Proceedings of the World Tunnel Congress 2017 – Surface challenges – Underground solutions. Bergen, Norway.

Conventional Tunneling in Difficult Grounds.

Vojtech Gall and Sandeep Pyakurel
Gall Zeidler Consultants, Ashburn, Virginia, USA.

Nasri Munfa
WSP | Parsons Brinckerhoff, New York, USA

ABSTRACT: Conventional tunneling as defined by ITA's Working Group 19 is being used more and more in difficult grounds. This occurs in rural settings for tunneling through shear and fault zones and in squeezing ground conditions where tunneling by TBMs would be risky, as well as in urban areas in soft ground, under low cover, and in overbuilt conditions or for the construction of subway station caverns, highway tunnels, and cross passages between TBM driven tunnels. To enable open face excavation ground improvement methods are used and include various methods of dewatering, grouting, and ground freezing. This paper provides a preview of ITA's WG 19 upcoming report on the implementation of conventional tunneling in difficult grounds and it portrays examples from recent projects including cross passage construction for Sound Transit's University Link and Northgate Link in Seattle and for San Francisco Central Subway Chinatown Station.

1 INTRODUCTION

Conventional tunneling has transformed from the traditional rock tunneling method in mountainous areas to soft ground in urban areas resulting in the need to deal with difficult ground conditions and challenging settings. It is being utilized more often when presented with difficult ground and ground water conditions, and with limited cover. This specifically includes tunneling in running and flowing ground, tunneling under high water pressure, encountering mixed face conditions, having low cover, presence of sensitive and fragile buildings, and utilities/services within the influence zone of the excavation, and complex geometrical configurations having multiple intersecting galleries. Using such tunneling method in urban settings minimizes impact on traffic and utilities/services and reduces disruption of everyday life. Conventional tunneling can accommodate cross sectional geometries of large, non-circular excavations for roadway tunnels, transit stations and bifurcations, as well as other infrastructure for miscellaneous underground storage and water conveyance.

Although there are available guidelines and standards for conventional tunneling in rock, such guidelines do not extend to specifically cover soft ground and difficult ground conditions, nor urban setting with limited cover. Therefore, engineers have adapted other existing knowledge and technologies to deal with these situations, often on a case by case basis. They have developed technical approaches and implementation techniques, and established sophisticated collaboration in the field among various parties for successful implementation; however, these techniques and practices vary widely. It is the ITA's WG 19 intent to formulate a guidance document for the successful implementation of conventional tunneling in such difficult ground conditions and urban settings. The following sections provide a preview of the document under preparation.

2 CONVENTIONAL TUNNELING CHALLENGES

2.1 *Difficult Ground Conditions*

Difficult ground conditions in tunneling can be referred to a set of conditions that could potentially trigger instability during tunnel excavation. This is especially critical for conventional tunneling since unlike in a TBM, the excavation is commenced without any immediate ground and face support. Typical instability challenges during conventional tunneling may result from following type of ground conditions:

- Fractured and decomposed rock and fault zones – These conditions are mainly associated in ground that has heavily fractured and decomposed rock including fault zones and alteration zones where properties are completely altered compared to the host rock and have significantly lower strength.
- Squeezing, swelling and high stress environments in rock (rock bursts) – These conditions trigger instability from yielding of the ground on one side of the spectrum to sudden loosening and spalling of blocks of rock.
- Mixed face conditions – Two (or more) different types of soil/rock units or different soil or rock properties encountered in the face of the excavation leading to significant variations in ground property and ground behavior between the units.
- Soft ground (cohesive and non-cohesive) and low ground cover – Conditions leading to lack of standup time in non-cohesive ground such as in sand and gravel and in weak cohesive ground such as in soft clay.
- High ground water pressure – High water pressure can lead to flowing condition in non-cohesive soil with influx of large water volumes into the excavation; High ground water pressure also triggers instability of the face.

Although difficult ground conditions pose considerable challenges for the open face of conventional tunneling, its flexibility and adaptability allow for proper dealing with the difficult ground conditions by identifying anticipated ground behavior and providing measures suitable for such conditions. Using a robust predefined excavation and support systems and the ability to make adjustments in the support measures at the face during tunneling to mitigate encountered conditions, provide a suitable tunneling approach in difficult grounds.

