POINT OF BEGINNING
POB

Tunnel Beneath the Bay

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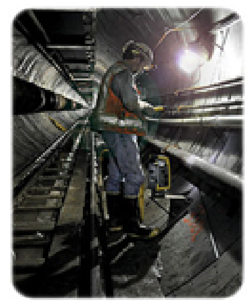
For decades, California's Hetch Hetchy water system has supplied water to the San Francisco Bay Area. But the aging system is nearing the end of its useful life and is seismically vulnerable. Constructing a solution requires accurate, nerve-racking surveying.



Working deep beneath San Francisco Bay, Party Chief Russ Mello prepares to collect survey data. Precision measurements and analysis produce millimeter accuracy for guiding the tunnel boring machine.

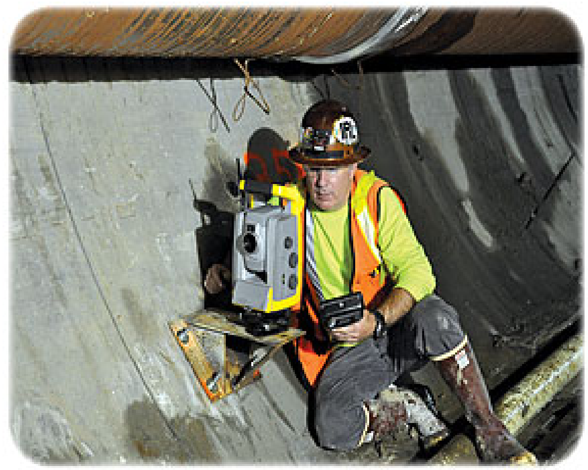
Stretching from the Sierra Nevada Mountains across central California to the San Francisco Bay, the Hetch Hetchy water system is one of the largest water collection systems in the U.S. The system collects water from the Tuolomne River watershed in the Sierra Nevada and stores it in three reservoirs in Yosemite National Park. From there, a series of tunnels and pipelines carry the water 150 miles west to consumers in the Central Valley and in the San Francisco region. Handling more than 220 million gallons of water every day, the system serves more than 2.4 million residents and businesses. In addition to supplying 85 percent of San Francisco's water demand, the Hetch Hetchy system generates roughly 1.7 billion kilowatt-hours of electric power every year.

But Hetch Hetchy is showing its age. Many of its reservoirs, aqueducts and support facilities are 75 to 100 years old. Because of the deteriorating facilities, maintenance costs are significant drains on the system's financial resources. And, in addition to the normal aging and wear, the system is susceptible to damage from potential earthquakes in the seismically active region. Many structures do not meet modern building codes for seismic protection, and a major earthquake could disrupt Bay Area water service for weeks or longer.

To reduce the risk, the San Francisco Public Utilities Commission (SFPUC) embarked on a multibillion dollar project in 2002 to upgrade and modernize the Hetch Hetchy water system. Known as the Water System Improvement Program (WSIP), the effort is the largest infrastructure program ever undertaken by the City of San Francisco, and one of the largest water infrastructure programs in the nation. With more than 10 years of work already completed, WSIP work continues on replacement, repair and seismic mitigation to pipelines, dams, tunnels and other facilities. One of the biggest needs is to replace aging pipelines near the south end of San Francisco Bay.

When water from the Tuolomne reaches the Bay Area, it goes into four pipelines that transport it around and over the southern reaches of San Francisco Bay to the final destination at the Crystal Springs Reservoir. Two of the pipelines cross the bay, resting on the bay floor or supported on antiquated trestles crossing environmentally sensitive areas. To increase pipeline capacity and reliability while protecting the area's wetlands, SFPUC decided to replace the pipes with an underground pipeline. The pipeline project is overseen by SFPUC's Project Manager Johanna Wong, PE, MS.

