Geotechnical Conditions and TBM Selection for the Bay Tunnel

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ABSTRACT: San Francisco Public Utilities Commission is planning to replace 5 miles of pipeline under San Francisco Bay. The tunnel will be constructed using an Earth Pressure Balance (EPB) TBM and will be the first TBM-driven tunnel under the Bay. The alignment passes under environmentally sensitive habitats, through interbedded layers of sands and clays, and through a buried bedrock ridge. This paper discusses the geotechnical characterization and anticipated tunneling conditions and presents the analysis of various construction methods that resulted in the selection of an EPB TBM. Considerations related to tunneling with an EPB TBM are described in detail, including ground conditioners, TBM cutterhead wear, muck control, and squeezing ground.

PROJECT BACKGROUND

The San Francisco Public Utilities Commission (SFPUC) is upgrading its water system, which serves residential customers in the City of San Francisco and wholesale customers throughout the Bay Area. The Bay Division Pipelines Reliability Upgrade Project, one component of these upgrades, consists of constructing the 21-mile Bay Division Pipeline No. 5 (BDPL No. 5) from Irvington Tunnel Portal in Fremont to Pulgas Tunnel Portal near Redwood City, including a tunnel (Bay Tunnel) under the San Francisco Bay. The project will provide seismic and delivery reliability to the SFPUC's customers and contribute to the SFPUC's goal of ensuring a high-quality water supply.

The Bay Tunnel segment of BDPL No. 5 will consist of a 108-inch-internal-diameter pipeline that will extend 5 miles from Newark Valve House to Ravenswood Valve House, crossing under the San Francisco Bay, adjacent marshlands, and salt ponds (see Figure 1). Existing BDPLs Nos. 1 and 2 will tie in to the tunnel at both ends. The presence of environmentally-sensitive habitats on the Bay margins requires that the 5-mile-long tunnel be constructed only with launching and receiving shafts; there will be no intermediate construction shafts. The shafts will be constructed using diaphragm slurry wall or sunken caisson construction methods with tremied structural concrete slabs tied into the shaft bottoms. The TBM launching and tunnel construction shaft located at the Ravenswood site on the west side of the Bay will be approximately 58 ft in diameter and 110 ft deep. The receiving shaft located at the Newark site on the east side of the Bay will be approximately 28 ft in diameter and 74 ft deep. The tunnel depth ranges from about 70 to 100 feet below the mean surface (sea level) of the San Francisco Bay and was selected to maintain minimum clearances under the bottom of the Bay and to situate the tunnel in materials favorable for tunnel excavation and long-term pipeline performance.

The Bay Tunnel will be constructed as a two-pass system. In the first pass the tunnel will be excavated with a Tunnel Boring Machine (TBM) and precast concrete segmental lining will be erected as initial ground support immediately behind the TBM. In the second pass, the 108-inch steel pipeline will be installed inside the tunnel, and cellular concrete will be used to backfill the annular space between the outside of the pipe and the initial support.

GEOLOGIC CONDITIONS

Site Investigations

Geotechnical investigations included a series of marine-based borings across the San Francisco Bay, as well as land-based borings and cone penetrometer tests on the Newark and Ravenswood site locations. In most borings, sampling was continuous, and laboratory testing was conducted on selected samples from the borings. In addition to the conventional exploration, an extensive marine- and land-based geophysics program was performed along the majority of the proposed alignment corridor to facilitate interpretations between boreholes. Suspension logging was performed in selected boreholes at the Ravenswood

