Large cross sections for soft ground and soft rock conventional tunneling projects in urban areas – recent developments in the US

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1. Introduction

With the demand for tunnels growing, especially in urban areas, the ability to construct these tunnels without disrupting congested areas on the surface has become more important. Conventional tunneling has become increasingly popular as it is very useful in these urban environments, as well as in soft ground. Conventional tunneling, also known as the New Austrian Tunnel Method (NATM) or the Sequential Excavation Method (SEM), is the construction of tunnels utilizing sequential processes and sections to excavate and support the ground. By referring to case studies, this paper discusses the importance of conventional tunneling and other state of the art ground improvement methods which have been used to great success in large cross section projects in the United States.

2. Conventional Tunneling Methods in Development and Selected Case Histories





Fig. 1: NBX Tunnel with adjacent infrastructure

The Northern Boulevard Crossing is part of the East Side Access Project, which will extend the Long Island Railroad to Grand Central Terminal in New York City and was constructed from 2010 to 2013. The Northern Boulevard Crossing (NBX) is located underneath three busy transportation arteries in New York City. The first is the five track NYCT IND tunnel box structure located 12m below grade. The NYCT IND tunnel box is 23m wide and 7.6m tall. The East Side Access tunnel also runs below the elevated NYCT BMT Line, which services approximately 290 trains per weekday, as well as the Northern Boulevard, a 6 lane roadway on the surface (see Fig. **1**).



Fig. 2: Thermal model of built-in-pipe system showing temperature distribution at the frozen arch

Groundwater at the Northern Boulevard Crossing existed within an unconfined aquifer, which was prohibited to lower by dewatering due to existing contaminated plumes from nearby vard and to avoid а settlements of the adjacent subway structures. Therefore, ground freezing presented the best option to mitigate the risks of high groundwater level that was present in the project area. The ground freezing operation overcame obstacles such as boulders, steel pipes and limited work space. 45 horizontal pipes were installed in an surrounding the tunnel arch excavation area. The soils were frozen to -32 degrees Celsius and created a

1.8m thick arch around the tunnel within the soils (see *Fig. 2*). To prevent the advancement of ice lenses and heave-induced moments within the horizon as well as to control the freeze pipe arch closure, heat pipes were installed between the freezing arch pipes and the existing subway box structure. Besides ground freezing for pre-support and ground water cut off, the Northern Boulevard tunnel utilized void filling, compensation grouting, vacuum dewatering and partial underpinning methods.

The NBX tunnel was implemented using a very large cross-section with a width of 18.4m and height of 11.8m (see **Fig. 3**). The geology at the project area consists of Mixed Glacial Deposits (non-plastic silts to clays of low plasticity containing sand and gravel) below the water table, underlain by Ordovician/Cambrian Age metamorphic bedrock. The bedrock encroached the excavation by \sim 1.2m at the invert level.



Fig. 3: Excavation drifts and dimensions

As the only viable excavation technique, conventional tunneling by using the Sequential Excavation Method was chosen. The tunnel cross section was divided into two side drifts and one center drift. Each drift itself was divided into top heading, bench and invert levels (see *Fig. 3*). The excavation started with drift #1a/1b and installation of a temporary invert, followed by drift #2a/b approximately 10-12m staggered behind drift #1a/b. After both side drifts were completed (drifts #3 and #4), the center drifts (drifts #5 to #7) were excavated in a similar fashion and the temporary sidewalls of the side drifts were removed. The excavation round lengths were 1.2m in the top headings and 2.4m in the lower levels [1].

The initial support system included an insulating 7.5cm thick layer of shotcrete, followed by a 30cm thick WWF reinforced shotcrete lining and lattice girders at 1.2m/2.4m distance, depending on the excavation round lengths. Due to thawing issues during construction, the 7.5cm thick insulating shotcrete layer was combined with the 30cm thick initial shotcrete layer. The temporary sidewalls were 30cm thick with the same reinforcement.

A complex geotechnical instrumentation and monitoring program was established for the NBX project, consisting of robotic total stations, surveying points, inclinometers, extensometers,

observation wells, tilt meters, seismographs, strain gauges and liquid settlement systems. Deformations around the opening were documented with a maximum settlement of 22mm at the tunnel crown, which was well below the predicted level of 30mm. No settlements could be registered at the ground surface or the adjacent structures.