2.2 *Complex Urban Settings and shallow cover*

Significant challenges of conventional tunneling are present in a complex urban setting. Complexity involves the presence of major roadways, potential shallow ground cover, existing foundations and buried structures, and large and intricate networks of utilities. While space constraints and space restrictions already impose great challenges of tunneling in urban areas, it has to be implemented in such a fashion that it will avoid damaging movements to the adjacent facilities, structures and utilities. However, carefully designed excavation and support sequencing, including adequate instrumentation and monitoring, has made conventional tunneling possible in these complex urban settings and even in areas with very shallow cover (Gall and Zeidler, 2008).

2.3 *Tunnel Geometry and Excavation Sequences*

The size and shape of the tunnel cross-section and subdivision into multiple headings is the main aspect for conventional tunneling. It is important to develop a shape that is smooth and has concavely rounded excavation surfaces that initiate confinement forces and reduce bending in the tunnel lining. Furthermore, subdivision of the tunnel cross section into multiple headings suitable for the ground condition enhances the face stability and safety during excavation. Recent advancements in conventional tunneling have included the use of very large cross sections of complex geometries to be constructed under overbuilt areas at shallow cover (Munfah et al., 2016). Conventional tunneling can accommodate any shape due to the flexibility of the tunneling method. Further, such large and irregular shapes are handled in conventional tunneling by dividing the face into multiple drifts and selecting the appropriate round length for each drift and implementation of suitable pre-support and ground improvement techniques, resulting in better control of ground movement and face stability.

3 CRITERIA FOR SUCCESSFUL IMPLEMENTATION OF CONVENTIONAL TUNNELING

3.1 *Ground investigation and assessment of ground behavior during excavation*

A thorough ground investigation including assessment of geotechnical and hydrogeological conditions is a key to the success of any conventional tunneling work. Such investigation facilitates collection of information to assess the anticipated ground behavior during excavation and to select suitable support measures. Ground behavior and standup time will dictate the type of ground support to be chosen. Further this information will allow an assessment of the need for ground improvement or treatment such as dewatering, grouting or ground freezing. It is important that such investigation starts at the very early phase of the project. Along with the assessment of soil and rock properties and groundwater regime, the presence of existing structures and utilities, and the available ground cover will govern the tunnel stability during excavation and will influence the layout of the ground support. These investigations must also allow for the planning of special measures if tunneling is through contaminated ground or in the presence of substances such as hydrocarbons, gas or other hazardous materials (FHWA, 2009).

3.2 *Instrumentation and monitoring measures*

Instrumentation and monitoring is an integral part of conventional tunneling as it allows the verification of design assumptions in regard to the interaction between the ground and the support system during excavation (FHWA, 2009). The main purpose of the instrumentation for conventional tunneling is to measure the initial lining deformation systematically as the excavation progresses in comparison with the anticipated deformations. Whenever the monitoring data shows the lining movement has exceeded the critical threshold value, mitigation measures such as the use of additional support, reducing the round length or implementation of ground improvement can be executed. The instrumentation and monitoring system also assesses potential impacts on existing facilities and utilities and the implementation of remedial and corrective measures as needed. Instrumentation and monitoring systems are usually implemented from the surface, for buildings and utilities settlement; from inside the tunnel to measure convergence of the tunnel itself; and in the ground surrounding the tunnel to assess ground losses and settlement within the ground mass. The instrumentation usually includes surface settlement markers, total stationing, inclinometers, multiple point borehole extensometers, piezometers and shallow and deep settlement indicators. The in-tunnel instrumentation includes deformation measuring monitoring points installed in the tunnel roof and at selected points along the tunnel walls to monitor vertical, horizontal and longitudinal components of the total convergence. Although instrumentation and monitoring are widely used for measuring deformation, it is also used for applications that require knowledge of stress and strain conditions such as in ground with very high in-situ stresses and areas subjected to very large loads. Stress cells and strain gauges are sometimes used for this purpose.

3.3 *Ground improvement measures*

Ground improvement includes measures to improve strength and stiffness of the ground. In case of conventional tunneling, ground improvement enhances the standup time during excavation and allows installation of optimized initial support and provides safe excavation (FHWA, 2009). Ground improvement also reduces potential settlement due to tunnel excavation and minimizes lateral deformations. Ground improvement methods are diverse and vary based on the ground conditions, groundwater situation, and the potential impact of the tunnel construction. Ground improvement methods include dewatering, jet grouting, cementitious or chemical permeation grouting, compaction grouting, freezing, etc. In addition, compensation grouting can be used as remedial measure to overcome settlement as it occurs.

