Recent Trends in Conventional Tunneling (SEM/NATM) in the US

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ABSTRACT

Conventional tunneling as defined by ITA WG19 is also known as the New Austrian Tunneling Method (NATM) or Sequential Excavation Method (SEM) was transformed in the US to deal with challenging tunneling conditions as an alternative to the more traditional tunneling methods. It is being used more often in urban areas, under difficult ground and ground water conditions, and with limited cover. Often the tunnel is of a large and non-uniform cross section in soft soils or weak rocks. The intent of using this tunneling method is to minimize impact on traffic and utilities and reduce disruption of everyday life of people and businesses.

To meet these challenges, the industry developed technical approaches and implementation techniques and established sophisticated contractual relationships and collaboration in the field among various parties for successful implementation.

This paper examines the development of conventional tunneling (NATM/SEM) in the US to deal with these challenges using recent examples such as Russia Wharf in Boston, Northern Boulevard Crossing, in New York, and Chinatown Station in San Francisco.

INTRODUCTION / HISTORY

Conventional tunneling or NATM/SEM is a concept that is based on the understanding of the behavior of the ground as it reacts to the creation of an underground opening. In its classic form the SEM/NATM attempts to mobilize the self-supporting capability of the ground to an optimum thus achieving economy in ground support. Initially formulated for application in rock tunneling in the early 1960's, NATM has found application in soft ground in urban tunneling in the late 60's and has since then enjoyed a broad, international utilization in both rural and urban settings. In the US the NATM/SEM tunneling method has been used successfully to address challenging tunneling conditions in urban areas.

A large number of tunnels have been built around the world using a construction approach which was loosely termed NATM. During the years of discussions and the application of NATM a variety of terms have been used for the same construction approach. These terms were primarily aimed at describing the construction approach rather than the region of its reported origin.

In the US, where NATM was systematically applied for the first time in the late 70's and early 80's for the construction of the Mount Lebanon tunnel in Pittsburgh and the Redline tunnels and Wheaton Station of the Washington DC metro the term adopted was NATM. Gradually, however, the term has been and is being abandoned in the US and replaced by Sequential Excavation Method or SEM.

Today, the SEM tunneling method has become popular in the US for the construction of tunnels, cross passages, stations, shafts and other underground structures.

The SEM offers flexibility in geometry such that it can accommodate almost any size of opening. The regular cross section involves generally a curvilinear shape to promote smooth stress redistribution in the ground around the newly created opening. By adjusting the construction sequence expressed mainly in round length, timing of support installation and type of support, it allows for tunneling through rock, soft ground and a variety of difficult and mixed ground conditions. Depending on the size of the opening and quality of the ground a tunnel cross section may be subdivided into multiple drifts.

A key support element for the SEM tunneling method is shotcrete mainly due to its capability to provide an interlocking and continuous support to the ground. Implementation of ground improvement measures in the form of dewatering, grouting, ground freezing and others and of pre-support measures in the various forms of spiling have further widened the range of NATM/SEM applications mainly in urban areas and in difficult grounds. These measures are usually specified to improve ground condition and increase stand-up time prior to and during the tunneling process. The NATM/SEM features typically a dual lining cross section by which a waterproofing membrane is inserted between the initial shotcrete and the final, typically cast-in-place concrete lining. Instrumentation and monitoring is vital for a successful NATM/SEM tunneling in which internal convergence and surface settlements are measured. Evaluation of monitoring allows for the verification of design assumptions and adjustment of the tunneling process to meet ground behavior.

REGULATORY DEVELOPMENTS IN THE US

Development of the FHWA Tunnel Manual

Following its first use at the Mt. Lebanon Tunnel in Pittsburgh and the Wheaton Station of Washington DC Metro’s Red Line in the 70’s and 80’s in rock conditions NATM/SEM was first utilized in the US within soft ground conditions at the Washington DC Metro’s Fort Totten Station at the Green Line (see Table 1) in the late 80’s and mid 90’s.

