EVALUATION OF LARGE TUNNELS IN POOR GROUND—ALTERNATIVE TUNNEL CONCEPTS FOR THE TRANSBAY DOWNTOWN RAIL EXTENSION PROJECT

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INTRODUCTION

The Transbay-Caltrain Downtown Extension (DTX) Project involves the construction of an approximately 1.5-mile rail line that will extend Caltrain commuter service and the future California High Speed Rail system into downtown San Francisco. The underground rail extension will be constructed by mined tunnel and cut-and-cover methods. Tunneling challenges include difficult ground conditions, low rock cover, the presence of historic buildings along the alignment, and the large tunnel span, ranging from approximately 50 to 65 feet. Three mined tunnel construction methods were evaluated: the Stacked Drift Method, the New Austrian Tunneling Method/Sequential Excavation Method (NATM/SEM), and Tunnel Boring Machines (TBM). This paper describes the challenges presented within the mined tunnel section, and summarizes the evaluation of tunneling methods that led to the selection of NATM/SEM.

PROJECT OVERVIEW

The existing Transbay Terminal opened in downtown San Francisco in 1939. This facility is antiquated, and does not meet current building seismic safety standards or the transportation needs of the Bay Area. For these reasons, San Francisco voters approved Proposition H in 1999, which proposed to construct a new or rebuilt regional transit center at the site of the existing terminal and extend Caltrain commuter rail service to the new transit center.

The new transit center is the hub of the Transbay Transit Center (TTC) Program, which will greatly enhance regional transit service by providing connectivity for six Bay Area transit providers at one facility. The program will be the largest inter-modal center west of New York City. The TTC Program is comprised of two major projects, the Transit

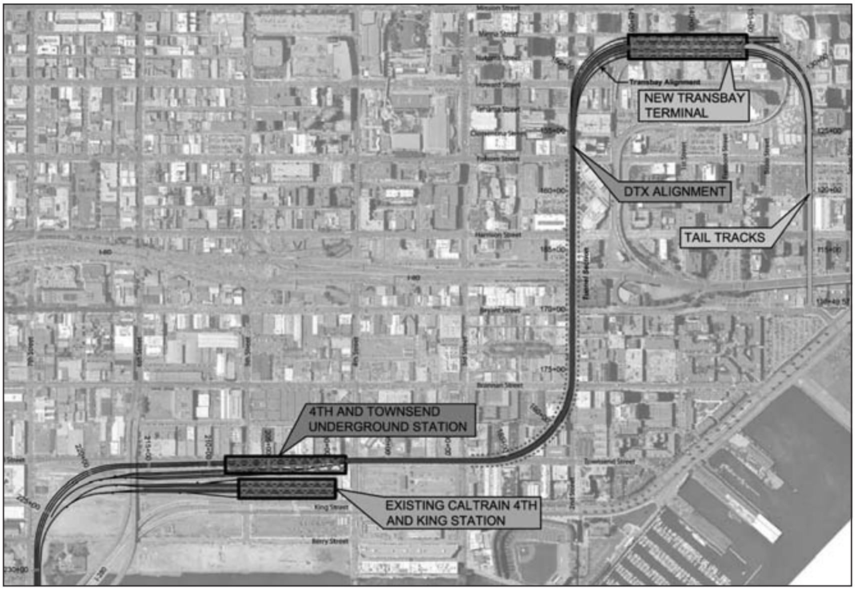

Figure 1. General plan of DTX alignment

Center and associated infrastructure, and the DTX Project (Figure 1). The DTX Project includes:

- A 1.5-mile underground rail extension along Townsend and 2nd Streets to the new TTC,
- A new underground station at the intersection of 4th and Townsend Streets, and
- Improvements to the existing rail yard facility and existing Caltrain terminal at 4th and King Streets.