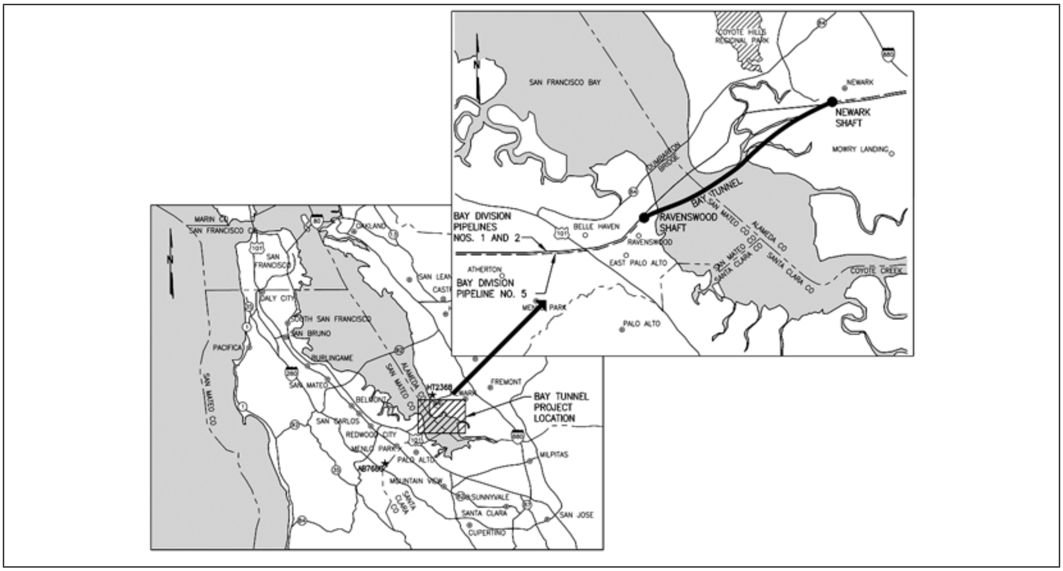

Figure 1. Bay Tunnel horizontal alignment

Table 1. Description of anticipated geology

Formation	Description
Young Bay Mud	Marine deposits consisting of soft to medium silty clay
San Antonio Formation	Alluvial deposits consisting of interlayered medium stiff to hard silt and clay, with dense sand lenses
Old Bay Clay	Marine deposits consisting of stiff to hard silty clay
Franciscan Complex	Sedimentary and low-grade metamorphic rock, highly weathered and fractured

and Newark sites to obtain in-situ horizontal shear wave and compressional wave velocities for determining ground motions. One outcome of the field investigation program was the identification of four primary geologic units along the tunnel alignment. Table 1 summarizes the anticipated geology.

After the geotechnical investigations, a geologic cross section was generated showing the interpreted stratigraphy along the proposed alignment. Figure 2 shows the anticipated geologic profile. An envelope consisting of one diameter above and below the tunnel profile was used to draw conclusions about the distribution of soil types along the alignment and to make recommendations about tunneling methods.

Expected Geologic Conditions

As indicated in Figure 2, the tunnel is primarily located within the San Antonio Formation, which consists of interlayered clays, silts, and sands. A 700-foot-long reach of the tunnel traverses a buried ridge of highly weathered Franciscan Complex bedrock. The TBM will need to be designed to accommodate the conditions within the buried bedrock ridge as well as the soil conditions along the rest of the nearly 26,000-foot-long tunnel alignment.

The Franciscan Complex is expected to be highly weathered and fractured but may contain relatively unweathered basalt, sandstone, and chert that can be very hard, strong, and abrasive, and is thus considerably different than the soil units to be encountered along the remainder of the tunnel alignment.

In selecting and specifying a TBM and excavation requirements (e.g., ground conditioning), the amount of soil with high fines content (clays and silts) and the amount of soil with coarse materials (sands and gravels) are important. In addition, it is important to characterize the stratigraphic distribution of the soil types, particularly for poorly-graded sands and gravels, as these soils can be problematic for some TBMs if they are encountered in excessively thick or laterally continuous layers as opposed to isolated lenses.

In order to draw some conclusions regarding the type of mechanical excavation most appropriate for the Bay Tunnel, laboratory testing, including

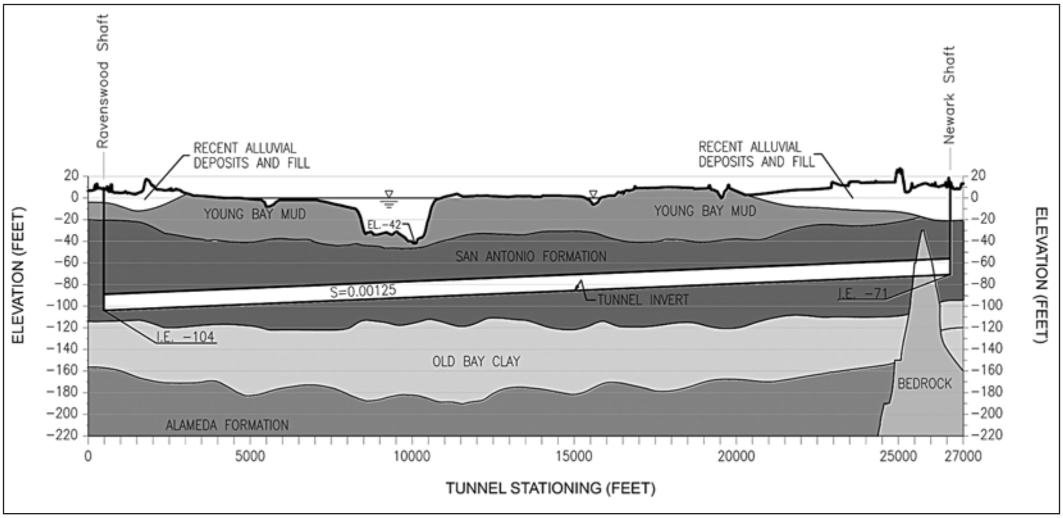

Figure 2. Geologic profile along the proposed Bay Tunnel alignment

sieve and hydrometer testing, was performed to determine the gradation curves for the various soil types sampled in the borings. These data, along with visual-manual soil classification of logged samples, were used to classify soil by the Unified Soil Classification System (USCS).

