

PLANNING AND DESIGN OF THE BAY TUNNEL

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ABSTRACT

The existing Hetch Hetchy water system, owned and operated by the San Francisco Public Utilities Commission (SFPUC), serves 2.4 million people within the San Francisco Bay Area. The system has existing 1920s-era pipelines crossing under the Bay that are vulnerable to seismic damage from the nearby San Andreas and Hayward fault zones.

The SFPUC plans to replace the pipelines with the first TBM-driven tunnel underneath the San Francisco Bay. The tunnel will be constructed using an Earth Pressure Balance machine. The new tunnel will pass under environmentally sensitive habitats and will be approximately eight kilometers (five miles) long with no intermediate shafts. The project challenges will include tunneling through a prominent buried bedrock ridge that transects the alignment and through soft soils under the Bay. Seismic performance criteria include maintaining service flows after a large earthquake on one of the active faults in close proximity to the project site.

BACKGROUND

The San Francisco Public Utilities Commission (SFPUC) manages a large water supply system of reservoirs, tunnels, pipelines, and treatment systems that stretches about 320 km (200 mi.) from the Hetch Hetchy Reservoir in Yosemite National Park to the City of San Francisco. The water comes from a protected watershed in the Sierra Nevada Mountains, and is some of the purest in the United States. The system is also economical, as it is almost entirely gravity-fed.

The SFPUC is the third-largest municipal utility in the State of California and serves 2.4 million residential, commercial, and industrial customers in the greater San Francisco Bay Area. Approximately one-third of the SFPUC's delivered water goes to retail customers in the City of San Francisco, while wholesale deliveries to numerous other suburban agencies in Alameda, Santa Clara, and San Mateo counties comprise the other two-thirds of deliveries. In November 2002, the SFPUC launched a \$4.3 billion Water System Improvement Program (WSIP) to repair, replace, and seismically upgrade the system's aging pipelines, tunnels, reservoirs, pump stations, storage tanks, and dams. The WSIP is funded by a bond measure approved by San Francisco voters. The program will achieve key service and operational goals related to seismic recovery, water quality, drought reliability, and sustainability. More than 75 projects in San Francisco and the surrounding region will be completed by the end of 2015.

The SFPUC found two major pipeline arteries in the system to be particularly vulnerable in a seismic event. The replacement or upgrade of these pipelines is a key

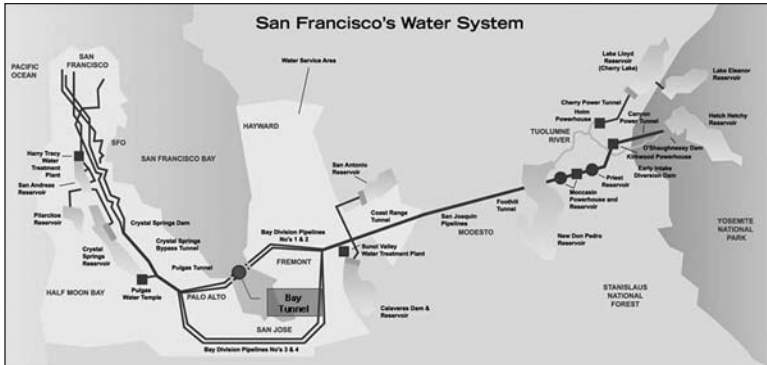


Figure 1. Schematic diagram of SFPUC's water distribution system



Figure 2. Bay Division Pipelines 1 and 2 at shoreline in East Palo Alto

element of the WSIP. The two important pipelines are Bay Division Pipelines 1 and 2. These aging pipelines travel from the City of Newark, under the southern portion of the San Francisco Bay, up into the Western Bay mudflats, and then across a pile-supported trestle into the City of East Palo Alto. (see Figure 2)

The SFPUC commissioned initial engineering studies to evaluate various replacement and upgrade options. Options included upgrading the existing pipelines, replacing them with cut and cover and submarine pipelines, and building a new tunnel. The studies showed that the preferred solution was to construct a new tunnel under the Bay.

The tunnel will be constructed while the existing pipelines remain in service. The existing pipelines, and a new pipeline to be constructed, will be tied in to the tunnel at either end during short outage windows. The shorter windows will limit system disruption and avoid customer supply issues.