The DTX Project comprises approximately 3,200 feet of mined tunnel, 4,700 feet of cut-and-cover tunnel, and 2,300 feet of open/retained cut construction. The excavated size of the mined tunnel—a single bore tunnel that could be 65 feet wide and 43 feet high—will be among the largest constructed in the United States.

PLANNING AND DESIGN BACKGROUND

Planning and conceptual design efforts for the project have focused on the development of a project configuration which meets the operational and functional requirements of the rail operators; Caltrain and the California High Speed Rail Authority (CHSRA). The mined tunnel concepts developed thus far include several potential configurations. It is recognized that the selected configuration will need to be refined as the design process progresses.

The configuration and cross-section of the mined tunnel are being determined by on-going parallel studies involving rail operation simulations and rail engineering evaluations. The outcomes of these studies have a significant impact on the tunnel construction methodology and the cost of the project. Some of the goals of these studies are to determine the:

- Rolling stock dynamic envelope and required tunnel clearances,
- Number of tracks required to provide sufficient operational capacity (e.g., two or three tracks), and
- Locations of crossovers and other special track work.

Tunnel Clearances

While the development of tunnel clearances would appear to be a straightforward matter, neither Caltrain nor CHSRA have identified the rolling stock they intend to employ for future operations. In the interim, a composite vehicle envelope has been developed based upon current technology which accommodates a range of vehicles that could potentially be used. Preliminary tunnel clearances have been developed using this vehicle envelope with appropriate provisions to generally satisfy California Public Utilities Commission (CPUC) General Order 26D. However, the CPUC requirements mainly address freight lines and the Transbay Joint Powers Authority (TJPA) Program does not intend to bring freight rail traffic into the new TTC. The current clearance diagrams developed to meet these requirements call for a tunnel 21.5 feet high (above top of the rail) and 40 and 55 feet wide for the two- and three-track options. Passenger dedicated lines (PDLs), like this proposed rail extension, would typically have smaller clearances. In due course, the project will seek a dispensation (variance) from CPUC to reduce clearances to those required for PDLs.

Two- and Three-Track Options

Construction of either a two- or three-track tunnel has obvious cost implications. This choice will also significantly impact the tunnel configuration and selection of the tunneling method. The DTX alignment is largely within the City-owned street right of way. Due to this width constraint a three-track tunnel can only be accomplished using a large single bore. In contrast, the two-track tunnel can be constructed in either a single bore or twin bore configuration, however the practical length of twin bore tunnel that can be constructed is limited to about 2,250 feet due to the necessity for crossovers between adjacent tracks to satisfy rail operations requirements.

GEOLOGIC CONDITIONS

The geologic conditions along the DTX alignment are known to be highly variable and complex. To develop a thorough understanding of the subsurface conditions an extensive geotechnical investigation program has been conducted over the past two years (Arup, 2006). To date, 25 borings have been completed along the mined tunnel section, totaling approximately 2,900 linear feet of borehole. A variety of in situ field and laboratory tests were completed to characterize geologic conditions.

The mined tunnel section of the DTX traverses an area of high bedrock associated with Rincon Hill, a prominent ridge on the southern side of the financial district in downtown San Francisco. Like most of the San Francisco peninsula, bedrock in this area is composed of Jurassic to Cretaceous sedimentary rocks of the Franciscan Formation. These rocks are generally highly fractured and sheared as a result of tectonic movements at the boundary between the Pacific and North American Plates. In the mined tunnel section, the Franciscan bedrock is generally within 5 to 10 feet of the ground surface, and groundwater levels are about 10 to 20 feet below the ground surface.