Statistical analysis was performed to synthesize the data and draw some preliminary conclusions. Figure 3 summarizes the visual-manual boring log descriptions of the material combined with the sieve test results. Groupings are based on the fines contents of each soil classification, with soils having the highest fines contents on the left and soils having the lowest fines contents (i.e., coarser materials) on the right. Figure 3 includes data from one tunnel diameter above and one tunnel diameter below the proposed tunnel alignment in order to provide a more complete picture of the types of soils expected and the variability which may exist within the tunnel horizon. It should be noted that the percentage of fine-grained material increases with tunnel depth, but a significant amount of coarser sand is also present at lower depths.

Groundwater

The land-based geotechnical investigation included the installation of piezometers near the Ravenswood Valve House and the Newark Shaft. The groundwater level in the piezometers has been consistently high at 0.5 to 10 feet below the ground surface (near or at sea level). The tunnel alignment is expected to be constructed under varying depths of groundwater.

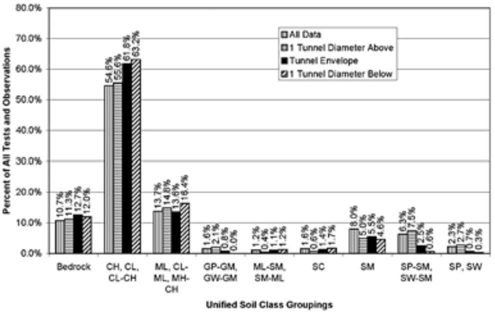

Figure 3. USCS visual–manual and sieve test summary from geotechnical investigations

Anticipated Tunneling Conditions

Ground behavior characterization was based on soil grain size distribution, undrained shear strength, and density/consistency. Ground behavior anticipated for tunneling was based on the 'Tunnelman's Ground Classification' developed from Heuer and Virgens (1987) and Brandt (1970). Ground classifications along the Bay Tunnel are expected to include firm, slow to fast raveling, squeezing, swelling, cohesive running to running, very soft squeezing and flowing ground conditions.

The Tunnelman's Ground Classification was created before the widespread use of pressurized-face TBMs and therefore assumes an open-face excavation method. Nevertheless, it is useful for evaluation of pressurized-face methods because ground conditions classified as unstable by this method indicate that pressurized-face methods may be more applicable.

Assessment of Soil Grain Size

Soil grain size distributions were evaluated by computing the soil's uniformity coefficient (C_u). The uniformity coefficient was computed using the following equation:

$$C_u = \frac{D_{60}}{D_{10}}$$

Where D_{60} is the grain diameter (in millimeters) corresponding to 60 percent passing and D_{10} is the grain diameter (in millimeters) corresponding to 10 percent passing.

A soil's uniformity coefficient (C_u) is a comparative indication of the range of particle sizes and is useful for determining if a soil is poorly or well-graded. Uniformity coefficients less than three correspond to very poorly graded soils while uniformity coefficients greater than six correspond to well-graded soils. Poorly graded soils are typically less stable as the particles are not as bonded, with very little clay binder or cohesion, while well-graded soils are typically more stable as the particles are bound with clay binder and are more cohesive.

The distribution of uniformity coefficients shown in Figure 4 illustrates the extent of well-graded soils along the Bay Tunnel alignment. As noted above, the percentage of fine-grained cohesive materials tends to increase with depth. At the tunnel horizon, more than 90 percent of the materials can be classified as well-graded soils, according to the uniformity coefficients. However, some of the soil uniformity coefficients are less than three, which indicates poorly graded sands within the tunnel horizon. These sands could cause running or flowing ground if the face is not adequately supported.

Since excessively thick or laterally continuous layers of sand can be problematic for some types of TBMs, it is important to characterize the thickness and likelihood of encountering a sand layer. Figure 5 summarizes the expected thicknesses of sand layers at three locations: one diameter above the tunnel crown, one diameter below the tunnel invert, and at the tunnel face. Of the sand that is anticipated to be encountered at the tunnel face, 25% is expected to be 10 to 20 feet thick. Referring to Figure 3 it can be seen that over 10% of the borings encountered sand within the tunnel horizon. This suggests that 2 to 3% of the sampled alignment may encounter full face sandy conditions. The data also indicates that the thickness of the sand layers decreases as the tunnel depth increases.

