess of allowable. A critical element to minimizing the impact on existing facilities, which is discussed in greater detail in the next section, is having experienced personnel that can recognize and react to deviations quickly and implement the necessary contingency measures to mitigate the issue.

8 RISK MANAGEMENT AND DESIGN ROBUSTNESS

All of the above-discussed considerations for a conventional tunneling project in urban areas, when thoroughly addressed, present the most effective manner of developing and executing a comprehensive risk managed tunneling program. Risk management begins during preliminary engineering with the identification of risks through the development of a risk register, which requires a thorough understanding of the project challenges, including existing structures and anticipated ground behavior. Through development of the risk register, preliminary engineering can address and mitigate the risks during the design by the development of ground improvement, pre-support measures, and a staged excavation with robust initial support.

During construction extensive geotechnical instrumentation and monitoring program as well as a strong Quality Assurance/Quality Control (QA/QC) plan are essential parts of risks mitigation. The effectiveness of a risk mitigated design program (design, monitoring, QA/QC) is also heavily dependent on the personnel chosen to execute it. A solid technical knowledge, suitable prior experience, and skills in assessing the ground behavior and interpretation of the monitoring program are required for successful execution of conventional tunneling. It is recommended to implement a pre-qualification process for the contractors including their key personnel to ensure requisite conventional tunneling capabilities. During construction daily communication and coordination between various project stake holders, including the contractor, tunneling crew(s), designer and owner's representative is very important for addressing challenges and mitigating risks as they materialize.

9 CASE HISTORIES

9.1 *Chinatown Station, San Francisco, California, USA*

9.1.1 *Background*

The San Francisco Central Subway is Phase 2 of the Third Street Light Rail Project and extends the existing Phase 1 initial operating segment from its current connection at Fourth and King Streets along Fourth Street to Market street, under the BART and Muni Metro tunnels and then north along Stockton Street to Chinatown, terminating in Chinatown Station (CTS). The project owner is San Francisco Municipal Transportation Agency. Station excavation has been completed and waterproofing and final lining construction are ongoing (Figure 1).

Chinatown Station was excavated as a mined cavern beneath Stockton Street, between Jackson Street and Clay Street, utilizing conventional tunneling. It was excavated after the completion of twin TBM tunnels passing through its location. The vicinity of Chinatown Station is one of the most densely populated areas in San Francisco, with many existing buildings and underground utilities as well as a large volume of bus and car traffic on the

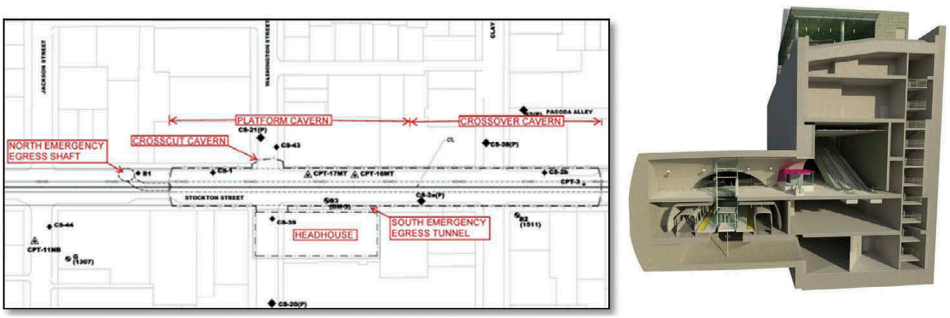


Figure 1. Location of Chinatown Station and architectural rendering of cross cut and head-house shaft.

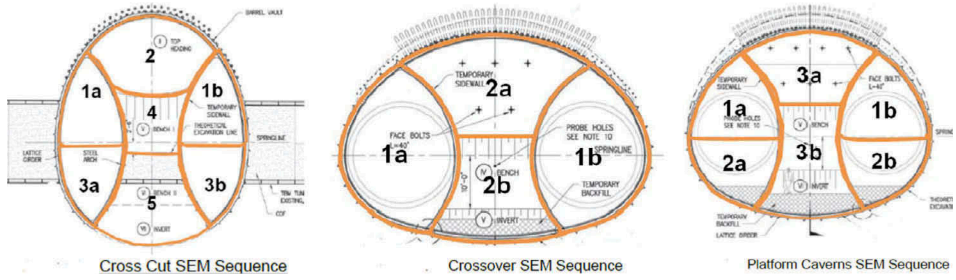


Figure 2. SEM excavation sequence for the caverns.

surface. The construction of Chinatown Station can be regarded as one of the most challenging tunneling projects in the US utilizing conventional tunneling method because of its exceptionally large size, limited access, presence of significant number of utilities, difficult ground and ground water regime, highly overbuilt neighborhood, and a very complex urban setting.