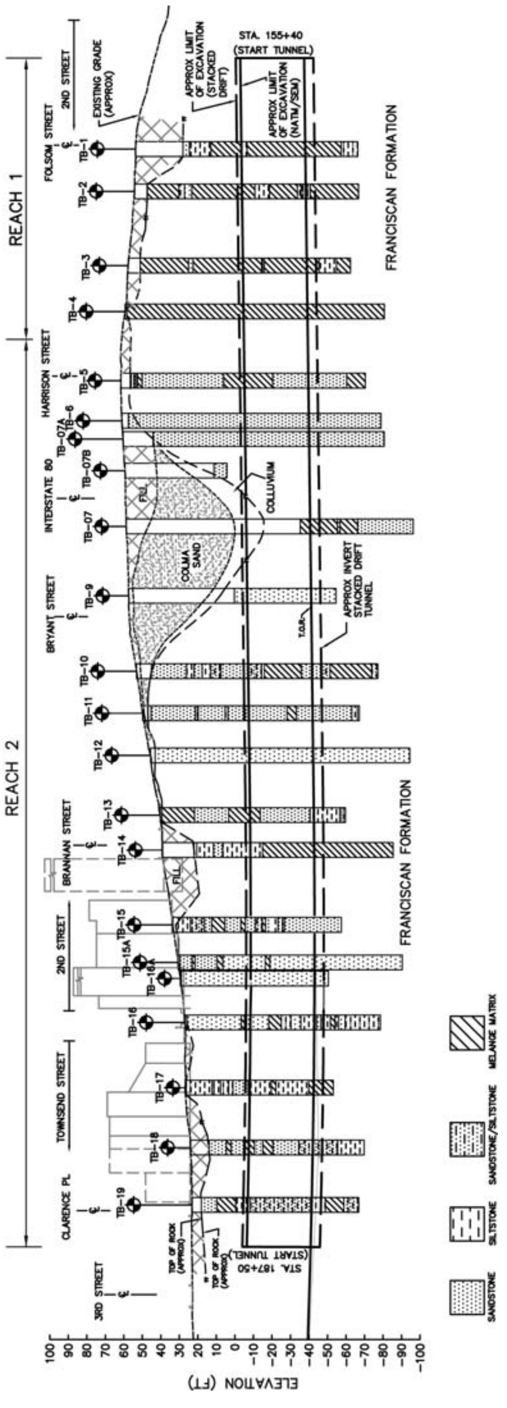

Figure 2. Summary geologic profile for DTX mined tunnel section

Soil deposits along the DTX alignment include artificial fill, Bay Mud and other marine deposits, Colma Formation, and colluvium. These deposits will only be encountered in one area of the tunnel, on 2nd Street between about Bryant Street and Interstate 80 (see Figure 2). In this area a paleovalley of colluvium and Colma Formation extends into the tunnel horizon. Ground improvement (such as jet grouting or similar techniques) may be required to treat these soils prior to tunnel excavation.

Franciscan Formation

The Franciscan Formation is a highly deformed rock mass that includes weak, sheared, fine-grained sediments and stronger rock blocks of various lithologies. The resulting rock mass is extremely variable and it possesses a chaotic structure of disconnected rock blocks surrounded by a weaker matrix. Locally these rocks are referred to as a "mélange." The mélange matrix is composed of stiff clay, sheared shale, and disaggregated rock fragments. Blocks within the mélange are predominantly sandstone and siltstone, although blocks of stronger rocks like chert and greenstone are sometimes present. For the purposes of the conceptual tunnel evaluation, the alignment was split into two distinct reaches, as indicated on Figure 2.

Reach 1. Borings in the northern 800 feet of the mined tunnel, referred to as Reach 1, found that over 85% of the rock mass in this area is composed of mélange matrix. The clay content of some core runs was as high as 90%, and only a small number of discrete blocks of sandstone and siltstone were observed. The mélange matrix in this reach is extremely weak and extensively sheared, and in places is pulverized to crushed rock fragments.

The strength of the clayey mélange matrix was evaluated based on UU triaxial tests. These tests indicate an average compressive strength of about 100 pounds per square inch (psi). The unconfined compressive strength (UCS) of sheared shale samples that could be tested are higher, ranging from about 160 to 400 psi. However, much of the mélange matrix was so pulverized that it could not be tested in the laboratory.

