

Urban EPB Tunneling in Limited Space: A Case Study of the San Francisco Central Subway Project

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ABSTRACT: The San Francisco Central Subway project is a challenging modern example of urban tunneling in limited space conditions. Two 6.3 m diameter Earth Pressure Balance Machines (EPBs) are excavating parallel 2.5 km long tunnels under low cover and in mixed ground conditions. The small launch site situated between an interstate and an off-ramp, highly curved tunnel alignment, and geology are particular challenges. These elements required customized tunnel and machine design, from TBM shipment and assembly, to launch and excavation.

This paper discusses the project challenges and solutions at the Central Subway project, with a focus on TBM and continuous conveyor logistics. Requirements of the project include explosion-proof electrical components, laser-guided survey, rubber-tired supply vehicles, and machine and back-up solutions for steep inclines and tight curves.

INTRODUCTION: CHALLENGES OF URBAN TUNNELING

Tunneling in urban areas lends itself to certain challenges to overcome during all stages of design and construction. While there are also many political, environmental, financial and logistical concerns with tunneling in urban areas, this paper will focus on the issues seen from a TBM manufacturer's standpoint. The main issue faced is that of space at the site level. More frequently, urban tunneling jobsites are relatively small. In the ideal situation there would be enough room at the jobsite for staging of all the TBM parts, services, and tunnel excavation support equipment. This is not the case in most urban environments as the ground level is usually congested with other infrastructure. Because of this, tunnel launching and reception shafts need to be squeezed into existing unused or underused areas. The TBM must be able to be broken down into smaller pieces in order to fit and navigate these small sites. The TBM must then be assembled, launched, operated, and disassembled under these same constraints. A large range of sizes of tunnels are used in urban environments, from micro utility tunnels to multiple lane highway mega-tunnels. This paper will focus on challenges specific for light-rail-sized tunnels. There are also considerations to be made in order to protect the surrounding infrastructure. Settlement monitoring and excavation volume monitoring are two such measures that can be used to ensure minimal disturbance at the ground level.

An efficient, inexpensive, and reliable transportation network is an important part of any

urbanization plan as it moves the people and goods inside, and through these urban areas. Generally, as cities grow their need for these networks increases, but the space required for them is in high demand from other forms of infrastructure. In the past and ever more so in the present and future, cities are utilizing underground space to create and expand their transportation systems.

Surrounding Infrastructure

Urban tunneling is a unique challenge for a number of reasons—one being that the surrounding infrastructure already exists. Designing and constructing a tunnel near other buildings, roads, highways, utilities and other tunnels must be done in a way to minimize risk. Usually this infrastructure needs to be kept in operation during all phases of tunneling. Caution must be taken to either design the tunnel in a way to avoid this infrastructure or to have proper mitigation plans in place in case something does go wrong. Also, due to the surface infrastructure that is in place, space is often limited for assembly, launching, operation, and recovery of the TBM and its related systems. It is of vital importance to the success of a project that specifics of the assembly, launch and reception sites are shared with the TBM manufacturer as early on in the design process as possible. The site requirements can greatly affect the design of the machine as it might require that the TBM be customized to meet special assembly/disassembly requirements.

Detailed assembly plans can also be created as the machine design progresses in order to confirm



Figure 1. Lowering of machine shield sections, MX12 Line, Mexico City, Mexico

the logistics of part delivery to the site, crane and lifting requirements, or special tools or procedures that need to be created (see Figure 1, a limited space assembly in Mexico City).

Often Difficult Soft or Mixed Ground Geology

One of the biggest under-defined variables in most tunneling projects is the geology of the tunnel alignments. Many people have theorized that you can never fully determine all the parameters of a particular geology, but only estimate them by sampling discrete areas and extrapolating the results. This is where the experience of the contractor and the history of tunnels in the area are invaluable. The past performance of tunneling projects near the proposed alignment can give huge insights into the predicted geology and performance of the current project. Another must is working with the TBM manufacturer to make certain that the TBM specifications are properly set so the machine can effectively operate in all expected conditions, and beyond.