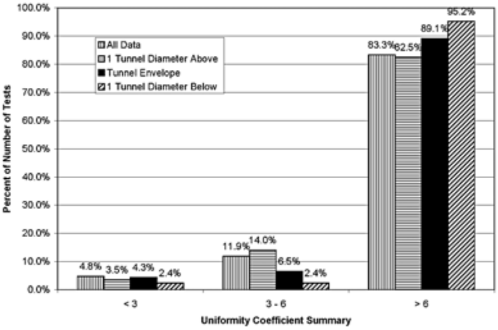

Figure 4. Uniformity coefficient summary from geotechnical investigations

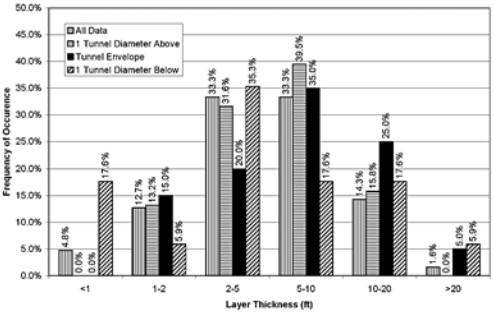

Figure 5. Sand layer thickness summary from geotechnical investigations

Assessment of Squeezing Ground

The potential for squeezing behavior of clay deposits was determined by computing the overload factor (also known as the stability factor). The overload factor (OF) was computed using the following equation:

$$OF = \frac{P_z - P_a}{S_u}$$

Where P_z is the total vertical pressure at tunnel depth, P_a is assumed to be atmospheric pressure (for an unsupported face), and S_u is the undrained strength from UU triaxial tests.

The overload factor was computed at the springline of the tunnel for each boring. This analysis is summarized in Figure 6.

This analysis, which is for an unsupported face, illustrates why pressure face methods are required. Because approximately 70 percent of the tunnel could experience moderate to extreme squeezing conditions, it is required that face pressure be controlled and regulated. The degree of squeezing tends to decrease with depth, so the majority of extreme

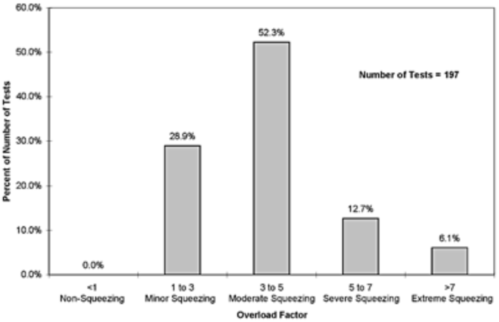

Figure 6. Potential for squeezing clays in an unsupported face as determined by Overload Factor analysis

squeezing and severe squeezing occurs at shallower depths. The deeper the tunnel is placed, the higher the shear strength of the material relative to the *in situ* stress, and the lower the degree of squeezing.

Pressurized face TBMs handle squeezing ground conditions better than other methods since face pressures are balanced, preventing the soil at the face from squeezing. The main area of concern is along the body of the TBM, where high friction forces can occur as the result of relaxation of material into the steering (i.e., overcut) gap created by the cutterhead.

TUNNEL CONSTRUCTION METHODS

Potential tunnel construction methods are described below, along with their overall feasibility (based on previous experience with the construction method and project impacts). Manual and partially-mechanized tunnel construction methods such as the Sequential Excavation Method, also known as the New Austrian Tunneling Method, were ruled out due to cost and schedule inefficiencies as compared to TBM methods. Feasible tunnel construction methods are: pressurized-face machines and shielded TBM methods, including open-face shields (with compressed air or ground modification).

Shielded Tunnel Boring Machines

Based on the available geological and geotechnical information for the Bay Tunnel, a tunneling shield may be used in one of the configurations below:

1. Compressed air support;
2. Slurry support, also referred to as 'pressurized-face' support; or
3. Earth pressure balance support, also referred to as 'pressurized-face' support.

Pressurized face techniques are used where control of the face is desirable due to face instabilities and high groundwater pressures. In the case of Bay Tunnel, there are anticipated zones of non-cohesive materials and areas of squeezing ground. Such conditions would likely be dangerous if an open, unpressurized TBM were used. Additionally, instabilities can lead to lost ground and unacceptable settlements or sinkholes at the ground surface. Significant portions of the Bay Tunnel alignment are affected by these conditions, so pressurized face techniques must be used to address worker safety, groundwater inflow, and settlement concerns.

Compressed Air Shields

Although the use of compressed air to control groundwater has decreased with the advent of pressurized-face TBM technology, compressed air can be an effective method of stabilizing soil and controlling groundwater in open-face tunnel excavations. Compressed air can be especially useful in squeezing, soft, clayey (cohesive) soils, and was used for construction of the BART and Muni tunnels along Market Street in San Francisco nearly 40 years ago.