3.4 *Pre-support measures*

Pre-support measures improve the standup time of the round during and upon excavation in weak ground. Common methods of pre-support are spiling, pipe arch canopy and sub-horizontal jet grouting. It should be noted that pre-support functions are suitable support measures only when they have close contact with the ground such that there is sufficient interaction between the ground and pre-support elements to work as a reinforcement integrated into the ground.

3.5 *Ground classification and excavation and support classes*

Conventional tunneling is an observational method that relies on the on the ground behavior and its interaction with the installed support system. Therefore it is crucial for the success of conventional tunneling to use a pre-defined classification system for the assessment of the ground behavior during excavation and assign a unique ground class associated with each type of anticipated ground behavior. The excavation and support classes are developed in line with the ground behavior classes by assessing the ground support needs, number and length of drifts, timing of support installation, pre-support requirements, and the excavation sequencing. The excavation and support classes also provide additional support measures if required to complement the standard support classes as part of the "tool box" of conventional tunneling.

Along with the excavation and support classes, design robustness is also a crucial factor for successful execution of conventional tunneling in particular in urban settings. Robustness typically provides redundancy in the support measures and thus enhanced protection of adjacent surface and subsurface facilities and utilities.

3.6 *Contractual requirements*

Because of the observational character of conventional tunneling, a solid technical knowledge, past experience, and skills in assessing the ground behavior and interpretation of the monitoring program are required for a successful execution. Skills also relate to the use of construction equipment and handling of materials for installation of the initial support elements, in particular application of a high quality shotcrete are critical. Therefore, it is recommended to implement a pre-qualification process for the bidding contractors to ensure skilled conventional tunneling capabilities. Furthermore, it is recommended that payments to be made on a unit price basis (Munfah et al., 2016). Unit prices are suitable for conventional tunneling due to its observational character and the need to install initial support per predefined excavation and support classes along with any additional support as required by field conditions actually encountered using the "tool box" measures.

4 CASE HISTORIES

4.1 *Sound Transit's U230 and N125 contracts, Seattle, Washington, USA*

U230 and N125 are major tunnel construction contracts, forming part of Sound Transit's University Link and Northgate Link projects respectively in Seattle. These projects represent part of a large-scale expansion of Seattle area's light rail system (Figure 1). U230 includes 1.6 km (one mile) long twin bore tunnels running between Downtown Seattle and Capitol Hill neighborhood to the north with five cross passages between the TBM tunnels and was completed in 2013. N125 includes approximately 5.4 km (3.4 miles) of twin bore running tunnels and 23 cross passages extending from University of Washington to the Maple Leaf Portal in north Seattle and is expected to be completed in 2018. The cross passages for both U230 and N125 were constructed in soft ground utilizing conventional tunneling also referred to as Sequential Excavation Method (SEM) in the US. The tunnel alignments follow under the central business district of Seattle. The alignments also go under densely populated neighborhoods including multistory building with many underground utilities as well as a large volume of bus and car traffic on the surface streets making these challenging projects in an urban environment.

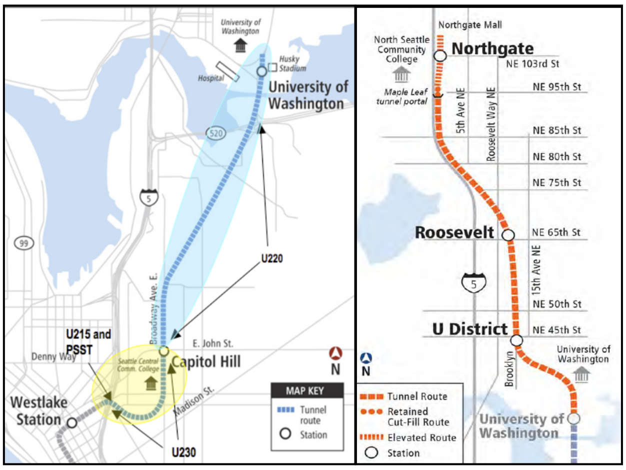


Figure 1.Alignment Locations for U230 and N125(Courtesy: Sound Transit).