Rock mass quality was assessed from the Rock Quality Designation (RQD) values indicated on the core logs and estimates of the Rock Mass Rating (RMR) and Tunneling Quality Index (Q) determined following the procedures of Bieniawski (1989) and Barton et al. (1974), respectively. For this reach, almost 70% of the core runs had a RQD of zero, and none of the values were above 25, which is the upper bound value for "very poor" quality rock (Deere, 1989). RMR and Q values also indicated low rock quality for this reach with overall ratings of "very poor" for the RMR system and "exceptionally poor" for the Q system.

Reach 2. Borings drilled in the southern 2,400 feet of the mined tunnel section, referred to as Reach 2, found a rock mass that was much different than that encountered in the Reach 1 borings. The rock mass encountered in Reach 2 was mainly strong sandstone and siltstone blocks (about 75%), and contained much less of the weak mélange matrix. The rock in Reach 2 is still highly fractured, but in general, the sandstone and siltstone blocks are much stronger than the mélange matrix.

The sandstone in this reach varies considerably in strength, from weak to strong. High variability in the UCS test results appears to be a result of defects in the rock samples caused by shear failures along preexisting, but healed, fractures, rather than through intact rock. UCS values for the sandstone range from about 1,300 to 19,000 psi, with an average of 7,700 psi, although one test result from a previous investigation program recorded an UCS of 27,200 psi. These results imply that the fresh, unfractured sandstone can be very strong, but most of the test samples contained healed fractures or other defects that tended to reduce their strength. The siltstone is considerably weaker than the sandstone, with strengths ranging from approximately 200 to 4,000 psi.

Figure 3. Existing buildings on Townsend Street above DTX alignment

RQD values in this reach are typically higher than those in Reach 1. Approximately 45% of the rock core in Reach 2 is classified as “poor” or “fair” (RQD of 25 to 75) and only about 55% as “very poor” (RQD less than 25). Less fracturing and higher rock strength in Reach 2 resulted in higher RMR and Q ratings, but the abundance of discontinuity fillings with sheared shale and clay tended to lower the ratings. Ratings in Reach 2 are generally “fair” to “poor” for the RMR system and “extremely poor” to “very poor” for the Q system.

HISTORIC BUILDINGS

As the DTX alignment transitions from Townsend Street to 2nd Street, the mined tunnel passes beneath 11 existing buildings. Figure 3 is a photograph of some of these buildings, which range in height from one to six stories. The buildings were constructed in the early 1900s. All are part of the Rincon Point/South Beach Historic Warehouse-Industrial District, and may be eligible for the National Historic Register. The mined tunnel will pass beneath these buildings with low rock cover (relative to the tunnel span) that ranges from about 20 to 35 feet. To the north, along 2nd Street, the alignment does not pass directly under any buildings because it is located under the street. However, there are numerous existing buildings on both sides of the street adjacent to the tunnel. Most of them are low rise buildings two to seven stories high, but there are some newer high-rise buildings north of Harrison Street. Limiting ground movements and associated surface settlements to avoid damage to the adjacent and overlying buildings is a critical concern for the project.

MINED TUNNEL ALTERNATIVES EVALUATION

The goal of the mined tunnel alternatives evaluation was to identify the preferred method of constructing the mined tunnel in terms of cost and schedule, while seeking to mitigate the inherent risks posed by the difficult and variable geologic conditions and the physical requirements of the project.