Since then, the NATM/SEM tunneling method became more popular as well as versatile in the US, especially within difficult and varying ground conditions, peaking around the early 2000’s with several projects on the US east and west coasts. Among them are: Russia Wharf in Boston, Massachusetts, Stanford Linear Accelerator extension in California, followed by Devils’ Slide and Caldecott Tunnels in the mid 2000’s also in California, and early to mid 2010’s such as the East Side Access Northern Boulevard Crossing in New York. Several projects are underway and in the bidding stages including Chinatown Station in San Francisco, the Bellevue Tunnels in Seattle, and the Plymouth Tunnel. A brief summary of the timely development of major NATM/SEM tunnels in the US is given in Table 1. This table is not all exhaustive and is related to tunneling projects that were explicitly referred to as NATM or SEM tunnel projects by the individual clients and portrayed as such in the contract documents. Many other tunnel projects were constructed by the NATM/SEM concepts including for example the LIRR station main caverns for the East Side Access program, the No. 7 Line, 2nd Avenue subway, as well as the Weehawken and Bergen Tunnels in the New York City / New Jersey region.

In contrast to developments in the tunneling industry in Europe or Japan for example, only limited national guidelines, standards, or specifications were available in the US for tunnel design, construction, safety inspection, traffic and incident management, maintenance, security, and protection against natural or manmade disasters. Starting with the creation of the AASHTO Technical Committee for Tunnels (T-20) around 2005, the Federal Highway Administration (FHWA) developed a national technical manual, providing guidelines and recommendations for the planning, design, construction and rehabilitation of road tunnels. As part of the development of this Manual, the SEM tunneling method was included in the guideline's Chapter 9, providing insights and recommendations for the design and construction of tunnels, utilizing the sequential excavation method.

Table 1: Development and summary of major SEM tunnels in the US

Tunnel	**Owner/City**	**Geology**	**Year completed**
Mt. Lebanon Tunnel	Port Authority of Allegheny County, Pittsburgh, PA	Rock	Late 1970's
Wheaton Station/Red Line Tunnels	WMATA, Washington DC	Rock	Early 1980's
Fort Totton Station and Tunnels	WMATA, Washington DC	Soft ground	Late 1980's
Rock Creek Tunnel/Green Line	WMATA, Washington DC	Soft ground	Mid 1990's
Branch Ave. Tunnels/Green Line	WMATA, Washington DC	Soft ground	Late 1990's
Russia Wharf Tunnel Segment	Massachusetts Bay Transit Authority, Boston, MA	Soft ground	1998 - 2004
Northern Blvd. Crossing/East Side Access	MTA / LIRR, New York	Soft ground	2001 - 2013
Dulles Airport Pedestrian Walkback Tunnel	MWAA, Washington DC	Soft ground	2001 - 2002
Automated People Mover Tunnels	MWAA, Washington DC	Soft ground	2003 - 2010
Tysons Corner Tunnel, Silver Line, Phase 1	MWAA, Washington DC	Soft ground	2004 - 2014
Beacon Hill Station	Sound Transit, Seattle, WA	Soft ground	2005 - 2007
Stanford Linear Accelerator Extension	Stanford University/DOE, CA	Weak rock	2006 - 2008
Devil's Slide Tunnels	Caltrans, Pacifica, CA	Rock	2007 - 2010
Caldecott 4^{th} Bore Tunnel	Caltrans, Walnut Creek, CA	Weak rock	2009 - 2013
Plymouth Tunnel/MD Purple Line	Maryland MTA	Rock/Soft	Pending
Chinatown Station	MTA San Francisco, CA	Rock/Soft	Pending
Crossover Cavern/Regional Connector	Metro Los Angeles, CA	Soft ground	Pending
Downtown Bellevue Tunnel	Sound Transit, Seattle, WA	Soft ground	Pending

Contractual considerations for NATM/SEM Tunnels

One of the key advantages of the NATM/SEM tunneling method is the flexibility in excavation geometry and application of initial support elements, depending on the actually encountered ground conditions and the behavior of the ground during excavation. Therefore, NATM/SEM construction requires solid technical knowledge, past experience, and skills in assessing the ground behavior in combination with rigorous instrumentation and monitoring program. This skill relates to the use of construction equipment and handling of materials for installation of the initial support elements, and even more importantly observation and evaluation of the ground as it responds to tunneling. It is therefore important to invoke a bidding process that addresses this need formally by addressing contractor qualifications and skills and payment on a unit price basis.

