Design and Construction Challenges of SEM Construction in Urban Area: Chinatown Station, San Francisco, CA

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ABSTRACT

Sequential Excavation Method (SEM) is being used more and more in urban settings in soft ground, mixed ground conditions, low cover, and overbuilt conditions for the creation of tunnels, station caverns and cross passages. To enable open face excavation, various methods of ground improvement are used in conjunction with a rigorous instrumentation and monitoring system and remedial measures to be implemented as needed. The paper examines approaches being used for the implementation of SEM tunnelling in urban areas with discussion on the impact on existing facilities, ground improvement measures, instrumentation and monitoring, and risk mitigation measures. These aspects will be illustrated through the recently completed Chinatown Station in San Francisco, California, USA.

As part of the Central Subway program in San Francisco, Chinatown Station was constructed as a mined cavern using SEM tunnelling. The station is in one of the most densely populated areas in San Francisco, with many existing buildings and underground utilities. The overall length of the mined cavern is approximately 192 m (630 ft) with variable width cross-sections up to 16.7 m (55ft) springline width with a cross sectional area of 186 m^2 to 202 m^2 (2000 – 2175 sf). The soil cover over the caverns was limited and it varied from 16.7m (55 ft) at the north end to 25m (82ft) at the south end. The excavation encountered mixed face conditions, with soft soils at the crown to weak rock of the Franciscan Formation at the lower elevations. SEM construction was selected to minimize surface disruption and the impact on the public, traffic and businesses.

The paper discusses the challenges of SEM tunnelling in urban areas using Chinatown Station to illustrate the issues encountered and the mitigation measures.

1. INTRODUCTION

Tunnelling and underground construction in urban areas is increasing throughout the world due to increase in population growth; migrations to cities; the need of resilient cities; and the growing needs for sustainable, efficient, economical, and environmentally friendly transportation and infrastructure systems. Underground construction reduces environmental, property, and visual impacts, and minimizes surface disturbance. In addition, recently we have seen the public demands the use of underground space for infrastructures to allow more noble uses of the surface such as parklands, recreational spaces, and public amenities.

Tunnelling in 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, and potentially mixed ground, existing or abandoned foundations and buried structures, and large intricate networks of wet and dry utilities. Additionally, space constraints in urban settings magnify the challenge of implementing tunnelling in such a manner as to avoid inducing displacements damaging to adjacent facilities, structures and utilities.
The use of cut and cover construction will further impact traffic, require utility relocation and/or support in place, affect businesses and expose the public to noise, dust, and vibration and impact the people quality of life during construction.

These challenges can be addressed with carefully designed tunnelling methods, the use of the latest technologies in tunnelling, improvement in safety, efficiency in implementation, the use of prudent excavation and support sequencing, implementation of ground improvement as needed, and a robust instrumentation and monitoring program that will identify potential issues early and implement corrective actions. With risk mitigation approach during the design phase, rigorous implementation during construction, and the use of the latest technologies, tunnelling has proven successful in complex urban settings.

2. FLEXIBILITY AND ADAPTABILITY OF SEM TUNNELING INCREASE ITS USE IN URBAN AREAS

Sequential Excavation Method (SEM) has become the method of choice for tunnelling in urban areas to construct complex underground structures such as subway stations, multi-track subway lines, rail crossovers, short tunnels, underground grade separation passages, and underground road ramps in order to avoid cut and cover construction with its impacts on streets, utilities, traffic, businesses and the public. Examples of recent projects completed using SEM Tunnelling in major urban areas include the Confederation Line in Ottawa, the Central Subway in San Francisco, the Vienna Metro U2 Extension, and the East Side Access Tunnel under Northern Blvd in New York. Under these conditions and where complex and challenging ground conditions exist, underground construction requires a flexible and adaptable design that can be executed effectively and safely, while minimizing impacts to existing structures.

Figure 1 - Multiple drifts and ground freezing allowed successful SEM construction of Northern Blvd Crossing in New York

The use of SEM toolbox approach allows modifications in the field as conditions are encountered such as different ground conditions, presence of boulders, abandoned foundations or unchartered utilities. In addition, SEM tunnelling can accommodate complex geometrical configurations that other tunnelling methods cannot such as variable dimensions, irregular shapes, or special unique encounters.