In granular soils, compressed air can be used to offset the water pressure at the tunnel face, preventing the flow of groundwater (and fine-grained soils) into the face. In cohesive soils, the objective is to provide enough air pressure that the combination of the soil's natural strength and the air pressure stabilizes the tunnel for excavation and support operations. The use of compressed air is usually limited to situations in which soil grain sizes range from fine silt to medium sand; in coarse sand and gravel, air losses are often unacceptably high. The use of compressed air has several substantial disadvantages, including:

- Air locks must be installed between the tunnel face and the construction access shaft. In some cases, more than one airlock must be installed. These airlocks severely restrict space in the tunnel.
- Construction labor crews may have limited work time under compressed air and must undergo decompression after work periods, increasing labor costs and adding inefficiencies. If the air pressure is suddenly lost due to unforeseen conditions, labor crews may experience decompression sickness (i.e., 'the bends').

Because of these disadvantages, compressed air is often more expensive than other tunneling methods. However, due to the requirement for periodic inspection and maintenance of the TBM cutterhead (often referred to as interventions), compressed air support will be specified, albeit limited to the compressed airlocks mounted within the TBM shield and the excavation chamber itself. The compressed air pressures used will be related to the groundwater depth but are not expected to exceed 50 psi.

Pressurized-face Shields

TBMs that are capable of exerting a balancing pressure against the tunnel face can be used to control excavation rates and groundwater inflow, as well as maintain stability of the tunnel face. A pressurized-face TBM is well suited to Bay Tunnel, due to the mixed face conditions, presence of a high groundwater table, and varying permeabilities and strengths of the materials along the alignment. The two most common types of pressure-balancing TBMs are Earth Pressure Balance (EPB) TBMs and slurry shield TBMs.

The choice between slurry shield and EPB TBM excavation methods is influenced by several geotechnical factors, including: grain size distribution, cohesion, occurrence of boulders or obstructions, presence of gas and contaminants, feasibility of soil separation and muck disposal, and settlement considerations.

EPB TBMs hold the excavated material (along with water or added conditioners) under pressure in the plenum (excavation chamber), and use the pressure of the excavated material itself to balance earth and hydrostatic pressures. The pressure is maintained by the controlled release of excavated material via a screw conveyor. The screw conveyor is designed to develop a pressure gradient from the plenum to the outlet so that material is discharged in a controlled manner at atmospheric pressure. Muck is discharged from the screw through a closable guillotine door into muck cars or onto conveyors to be removed off-site.

Slurry shields rely on bentonite slurry to apply pressure to the tunnel face in the plenum, which counterbalances earth and hydrostatic pressures. This is achieved by a mud cake or membrane that forms on the tunnel face as excavation proceeds. The excavated material is suspended in the slurry and pumped through closed-circuit piping to a separation plant on the surface, where the suspended material is removed from the slurry at a separation plant. The resultant muck is disposed of off-site, while slurry is reconditioned and recirculated back to the tunnel face.

Slurry shields are available in two categories, depending on whether an air cushion is used for precise regulation of the face-support pressure. TBMs that incorporate this air cushion system are known as mixshield TBMs, which have been used successfully for over 20 years. The air cushion system consists of a partial bulkhead or buffer wall that separates the fluid-filled excavation chamber from a pressure chamber that contains an air cushion above the slurry surface. The air cushion system effectively eliminates large pressure fluctuations that can occur in standard slurry shields or EPB TBMs. In cohesive soils or in rocky conditions, which do not require such a sensitive support mechanism, a mixshield TBM can be used as a simple slurry machine (i.e., without the air cushion).

Slurry shield TBMs can be used in a wide range of ground conditions, but the system requires the use of a surface separation plant. The finer the muck grading, the more complicated and expensive the separation plant becomes.

For either a slurry shield or EPB TBM, the face is excavated with a rotational cutterhead equipped with cutting tools to remove the intact ground and draw the loosened material into the cutterhead. To efficiently remove the spoil, EPB cutterheads need to have at least a 30 percent opening ratio. For Bay Tunnel, the cutterhead also needs to be fitted with cutting tools that can excavate through soft ground as well as mixed-face reaches in the Franciscan Complex. The cutterhead must include: scrapers to bring loosened material into the cutterhead openings, rippers (drag bits), and disc cutter mounts which can be back-loaded (fitted from the safety of the excavation chamber).

EVALUATION OF TUNNEL CONSTRUCTION METHODS

Table 2 evaluates the pros and cons of each construction method considered for Bay Tunnel.