Unit Prices

It is recommended that NATM/SEM tunneling be procured within a unit price based contract. Unit prices suit the observational character of NATM/SEM tunneling and the need to install initial support in accordance with a classification system and amount of any additional initial or local support as required by field conditions actually encountered. While several major NATM/SEM contacts followed this recommendation, not all tunnel contracts were procured on that basis. Often they are procured on lump sum with additional supports on unit prices basis.

Waterproofing and final lining installed to complete the typical SEM dual lining structure may be procured on either lump sum basis or on a per tunnel foot basis. It is recommended that the quantity of local support (additional initial support, often referred as “tool box items”) measures should be on unit prices basis and should be part of the contract to establish a basis for bid.

The unit price approach in the US is historically associated with the Design-Bid-Build (DBB) project delivery method, which gives the owner the most control over the project, but also implements a certain risk allocation on the owner’s side. Since the beginning of the 21st century, the trend has shifted to Design-Build (DB) which includes Public Private Partnerships (P3) or CM-at-Risk project delivery methods. These procurement models are often based on lump sum/fixed price basis. Those delivery methods transfer the project into a low-bid environment, often with less control over the designer’s and contractor’s qualifications. Consequently the owner has less control otherwise afforded in the traditional Design-Bid-Build framework. It is recommended for NATM/SEM elements of a project being procured using DB or P3, that contractual provisions be provided to meet the uniqueness of this tunneling method. Provisions such as pre-qualifications, work statement, decision process, unit prices, etc… should be incorporated in the contract documents.

Like any other project, independent from its contractual framework, a good communication and coordination between the parties involved is a key factor for the success or failure of the endeavor. The setting up of a so called “RESS” meeting is a well-established tool for such a communication and coordination in SEM tunneling projects.

Required Excavation and Support Sheet (RESS)

An essential component of the daily NATM/SEM tunneling operations is the so called “Required Excavation and Support Sheet (RESS) Meeting”. Those meetings are usually held every workday at a defined time, and conducted by the Senior SEM Tunnel Engineer. Those meetings are typically attended by the contractor’s Tunnel Project Manager, NATM/SEM Design Engineer, Superintendents, Project Geologist, Geotechnical Engineer, Surveyor, Quality Control Manager, Construction Manager, and the Owner’s and Design representatives. It is recommended and standard practice that the RESS meeting be held on a daily basis to provide a frequent and quasi concurrent agreement on the tunneling process between the contractor’s and owner’s representatives.

In addition, the RESS meeting can be open to any of the project’s stakeholders, who have facilities that can be affected by the mining operations. This openness can go a long way towards allaying concerns associated with potential risks resulting from the tunneling operation. Thus the RESS meeting supports risk management and offers a risk mitigation tool on a daily basis.

The RESS meeting usually closes with signing of the RESS sheet by the responsible parties. The intent of the RESS sheet is, to summarize and document simply all the pertinent information for communication to the field personnel. The mantra always being that this sheet identifies the minimum support measures that must be applied and that field personnel can always locally add additional support measures, if needed, but never less. The sheet also identifies monitoring requirements and typically it also includes a plan view indicating the location of the excavation in relationship to the surface buildings, roads and facilities. Figure 1 shows an example for a RESS sheet from the Tysons Corner NATM/SEM tunnel construction.