Several factors were of great concern during the construction of the station such as presence of numerous buildings, structures, and utilities in the area. Geology of the area is complex with varying soil and rock groups and high groundwater head along with restrictions on groundwater drawdown. Additional restrictions were also in place to ensure the major surface road remain open and unaffected by tunneling activities.

The major components of the station are the Crosscut Cavern, the Platform Cavern, the Crossover Cavern, the Head house, and two Emergency Egress Shafts (Figure 2). The Cross Cut cavern is approximately 13.1m wide, 16.1m high and 22.3m long. The Platform cavern is excavated in multiple drifts using a saw tooth profile to allow installation of pipe arch canopies. The cavern cross section is approximately 16.8m wide by 14m high. The Crossover cavern is also excavated in a similar saw tooth profile using multiple drifts. Its cross-sectional dimensions are 16.8m wide by 12m high. The overall length of the mined cavern is approximately 192m and at a depth from surface to the track level varies from 26.2m along the northern end of the station to 34.1m along the southern end of the station due to the change of the street level. All three caverns have similar structural support systems comprising of fiber reinforced shotcrete and lattice girders as the initial lining and cast in place final lining. The Crosscut Cavern has 450mm thick initial lining while the Crossover Cavern and the Platform Cavern has a 400mm thick initial lining.

9.1.2 *Geology*

The ground within the station area is grouped into two soil and rock groups. The soil group includes Colma Formation (Qc) and Colluvium (Qcol) and the rock group includes the Franciscan Complex Bedrock (KJf). The Colma formation (Qc) consists of dense to very dense sand or silty sand interbedded with stiff to very stiff clay and sandy/silty clay. The Colluvium (Qcol) consists of very dense, medium to fine brown sand with silt derived from complete weathering of the bedrock. The Franciscan formation (KJf) bedrock is highly variable in composition, degrees of fracturing, strength, hardness, and weathering. The rock mass is extensively sheared and a chaotic, heterogeneous mixture of small to large masses of different rock types, including sandstone, shale, siltstone, and various metamorphic rocks (such as metasandstone), surrounded by a matrix of pervasively crushed rock materials. The RQD values were consistently 0%. The rock/soil contact is locally undulating and irregular with an overall slope downward towards the east, and also towards the north.

9.1.3 *Ground Improvement*

The project also implemented dewatering and a complex compensation grouting scheme as ground improvement measures and building protection methods during construction. The dewatering was chosen to provide a stable face during excavation while the compensation grouting was selected to restore any potential settlement of the surrounding buildings.

Dewatering of the Colma Formation (Qc) prior to tunneling was carried out by deep wells. Supplemental dewatering from within the excavation was also required in the Qc formation where pockets of perched groundwater are encountered that were not effectively dewatered by the deep well system. In these cases, a well-point dewatering system was provided as a backup system to reduce perched water pressures to maintain excavation stability and acceptable working conditions.

Dewatering of the Franciscan formation (KJf) material was accomplished with pre-drainage ahead of the excavation face or with well-point dewatering as needed. Additionally, pre-drainage of the face with gravity-flow well-points within the KJf rock units, and/or vacuum well-point dewatering to dewater local depressions or water-filled lenses that cannot be dewatered with the prescribed deep well system were used as additional contingency measure for groundwater control.

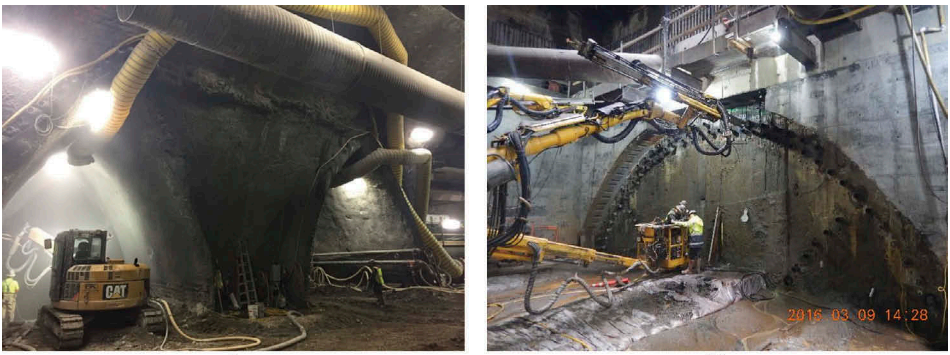
9.1.4 *Pre-Support & Excavation*

The caverns were excavated using a double sidewall drift excavation sequence. The design provided two side drifts and a center drift with multiple headings each (Figure 3a). Pre-support of the side and center drift excavations mainly consist of pipe arch canopies at the crown, to allow for micro-fine cement or chemical grouting of the surrounding ground mass.