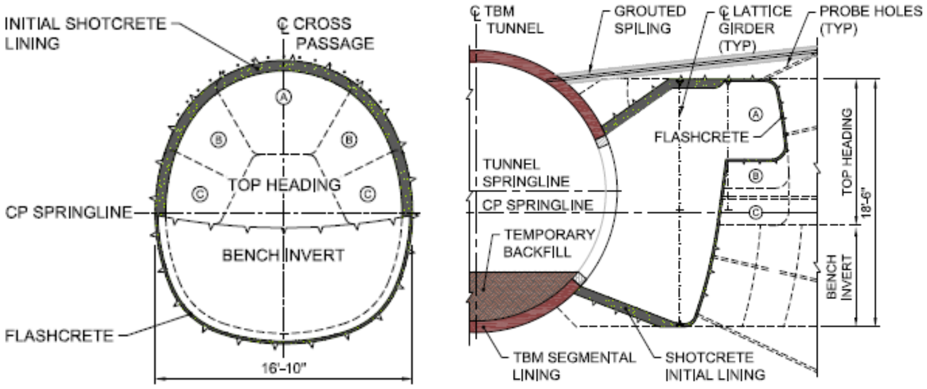


Figure 2. Typical Section of a Cross Passage for Ground Support Category 2

The U230 and N125 cross passages have similar structural support systems, comprising of shotcrete and lattice girders as the initial lining and cast-in-place concrete final linings. The U230 cross passages have a “dog-bone” longitudinal profile, with larger cross-sections at each end, adjacent to the running tunnels and a smaller cross-section in the middle. The section varied in height from 4m to 4.7m and in width from 3.9m to 4.5m. The N125 cross passages have a uniform, slightly larger cross section, being 5.8m high and 5.2in wide. Such larger cross-section – similar to size as that of the running TBM makes the N125 cross passages some of the largest in North America, relative to the running tunnel size. The ground support system was categorized into three excavation and support classes to reflect the soil and groundwater conditions and anticipated behavior for the corresponding ground classes. Ground Support Category 1 comprised of systematic pre-support within a competent ground that did not require any additional support measures. Ground Support Category 2 comprised of systematic pre-support accompanied with pocket excavation and dewatering prior to excavation (Figure 2). Ground Support Category 3 comprised of excavation in treated ground using jet grouting or ground freezing methods. However, during construction ground freezing was selected as the preferred method in order to reduce risk and improve excavation performance.

The geology of the area comprised of glacial and non-glacial deposits of the quaternary period overlying tertiary volcanic and sedimentary bedrock leading to considerable and frequent changes in the soil behavior along the tunnel alignment. The soil consisted of highly over-consolidated clays, silts, sands and gravels in various proportions, combinations, and densities. Due to the considerable variability in the soil units, the ground conditions were described in terms of soil groups (SG) that exhibit similar behavior and characteristics. The soils were classified in Engineering Soils Units (ESU) comprising of Till and Till-Like deposits (TLD), Cohesionless Sand and Gravel (CSG), Cohesionless Silt and Fine Sand (CSF) and Cohesive Clays and Silts (CCS). Most of the cross passages were excavated entirely below the groundwater table in the glacial deposits of the various ESUs. The groundwater system mostly comprises of aquifers and aquitards with changes in hydrologic heads when transitioning from one hydrologic regime to another.

Several factors were of great concern during the construction of the cross passages, including challenging geological and geotechnical conditions, applicability of ground improvement method for particular soil group, groundwater inflow along with constraints associated with groundwater disposal and challenges to protect above ground buildings, structures, and utilities from the tunneling induced settlement. These issues were remedied by implementing extensive ground improvement measures which included dewatering, grouting and ground freezing along with selection of robust ground support methods, selection of excavation and support sequence including round length and ground probing ahead of the excavation face.

The uncertainty in the ground conditions posed significant challenges during the cross passage construction. For example, at a given cross passage elevation, the boring at one end showed the soil type as gravel while the other end showed it to be sand. This led to a very complex and non-uniform geology along the cross passage alignment. A thorough ground probing program comprising of both, horizontal and inclined probe holes was conducted to identify the geology along the cross-passages ahead of the tunneling face to reduce the risk of encountering unanticipated soil or groundwater conditions.