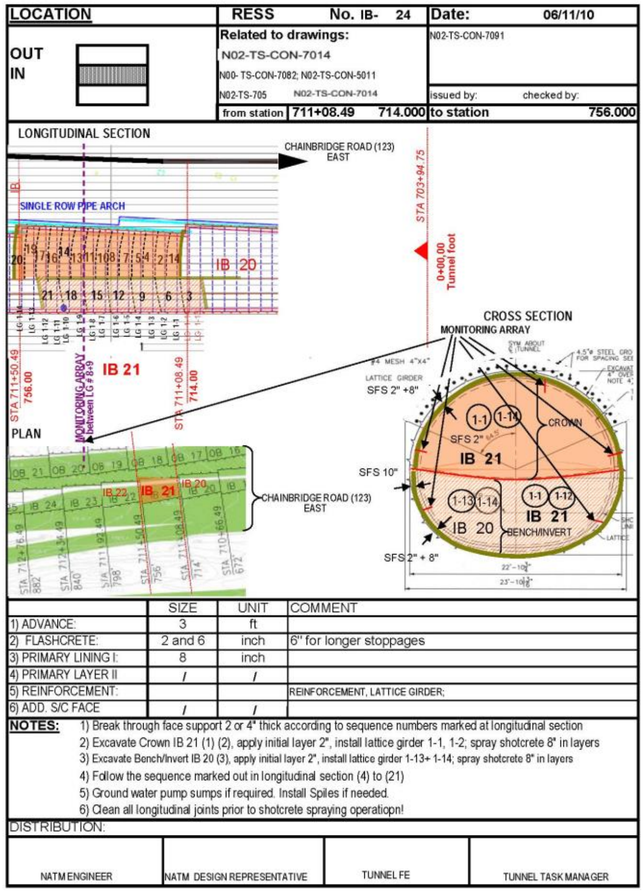

Figure 1: Example of a RESS sheet

CASE HISTORIES IN THE US

The following provides four example projects of NATM/SEM tunneling work under extremely difficult ground and ground water conditions in dense urban settings. Three have been successfully completed: the Russia Wharf, the Northern Boulevard Crossing and the Tysons Corner Tunnels whereas NATM/SEM Construction of Chinatown Station in San Francisco is due to begin in early 2016.

Russia Wharf Tunnel, Boston, Massachusetts

The Russia Wharf segment was the most challenging section of the Silver Line Phase II construction for the Massachusetts Bay Transportation Authority (MBTA). The line is designed to provide a rapid bus transit connection between the central business districts in South Boston to the new Convention Center. The tunnel passes diagonally under the 100 year old Russia Wharf complex, which comprises of three seven-story buildings with steel frames and brick facades listed in the National Register of Historic Places. The chosen construction method was NATM/SEM in conjunction with ground freezing, which was applied for the first time in the US. The advantages are preservation of the buildings' historic value, undisturbed operation of the fully occupied buildings during construction, reduced impact on the building structure and comparable cost. The "binocular"-shaped tunnel passes just 10 ft (3 m) below the historic Russia Wharf Buildings (see Figure 2).