Double rows of grouted pipe arch canopies were installed at the crown of the cross-cut cavern and a single row over the two side drifts of the cross-cut cavern; while a single row of pipes was installed at the crown for platform cavern and cross-over cavern (Figure 3b). Each pipe was 27m in length and 139mm in diameter; perforated steel pipes were installed at 300mm c/c spacing; GFRP pipes were used for the sidewall drifts to allow future easier removal when connecting the platform cavern with the cross-cut cavern. Pressure grouting was followed by the backfill grouting inside of the pipes. In addition to the pre-support, 12.2m long five to seven face bolts were used in the center drift top heading every 12.2m along the length of the drift depending on the cavern geometry.

9.1.5 *Risk Mitigation*

To protect the buildings and infrastructure near the station, a thorough instrumentation plan with monitoring details was developed. Existing buildings and structures in the excavation zone of influence were analyzed for impacts due to station construction, taking into account the proposed construction sequencing and excavation method. When the settlement of a major building across the excavation reached the initial threshold value, the compensation



a) b)

Figure 3. a) Crosscut Cavern showing top heading of the side and center drifts, b) Installation of Barrel Vaults for the Cross Cut Cavern.

grouting program was implemented arresting the settlement and partially restoring the building to its initial level.

An essential component of the daily conventional tunneling process is the use of the "Required Excavation and Support Sheet (RESS) Meeting". The project requires these meetings to be held every workday at a defined time, and conducted by the Senior Tunnel Engineer. These meetings are typically attended by the contractor's tunnel project manager, the design engineer, construction superintendent, project geologist, the geotechnical engineer, the surveyor, the quality control manager, the construction manager, and the owner's representatives. The RESS meetings provide an essential communication forum among the various parties and frequent and quasi-concurrent agreement on the tunneling process between the contractor's and the owner's representatives to reduce risk and improve tunneling performance.

9.2 *Bellevue Tunnel, Seattle, Washington, USA*

9.2.1 *Background*

Sound Transit's East Link Project is a 22.4 km (14-mile) long light rail transit (LRT) extension that will provide patrons a fast, frequent and reliable connection from Bellevue and Redmond, the largest population and employment centers east of Lake Washington, to downtown Seattle, Sea-Tac Airport and University of Washington (Figure 4).

While the majority of the East Link alignment will be at-grade or on elevated guideways, one of the most technically challenging components of the project is the Downtown Bellevue Tunnel. The Downtown Bellevue Tunnel is 740m long, as measured from the South Portal to the Bellevue Transit Center Station Interface, and runs under 110th Avenue Northeast through downtown Bellevue. The tunnel alignment is constrained by utilities and bounded on both sides by major buildings, including several high-rise structures and Bellevue City Hall (Figure 5).

Conventional tunneling, was chosen for the construction of the 605m long central portion of Downtown Bellevue Tunnel (DBT). The typical cross section is an 11.2m wide by 9.3m high ovoid, with a central fire separation wall. Near its mid-length, the tunnel cross section is enlarged to overall dimensions of 12.9m width by 11.5m height to provide space for an emergency ventilation fan room above the tracks. Maintenance access to the mid-tunnel ventilation fan room is provided through an access shaft (5.2m internal diameter and 15.5m depth) and a connecting adit, which was sequentially excavated from the enlarged tunnel towards the shaft.