The risk from groundwater inflow and water induced instability were controlled using systematic dewatering. Dewatering was successfully achieved using a combination of surface wells, gravity drainage from within the excavation and vacuum dewatering system. Surface dewatering was used to dewater the ground associated with coarser soil deposits particularly in areas where larger flows were expected. In the case of fine grained soil deposits, dewatering was implemented from inside the TBM tunnels using well points with gravity drainage. Although the dewatering worked well in areas with lower permeability, it became expensive and risky in soils with high permeability that have hydraulic connections with high groundwater recharge zones. In such scenarios, dewatering requires very long pumping times and will produce large quantities of pumped water which needs to be disposed. In areas where pumping test results indicated very high flow rates and where layered geology made dewatering impractical, ground freezing was used. Such changes of ground treatment from dewatering to ground freezing reduced risks related to ground stability, risks associated with managing a high volume of groundwater, and eliminated cost for its treatment and disposal.

Ground freezing creates a frozen arch to act as both pre-support of the excavation and as a groundwater cut-off means (Figure 3). Ground freezing was implemented at eleven locations using two different methods: ground freezing from the surface and ground freezing from inside the TBM tunnel. Ground freezing from the surface was performed by installing vertical freeze pipes from the ground surface and short angled haunch freeze pipes through the tunnel liners. Ground freezing from inside the TBM tunnel is implemented by installing horizontal freeze pipes around the periphery of the cross passages (Figure 3). The freeze design was intended to freeze the soil between the two running tunnels to 7m above and below the tunnel springline at a minimum distance of 4.1m either side from the cross passage center line.

Monitoring instrumentation were placed with pre-defined trigger levels to monitor movement associated with ground freezing. The trigger levels dictate further actions to be taken once set levels are reached such as adjusting the temperature of the brine and selectively turning off parts of the freeze temporarily or permanently, as allowed by the ongoing cross passage construction.

Figure 3. Ground freezing from inside the TBM tunnel

One important aspect of addressing challenges and risk mitigation during cross passage construction is communication and coordination between various stake holders including contractor, SEMs crew and owner's representative. Daily site meetings were held between SEM crew, contractor staff, design team and owner's representatives to ensure efficient communications and planning for each day of operation including discussion of construction progress, encountered difficulties during construction and remedial measures. These meetings greatly helped to allow different crew members working synchronously during construction to avoid conflicts in schedule and efficiently utilize logistics.

4.2 *Chinatown Station, San Francisco, California*

The San Francisco Central Subway is Phase 2 of the Third Street Light Rail Project and will extend 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. The project is currently in construction including the excavation of the Crosscut Cavern of Chinatown Station (Figure 4).

Chinatown Station is being excavated as a mined cavern beneath Stockton Street, between Jackson Street and Clay Street, utilizing conventional tunneling. 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 surface streets. 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 and a very complex urban setting.

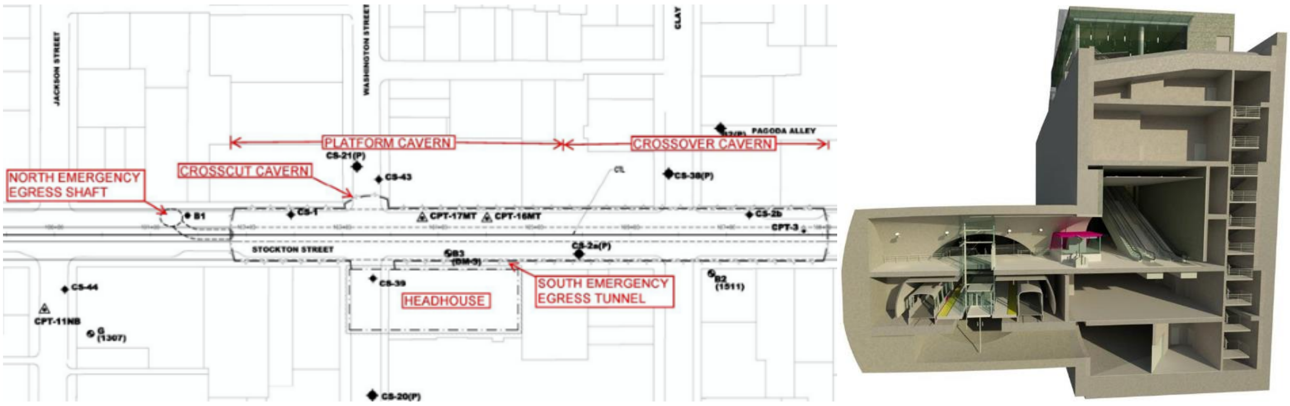
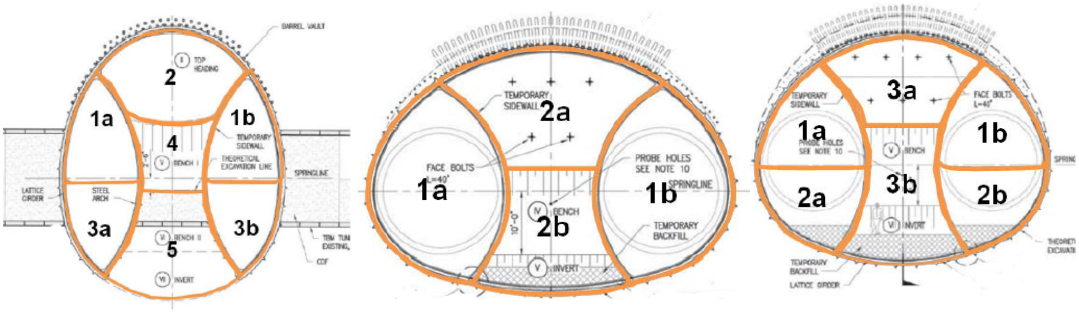