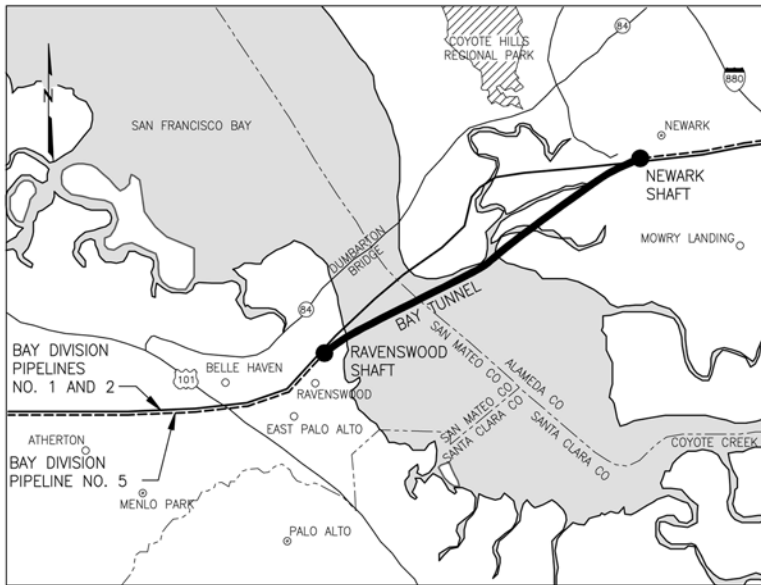


Figure 3. Proposed Bay Tunnel horizontal alignment

FACILITY LAYOUT

The Bay Tunnel will be located between two shafts. The presence of environmentally-sensitive habitats on the Bay margins resulted in the need for an 8 km (5 mi)-long tunnel with only launching and receiving shafts and no intermediate construction shafts. These two shafts will be located on properties owned by SFPUC in the City of Newark (Newark shaft) and the City of East Palo Alto (Ravenswood shaft), as shown on Figure 3. The shafts are expected to be constructed using diaphragm slurry wall construction methods with tremied structural concrete slabs tied into the shaft bottoms. The TBM launching and construction shaft located at the Ravenswood site will be approximately 17.7m (58 ft) in diameter and 33.5m (110 ft) deep. The receiving shaft located at the Newark site will be approximately 8.5m (28 ft) in diameter and 22.5m (74 ft) deep.

The preferred horizontal alignment was chosen to meet identified design and constructability criteria. Criteria included providing straight departures from the shaft sites and maintaining minimum 305m (1,000-ft) radius curves. Pile supported structures planned along the shoreline of the adjacent rail corridor made it desirable to cross this corridor onshore and at some distance from the shoreline on the Ravenswood side of the Bay. In the Newark area, a horizontal curve was placed in the alignment to avoid schedule delays that might be caused by passing under a parcel owned by a private party that was unwilling to grant an underground easement. The total length of the preferred alignment is 7,994m (26,226 ft).

The preferred vertical alignment was based upon a number of different design and constructability criteria, including maintaining minimum clearances under the bottom of the San Francisco Bay and keeping the tunnel as shallow as possible to reduce construction costs. It was also necessary to keep the tunnel alignment under the Young Bay Mud deposits to avoid negative impacts to seismic performance.

Table 1. Description of anticipated geologic units

Formation	Description
Young Bay Mud	Soft to medium silty clay
San Antonio Formation (also described as the Merritt-Posey-San Antonio Formation)	Interlayered medium stiff to hard silt and clay, with loose to dense sand lenses
Old Bay Clay	Stiff to hard silty clay with dense sand lenses
Franciscan Complex	Sedimentary and low-grade metamorphic rock, highly weathered