MECHANIZED EXCAVATION CONSIDERATIONS

Geotechnical

Based on various key factors, the most suitable TBM excavation methods for the Bay Tunnel are EPB and slurry. Due to the large percentage of silts and clays, and the cohesive nature of the soils, an EPB TBM is the most appropriate mechanical excavation method. As can be noted in Figure 3, almost 90 percent of the materials encountered within the borings at tunnel level are fine grained and cohesive materials. The other 10 percent of material will be mixed face or, rarely, a full face of sandy soil. In conditions where sand and clay are present in the face, the cutterhead will tend to mix the soils and prevent sand under groundwater pressure from becoming uncontrollable.

Ground Conditioners

Developments in ground conditioning have steadily increased over the past decade. With these developments, EPB TBMs have become viable for applications for which only slurry TBMs would have been

Table 2. Construction method evaluation for Bay Tunnel

Tunneling Method	Pros	Cons	Recommended for Bay Tunnel?
Open-face shield with internal compressed air	• Simple technology • Ideal for short drives	• Would need to be in combination with compressed air • Health and safety issues due to compressed air • Increased cost	Not recommended
Open-face shield with dewatering	• Simple technology • Ideal for short drives	• Dewatering not feasible in San Francisco Bay • Settlement associated with dewatering on land	Not recommended
Open-face shields with permeation or soil fracture grouting	• Simple technology • Ideal for short drives	• Grouting not feasible due to lengths of drives, access, and cost	Not recommended
Earth Pressure Balance (EPB) machine	• Ideal for high groundwater • Ideal for soft alluvial ground • Better for long drives with mixed ground • Reduced settlement	• Very coarse granular materials under ground water pressure are difficult to control without special equipment and techniques	Recommended
Slurry shield	• Ideal for high groundwater • Ideal for soft alluvial ground • Better for long drives with coarser granular materials which could include cobbles and boulders • Reduced settlement	• Not suitable for clays due to increased slurry treatment • Increased cost due to slurry treatment	Not recommended

considered in the past. With an EPB TBM the tunnel face is supported by pressure from the mass or plug of remolded soil (muck) within the cutterhead and screw conveyor. For soils with high permeability or high clay content, ground conditioners are required to achieve a stable soil mass or plug. In addition to supporting the face, ground conditioners lower friction and permeability, thus preventing or reducing water inflows through the screw conveyor. Ground conditioners also enhance excavation efficiency by creating muck that is more plastic.

Early EPB TBMs utilized water and bentonite for soil conditioning. Recently, these have been replaced or augmented by polymers and foams. Foam is essentially a mixture of air and diluted foaming agent in water. Foam is used to reduce the level of torque required to cut the ground, which in turn reduces the power input to the motors and is useful in preventing excessive heating of the excavated ground and blocking of the soil in the cutterhead (O'Carroll, 2005). To create tunnel foam, air and diluted foam agent has to simultaneously be pumped through a foam generator and injected through the cutterhead into the tool gap between the intact soil and the cutters. At times, it may be useful to add foam to the excavation chamber or the screw conveyor—particularly when blockages occur. Foam makes the cuttings more plastic and less permeable. Foam also helps to reduce abrasion and wear on the cutter tool and screw conveyor.

Polymers are used to condition the soil, either by absorbing water to dry out wet soils or by affecting the deformation and flow characteristics of the soil structure (O'Carroll, 2005). The main purpose of polymers is to help support the face and encourage loose, coarse-grained soils to move smoothly through the excavation chamber. Polymers can also be used to reduce the tendency of soils with large amounts of highly plastic clay (i.e., "fat" clays) to stick to the cutterhead or conveyors.

Polymers used in tunneling can be either natural-based (e.g., sugars, starches, and proteins) or synthetic (e.g., polyacrylamides, caboxy-methyl-cellulose, and biopolymers). Biopolymers are water soluble, biodegradable polymers that are compatible with foam surfactants and are becoming more widely used with EPB TBMs.

Figure 7 shows the Bay Tunnel sieve analysis results plotted over the recommended ground treatment regimes (per Langmaack, 2001). In the case of the Bay Tunnel, the TBM will occasionally traverse coarser-grained sandy materials which are expected to require ground treatment in some combination of foam, polymers, and bentonite. One sieve analysis indicates course-grained material which could be problematic to control with ground treatment. In