Figure 4. Location of Chinatown Station and architectural rendering of cross cut and shaft

The major components of the station are the Crosscut Cavern, the Platform Cavern, the Crossover Cavern, Head house, and two Emergency Egress Shafts (Figure 5). The Cross Cut cavern is approximately 13.1m wide, 16.1m high and 22.3m long which tapers down progressively to approximately 13.1 wide by 15.8m high oval shape at the headwall. The North and South Platform caverns will be excavated in a saw tooth profile to allow installation of a pipe arch canopy starting from a cross-sectional dimension of approximately 16.8m wide by 13m high to an enlarged dimension of approximately 16.8m wide by 14m high. This pattern repeats every 12.2m of tunnel. The Crossover cavern is also excavated in a similar saw tooth profile starting with a cross-sectional dimension of approximately 16.8m wide by 11m high, and enlarging to a 16.8m wide by 11.9m high section every 12.2m. The overall length of the mined cavern is approximately 192m and at a depth from grade 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. All three caverns have similar structural support systems comprising 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



Cross Cut SEM Sequence

Crossover SEM Sequence

Platform Caverns SEM Sequence

Figure 5. SEM excavation sequence for the caverns

Platform Cavern has a 400mm thick initial lining.

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). Qc consists of dense to very dense sand or silty sand interbedded with stiff to very stiff clay and sandy/silty clay. The Qcol consists of very dense, medium to fine brown sand with silt derived from complete weathering of the bedrock. The 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 (greywacke), shale, siltstone, and various metamorphic rocks (such as meta-sandstone), surrounded by a matrix of pervasively crushed rock materials. The rock/soil contact is locally undulating and irregular with an overall slope downward towards the east, and also towards the north.

The excavation of CTS is anticipated to encounter both mixed face conditions (constituting both soil and rock group) and a full face conditions (either rock or soil present entirely). In the mixed face condition, soft soils (dense, stiff and sandy clays of the Colluvium and Colma Formation) are present at the crown while weak rock of the Franciscan Formation (sandstone, shale, mélange) are present at lower elevations of the face. In a full face condition either Qc and/or Qcol are present in the excavation face or only kJF is encountered in the excavation face. Mixed face conditions are particularly anticipated in the Crosscut Cavern and Crossover Cavern.

A fundamental requirement for safe and stable support of excavation is to select an excavation and support sequence that provides ring closure at distances of such length for each individual drift and for the fully excavated cavern cross section as a whole to maintain ring action within the section. Excavation in multiple drifts reduces excavation face size of each drift and maintains adequate face stability during the excavation. Therefore the caverns are being excavated using a double sidewall drift excavation sequence. The design provided two side drifts and a center drift with multiple headings each (Figure 6).

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. The project also includes a complex compensation grouting scheme, in order to compensate for potential settlement of the surrounding buildings.

Several factors are of great importance for the construction of the station including the large size of the caverns, challenging geological and geotechnical conditions, varying soil and rock groups, presence of high groundwater and restrictions on ground water drawdown, and the major surface road that is to remain open and unaffected by tunneling activities as well as numerous buildings, structures, and utilities in the area.