The new pipe will be installed in a dedicated tunnel constructed roughly 100 feet below the bay floor. Known simply as the "Bay Tunnel," the new conduit is 15 feet in diameter and more than five miles long. The digging is done by an earth pressure balance tunnel-boring machine (TBM), a type of tunneling system well suited to the dense clays that make up much of the bay floor. To launch the TBM, the project's tunnel contractor, Michels/Jay Dee/Coluccio Joint Venture (MJC) excavated a shaft 58 feet in diameter and 124 feet deep in East Menlo Park on the west side of San Francisco Bay.



Project Surveyor Sean Fitzpatrick, PLS, operates a Trimble S6 in the Bay Tunnel. Remote control and automated pointing enables him to quickly capture precise measurements to tunnel control points.

According to MJC Project Engineer Ed Whitman, the TBM and launch shaft are normal parts of a major tunneling project. But the Bay Tunnel contains an important distinction from Whitman's past projects. In other TBM-built tunnels, several vertical access shafts (Whitman calls them "manholes") are built at intervals along the tunnel. In a similar sized-tunnel that Whitman worked on in Ohio and California, manholes were spaced roughly 1,000 to 1,500 feet apart. Among other functions, the shafts enable project surveyors to connect geodetic control points on the surface to the control points in the tunnel, making adjustments and corrections as the TBM moves ahead. Because the Bay Tunnel is under a body of water, manholes aren't possible. As a result, all the survey control (essential to steering the TBM) is tied to one end of the tunnel. "It's like taking a five-mile shot off a 50-foot backsight," says Whitman. "From the survey perspective, it's not for the faint of heart."

MJC selected Towill, Inc., of Concord, Calif., to provide surveying services for the Bay Tunnel project. Whitman said that Towill--which specializes in surveying and mapping--had the experience and confidence needed to control a 27,000-foot run without intermediate manholes. In turn, Towill assigned Sean Fitzpatrick, PLS, to serve as project surveyor. Fitzpatrick has worked on several major tunnel projects and has gained extensive experience with guidance systems for TBMs. Assisted by Party Chiefs Eric Jones (initially) and Russell Mello (who completed the project) and Chainman Emililano Gaytan, Fitzpatrick is responsible for all surveying activities in the tunnel.

One of Fitzpatrick's first tasks was to verify control supplied by SFPUC's design engineer. He used Trimble R8 GNSS receivers to connect the ends of the project, switching to Trimble S6 1-second total stations as the work approached the shafts and moved underground. At each shaft location, the Towill team used total stations to check the internal consistency of the control and to densify the control around the collar of the shaft. Once a shaft was laid out and excavated, the team brought in control to the concrete collar around the top of the shafts. The Towill team used Trimble DiNi Digital Levels to carry the elevations from the control points to the shaft collar. Both the GNSS and optical systems are controlled with a Trimble TSC2 Controller running Trimble Access software.

Moving the control down the shafts called for special procedures. The surveyors installed spherical prisms into three high-precision mounts at the top of the shaft, and used the total stations to establish 3D coordinates for each prism's positions. At the base of the shaft, they bucked in under the prisms. Using a zenith plummet mounted on a translation stage on each tripod, the team established instrument points to high precision. They then placed a total station on each bracket and used the EDM to measure to the prisms above, thereby establishing the elevation of the instrument trunnion axis. Simple leveling with the Trimble DiNi then moved the elevations to spads driven into the shaft walls. (A spad is a flat spike installed into the wall or ceiling for use as a survey mark.)

Aerial view of the tunnel location using Google Earth.

As a final check, the crew measured the distance between the two main points at the top of the shaft, and the two main points transferred to the bottom. The distances differed by just 0.3 millimeters (0.001 foot). "You have this very short line and check angle," Fitzpatrick explains. "If you are very precise, which means you are 2 millimeters or better in all of your points, then you can go ahead and launch the TBM."

With the control in place, the TBM started mining in September 2010.
At the Menlo Park site, construction crews lower the TBM into the launching shaft in pieces. As it bores its way out of the shaft, additional components are lowered and attached to the TBM. When fully assembled, the machine is roughly 750 feet long. As the TBM advances, it installs precast concrete rings to line the tunnel. Each ring is 5 feet long, and the machine places 14 to 16 rings per 10-hour shift. The TBM's guidance system helps the TBM operator steer the machine by measuring the TBM position based on Towill's network of control points.