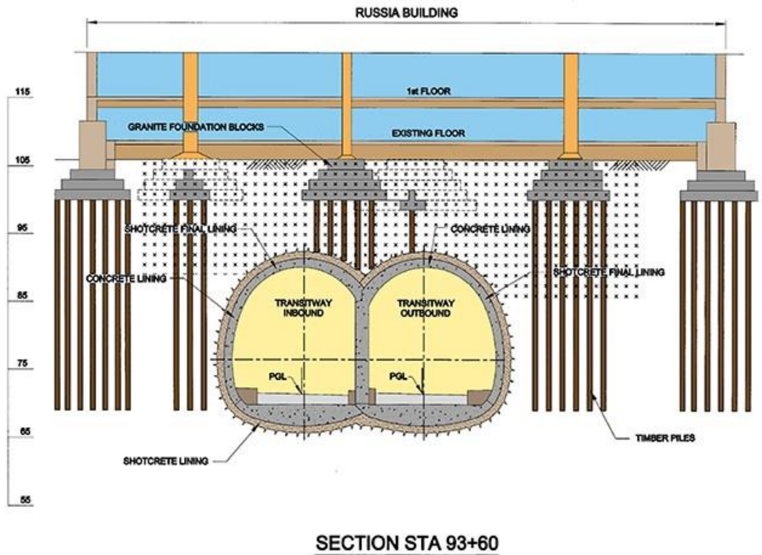

Figure 2: Cross section of the tunnels underneath the Russia Wharf

Mini-piles and ground freezing methods were utilized to support the Russia Building while under the Graphic Arts Building, where cover between the tunnel crown and the pile caps is greater, freezing alone provided the construction pre-support. At the same time it provided building underpinning for the Graphics Art building. During excavation in the 2-6 m (6-20 ft) thick arch of frozen ground, about 600 of the building's old wooden support piles were cut through. Once the ground was thawed, the cut-off wooden piles rested directly on the tunnel lining, which provided the long term support for the building. The ground was kept frozen during most of the 33-month construction period. Although the frozen soil did support the buildings in some areas, the perimeter of the project was kept frozen to inhibit groundwater infiltration. The construction sequence was defined by completing one tunnel first, including installing the PVC waterproofing system and casting the final tunnel lining and center wall. After the final lining achieved sufficient strength, the other tunnel was excavated and connected to the finished tunnel lining of the first tunnel. A sophisticated jacking system was installed between the frozen ground and the building supports which could lower the building to compensate for heave of the frozen ground and raise the building foundations to compensate for induced settlements by tunneling and thawing of the frozen ground.

Northern Boulevard Crossing (NBX), New York City, New York

The East Side Access project is being constructed by the Metropolitan Transportation Authority Capital Construction (MTACC) in New York City to provide Long Island commuters with direct access to Manhattan’s Grand Central Terminal. This infrastructure project requires extensive tunneling in the highly urbanized environments of the boroughs of Manhattan and Queens. The Northern Boulevard Crossing (NBX) is considered the most technically challenging and is also the keystone of the project.

The NBX is located underneath three busy transportation arteries in New York City. The first is the five track NYCT IND subway 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 Elevated Subway Line, as well as the Northern Boulevard, a 6 lane roadway on the surface (see Figure 3).

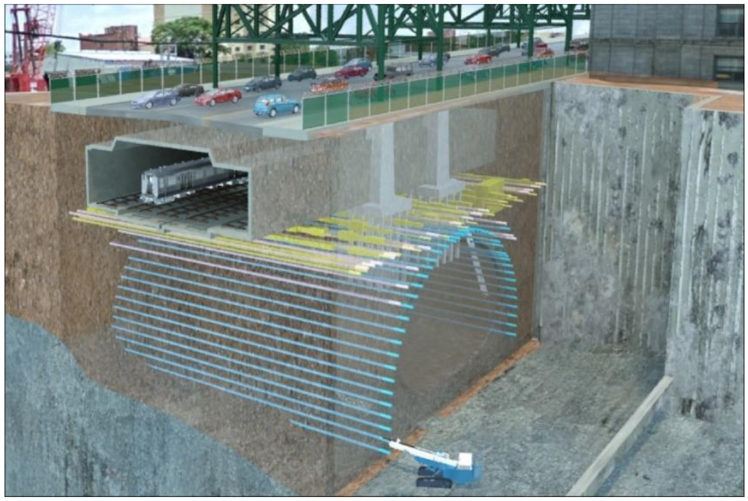

Figure 3: NBX Tunnel with adjacent infrastructure

Several factors were of great concern during the construction of the Northern Boulevard Crossing, including challenging geological and geotechnical conditions, groundwater and restrictions on ground water drawdown, proximity to major traffic arteries that were to remain open and unaffected by tunneling activities during the project as well as other buildings, structures, and utilities in addition to the shallow overburden between the tunnel crown and the NYCT subway box structure that was located just meters above the alignment.

These issues were remedied by extensive ground support methods, including the creation of a frozen arch to act as both pre-support of the tunneling and as a groundwater cut-off. ,In addition, void and compensation grouting were provided to deal with the potential heave during freezing and settlement during excavation and thawing. Modeling of the tunneling works and the frozen arch provided a sound approach to mitigate the various geotechnical uncertainties encountered, and NATM/SEM excavation was performed in a safe and satisfactory manner, with actual ground and structural deformations less than the numerical modeling indicated.