A full round PVC waterproofing system was installed around the tunnel perimeter after excavation. The final lining is a 1m thick reinforced concrete shell, which was constructed by pneumatically applied concrete (PAC), due to the complex geometry of the tunnel.

Several factors were of great concern during the construction of the NBX, including challenging geological and geotechnical conditions, groundwater and restrictions on groundwater drawdown, proximity to major traffic arteries that were to remain open and unaffected by tunneling activities during the project as well as other buildings and structures. The conventional tunneling was executed in a safe and satisfactory manner, with all ground deformations within the anticipated range and negligible ground loss occurring around the tunnel opening [2].

2.2 4th Bore Caldecott Tunnel, Oakland, CA

The original Caldecott Tunnels consisted of three bores, but a fourth one was built to add two additional traffic lanes. The California Department of Transportation (Caltrans) and the Contra Costa Transportation Authority proposed these additional lanes to help relieve congestion on State Route 24 (SR 24) through the Berkeley Hills near Oakland, California. The fourth tunnel bore is horseshoe shaped and stretches 1,036m long, 15.2m wide, and 9.7m high. The tunnel includes cut-and-cover sections at each portal, a jet ventilation system, seven cross passages between the original third bore and new fourth bore, as well as a new Operations and Maintenance Control (OMC) building. The new bore includes two traffic lanes at 3.6m each, two shoulder lanes with one at 3m and the other at 0.6m as well as a sidewalk and emergency walkway (see *Fig. 4*). The tunnel construction was completed and traffic opened at the new bore in November 2013.



Ground conditions at the Caldecott Tunnel vary along the tunnel alignment. They are characterized by Middle to Late Miocene-age marine and nonmarine sedimentary which rocks, strike northwest with high dip angles and are locally overturned. The geology consists of three formations, which have different geotechnical conditions and consisted mainly of highly weathered and sheared shale, sandstone, siltstone, cert and The tunnel alignment conglomerate. encountered four major inactive faults, which occur at the contacts between the geological units. In addition to the major faults, many other zones of weak ground were encountered, such as smaller faults,

shears, and crushed zones. The active Hayward fault lies in close proximity to the tunnel at \sim 1.4km distance in the west [3].

Fig. 4: Typical cross section of Caldecott Tunnel

Due to the varying geologic conditions and the large tunnel shape, the Caldecott 4th Bore was built using the conventional tunneling method (SEM). The excavation was divided into top heading, bench and invert drifts. Further, four basic support categories (SC) were developed in the design in order to establish a flexible contractual basis to adjust the excavation scheme according to the actual encountered ground conditions. The excavated round length varied between 1.0m for the heaviest (SC IV) and 1.8m for the lightest (SC I) support category. The initial support system included fiber reinforced shotcrete, rock dowels, lattice girders and face dowels. Support categories III and IV also included a temporary top heading invert as well as spiles and pipe arch canopies.

The deformations at the tunnel opening were continuously monitored and stayed well below the predicted values. Only about 9% of the tunnel length encountered some different ground conditions, which could be successfully negotiated with the contractor [4].

The tunnel final lining was composed of reinforced cast-in-place concrete, using a 15m long steel formwork. Between the initial and final lining, a PVC waterproofing system was installed around the tunnel arch, which drains the ground water inflow to existing facilities at the portal. In addition, seven cross passages have been constructed, to connect the 3rd and 4th bore as emergency exits.

In sum, the Caldecott 4th tunnel bore was successfully constructed, within predicted schedule and below budget. It proofs, that the conventional tunneling method is suitable to support large cross sectional tunnel openings within difficult and variable ground conditions. Further, the conventional tunneling method allows for the adaptation of flexible support categories which can be suited to meet the actually encountered ground conditions.