SEM method minimizes impacts on traffic and utilities/services throughout construction, reducing disruption to everyday life. However, SEM tunnelling in an urban setting presents a number of special challenges. Space constraints in urban settings magnify the challenge of implementing SEM tunnelling in such a manner as to avoid inducing displacements and potentially damaging adjacent facilities, structures, and utilities. Such challenges can be addressed with carefully designed excavation and support sequencing, inclusion of potential ground improvement and a implementation of a robust instrumentation and monitoring program.

For example, on the Northern Blvd Crossing in New York the tunnel was constructed using SEM accommodating a very large cross-section with a width of 18.4m (60’-4”) and height of 11.8m (38’-9”) under existing transit lines and with a shallow cover and unfavourable geology of mixed glacial deposits below the water table. To enable the construction, the cross section was subdivided into multiple drifts and using ground freezing to stabilize the ground and enable safe construction (refer to Figure 1). Similarly, for the Chinatown Station as part of the Central Subway project in San Francisco, the station was constructed in a highly developed urban area under a narrow street, congested businesses, residential dwellings, and historical and institutional buildings. This project will be used in this paper to illustrate the challenges of SEM tunnelling in urban areas.

3. CHINATOWN STATION – SAN FRANCISCO

Chinatown Station is one of three stations for the Central Subway Program, a north-south LRT extension connecting the Muni Metro T Third Line through SoMa, Union Square and Chinatown. It will improve public transportation in San Francisco by providing a direct, rapid transit link between downtown and the existing T Third Line route on 3rd Street. The Central Subway will vastly improve transportation to and from some of the city's busiest, most densely populated areas. When the Central Subway opens in 2022, T Third Line trains will travel mostly underground from the 4th Street Caltrain Station to Chinatown, bypassing heavy traffic on congested 4th and Stockton streets. Four new stations were built along the 2.7km (1.7-mile) alignment, three of which are underground. All three stations are constructed under a single contract for a total contract value of $850M with Chinatown Station valued at $350M USD.

The Central Subway program and in particular Chinatown Station, is considered a key element in revitalizing Chinatown, which was weakened economically following the 1989 Loma Prieta earthquake. The project will serve a highly congested, transit-dependent corridor, where over 70% of the residents are without access to a vehicle and rely on a congested bus line that is subject to traffic delays. Upon its operation in 2022, the Central Subway will reduce travel time and provide a direct link to the Bay Area Rapid Transit (BART) system, Muni Metro, Caltrain, cable car lines, and bus routes. It is projected to have over 35,000 daily riders and to attract extremely high usage compared to other light rail systems in the U.S.

The construction of Chinatown Station is one of the most challenging engineering and underground construction projects in the U.S. due to its setting in narrow streets, adjacent to historic buildings, numerous utilities and poor ground conditions.

3.1 Chinatown Station Setting

Located under Stockton Street between Washington and Clay Streets in the heart of Chinatown in San Francisco, the most congested area of the city with narrow streets, historic buildings, crowded with commercial and residential buildings, heavy traffic and numerous above and underground utilities. See Figure 2. In addition, the location of the station encountered one of the most challenging poor ground conditions along the project alignment.