The geology of urban sites, just like every part of the world, is greatly varied, but many urban areas are located in alluvial zones. People have historically settled near water and many urban areas have grown from these settlements over the centuries. It is imperative that detailed geological and hydrological studies be done when urban tunneling. The

risk and consequences of something going wrong due to encountering unexpected geological conditions is greater in urban areas due to the proximity of vulnerable infrastructure. A thorough geological study should identify the location of all the expected ground types and water table levels throughout the tunnel alignment. This information must be shared with the TBM supplier from the initiation of the design as well, to ensure that the machine is capable of operating under those conditions. Because of the alluvial geology of most urban sites, the majority of recent urban tunneling projects have been completed with Earth Pressure Balance or Slurry TBMs. The acceptance and performance of these machines has grown greatly over the past few decades. The risk for settlement is greatly reduced with the technology of these machines if they are properly operated. They have become much more industrialized over the years, increasing the speed and efficiency of the boring cycle (see Figures 2 and 3, showing the variety of cutterhead setups).

Tunnel Alignment

The alignment of urban tunnels can also be quite curvy both horizontally and vertically. In most cases the tunnel profile will follow along with the contour of the terrain. Also, the alignment may follow the path of surface streets in order to connect between stations placed along those streets. These streets are rarely arranged in straight lines; so consequently, the overall metro route can have complex curves in the design. The TBM must be designed to be able to handle these curves plus some margin of error to allow for steering corrections.

Low Cover

Many urban tunnels are designed with low cover along their alignment. An average of 1.5 to 3 times the diameter is commonplace. With this amount of cover, settlement due the operation of the TBM is a huge risk. Settlement monitoring and mitigation plans, like ground improvement or ground freezing, must be in place to cover this risk. Operating the TBM with the correct parameters is also a huge factor in minimizing the amount of settlement seen at the surface. If these parameters are not vigilantly monitored and maintained then surface ground disturbances due to over excavation, blowouts or incomplete tail void filling can occur. Over excavation at the beginning of the bore must also be addressed. Every machine and geology has a learning curve and this must be expected and appropriate countermeasures implemented. Ground freezing, pre-excavation grouting, jet grouting, etc. can be implemented both at the start of boring and at certain key areas along the alignment to mitigate the risk of settlement. During the



Figure 2. Mixed ground cutterhead



Figure 3. Soft ground cutterhead

bore, instruments and controls such as ground settlement monitors, belt scales, annular grout volume calculations, etc. can and should be in place to identify when unacceptable settlement is occurring and when the mitigation plans need to be put in place.

Cost and Project Schedule

Cost and project duration are always concerns in any project, but especially so in urban environments. Since urban tunnels have a higher visibility and they affect more people and infrastructure, the timeframe for construction must be kept in mind and usually minimized as well. The decision must be made early on if it is more efficient to operate multiple machines and reduce the duration of the project or bore with fewer machines and increase the duration. In shorter parallel tunnel runs, one machine may be a better option, but as the tunnel length increases more machines becomes the efficient solution. The project owner or contractor must study the tunnel plan and determine the optimum solution for the situation. One of the biggest factors is weighing the additional cost and complexity to operate multiple machines against the increased duration of the project with fewer TBMs.

URBAN TUNNELING CASE STUDY: SAN FRANCISCO CENTRAL SUBWAY

San Francisco's Central Subway extension project will add a vital north-south link to the city, connecting commerce, tourist and historical locations with fast and efficient public transport. The project will create a twin tube extension to the Third Street T line,

extending it from the 4th street Cal Tran station to Chinatown. The planned opening date for the extension is in 2019. JV Contractor Barnard Impregilo Healy was selected to complete the major tunneling works by the project owner San Francisco Mass Transit Authority, or SFMTA. The contractor selected and purchased two 6.3 m Robbins Earth Pressure Balance machines to bore the 2.5 km long parallel tunnels. Both machines were launched sequentially from 4th and Bryant Street north towards Chinatown. They will be removed from a reception shaft situated across the street from Washington Square Park.