Tysons Corner Tunnel, McLean, Virginia

The Tysons Corner Tunnel is part of Phase I extension of Washington DC's Metro system into Fairfax County in Northern Virginia (Silver Line). The Tysons Corner Tunnel is a twin tunnel each with a diameter of 6.7 meters (22 ft) and a total length of 520 meters (1,700 ft), utilizing the NATM/SEM tunneling method as the most feasible option due to shallow overburden and soft ground conditions (see Figure 4). The approximately 12 mile long Phase I of the Silver Line project was pursued in a Design-Build contract and was opened to the public in July 2014.

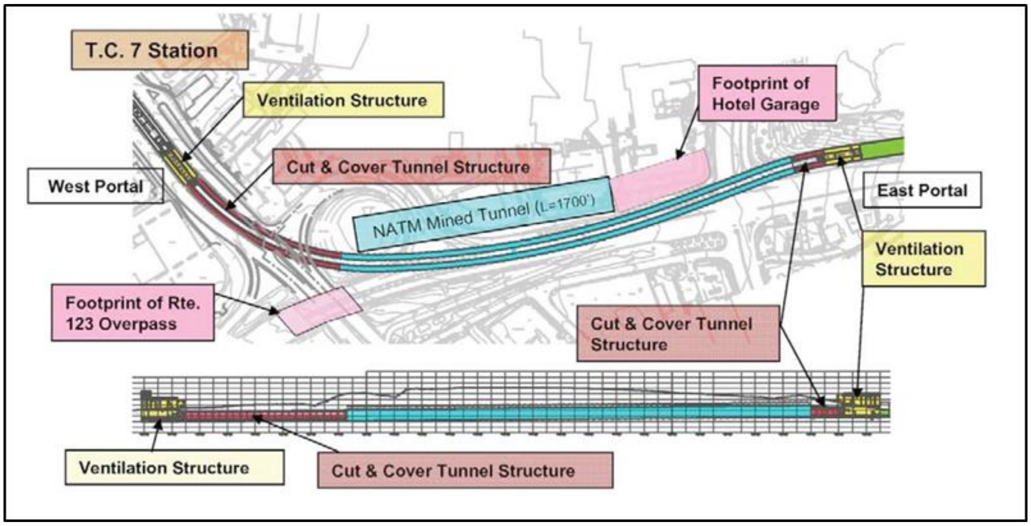

Figure 4: NATM/SEM tunnel alignment at Tysons Corner

The soils encountered along the Tysons Corner tunnel alignment included mainly residual soils and soil-like completely decomposed rock. The residual soils are the result of in-place weathering of the underlying bedrock and were typically fine sandy silts, clays and silty fine sands.

Because of the shallow depth, the prevailing soft ground conditions, the need to control settlements, and risk mitigation issues the NATM/SEM initial shotcrete lining was supplemented by a grouted pipe arch canopy for the entire length of the tunnels (see Figure 5). This provided sufficient pre-support where the overburden. Figure 5 displays a single row pipe arch umbrella above the tunnel section along with a typical SEM tunnel excavation and support sequence.

An extensive real-time monitoring program was installed along the tunnel and produced a vast amount of surface settlement data, which led to the as-built effects of the tunneling efforts on the existing facilities and utilities to be minor; the total settlements recorded did not exceed the maximum threshold values.

The successful implementation of NATM/SEM tunneling methods can be achieved while tunneling through soft ground conditions in an urban environment, provided that existing structures, facilities, and utilities, as well as groundwater and ground conditions are strictly monitored throughout the excavation and construction of the tunnels. A complex real-time monitoring ensures public safety and the safety of workers, assisting in the success of the pre-support and initial lining systems, and creating an open working relationship between all entities involved in the project.