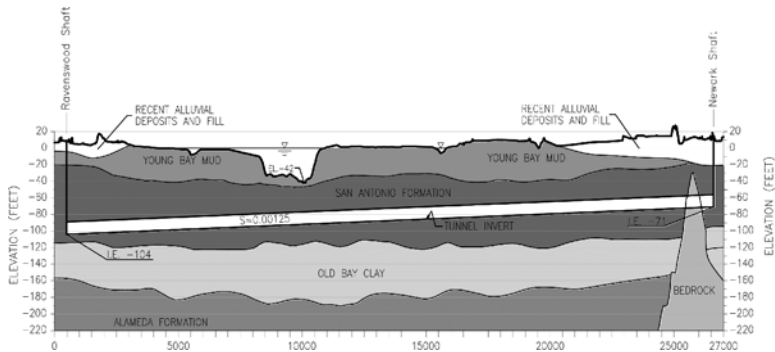


Figure 4. Geologic profile along the proposed Bay Tunnel alignment

GEOLOGIC CONDITIONS

Site Geology

The initial phase of the field geotechnical investigation was completed in 2006. The field investigations included a series of marine-based borings across the San Francisco Bay, and land-based borings and cone penetrometers on the Newark and Ravenswood site locations. 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 help the design team make interpretations between boreholes. Suspension logging was also performed in selected boreholes at the Ravenswood and Newark sites. As a result of the field investigation program, four primary geologic units were identified as underlying the proposed tunnel alignment corridor. These geologic units are summarized in Table 1.

After the initial geotechnical investigation and associated laboratory testing were complete, a long section plot was generated showing the stratigraphy of the proposed alignment. The anticipated geology based on the results of this stratigraphy plot is summarized on Figure 4.

Groundwater

The geotechnical land-based investigation included the installation of multilevel, vibrating-wire piezometers to monitor groundwater pressures near the two shaft sites. Piezometer readings indicate that the groundwater pressures are generally consistent at 1 to 3.4m (3 to 11 ft) below the ground surface and are influenced by tidal variations.

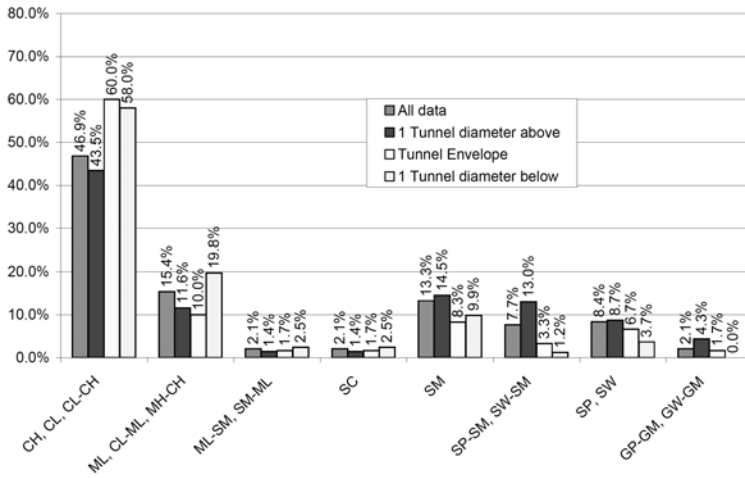


Figure 5. Distribution of USCS soil types along the proposed tunnel alignment

Readings between piezometer levels indicate that there is some hydraulic conductivity between the individual geologic units.

Anticipated Tunneling Conditions

Geotechnical evaluations resulted in the tunnel being situated in the San Antonio Formation to optimize tunneling conditions, depth, and seismic performance. The tunnel section was superimposed on the geologic profile such that it was possible to locate localized intersections of the stratigraphy within the tunnel envelope. Using the tunnel envelope stratigraphy, including one tunnel diameter above and below, it was possible to develop a preliminary assessment of the distribution of soil types anticipated to be encountered along the alignment. This allowed the design team to make a recommendation about what tunneling methods would be most appropriate.

Laboratory testing, including sieve analyses and hydrometer testing, was done on selected soil samples to determine the gradation curves for the various soil types sampled in the borings. This data, along with Atterberg Limits testing and visual/manual soil classification were used to classify soil with the Unified Soil Classification System (USCS).

The San Antonio Formation consists of interbedded clays, silts and sands. The entire tunnel alignment is under the water table, subject to approximately 3.2 bars (48 psi) of hydrostatic pressure. To select and specify a TBM, it was important to quantify the amount of soil with a high fines content (clays and silts) and the amount of soil comprised of coarse materials (sands and gravels). It was also important to characterize the stratigraphic distribution of the soil types, particularly for poorly-graded sands and gravels, which can create problems for some TBMs if they are encountered in excessively thick or laterally continuous layers rather than isolated lenses.