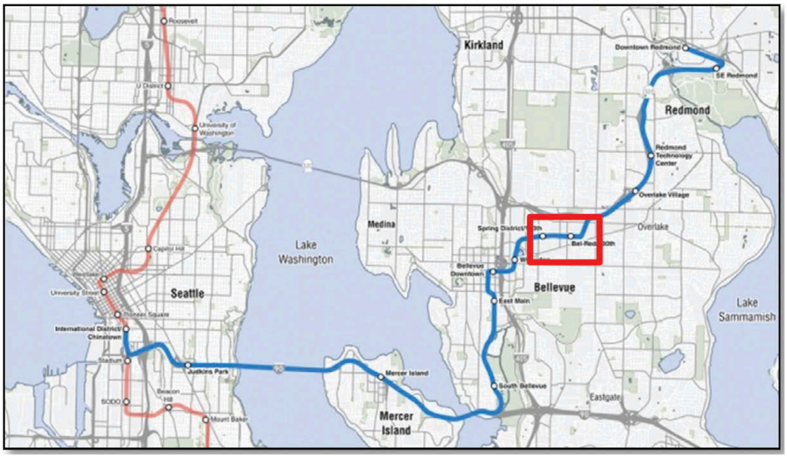


Figure 4. Location of Downtown Bellevue Tunnel (Plan view Eastlink).

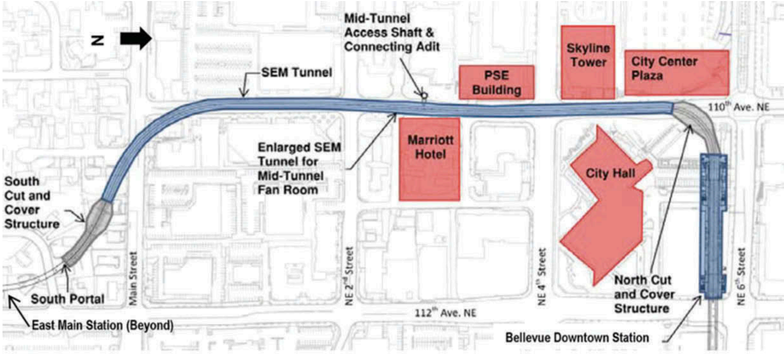


Figure 5. Location of Downtown Bellevue Tunnel (*from* Wongkaew et al. 2018).

9.2.2 *Geology*

The geologic profile along the tunnel indicates glacial deposits consisting of glacially over-consolidated stratigraphic sequence that includes Vashon till, Vashon advance outwash deposits, and pre-Vashon glacio-lacustrine deposits (Figure 6). North of the enlarged section the profile indicates an "anomaly zone". During the design an extensive ground investigation program was executed but no conclusive geological model could be established for this zone. During excavation of the tunnel a change of the ground behavior has not been observed, however offsets in the stratigraphy have been encountered. The design groundwater table generally follows the top of the advance outwash which were expected to be encountered in the tunnel face during the second half of the tunnel. During excavation of the Tunnel the ground showed more favorable conditions than anticipated. In particular the groundwater table was much lower than expected and the planned dewatering measures which included dewatering with surface wells and vacuum dewatering from within the tunnel was not required. However perched ground water with a water inflow rate of approx. 0.75 l/min (0.2 gpm) from within sand layers in the till was encountered.

9.2.3 *Tunnel Support & Pre-Support Measures*

The DBT was designed as a single side-drift excavation with five Ground Support Classes and a round length from 1 to 1.5 m and systematic spiling (Figure 7a). From the South portal to the start of the enlarged section (approx. 50 % of the tunnel length) the Contractor suggested

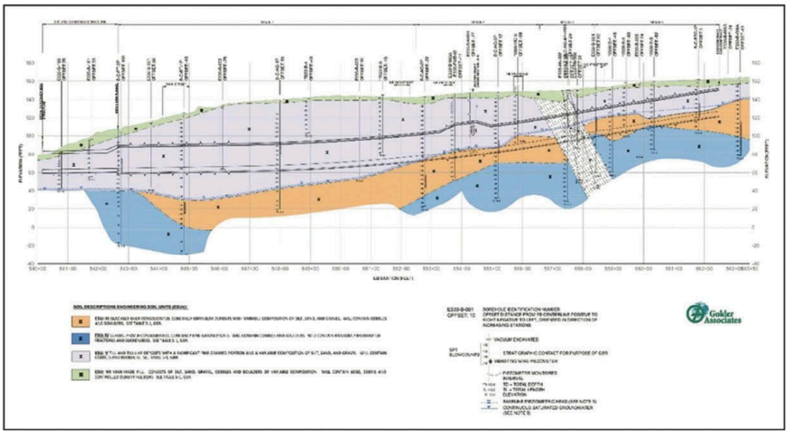


Figure 6. Geologic profile along tunnel alignment.

a) b)

Figure 7. a, b) Photos of tunnel excavation showing left and right drifts and short round excavation within each drift.

to change the excavation to a three heading sequence which included Top Heading, Bench, Invert (Figure 7b). From the enlarged section to the North portal a single side-drift excavation was implemented. Due to favorable ground conditions only, a small number of the designed spiles was installed. However, further investigation of utilities and basement of buildings showed that pre-treatment of the ground was required in the proximity of the Skyline Building and at the Intersection of 110th and 4th Street.