This was accomplished by identifying conservative tunneling methods that are appropriate for the challenging ground conditions and have the ability to control ground movements, reducing the potential for damaging the existing buildings. The combination of challenging ground conditions, existing buildings above the alignment,

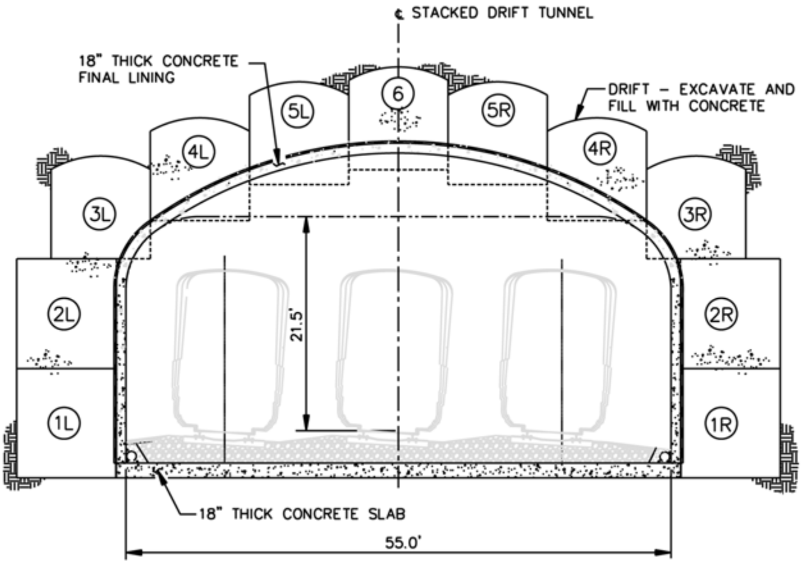

Figure 4. Typical tunnel section for stacked drift tunnel alternative

low rock cover, and the large tunnel span required an approach that would allow the tunnel to be excavated and supported in stages, thereby limiting the unsupported span and maintaining the stability of the excavation. The Stacked Drift Method and the NATM/SEM satisfy these requirements. Tunnel Boring Machines (TBMs) were also considered, as this method is often a cost effective and an attractive approach for constructing tunnels in urban areas.

Both two- and three-track single-bore tunnels were evaluated for the Stacked Drift Method and NATM/SEM. For the NATM/SEM, a two-track twin-bore tunnel concept was also evaluated. TBMs were considered for a twin-bore tunnel configuration (one track each) only. The inability to develop a three-track tunnel configuration was a limitation of the TBM method. A three-track extension is the current base track configuration for the project.

Stacked Drift Method

The Stacked Drift Method was developed specifically for the construction of large tunnels in poor ground conditions. Basically, this method involves mining a series of interconnected concrete-filled drifts in a certain sequence around the tunnel perimeter. After all of the drifts are backfilled with concrete, a continuous and robust structural arch has been constructed over the core of the tunnel entirely pre-supporting the ground before any excavation of the central core. For the DTX Project this means the central core can be safely excavated without inducing significant ground movements, reducing the risk of surface settlement which could damage historic buildings. Figure 4 shows a typical cross section for the three-track Stacked Drift tunnel alternative. This approach has been successfully used in the U.S. for other large tunnels in difficult, poor-quality ground. One project was the Eisenhower Tunnel on Interstate 70 in Colorado (Hopper et al., 1972). Another was the Rio Piedras Station for the Tren Urbano Project in Puerto Rico, which was a 62-foot-wide by 52-foot-high excavation in soft ground directly beneath several historic structures (Romero et al., 2001).

For the DTX Project, small drifts of approximately 10 feet by 10 feet would be excavated by hand-mining operations using a small roadheader or excavator and a tunnel loader for spoil removal. Some blasting could be required in strong, less fractured sandstone. Given the anticipated difficult ground conditions, 3-foot rounds were assumed, with one steel set being installed in each advance cycle. Shotcrete is provided for ground support between the sets, and timber lagging could be used where it projects inside the final excavation lines and would be removed by subsequent excavation operations. In unstable ground, special precautions could be required, such as the use of spiling installed in advance of the excavation and/or breasting or shotcrete to support the face. Such measures would maintain excavation stability and minimize overbreak that could lead to surface settlement.