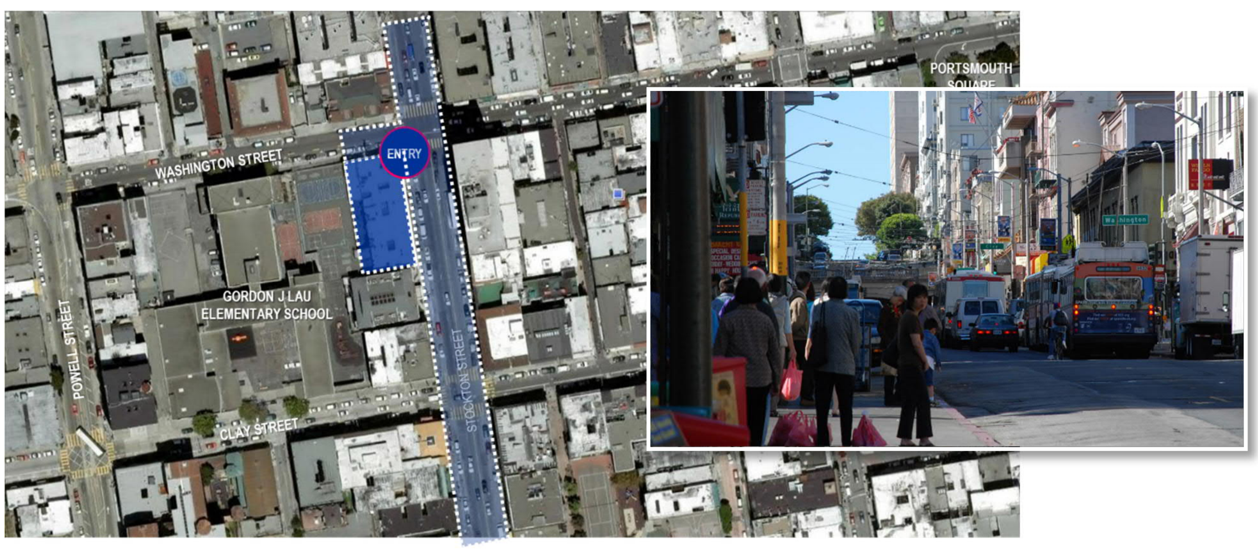

Figure 2 – Chinatown Station is located in one of the most congested area in San Francisco.

The Station Headhouse will occupy an off-street parcel at the southwest corner of Washington and Stockton Streets; A Crosscut Cavern will extend to the west under Stockton Street from the Headhouse to the edge of the property line of the Mandarin Tower, a mix-use commercial/residential tall building; and the Platform Cavern and the Crossover Cavern will extend north and south, respectively, under Stockton Street from the Crosscut Cavern. The crosscut cavern will become the station mezzanine. The North Emergency Egress is a vertical shaft that is located above the roof of the north end of the Platform Cavern. The South Emergency Egress is a sloping shaft that is located above the roof near the north end of the Crossover Cavern and leads to the sidewalk outside the Headhouse. The headhouse is located adjacent to an elementary school, a historic presbyterian church, and across from the Mandarin Tower on the southeast corner of Stockton and Washington Streets.

3.2 Station Configuration

The main elements comprising Chinatown Station are the Platform Cavern, Crosscut Cavern, Crossover Cavern, Headhouse, and two Emergency Egresses. Figure 3 shows schematically the station layout. The station's main elements are the Station Platform and Crossover caverns combined into the main cavern excavation. The overall main cavern dimensions are 192m long (630ft) by 16.7m (55ft) wide and 13.1m (43ft) high with an excavated cross section of 186 m^2 to 202 m^2 (2000 – 2175 sf) making it one of the largest SEM tunnelling excavation in poor ground and soil-like materials in the U.S. The Crosscut cavern is egg-shape and is approximately 13.1m (43 ft) wide, 16.1m (53ft) high and 22.3m (73ft) long. This enables the construction of the station cavern in two directions simultaneously, running as many as four operations if needed. Figure 4 show isometric configuration of the station.

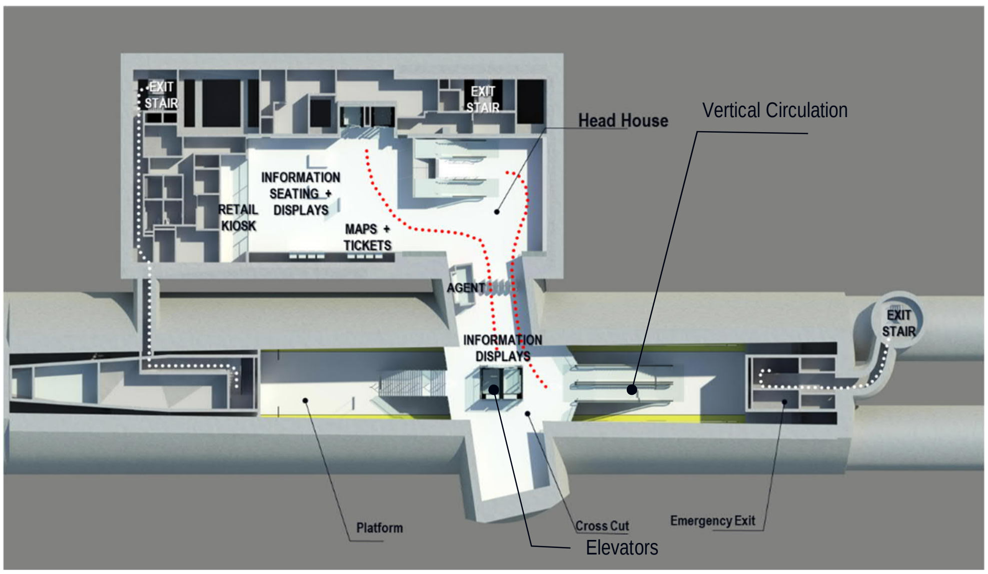

Figure 3 – Chinatown Station General Arrangements.