2.3 Regional Connector, Los Angeles Metro, CA

The LA Metro Regional Connector Project will pass through the urban business district of downtown Los Angeles and will allow two train services connecting all existing lines - Eastside to Santa Monica and Pasadena to Long Beach, enabling passengers to go north and south and east and west through downtown on a one seat ride. The tunnel construction includes boring twin, 6.7 m diameter, Tunnel Boring Machine (TBM) tunnels through difficult ground conditions of cohesive alluvium soils and soft rock beneath the downtown urban environment, with shallow cover, a narrow city street, tight curves, numerous obstructions and the underpinning of several building foundations. Adjacent to the tunnel alignment are a historic Japanese Village Plaza area, Disney Hall Auditorium and the newly constructed Broad Museum, both sensitive to noise and vibrations; structures founded on shallow spread footing foundations; high rise buildings on deep foundations; and a highway structure supported on drilled shaft foundations. The project includes approximately 1,600m of cut-and-cover concrete box construction and three underground stations - 2nd/Hope, 2nd/Broadway and 1st/Central Stations and connection to the existing underground 7th/Metro Station, as well as an underground cross-over cavern [5].



Fig. 5: Profile of LA Metro cross-over cavern

Efficient rail operations require cross-overs to be able to singletrains to deal track with equipment failure, emergency conditions, and maintenance. The proposed crossover cavern is located immediately east of 2nd/Broadway the station, approximately extending for 120m along 2nd Street. The cavern theoretical crossover excavation as developed in support of the Design/Build bid design by the authors is

approximately 17.9m wide and 9.45m high (see *Fig. 5*). The cavern will be excavated in the

Fernando formation with approximately 9.1 m cover of this soft rock. Early in conceptual design, construction of this crossover was assumed to be as a cut and cover excavation, like for the immediately adjacent station. However, upon further investigation during Preliminary Engineering, legal encroachments by an underground garage and sidewalk vaults associated with the adjacent structures meant that a full-width excavation could not be without costly underpinning. After study, the SEM-excavated cavern was determined to be constructible and was adopted in the project configuration [6].

The crossover cavern was planned to be excavated by conventional tunneling method (SEM), so that the two TBMs can "walk-through" the cavern after excavation and initial support of the cavern are completed. The crossover cavern excavation sequence includes two roughly similar size side drifts with an initial liner of lattice girder and steel fiber reinforced shotcrete and a 0.45m final liner of cast in place concrete. Excavation sequence and support system were designed to ensure stability of the soft rock mass and safety of the adjacent existing structures.

A complex instrumentation and monitoring program was to be utilized, to verify that constructionrelated movements meet the performance criteria for the project and to quickly identify construction-related movements that exceed performance criteria or that could adversely impact streets, structures, and utilities so that mitigating and corrective actions can be implemented.

The project has been awarded and at the time of writing in early 2015 is moving into construction. To the best knowledge of the authors the SEM cross–over cavern is scheduled to be constructed in a similar size arrangement as portrayed herein.

2.4 Chinatown Station (CTS), San Francisco, CA

The 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 to the Embarcadero Line 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 Station.



crosscut cavern will extend to the east under Stockton Street from the head house across the twin driven tunnels, which are scheduled to be constructed before the CTS excavation starts.

The platform cavern will extend north and south, under Stockton Street from the crosscut cavern. The crossover cavern is located south of the platform cavern. The north emergency egress consists of a vertical shaft located on the east side of Stockton Street that connects the north end of the platform cavern with a 10.7m long emergency egress tunnel. The south emergency egress is a horizontal tunnel located at the south end of the head house structure and connects the south end of the platform cavern.

The underground portions of CTS will be the

Fig. 7: Cross section of Platform Cavern

Chinatown Station (CTS) will be excavated as a mined cavern beneath Stockton Street, between Jackson Street and Clay Street. The vicinity of the CTS 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 main structure elements comprising CTS are the crosscut cavern, platform cavern, crossover cavern, head house, and two emergency egress shafts (see *Fig. 6*). The head house will occupy an off-street parcel at the southwest corner of Washington and Stockton Street; the

Fig. 6: Schematic Layout of Chinatown Station



method (SEM), in a series of staged construction of small multiple drifts (see *Fig. 7*). This method of construction was selected to minimize surface disruption, and if constructed with the standard of care specified, will minimize subsurface movements and effects on below grade utilities. An off-street excavation shaft, with lateral support of excavation comprised by concrete diaphragm slurry walls, will be constructed in an open excavation. Following the station cavern construction, the excavation shaft will be built out to serve as the head house containing the access to the station, ticketing, ventilation and mechanical plant and other ancillary features. From the shaft (head house), the crosscut cavern will be mined using the SEM. The platform cavern will then be mined concurrently north and south, respectively, from the crosscut cavern using the SEM, and then the platform cavern. It should be noted that, prior to the mining of the CTS station caverns, the TBM driven twin running tunnels, through the Crossover and Platform caverns will have been already completed.