A robust design that properly reflected these project conditions was absolutely critical to the success of the project. The properly-designed pre-support system comprised of grouted steel pipe arch canopies was necessary in order to mitigate any potential risks during excavation and construction by providing adequate support of the shallow overburden through which construction took place. This resulted in minimal settlements with no damage to existing roads, structures, or utilities.

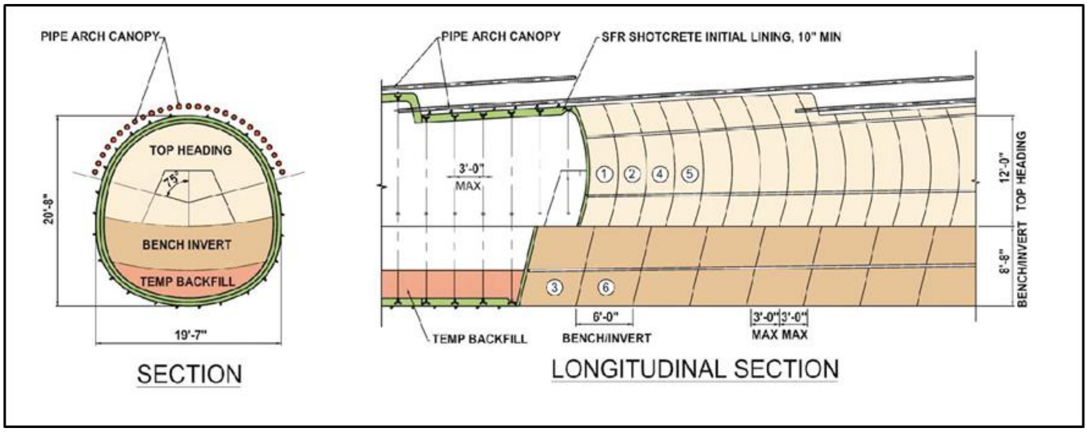

Figure 5: NATM/SEM Tunnel with single pipe arch pre-support for shallow soft ground tunneling

OUTLOOK

Upcoming SEM Project: 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 is currently in progress and preparation works for starting the Chinatown Station are on their way.

The Chinatown Station will be excavated as a mined cavern beneath Stockton Street, between Jackson Street and Clay Street, utilizing the NATM/SEM tunneling method. 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 a crosscut cavern, platform cavern, crossover cavern, head house, and two emergency egress shafts (see Figure 6).

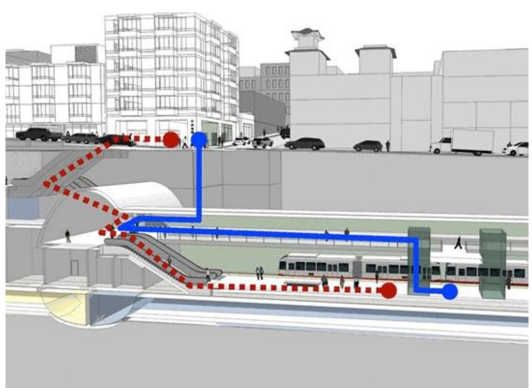

Figure 6: Schematic Layout of Chinatown Station

The excavation of the CTS will likely 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.

The design provided for two side drifts and a center drift with multiple headings each. Pre-support of the side and center drift excavations will mainly consist of pipe umbrellas 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 prevent settlements of the building surrounding the Chinatown Station excavation area.

Because of its sheer size, limited access and complex urban setting the construction of the Chinatown Station will be one of the most challenging tunnel projects in the US, utilizing the NATM/SEM method.

Other upcoming NATM/SEM Projects

There are a series of NATM/SEM tunnel projects in the US currently in the bidding phase, legislative approval process or under design. The most notably projects include the Downtown Bellevue Tunnel in Seattle, the Crossover Cavern along the Regional Connector project in Los Angeles, and the Plymouth Tunnel along the proposed Maryland Purple Line north of Washington DC.

This demonstrates the continued acceptance and success of the NATM/SEM tunneling method for difficult and complex infrastructure in the US. Due to increasing population density and limited space available in urban environments, other NATM/SEM tunnel projects will become a necessity and will materialize in the near future.

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