Project Challenges

- Densely populated urban setting in a historic city.
- Small launch pit with low head height and mostly covered with steel plates, situated below an interstate freeway that allows assembly of only one TBM at a time.
- Steep grades—Sections of $\pm 7\%$ do not allow the use of conventional locomotives.
- Curvy alignment—there is a 137 m radius curve followed by a 260 m curve
- Complex geology—753 m of the alignment will be in the "Franciscan Complex": Abrasive sandstone that is tough on the cutterhead, disc cutters, and the screw conveyor.
- Classified as "Potentially Gassy."
- Cal/OSHA and numerous regulatory bodies with complicated, contradictory and extremely strict safety and environmental codes.

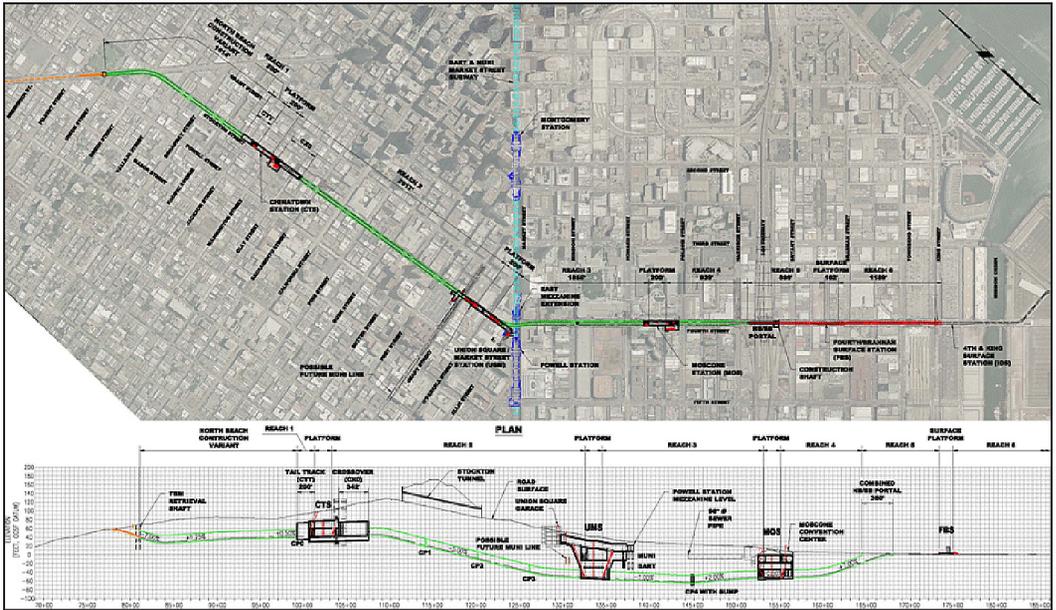


Figure 4. Tunnel and station alignment (Image credit: SFMTA Pre-bid Presentation)

Alignment

Much like the city of San Francisco itself, the tunnel alignment has nearly continuous elevation and grade changes (fix this)The alignment begins at the intersection of 4th and Bryant streets. The machines will be launched heading to the northwest below 4th street, diving immediately. The tunnels will level out then take a sharp right turn (R 137 m) towards the north at Market Street, where they will pass under two other operational subway lines. In order to ensure the safety of those lines during boring operations, a liquid level system working in concert with longitudinal and transverse strain gauges and other instrumentation will be used to monitor ground disruption. The system will be used under the live tracks and determine if settlement mitigation measures must be executed.

After leaving the Union Square/Market Street Station the TBMs continue along below Stockton St. at a steep 7% climb for approximately 800 m through Franciscan bedrock. The tunnels travel under Nob Hill and the Stockton St. Tunnel, which will present more settlement monitoring activities and the additional challenge of increased overburden. After the Chinatown Station there is another long R 850 m curve just before the final, approximately 100 m, 7% climb to the retrieval shaft. The exit shaft for the two machines is located at Columbus Ave. and Union St. across from Washington Square Park (see Figure 4).

Geologic Setting

The geology of the tunnel alignment is mixed and it ranges from mud deposits, sand and clay to sandstone, mudstone, and shale. The TBMs will encounter three disparate geological formations: the Colma, Old Bay and Franciscan. However, stating that there are only three types of ground is a vast oversimplification. There is certain to be a wide range of diverse and fluctuating ground conditions between these three generalized formations.