The drifts would be mined from the lowest drift to the top drift with drifts at the same elevations being mined simultaneously (see Figure 4). Excavation for each pair of drifts would be completed and the drifts backfilled with concrete before excavation of the next drifts in the sequence began. Constructing each subsequent drift above the previously concreted drifts minimizes potential surface settlement by establishing a stable foundation for the base of the arch. Once all the drifts have been excavated and concreted, the core inside the arch would be removed in several excavation stages and a concrete invert slab cast to serve as a strut at the base of the tunnel. This would limit potential convergence of the sidewalls of the tunnel.

After tunnel clean-up, a cast-in-place concrete final lining would be placed as a finish for the tunnel. Groundwater would be continuously drained to avoid the build-up of hydrostatic pressure on the final tunnel lining. Drainage would be accomplished by installing a drainage geotextile and a PVC waterproofing membrane along the crown, arch, and sidewalls of the tunnel that is connected to an invert drain system. Design of watertight tunnel is not cost-effective because of the flat tunnel invert and high groundwater levels.

Conceptual design analyses included several preliminary structural and geotechnical calculations. For example, soil-structure interaction analyses were conducted to check the stability of the drift arrangement and to evaluate the need for shear reinforcement between adjacent drifts. Settlement estimates were prepared indicating that only minor surface settlement is expected with this method—approximately ½ to ¾ inch.

NATM/SEM

The NATM/SEM is in use worldwide. The method has been used in the United States since the early 1980s, with the first applications being in the Pittsburgh and Washington D.C. areas. Since then, the NATM/SEM has been used on a variety of transit projects in Dallas, Boston, Seattle, and San Juan, Puerto Rico. The basic principle of NATM/SEM design is to allow small ground movements to occur around the tunnel in order to mobilize the strength of the ground. These limited movements significantly reduce the loads on the final lining. Rock bolts, lattice girders, shotcrete, and wire mesh are employed instead of heavy timber or steel supports to develop the strength of the ground without compromising excavation stability.

For large tunnels constructed using a NATM/SEM approach, the tunnel excavation is divided into a number of drifts and the tunnel is gradually enlarged and supported to maintain the stability of the tunnel and control ground movements. Drift sizes and the excavation sequence are based on anticipated ground behavior and construction logistics. The drift advance lengths are primarily controlled by the anticipated stand-up time of the ground and the size of the drifts. For the two-track tunnel, a total excavated width of about 49 feet and an excavated height of about 39 feet would be advanced

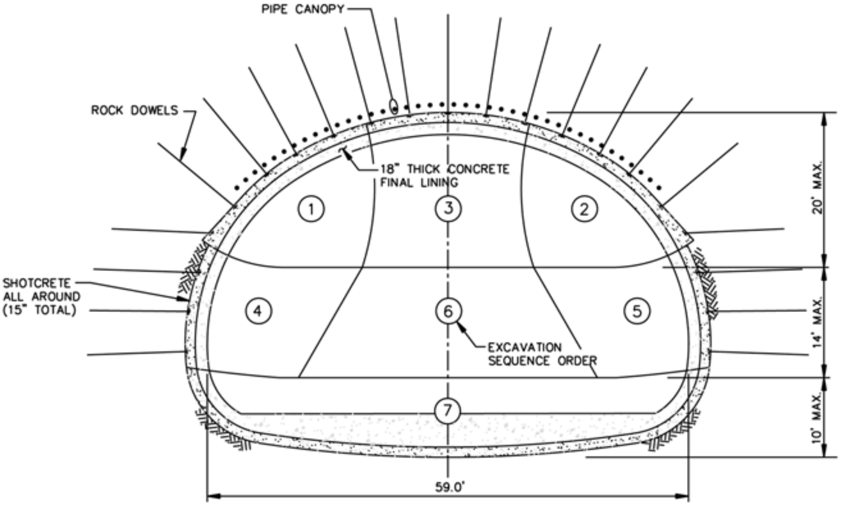

Figure 5. Typical tunnel section for NATM/SEM tunnel alternative

using seven individually mined drifts: three in the top heading, three in a top bench, and one at the invert. The same total number of drifts and sequencing would be used for the three-track tunnel, which has a total excavated width of about 66 feet and an excavated height of about 43 feet. Figure 5 shows a typical cross-section for the three-track tunnel alternative, including the drift excavation sequence. This is a conservative drift configuration which could be necessary when tunneling beneath the existing buildings along Townsend and 2nd Streets. In other areas, a less conservative drift configuration may be feasible allowing more efficient mining rates and reducing the construction schedule. During future design analyses, the drift configuration will be reevaluated and modified based on geologic conditions and potential impacts to surface facilities.