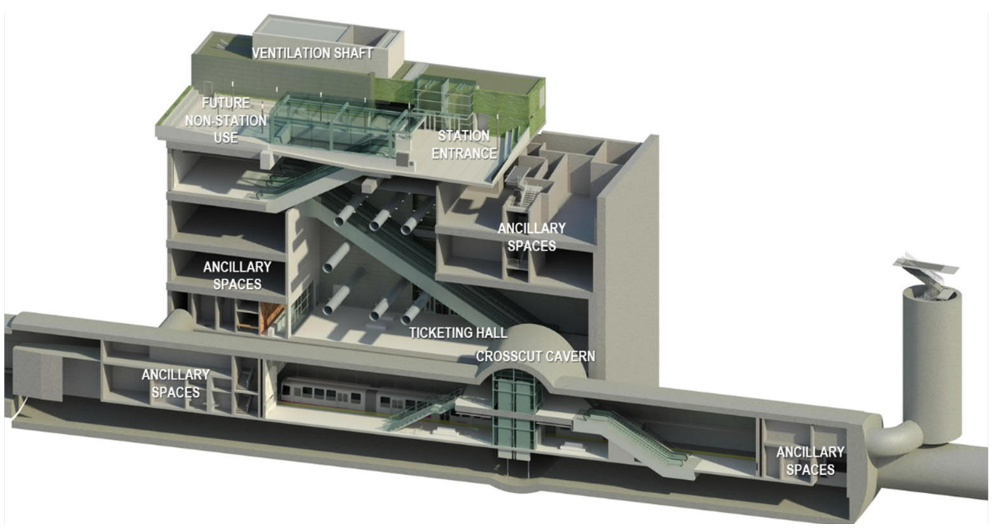

Figure 4 – Chinatown Station Isometric

3.3 Geological Setting

The station is located in a mixed ground condition. The ground is categorized into two groups: 1) Soil, mainly including Colma Formation (Qc) and Colluvium (Qcol); and 2) Rock, including any variety of ground described as Franciscan Complex Bedrock (KJf) or 3) a combination thereof. Therefore, the excavation conditions for the SEM are subdivided into two groups: 1) Mixed Face Conditions in which both rock and soil are encountered in the complete excavation face during excavation; and 2) Full Face Conditions, either rock or soil are encountered in the complete excavation face of a SEM. The two sub-groups of Full-Face conditions that are encountered: 1) Full-Face condition of Soil, only the Colma Formation, or a full face conditions of Rock only, the Franciscan formation. Figure 5 shows the geological setting of the Station.