Figure 6. Crosscut Cavern showing top heading of the side and center drifts

The variability in geology in terms of either mixed face or full face conditions requires a thorough assessment and probing of the face to identify soil/rock conditions ahead of the face. The ground probing provides a sound approach to mitigate various geotechnical uncertainties encountered as it provides means to identify geologic conditions ahead of the face and adopt necessary support measures as the excavation progresses. The probe drilling is also a key to assess the presence of localized wet zones requiring drainage. Three probe holes are drilled for each of the side drifts and the center drift for the top headings of the cross cut cavern, and two probe holes are drilled for the center drift bench/invert and one probe hole for the side drifts bench/invert. The probe holes are maintained approximately 6m ahead of the advancing face and additional probe holes are used as required and determined during excavation.

A robust design is implemented for the excavation of the station. A properly-designed pre-support system comprising of grouted steel pipe arch canopies are provided. Double rows of grouted pipe arch canopies are installed at the crown of the cross-cut cavern and a single row over the two side drifts of the cross-cut cavern; while single row of pipes is installed at the crown for platform cavern and cross-over cavern (Figure 7). Each pipe is 27m in length and 139 mm in diameter perforated steel pipes installed at 300mm c/c spacing; GFRP pipes are used for the sidewall drifts to allow future easier removal when connecting the platform cavern with the cross-cut cavern. Pressure grouting is followed by the backfill grouting inside of the pipes. In addition to the pre-support, 12.2m long five to seven face bolts will be used in the center drift top-heading every 12.2m along the length of the drift depending on the cavern geometry.

Figure 7. Installation of Barrel Vaults for the Cross Cut Cavern

Dewatering is an important method of ground treatment to provide a stable face during excavation. Dewatering of the Colma Formation (Qc) prior to tunneling was carried out by deep wells. Supplemental dewatering from within the excavation is 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 vacuum wellpoint dewatering system is 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 is expected to be accomplished with pre-drainage ahead of the excavation face or with wellpoint dewatering as needed. Probe holes will be drilled ahead of the face in each heading to estimate potential groundwater inflow. Higher flows are anticipated where open joints or fractures, or major lithologic contacts are encountered that have connection to overlying water sources. Additionally, pre-drainage of the face with gravity-flow wellpoints within the KJf rock units, and/or vacuum wellpoint dewatering to dewater local depressions or water filled lenses that cannot be dewatered with the prescribed deep well system will be used as additional contingency measure for groundwater control.

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.

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 owner’s representatives to reduce risk and improve tunneling performance.

5 CONCLUSION

Conventional tunneling is being used in difficult ground, under high hydrostatic heads, in urban settings, and with limited cover. To enable open face conventional tunneling under these circumstances, a robust design is required with detailed pre-support systems and potential ground improvement methods used to mitigate potential risks. Excavation and support classes for conventional tunneling should be developed in line with the anticipated ground behavior, acceptable deformation limits, and the potential impact on existing facilities and structures. A tool box of additional support measures to complement the standard support classes should be specified and be available on site for implementation if needed. Furthermore a comprehensive instrumentation and monitoring system should be provided with predetermined threshold limits and potential remedial measures when these limits are reached. And finally, prequalification of all involved parties and collaboration among the designer, contractor and owner's representatives is essential for the successful implementation of conventional tunneling in difficult grounds and under difficult settings.

REFERENCES

Federal Highway Administration (FHWA), *Technical Manual for Design and Construction of Road Tunnels– Civil Element*, Chapter 9, FHWA-NHI-09-010, Washington, D.C., 2009.

Gall, V.; Zeidler, K. (2008): *Pre-Support Measures for shallow NATM Tunneling in Urban Settings*. In: 2008 North American Tunneling Proceedings, Washington, D.C.; Society for Mining, Metallurgy, and Exploration, Inc. pp. 152-162.

Munfah, N.; Gall, V.; Matthei, S.; (2016*): Recent Trends in Conventional Tunneling (SEM/NATM) in the US*; In: 2016 WTC Proceedings, San Francisco, ITA-AITES. pp. 505-514.

SFMTA (City and County of San Francisco Municipal Transportation Agency): *Geotechnical Baseline Report – Chinatown Station*, Revision 0; December 2011.

.