Some basic statistical analysis was performed to synthesize the data and draw some preliminary conclusions regarding soil type distributions. Figure 5 summarizes the results of the statistical analysis. This table includes data from one tunnel diameter above and one diameter below the proposed tunnel alignment in order to provide a

Table 2. Review of squeezing conditions in clay and silt deposits along the proposed tunnel alignment

Degree of Squeezing	Probability of Occurrence Based on Number of Test Samples
Minor	29%
Moderate	52%
Severe	13%
Extreme	6%

more complete picture of the kinds of soils expected and the variability which may exist within the tunnel horizon.

Within and near the tunnel envelope, the majority of materials are low to high plasticity clays. Smaller amounts of silty and sandy materials are present. The percentage of fine grained material (relative to coarse grained material) tends to increase with tunnel depth. However, within the tunnel envelope a significant amount of coarser sands are also present. Stratigraphic thicknesses were also analyzed and it was concluded that when the excavation does encounter the coarser grained materials, much of the time it will encounter a full-face of coarse materials, as opposed to a mixed-face of coarse and fine materials.

The stability behavior of clay and silt deposits was reviewed by computing the overload factor (also known as the stability factor) along the proposed alignment depth. The overload factor (OF) was calculated using the following equation:

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

Where

P_z = the total vertical pressure at tunnel depth

P_a = assumed to be atmospheric pressure (for an unsupported face)

S_u = the undrained strength from unconsolidated-undrained triaxial tests

A breakdown of the degree of squeezing behavior within the clay and silt deposits is summarized in Table 2.

It should be noted that the above analysis assumed an unsupported face, which will not be the case with the Bay Tunnel, since pressure-face methods will be specified. However, this analysis illustrates why pressure-face methods are required for most of the excavation. Because approximately 70% of the tunnel could experience moderate to extreme squeezing conditions, it was recommended that control and regulation of face pressure be maintained through pressurized mode excavation. The majority of extreme squeezing and severe squeezing behavior occurs at shallower depths and the degree of squeezing tends to decrease with depth. This is because the shear strength of the material increases significantly with depth, and governs the degree of squeezing.

The pressurized-face TBM handles squeezing ground conditions better than other methods since face pressures are balanced, preventing the soil at the face from squeezing. However, the main area of concern in the Bay Tunnel is along the body of the TBM, where high friction forces may occur due to the relaxation of the material into the steering gap created by the cutterhead overcut. Solutions for these conditions include using shield lubrication with bentonite, limiting work stops in high risk areas, making provisions for sufficient overcut on the cutterhead and providing additional thrust capacity.

In addition to the potential squeezing behavior of the cohesive fine grained materials, the silts and sands present along the alignment could present running or flowing ground conditions if the face is not pressurized during excavation.

In addition to the San Antonio Formation, the tunnel excavation is expected to encounter a short section of highly weathered Franciscan Formation bedrock. The bedrock is expected to consist of highly weathered sandstone, shale, serpentinite, and other rock types typically associated with the Franciscan Formation.

SEISMIC CHARACTERIZATION

Characterizing the potential seismic impacts on the facility and developing seismic design parameters were critical activities in the design process. The SFPUC expects the water system to be fully operational following a major seismic event.

The proposed Bay Tunnel is located in a seismically active area—central coastal California. Although the proposed alignment does not cross any identified active faults, it is situated between the San Andreas and Hayward faults, which are capable of generating large (M [moment magnitude] ≥ 7) earthquakes. There are also numerous smaller active faults within 50 km (30 mi) of the proposed alignment. A total of 15 earthquakes of $M \geq 6.0$ have occurred in the San Francisco Bay region between 1850 and the present. These include the 1906 M7.9 San Francisco earthquake and the 1989 M6.9 Loma Prieta earthquake. The Bay Tunnel project is expected to experience significant ground shaking during its design life of 100 years.

As required by the SFPUC's general seismic design requirements, the Bay Tunnel will be designed for ground motions that will have a 5% probability of exceedance in 50 years (975-year approximate return period).

As part of preliminary design studies, a probabilistic seismic hazard analysis (PSHA) for ground shaking along the alignment was performed. The purpose of this evaluation was to estimate the levels of ground motions at a specified exceedance probability. Deterministic scenario ground motions were also calculated and compared to the probabilistic ground motions. An evaluation of liquefaction was also performed.