After completion of the tunnel excavation and installation of the shotcrete lining, a waterproof membrane would be installed on the inside of the initial lining before placement of the final concrete lining. The waterproofing system would likely consist of a flexible PVC waterproofing membrane that is heat-welded to create a continuous watertight seal around the tunnel opening. Design of a watertight tunnel is considered feasible structurally for an NATM/SEM tunnel because the invert can be curved to reduce the bending moments induced by the hydrostatic pressure. This approach is beneficial in minimizing long-term impacts on the local groundwater system and reducing tunnel maintenance requirements.

Preliminary numerical analyses using finite difference methods and the computer program FLAC were done to predict the stresses and displacements in the ground and support elements during the various excavation stages. These analyses were used to check the drift size, round length, and excavation and support sequence. Generally, the results indicated that the proposed drift arrangement and sequence were conservative. Surface settlement with NATM was estimated to be slightly greater than the settlement associated with the stacked drift method—approximately ¾ to 1 inch. To mitigate the risk of damage to overlying buildings, it was proposed that additional ground support be provided in the form of a grouted pipe canopy. The pipe canopy

Table 1. Construction cost and schedule estimates

Alternative Description	Construction Cost	Construction Duration (months)
2-Track Stacked Drift	$297 M	71
3-Track Stacked Drift	$329 M	80
2-Track NATM/SEM	$226 M	48
3-Track NATM/SEM	$253 M	53
2-Track Twin Bore NATM/SEM	$260 M	45

would consist of 3- or 4-inch diameter pipes installed about 12 inches apart in the tunnel arch. The pipes would provide positive presupport/reinforcement for the tunnel arch, reducing loss of ground and minimizing surface settlement. Additional rock bolts, greater shotcrete thickness, and reduced round lengths would be considered for improved control of ground movements within sections of the tunnel where there is a greater risk of damage to adjacent properties and utilities from ground movements.

TBMs

TBMs can be used to construct tunnels in a wide variety of geologic conditions, including the Franciscan Formation. A shielded TBM was used to successfully construct the Richmond Transport Tunnel in San Francisco. It extended through Franciscan mélange and sandstone (Klein et al., 2001). One advantage of TBM methods is that there is minimal ground disturbance during excavation, although some minor vibrations are produced.

TBMs were not evaluated in detail because early evaluations determined that this method was probably not practical for the DTX project. This was primarily because of economic and right-of-way considerations. To accommodate the established tunnel clearances, a 33.5-foot-diameter TBM would be required. Given the short length of the mined tunnel section (only about 3,200 feet) and the cost of a TBM of this size, TBM methods did not appear to be cost-effective. In addition, the public right-of-way beneath 2nd Street is only about 82 feet wide, and twin TBM tunnels located at the edge of the right-of-way on each side would only be about 15 feet at the center. Such a small pillar might be acceptable in competent rock, but is questionable in the weak rock along the DTX alignment, and any settlement resulting from tunnel excavation would affect the existing buildings on 2nd Street unless mitigation measures were implemented. For these reasons TBM methods were not considered further in the conceptual design evaluations and cost and schedule estimates were not developed for this method.