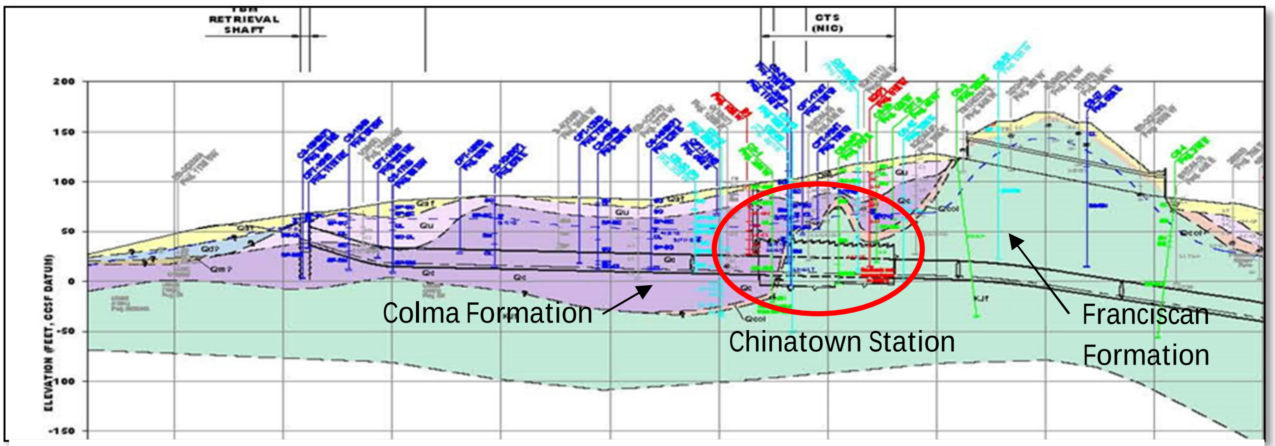

Figure 5 – Geological Setting

The Colma formation consists of dense sand or silty sand interbedded with stiff clay and sandy/silty clay. The Colluvium formation consists of very dense, medium to fine brown sand with silt derived from weathering of the bedrock. The Franciscan 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 meta-sandstone), surrounded by a matrix of pervasively crushed rock materials. The rock/soil contact is locally undulating and irregular.

3.4 Design and Construction Challenges

The challenges of constructing SEM caverns in difficult grounds under high water pressure with low cover in an urban setting required a robust design and thorough construction for safe implementation. All three caverns have similar structural support systems comprising of fibre reinforced shotcrete and lattice girders as the initial lining and cast in place final lining over PVC waterproofing membrane. The Crosscut Cavern has 450mm (18in) thick initial lining while the Crossover Cavern and the Platform Cavern has a 400mm (16in) thick initial lining.

A fundamental requirement for safe and stable support of excavation is to select an excavation and support sequence of such length that provides ring closure at distances, for each individual drift and for the fully excavated 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 design provided two side drifts and a centre drift with multiple headings each. Figure 6 illustrate the sequential excavation drifts of the three caverns.

Due to ground variability and the risk of SEM construction in the encountered conditions, a robust design was implemented. A pre-support system comprised of grouted steel pipe arch canopies consisting of a single or double 5.5 inch grouted pipe canopies 18m (60ft) long were provided and face bolts were used in the centre drift. The excavation was advanced up to 12m (40ft) before the installation of the next arch canopy pipes. Probing ahead of the excavation was done because of ground variability and potential localized wet zones. To improve stand-up time, the Colma Formation was dewatered by a series of deep wells on both sides of the cavern drawing the water table and reducing the water pressure. This dewatering system was supplemented from within the excavation by a vacuum dewatering system to reduce perched water pressures and to maintain the excavation stability.

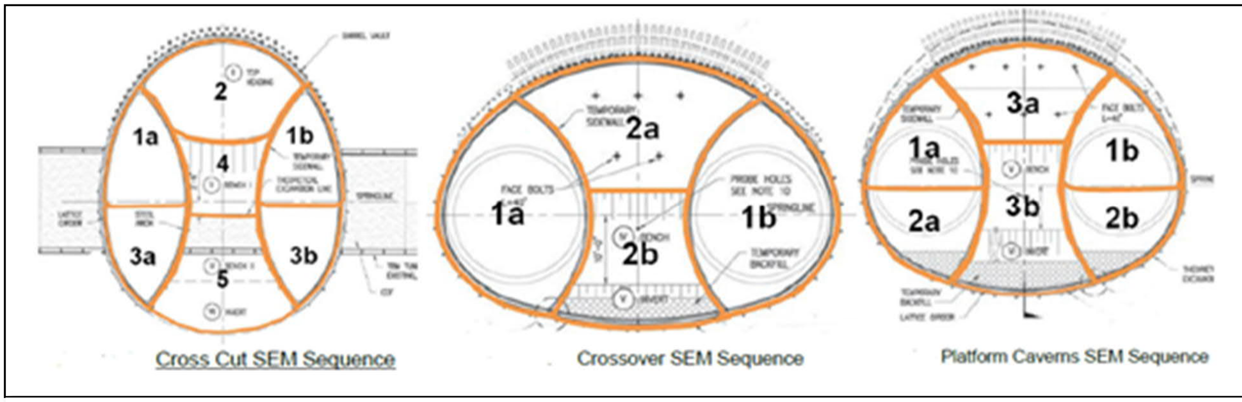

Fig 6 – SEM excavation sequence for the caverns

To protect adjoining buildings, including “the Mandarin Tower” and a historic Presbyterian Church, an instrumentation and monitoring plan was developed using multi-point extensometers, inclinometers, and Total Stationing. Calculations showed that the potential settlement due to the open face excavation of the SEM tunnelling up to 75 mm (3 inches) which the building cannot tolerate. Compensation grouting was implemented to maintain the settlement of impacted structures to less than 12mm (1/2 in). Figure 7 shows the compensation grouting program which consisted of the installation of various levels of tube-a-manchettes covering all adjoining structures. An initial grouting through the tubes was implemented prior to the excavation to condition the ground and to solidify and stiffen the soils. Settlement thresholds of alert and action levels were specified. Daily readings of the instrumentations were taken and when the settlement value reached a threshold level, compensation grouting was injected at certain locations to arrest the settlement and adjust the structure. Maximum settlement on the Mandarin Tower was 12mm (1/2 inch) which is within the tolerable level.