The overall length of the mined caverns is approximately 192m beneath Stockton Street. Depths below grade of Stockton Street to the track level vary from 26m at the north end of the station to 34m at the south end of the Crossover Cavern. Thicknesses of the overburden soils to the cavern crown vary from 17m at the north end to 25m at the south end of the caverns. The cross-sections of the caverns and egresses are egg-shaped formed by compound curves [7].

The excavation of the CTS will encounter mixed face conditions, with soft soils (dense, stiff and sandy clays of the Colluvium and Colma Formation) at the crown to weak rock of the Franciscan Formation (sandstone, shale, mélange) at the lower elevations.

Pre-support of the side and center drift excavations will mainly consist of pipe umbrellas at the crown, to allow for microfine cement or chemical grouting of the surrounding ground mass.

2.5 Beacon Hill Station, Seattle, WA

The Beacon Hill Station is part of Sound Transit's Central Link Light Rail Line in Seattle, Washington. With an excavated depth of ~49m below ground, the station is one of the deepest structures in North America built in soft ground by utilizing conventional tunneling method (SEM). The Station excavation was completed using shotcrete for both, the initial excavation support lining and for portions of the final structural lining [8].



Fig. 8: SEM excavation sequence at Beacon Hill Station

The geology of the underground station was a complex sequence of glacially overridden deposits consisting of very dense and hard clays, silts and sands, gravel and cobbles. Multiple ground water levels were detected in granular deposits, typically due to perched groundwater overlying clay and till units. The SEM station cavern was excavated using multiple drift excavation sequences (see *Fig. 8*) and ground treatment, dewatering and presupport measures. The main pre-support around the arch for the side and center drifts consisted of a grouted double arch pipe umbrella [9].

Various sizes of tunnels have been excavated for the Beacon Hill station, with the biggest tunnel (concourse cross adit) of $\sim 140m^2$, platform tunnel of $\sim 93m^2$ to cross

passages of $\sim 12m^2$. The station length was about 115m. The excavation sequence varied with the size of the tunnels. The excavation sequences were designed to make the ring closure as soon as possible to minimize the load distribution, minimize ground relaxation and to minimize tunnel deformations (see **Fig. 9**).



Optical survey and geotechnical instruments were used to monitor buildings utilities and during construction and detect any settling of the ground. A 24-hour work schedule allowed the ground to be excavated and supported in a way that maximized safety and the stability of the soil. A noise wall was constructed to reduce noise from the site. The TBM twin tunnels were designed with three cross-passages to meet the egress requirements of the National Fire Protection Association's NFPA 130 standard.

Fig. 9: Beacon Hill Station Access Shaft and Adits

The Beacon Hill station was opened for revenue service in July 2009. It includes four high-speed elevators, emergency staircases, ventilation shafts, and artwork on the platform, concourse, head house and plaza.

2.6 Stanford LCLS Project, Menlo Park, CA

From 2006 to 2008 the Stanford University expanded their Linear Coherent Light Source (LCLS) facility, which included the construction of a series of new tunnels and caverns. The Far Experimental Hall (FEH cavern) is an underground research laboratory at the very east end of the LCSL extension near Menlo Park, CA.



Fig. 10: 3D Model of the Access Tunnel Intersection to FEH Cavern

The excavation dimensions of the FEH are 67m length, 15m width and 10m height. The geology of this cavern was a weak sandstone with an average uniaxial compressive strength (UCS) of 2-5 MPa. The complete cavern was situated above the water table and water was prohibited to be used for rock drilling, since this would decrease the strength of the sandstone dramatically. In order to get access to the FEH cavern, a smaller Access Tunnel had to be excavated approximately to the midsection of the cavern (see *Fig. 10*). From there, the cavern could be excavated in 3 separate drives in both directions from top to bottom, using 3

excavation levels (top heading, bench and invert). The intersection between Access Tunnel and FEH Cavern was over-excavated in order to create sufficient room for the lattice girders and shotcrete of the cavern final lining.

The initial support measures included lattice girders, fiber reinforced shotcrete and rock dowels (see *Fig. 11*). The rock dowels have been galvanized and grouted, because they were considered part of the permanent ground support system.