ENVIRONMENTAL CONSTRAINTS

The San Francisco Bay margins consist of environmentally sensitive mudflats, salt marshland, and vernal pool habitat. The Don Edwards Wildlife Refuge, the first urban National Wildlife Refuge established in the United States, is located along the eastern portion of the project site. Many endangered species, like the California clapper rail and salt marsh harvest mouse, live in the wildlife refuge. One of the key motivations for the proposed tunnel system was the benefit of putting the system underground so that environmentally-sensitive areas would not be disrupted. In fact, the geologic investigations for the project were very difficult to permit and to obtain access for field work. Only specific windows of opportunity were available for the investigations and many constraints were placed upon the work operations.

Another environmental issue at the project site is hazardous waste contamination. Within the area surrounding the Newark receiving shaft, elevated levels of chlorinated volatile organic compounds in the groundwater have been identified. The groundwater in this area will require pretreatment and special handling prior to discharge. The soil will require special handling and disposal.

Elevated levels of chrysotile asbestos were also found in some of the samples from the Franciscan Complex bedrock materials that were encountered. Portions of the materials excavated from this area will require disposal as hazardous waste.

SHAFT AND TUNNEL CONSTRUCTION METHODOLOGY

The Bay Tunnel will be constructed as a two-pass system. The first pass will involve a TBM-excavated tunnel, with initial ground support consisting of a bolted and gasketed, precast concrete segmental lining erected immediately behind the TBM. The final lining will consist of either a welded steel pipe or reinforced concrete cylinder pipe, either 2.74 or 3.05m (108 or 120 in) in finished diameter. Once the final lining is installed inside the tunnel, the annular space between the outside of the pipe and the initial support will be backfilled with cellular concrete.

The shafts on this project are required to be watertight to reduce the risk, particularly at the Newark site, of disturbing contaminated groundwater plumes. Excavation support systems that were identified as potential alternatives included secant piles, slurry walls, and ground freezing. Each alternative was evaluated for construction cost and schedule, constructability of the wall to the required depth, water-tightness, and continuity of the wall. The diaphragm slurry wall option is best suited for construction of the Ravenswood and Newark Shafts. Diaphragm slurry walls provide maximum safety against leakage through the wall and can be constructed without any "windows." The stiffness of the wall also helps to reduce adjacent ground settlements resulting from wall deflection. Once tunnel excavation and final lining installation are complete, a steel riser pipe will be installed in the shafts and the annular space backfilled with a combination of concrete and controlled low strength material.

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 for the tunnel. As can be noted in Table 2, the majority of materials encountered within the borings at tunnel level are fine grained and cohesive material. The remainder will represent either a full-face or mixed 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. The coarser grained sandy materials are expected to require ground conditioners in some combination of foam, polymers and bentonite. In most cases it is expected that ground conditioning injected from the TBM cutterhead will cope with most, if not all, of the materials expected. The highly weathered bedrock materials are also expected along a short section of the alignment. The TBM cutterhead will be outfitted with appropriate excavation tools to handle these materials when they are encountered.

PROJECT SCHEDULE

The final design for the Bay Tunnel is currently underway and is expected to be complete in November 2007. The project environmental documentation is being performed in parallel with the design and is expected to be completed in 2008. The project is expected to go to construction in July 2009, with an anticipated completion date of August 2013.

SUMMARY AND CONCLUSIONS

The proposed 8 kilometer (5 mile) long Bay Tunnel is a critical lifeline water supply facility for the City of San Francisco and the San Francisco peninsula communities. It will be the first tunnel excavated by a TBM under the San Francisco Bay. The proposed tunnel is located in an area of high seismicity and will need to remain serviceable after a large earthquake on nearby active faults. It is expected to encounter soft sediments, primarily sandy and silty clays, that will be well suited to the Earth Pressure Balance excavation methodology.

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REFERENCES

- Jacobs Associates and Fugro West, December, 2006. Bay Division Pipeline Reliability Upgrade (CUW36801), Bay Tunnel Project, Draft Geotechnical Interpretive Technical Memorandum.
- Jacobs Associates and URS Corporation, November, 2006. Bay Division Pipeline Reliability Upgrade (CUW36801), Bay Tunnel Project, Draft Geotechnical Data Report.
- San Francisco Public Utilities Commission. May, 2006. Bay Division Pipeline Reliability Upgrade, Phase 3, Conceptual Engineering Report. Prepared by Engineering Management Bureau and Project Management Bureau and Parsons, Project CUW36801, Control No. 201441.