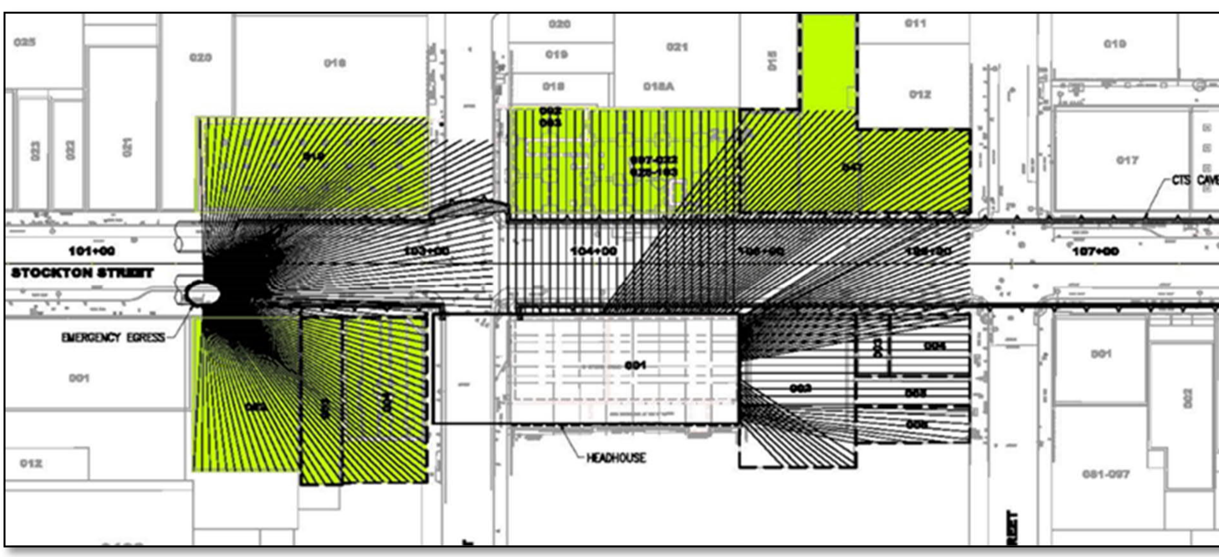

Figure 7 – Compensation Grouting Program

To minimize construction risks and enhance collaboration, daily Excavation and Support meetings were held during construction attended by representatives from the Contractor, the Designer, the Construction Manager and the Owner. They provided an essential forum and quasi-concurrent agreement on the tunnelling process and addressing risks by identifying issues uncovered and plan for the next rounds.

To meet the overall program construction schedule, two running tunnels had to be constructed first through the station location using EPB TBMs with single pass segmental liner. The excavation of Chinatown station encountered the existing tunnel liner that must be demolished sequentially in order to maintain the tunnels structural integrity. A concept was developed in which each excavation round length was the same as the segment length allowing for those segments to be dismantled while maintaining the rings' structural integrity. In addition, excavated materials were placed inside the tunnel acting as a brace of the tunnel liner. A detailed construction planning was developed during the design phase and implemented during construction. Figure 8 illustrates the coordinated plan of construction of the station cavern with the exiting TBM tunnel.