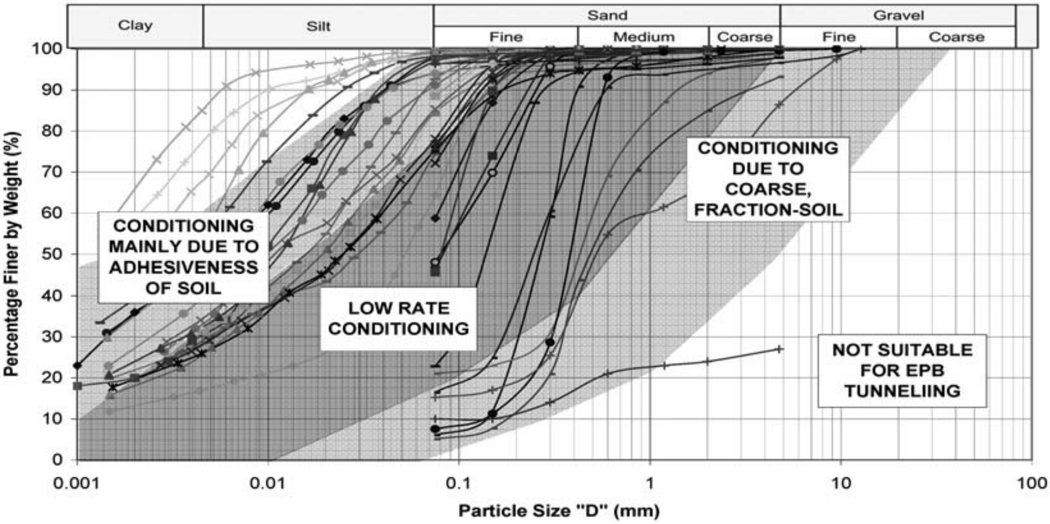

Figure 7. Gradation curves from sieve and hydrometer tests on borehole samples encountered at tunnel elevation (conditioning curve after Langmaack, 2001)

most cases, however, it is expected that ground conditioning injected from the TBM cutterhead will address most, if not all, of the materials.

The type of polymer or foam will be selected by the contractor based on functional requirements. Laboratory tests such as slump tests and permeability tests will be performed on conditioned samples to select the correct products and application for the desired purpose. Tests will also be conducted by the contractor in the field during start-up of the TBM to confirm laboratory results.

Treatment of Fine-Grained Cohesive Soils

As noted above, most of the materials the TBM will encounter will be fine-grained and cohesive in nature. Controlling face pressure and avoiding over-excavation are the primary concerns. However, clogging of the TBM cutterhead is also a significant practical concern. This can occur when materials stick together and adhere to the metallic surface of the cutterhead. To ensure efficient excavation and soil transport through the excavation chamber, conditioners such as foam and polymer can be injected through the cutterhead. Foam is a preferred soil treatment in this type of soil, because its surfactant nature, boosted by chemical dispersants, encapsulates the excavated soil and lubricates it, helping prevent it from re-agglomerating or adhering to the cutterhead.

Treatment of Coarser Permeable Soils

All of the tunnel works will be carried out below the groundwater table. When encountering coarser soils under these conditions, the water present in the pore spaces between the grains may tend to flow toward the TBM due to the slight depressurization that occurs within the chamber during excavation. At times the screw conveyor could be filled with permeable material and the soil "plug" may be lost, allowing uncontrolled flow of water and material to occur anytime an attempt is made to discharge material from the screw. In this case, hydrophilic polymers and fine-grained "artificial soils" can be injected through the cutterhead and into the screw to block the movement of water through the open pores and restore excavation control. During this period, a secondary mechanical means could be used to discharge the excess pressure in a controlled manner by keeping the screw conveyor closed and engaging a double piston pump, or alternatively with a primary and secondary screw conveyor arrangement.

TBM Cutterhead Wear

When discussing the longevity of the TBM cutterhead it is useful to discriminate between primary and secondary wear. Primary wear is the wear expected on the replaceable cutting tools, while secondary wear is the wear on the supporting structures of the cutterhead, which can lead to major overhauls underground, which is highly undesirable. Principal factors affecting primary and secondary wear are:

- The nature of the soil, including its abrasiveness and stickiness;
- Face confinement or support pressure;
- The type and style of cutting tools chosen;

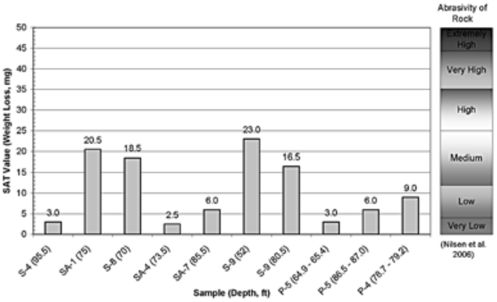

Figure 8. Soil abrasion test results of soils at the tunnel horizon from geotechnical investigation

- The opening area and the geometry of the openings on the cutterhead;
- The wear protection fitted to the cutterhead; and
- Ground conditioning and the volume and type of ground conditioning agent used.