It is anticipated that the three formations will be distributed roughly as follows:

- Colma Formation (Surficial soils): ~ 1,750 m
- Undifferentiated Old Bay Deposits: >500 m Interspersed
- Franciscan Bedrock (sandstone): ~ 750 m
- Maximum rock strength (UCS): 27 MPa

Machine and Back-Up Specifications

The TBMs were designed with a number of special features to efficiently manage the varied geology, navigate the steep and turning alignment, and bore in what has been rated as “Potentially Gassy with Special Conditions” by Cal/OSHA.

A mixed face cutterhead was selected and designed to excavate a wide variety of ground ranging from soft soils to hard rock, as well as diaphragm walls. The wear surfaces of the cutterhead are clad

in a combination of chromium carbide plating, hard facing, and tungsten carbide bits to ensure the life of the head in the abrasive environment. The TBMs can be equipped with either a full dress of soft ground tools (picks, rippers, scrapers, etc.) or a mixed dress that incorporates 17-inch, pressure compensated disc cutters when the machine will encounter rock or concrete. Forty specially designed housings have the ability to mount either disc cutter or soft ground tools. The opening ratio is 31% to allow efficient and controlled muck flow through the head. Grizzly bars are also incorporated to prevent boulders that are too large to pass through the screw conveyor from entering the mixing chamber. The cutterhead also features 5 foam and 2 water injection ports for soil conditioning and a programmable copy cutter to create additional overcut in order to negotiate tight turns. In order to detect the need for an intervention there are also 3 sets of wear detection bits to automatically detect when the wear of the cutters gets down to unacceptable levels.

The cutterhead is driven by five, 210 kW VFD-controlled electric motors that transmit power through multi-stage planetary gear reducers and a large diameter bull gear. This setup is integral to a high capacity three-axis main bearing design modeled on hard rock TBMs. The VFD motor control allows infinitely adjustable cutterhead speed.

Like all EPBMs the Central Subway TBMs are fitted with a screw conveyor. Fortunately the relatively low hydrostatic pressures on this project only necessitate the use of a single-stage screw. However, due to the abrasive quality of the muck, the owner has specified replaceable wear protection on both the flights of the screw as well as the screw casing. To accommodate this, the shell of the screw conveyor is built of multiple replaceable sections.

Due to the complex geometry of the alignment, steering the TBMs accurately through the tight curves (min R 137 m) is one of the key challenges of the project. To accomplish this it was necessary to articulate the TBM shields. An active articulation system was integrated as it allows the thrust cylinders to remain parallel to the tail skin and react evenly with the segments. This feature mitigates the risk of segment damage, ring deformation, or settlement during boring.

Like all highly urban tunnel projects, another key challenge is ground loss or settlement, especially where the alignment crosses under live metro rail tunnels. As noted above the owner and contractor have highly instrumented, key areas where settlement could pose a serious risk to existing property or infrastructure. To prevent ground loss a precise system of control and measurement of the excavated material must also be implemented to eliminate over-excavation. The machine is fitted with two electronic

scales and a laser system that constantly monitors the weight and volume of the tunnel muck travelling down the backup conveyor. These measurements are then compared to theoretical values to determine if over-excavation is occurring. The machines also have an active face support system that can detect if rapid pressure loss is taking place at the excavation face. The system will automatically inject pressurized Bentonite slurry into the mixing chamber to restore the lost pressure. The operator will then close the guillotine gates on the screw until face pressure is restored and it is safe to resume operation.

The geology of the alignment has the potential to contain ignitable concentrations of flammable gasses. For this reason, a requirement of the electrical design for both machines is to be ANSI/NFPA Class 1 Div 2 compliant. This was achieved using a combination of both inherently safe electrical designs and sealed or purged cabinets in all areas of the machines. The machines are also equipped with a gas detection system in order to identify the presence of multiple gasses in the tunnel.

Both machines and their respective backups were factory assembled and tested in Robbins' Pudong facility in Shanghai, China. The machines were then disassembled and shipped to San Francisco. Both machines were shipped in the largest sub-assemblies possible in order to reduce the assembly time at the site (see Figure 5).