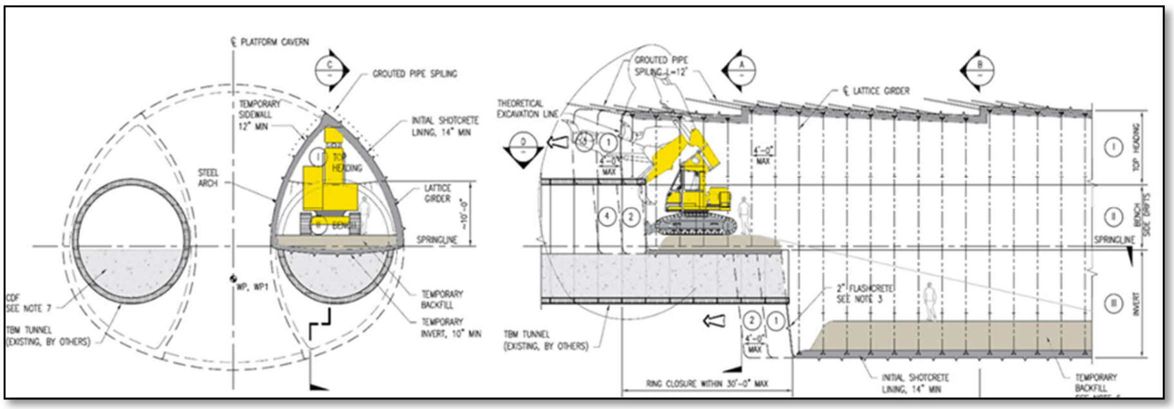

Figure 8 – Coordinated construction of the station cavern with the exiting TBM tunnel

Using the U.S. traditional SEM practice of descriptive systematic approach, the excavation sequence, number and size of drifts, pre-support, initial support, face support where needed, and groundwater control were specified. In addition, supplemental measures (toolbox) were provided such as face bolting, reduced round length, face shotcrete, face grouting, etc, to address unanticipated field conditions. This approach coupled with extensive instrumentation and monitoring resulted in safe construction and no impact on adjoining buildings or utilities.

In addition, a rigorous risk management plan was implemented, including the development of risk register identifying potential technical, commercial, regulatory and political risks that might be encountered during construction and applying mitigation measures during the design and construction. Elements of the mitigation measures included the qualifications requirements of the contractor and his key staff, full disclosure of the geotechnical information, the provision of the Geotechnical Baseline Report (GBR), and joint decision in the field between the designer, the contractor and the construction manager of the support measures based on the daily field observations of the ground behaviour.

In addition, the contract terms included the provisions of Dispute Resolution Board, the inclusion of the GBR, the provision of unit prices for contingent bid items such as the "Tool Box" measures, the use of different site condition clause, and the implementation of partnering framework.

3.5 Sustainability Aspects

The project generated and sustained close to 45,000 jobs in various trades and supply chains and provided opportunities to Small and Disadvantaged Businesses (SBE/DBE). The intent of the SBE/DBE program is not just to support those businesses but also to share and transfer knowledge in the design and the construction of specialty work.

One of the unique features of this project is the establishment of a technology transfer forum for the client and the community. Local engineers and junior staff from SFMTA and SBE/DBE firms were integrated into the design and construction teams working together to successfully completing their tasks providing “on the job” training and technology transfer.

During the design development and construction, the project team developed and implement an extensive public involvement/outreach program including the formation of Community Advisory Groups; holding over 100 public meetings and over 200 presentations to various community groups, agencies and stakeholders; implementing a project website with continual updates of construction progress; establishing strong social media presence including Twitter, Facebook, blog, You Tube, flicker, etc; establishing a project hotline; and producing project newsletter in English, Spanish and Chinese.

4. CONCLUSIONS

Chinatown Station Project was one of the most challenging and rewarding projects in the US. It did not just address the technical challenges, but also provided a sustainable solution to a highly populated area in San Francisco that was deprived of mass transit.

The project will improve the quality of life to Chinatown residents by increasing their mobility and decreasing their travel time; will increase transit capacity; improve connections to other transportation systems, relieve surface congestion; encourage further development; expand the economical standing in Chinatown and reduce air and noise pollution.

The project received the ITA Award for Project of the Year under €500M in 2020.

In general, SEM tunnelling is being used in urban settings, in difficult ground, under high hydrostatic heads, and with limited cover to meet the needs. To enable open face SEM tunnelling under these circumstances, a robust design is required with detailed pre-support systems and potential ground improvement methods to mitigate potential risks. Excavation and support classes for SEM tunnelling should be developed in line with the anticipated ground behaviour, acceptable deformation limits, and the potential impact on existing facilities, structures, and utilities. A toolbox of additional support measures to complement the standard support classes should be specified and be available on site for implementation if needed.

Furthermore, ground improvement as needed, and a comprehensive instrumentation and monitoring system should be provided with predetermined threshold limits and potential remedial measures when these limits are reached. Finally, prequalification of all involved parties and collaboration among the designer, contractor and owner’s representatives is essential for the successful implementation of SEM tunnelling in urban areas.

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