One of the goals of optimizing ground conditioner application is to reduce cutterhead torque and abrasion, thereby extending cutter tool life. This is particularly important for the Bay Tunnel, which has a long TBM drive with no intermediate shafts. During tunnel excavation, control of primary wear and minimization of secondary wear should be addressed by regular inspection of the cutterhead, especially primary wear elements such as the tools. Figure 8 shows the results from Soil Abrasion Testing (SAT) for the Bay Tunnel and the relative abrasiveness of the soil samples from west to east along the alignment. The SAT evolved from the hard rock TBM boreability test methods developed by NTNU (Norwegian University of Science and Technology, Trondheim) and SINTEF (Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology). The SAT method is a relatively new development and test values are currently correlated to the AV (Abrasion Value) for rock. As such, they cannot be used directly to accurately estimate cutter wear (Nilsen et al., 2006). The SAT values do, however, provide valuable information about areas of higher abrasion and areas where more frequent cutterhead tool inspections are recommended, which is useful for planning such inspections.

The Bay Tunnel alignment passes through different abrasive zones, including low to medium abrasive soils. For most of the alignment, the TBM is anticipated to encounter ”sticky” soils where clogging can impact advance rates and exacerbate abrasion. These soils will require consistent use of surfactant foaming agents to combat adhesion and stickiness caused by high fines content, which can prevent the smooth flow of excavated material through the excavation chamber. In the two areas identified as medium abrasive, lubricating polymer-enriched foaming agents can be used to help reduce abrasion wear and prevent clogging of the excavation chamber. Consistent ground treatment combined with regular cutterhead inspections will maximize TBM performance and minimize unexpected delays due to blockages, worn out tools, or damage to the cutterhead structure.

Muck Control

The most difficult materials for EPB TBMs are coarser materials such as poorly graded sands and gravel below the groundwater table. These are evident in at least one Bay Tunnel boring. To extend the application range of the EPB TBM and reduce the risk inherent in relying on ground conditioning alone, an option for a piston pump or a primary secondary screw arrangement was included in the TBM specifications. The double piston pump acts as a valve, permitting precise control of the release of material from the screw outlet in a case where the pressure gradient has not been maintained within the screw conveyor. This technique has been used on several projects, including the Botlek Tunnel in the Netherlands, Heathrow Airside Tunnel in England, and Porto Metro in Portugal. The primary-secondary screw conveyor arrangement is a viable alternative to the piston pump when the primary screw can be isolated from the secondary screw by means of an intermediate guillotine gate. The required muck discharge control is achieved by having the primary screw charge the secondary screw and by closing the intermediate guillotine, thus avoiding uncontrolled discharge. It should be noted however that TBM manufacturers have not yet demonstrated an automated charging cycle which could be engaged by the operator in an instance where the pressure gradient cannot be maintained by other means.

Squeezing Ground

To compensate for large frictional forces that could be imposed on the TBM shield, specific equipment and techniques must be implemented. Included amongst these are sufficient overcut on the cutterhead, the ability to inject and control the pressure of the bentonite in the steering gap along the shield, the ability to measure pressure along the shield, adequate TBM thrust capability, and limits on stoppages through areas identified as having the potential to trap the TBM. Figure 6 shows the potential for squeezing clays in an unsupported face, as determined by the Overload Factor analysis.

SUMMARY AND CONCLUSIONS

Based on the current understanding of the geology and the capabilities of EPB TBM technology, it is required that an EPB TBM be utilized for construction of the Bay Tunnel. Site investigations revealed that the tunnel will encounter interlayered medium stiff to hard silt and clay, with dense sand lenses within the San Antonio Formation. Due to the thickness and variability of the San Antonio Formation, data from one tunnel diameter above and one tunnel diameter below the tunnel alignment was analyzed to provide a more complete picture of the kinds of soils and the variability which may exist at the tunnel horizon. Results indicated that the percentage of fine-grained material increases with tunnel depth, but a significant portion of coarser sands are also present at lower depths. Of the soils present along the tunnel alignment, 90 percent are expected to be cohesive, fine-grained soils, and 10 percent are expected to be granular, sandy deposits.

Ground conditioners will be required to treat both fine-grained cohesive soils and coarser permeable soils. Fine-grained soils will require the addition of conditioners such as foam and polymer to lubricate the muck and prevent it from sticking. Coarse-grained soils will require the addition of polymers to prevent the flow of water through the TBM screw and maintain stability at the face, as well as reduce abrasion wear. SAT tests have been used to evaluate the relative abrasiveness of the soil samples, providing valuable information about areas of higher abrasion and areas where more frequent cutterhead tool inspections are recommended. To extend the range of the EPB TBM and reduce the risk inherent in relying on ground conditioning alone, special methods such as the piston pump or double screw conveyor are required to deal quickly and safely with coarse-grained materials and full face sand conditions below the groundwater table.

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