CONSTRUCTION COST AND SCHEDULE ESTIMATES

Conceptual construction cost and schedule estimates were prepared for the two- and three-track configurations using the Stacked Drift Method and NATM/SEM. Table 1 summarizes the construction cost and schedule estimates for each alternative. The cost estimates are production-based and account for all labor, material, and equipment costs. Some basic assumptions are:

- Prevailing labor rates from California Department of Industrial Relations;
- Equipment rates from the U.S. Army Corps of Engineers *Construction Equipment Ownership and Operating Expense Schedule (Region VII)*, published in 2003 for the Western States; and

- Material and subcontract costs based on current market prices. Quotes were obtained for construction equipment and for large-quantity items such as rock bolts, steel sets, and lattice girders.

Cost estimates were prepared in December 2005 dollars and they were not adjusted for inflation. The following were excluded from these estimates:

- Design and construction contingencies;
- Escalation to adjust costs to the time of expenditure;
- Program costs, such as design and construction management fees, right-of-way and land acquisition, permits, etc.; and
- Rail and tunnel operating system costs.

EVALUATION OF ALTERNATIVES

While many constructability factors were considered in the evaluation of the alternatives, ultimately the preferred construction method was determined on the basis of cost and schedule in relation to achieving the owner's requirements. A comparison of the Stacked Drift Method and NATM/SEM approach for the two- and three-track alternatives reveals that the Stacked Drift method is approximately 30 percent more expensive than the NATM/SEM approach and has a construction duration that is about two years longer. Therefore, the NATM/SEM approach has significant cost and schedule benefits over the Stacked Drift Method.

Though it was originally expected that the Stacked Drift Method would result in much less surface settlement than the NATM/SEM approach, preliminary analyses have indicated that by employing a pipe canopy and a conservative excavation and support sequence (including short round lengths), the NATM/SEM approach yields only slightly more settlement (about ¼ inch). In terms of risks the Stacked Drift Method minimizes the area of potential collapse to that of the drift currently being excavated; whereas with NATM/SEM the drifts are larger exposing a greater area that could be susceptible to collapse. This higher risk can be mitigated with NATM/SEM in the same way the potential for settlement is controlled, i.e., by use of a pipe canopy, conservative excavation and support sequence, and shorter round lengths.

Besides the cost and schedule advantages, some other identified advantages of the NATM/SEM over the Stacked Drift Method are:

- Less potential that blasting will be required, as the larger drift sizes will allow the use of larger, high-capacity roadheaders.
- More consistently manageable truck traffic volumes during tunnel excavation (Stacked Drift Method would produce a spike in traffic during excavation of the central core).
- More economical and efficient ground support as ground support measures are tailored to the ground conditions actually encountered.
- Feasible to design a watertight tunnel lining minimizing groundwater impacts and tunnel maintenance costs.

Considering the above comparison, it was concluded that the NATM/SEM approach is more cost effective, faster, and the resulting risks can be effectively mitigated. Therefore, the NATM/SEM approach has been adopted for preliminary design.

CURRENT PROJECT STATUS

The DTX Project is currently in Preliminary Engineering Part 1, which includes various project development studies, alternatives evaluations, conceptual design, and development of associated cost estimates. The objectives of this phase are to define the configuration of the DTX project in terms of the number of rail tracks and structure type and limits, and to refine the project cost and schedule estimates.

The Part 1 studies focus on the Locally Preferred Alternative (LPA) alignment, approved as part of the FEIS/EIR process and shown in Figure 1. Additional funding has also been made available to investigate the feasibility of several value management recommendations conceived to reduce the cost of the DTX project. It is anticipated that these parallel studies will converge in the summer of 2007, resulting in a recommended configuration and overall construction approach for the DTX Project. Preliminary Engineering Part 1 will conclude in late 2007.

While the design studies and conceptual engineering continue, TJPA will be identifying and securing the funding necessary to construct the DTX. Once the funding plan is finalized (which is currently scheduled for 2008), the project will proceed to Preliminary Engineering Part 2 (completion of preliminary engineering) and then detailed design. Construction is currently scheduled to commence in late 2011 or early 2012. If funding is identified earlier, construction could begin sooner.

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