Site Setup

The launching and service portal presents a unique challenge to the project. Most of the project site is located within the busy on-ramp/off-ramp interchange of Interstate 80 and 4th street. The launching pit (137 m × 11 m) for the machine is actually directly below 4th street with a small access window



Figure 5. First of two San Francisco Central Subway EPBs with mixed ground tool configuration



Figure 6. Small jobsite passes under Interstate highway 80 (Image credit: SFMTA)

(11 m × 11 m) to the pit on the southeast side of the intersection. All the tunnel services and operations are squeezed into the available space between and below the highway and ramps. When both machines were launched and boring became fully operational the tunnel service vehicles had to navigate a tight course through the jobsite and down to the tunnel portal. This includes a sharp 90 degree turn down a ramp to the launching pit (see Figures 6 and 7).

Continuous Conveyors

To get the muck out of the tunnels the contractor made the wise decision to source Robbins continuous conveyors designed and manufactured per the specific requirements of the site. In addition to its ability to transport muck on grades not serviceable by traditional locomotives, the system provides other benefits. These include greater system availability, less down time and more importantly, greatly simplified logistics when compared to rail-based muck cars. The material/personnel “supply trains” are free to come and go at any time.

Each TBM’s conveyor discharges muck onto the trailing-gear-mounted advancing tailpiece that

contains and aligns the tail pulley of the tunnel conveyor. The tailpiece has an “installation window” through which the carrying structure is assembled and troughing idlers are attached. As the TBM advances, the structure and troughing idlers emerge from the rear of the tailpiece, and the side rail supports and return rollers are installed. From there the muck is deposited onto the continuous tunnel conveyor.

Both of the extensible conveyor systems are equipped with a 500 m capacity belt storage cassette and splicing stand to allow the TBMs to bore approximately 250 m before more of the fabric-reinforced belt needs to be added. Belting is added during regularly scheduled TBM maintenance shifts. The continuous tunnel conveyors deposit onto a single stationary overland conveyor located in the aft end of the launch box that feeds a nearby radial stacker conveyor (see Figure 8).

Supply of Materials and Personnel

Supply of tunnel lining segments, utility extension supplies, other materials and personnel is handled using specially designed rubber tired vehicles (RTVs).

The RTVs are engineered to drive on the curved tunnel invert with automated self-centering, as well as flat ground with seamless transition from one to the other without operator input. To negotiate the tight curves and fit through the trailing gear of the TBM, the RTVs are articulated. Further insurance to prevent collision is provided by an auto pilot system that is engaged when the RTV approaches the backup and safely guides it through.

The single most important feature is that the RTVs have operator’s cabins on each end, allowing them to be driven in and out of the tunnel without being turned around or needing to be “backed out” (see Figure 9).

Project Status as of Press Time— Mid-December 2013

Presently the first TBM has been fully commissioned, has built 428 rings (652 m) and is boring at a rate of 16–20 rings per day. The typical operating “day” is 20 hours of operation comprised of 2 × 10 hour long excavation shifts and 4 hours for machine maintenance. The continuous conveyor system is fully installed on this drive and muck flows from it to the overland conveyor onto the radial stacker.

The second TBM has also been assembled and launched with the full trailing gear installed. After advancing 113 m (74 rings) using piston pumps to discharge muck, the initial section was completed in mid-November 2013. Boring is presently suspended while the contractor removes the piston



Figure 7. Lowering a section of machine shield (Image credit: SFMTA)



Figure 8. Horizontal conveyors going around a curve



Figure 9. RTV transporting segments (Image credit: sfmta.com)

pump mucking system, thrust frame and temporary free standing rings. Concurrently they will begin the installation of main drive, belt storage cassette and remaining components of the continuous conveyor system to complete the commissioning process and resume production.

CONCLUSIONS

Urban tunneling can be a difficult and risky endeavor, but working closely with the TBM manufacturer can greatly alleviate many of these difficulties. By having assurance that the most current technology is being used much of the risk of urban tunneling can be reduced. Also, having detailed assembly, startup, operational and settlement mitigation procedures in place at the outset of a project can greatly increase its chances of success.

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