The final lining of the FEH Cavern was composed of plain shotcrete in combination with welded wire fabric (WWF) and lattice girders. The gap around the intersection between FEH Cavern and Access Tunnel was backfilled with flowable fill.

Excavation of the cavern was carried out by a roadheader selected to ideally fit this geology and tunnel cross section. The ground deformations were controlled by in-cavern monitoring points, surface settlement points and multiple borehole extensometers. All deformations have been within the predicted range and even below, thus

several adjustments of the excavation sequence could be made in order to increase construction effectiveness. For instance, the originally planned *Fig. 11:* Finished excavation and initial support of the FEH cavern

three drifts of top heading excavation could be combined into one drift, by using a so called "face core" to temporary support the open tunnel face [10].

The FEH cavern as well as several other tunnel structures have been successfully completed in 2008 and the Stanford University is currently planning another extension of the Linear Accelerator Facilities.

3. Summary and Conclusion

In the United States, numerous large cross section tunnels and caverns have been successfully constructed, are currently under construction or in the design phase. All of the presented projects utilized a conventional tunneling method, in form of the Sequential Excavation Method in soft ground and/or weak rock conditions. All projects have in common, that those large cross sections generally had to be divided into several lateral and vertical sequences or drives in order to minimize ground deformations around the opening and on the surface. Further, most of those large cross sectional openings required heavy pre-support systems around the top heading side and center drifts in form of steel pipe canopies.

Careful consideration has to be given to the timely effect and load distribution in the design and construction of those large cross sections and their break down into different sequences and drives. An intensive monitoring program should be established during construction to control ground deformations and evaluate the original design assumptions with the actual encountered conditions.

It can be anticipated, that in the future more large underground cross sections will be necessary, since construction space for new infrastructures within congested urban areas is very limited.

4. References

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Project Name/ Owner	Tunnel/Cavern Size	Excavation Area	Geology (at tunnel elevation)	Pre-Support	Excavation & Support	Cross Section/Layout
Northern Boulevard Crossing, New York/ Metropolitan Transportation Authority (MTA), Long Island Rail Road (LIRR)	Width: 18.4m, Height: 11.8m, Length: 120m	~185 m ²	Mixed Glacial Deposits, Sandy Silts, Clays, Minor Portions of Bedrock in Tunnel Invert	Ground Freezing, Double Pipe Arch Canopy	Sequential Excavation Method (SEM), Ground Freezing	
Caldecott Tunnel, San Francisco/ Caltrans, Contra Costa Transportation Authority	Width: 15.2m, Height: 9.7m, Length: 1,036m	~115 m ²	Moraga Formation (Volcanic Rocks), Orinda Formation (Sandstone, Mudstone), Claremont Formation (Chert, Shale, Sandstone) Sobrante Formation (Sandstone and Shale)	Pipe Arch Canopy, Spiles	Sequential Excavation Method (SEM)	
Los Angeles Regional Connector/ Los Angeles County Metropolitan Transportation Authority	Width: 17.3m, Height: 9.14m, Length: 100m	~125 m ²	Alluvium fill which is underlined by Qal2 fill	Pipe Arch Canopy, Spiles	Sequential Excavation Method (SEM) for Stations	Tusketerna Tusketerna tusketerna
Chinatown Station, San Francisco/ San Francisco Municipal Transportation Agency	Width: 16.7m, Height: 13.1m, Length: 192m	~186-202 m ²	Highly Deformed Fraction Rock, Colluvium with Silty Clays, Old Bay Deposits, Sedimentary Marine Deposits, Fluvial Deposits	Double Pipe Arch Canopy, Spiles	Sequential Excavation Method (SEM)	Provide the second seco
Beacon Hill Station, Seattle/ Sound Transit	Width: 13.5m, Height: 13.5m, Length: 115m	~155 m ²	Firm to hard Clays, Water- Bearing Sand and Silt Zones	Double Pipe Arch Canopy, Spiles	Sequential Excavation Method (SEM)	
Stanford LCLS Project/ Stanford University	Width: 15m, Height: 10m, Length: 67m	~125 m ²	Weak Sandstone, Siltstone	Spiles at Portal areas	Sequential Excavation Method (SEM)	

Summary of large caverns/tunnel recently constructed and planned in the U.S.