9.2.4 *Construction Challenges*

9.2.4.1 SKYLINE BUILDING

The Skyline Building is a high-rise building located on the west side of the tunnel. The design drawings showed that the basement (parking garage) of the building is as close as 1m next to the tunnel (Figure 8). It was required to install additional support on the garage wall from within the tunnel. During this work a water filled void behind the garage wall was encountered. Due to the close proximity to the tunnel and the risk of water causing further deterioration, the thin pillar was grouted extensively. Additional monitoring points were installed in the garage which included tiltmeters, strain gages and structural monitoring points. During excavation no water inflow was observed and the garage did not show any significant movement.

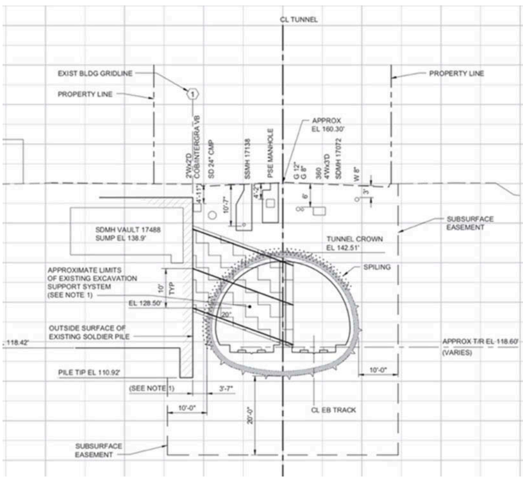


Figure 8. Cross Section of tunnel relative to the Skyline Building.

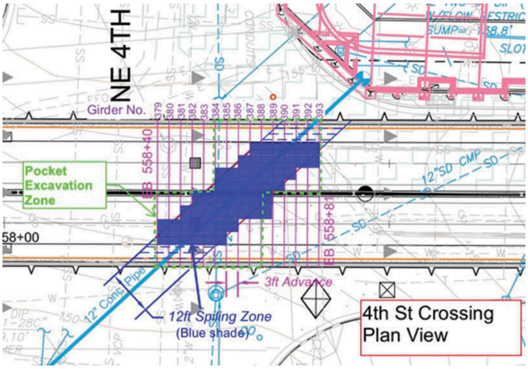


Figure 9. Plan view of 4th Street crossing showing utilities present.

9.2.4.2 INTERSECTION OF 110TH AND 4TH STREET

During the design phase it was identified that in the Intersection 110th Street/4th Street critical utilities such as storm drains, sewer pipes, water mains, high pressure gas lines, high voltage lines and fiberoptic cables are present (Figure 9). Further investigations of the storm drains revealed leakages in the storm drain. The proximity to the crown of the tunnel exhibited the risk of the leaking water to deteriorate the ground above or water inflow from sand layers in the Till. Since this would be very challenging to deal from within the tunnel the intersection was closed to traffic and the utilities exposed and the backfill replaced with controlled low-strength material (CLSM). As excavation below the leaking storm drain was not feasible the gravel below it was grouted instead. The excavation sequence and ground support during tunnel excavation was adjusted in this area. The advance length was limited to 1 m, spiles were installed and pocket excavation was utilized. Excavation of this area took place during the dry season.

10 CONCLUSIONS

Conventional tunneling is becoming highly effective method of tunneling in urban areas, in difficult ground, under high hydrostatic heads, and with limited cover. Properly implemented will avoid cut and cover construction and its associated impacts on traffic, utilities, businesses and the public. However, as was demonstrated for Chinatown Station, and Bellevue Tunnel, a robust design is required with detailed pre-support systems and ground improvement methods to mitigate potential risks. Excavation and support sequences were designed to address the anticipated ground behavior and limit the potential impact on existing facilities and structures. A comprehensive instrumentation and monitoring system with predetermined threshold limits and potential remedial measures is essential, along with pre-qualification of all involved parties. Effective communication and collaboration between the designer, contractor and owner's representatives is essential for successful implementation of conventional tunneling in challenging settings such as urban environments.

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