Fitzpatrick designed the control network in the tunnel as a series of braced quadrilaterals roughly 350 feet long. The instruments are mounted in brackets on the walls, with the actual control points marked by spads in the tunnel ceiling. The Towill team has an effective way of ensuring accurate positioning of their instruments. "We put a standard tribrach onto the bracket, and then we use a tribrach adjusting puck that has a level vial," says Fitzpatrick. "We fine level the puck, then place a tribrach with a laser plummet on it. The laser goes up and hits the little dot in the spad. In that way, we make sure the total station is directly under the point."

When extending the control, Jones and Gaytan use the Trimble S6 to measure ahead and back to passive prisms at the new and visible existing control points. Fitzpatrick checks the data and runs a rigorous network adjustment, supplementing the total station data with gyro-theodolite measurements to produce final coordinates on the new points.

To steer the machine along the correct horizontal and vertical path, the TBM guidance system uses a Trimble 5600 total station mounted on brackets placed high in the tunnel. The total station measures to a series of active prism targets mounted on the TBM and sends the results via cable to the giant machine's onboard guidance computer. The Towill surveyors keep the instrument as close to the TBM as possible. "We don't let the prisms on the TBM guidance system get more than 300 feet from the 5600," Fitzpatrick says. "Any farther than that, the view of the prisms from the total station can be obstructed. And we don't want to go beyond the length of the guidance communications cable."

When the time comes to move the guidance instrument, the team must work quickly. When the TBM stops mining to install a concrete ring, the surveyors remove the Trimble 5600 and install their Trimble S6 into the tribrach. Farther ahead in the tunnel, they install a prism into a new bracket that will serve as the next location for the 5600. The Trimble S6 automatically measures three direct/reverse sets to visible control points and the new bracket. The crew checks the results using the rounds of angles function in Trimble Survey Access, and Jones then enters the coordinates of the new bracket into the TBM guidance system. The process takes about 30 minutes, which is roughly the amount of time the TBM needs to install a concrete ring. As a result, the team can advance the control and guidance without disrupting the normal operation of the TBM.

Following the defined alignment, TBM operator Reese Tatge drives the TBM through the ground to construct the tunnel.

Once the move is completed, Fitzpatrick reviews the measurements and sends adjusted coordinates for the new instrument location to Jones. "Typically the coordinates don't change by more than 3 to 4 millimeters," Fitzpatrick says. "The calculations don't take long, so they have not advanced so many rings that it is a problem."

The tunnel surveyors move the instrument position one or two times each week. Between advances, the Towill team works on advancing the horizontal and vertical control. They also conduct as-built measurements on the more than 5,000 concrete rings that line the tunnel. Each ring is measured in four locations; Fitzpatrick uses the data to compute best-fit circles and prepare reports on each ring's circularity. With assistance from Trimble, Fitzpatrick developed a style sheet for Trimble Access that calculates and outputs the differences between the measured locations and design profiles.

Working in a tunnel presents unique challenges for the surveyors. They comply with the project's strict safety regulations and coordinate their work with the multiple trades and contractors working in the confined space. One of the key needs is to maintain the lines of sight needed for control and measurements to the prisms on the TBM. It's not a simple task: The tunnel is filled with machinery, piping, people and materials vying for access.

Even the tunnel environment itself can be an issue. The main portion of the tunnel can be as cool as 55 F. But when working near the TBM, the machine's powerful electric motors and hydraulics can drive the temperature up to 90 F, with a significant increase in humidity. The team must plan their work to include time for the instruments to acclimate to the variable environmental conditions.

"It's a very professional work setting, and everything is built on respect," Fitzpatrick says. "Your primary responsibility is safety for yourself and everybody else in that tunnel. You know your job and have a plan. You communicate your plan to your people and the people that are waiting on you."
As the TBM moves eastward beneath the bay, MJC has started work on the receiving shaft in Newark. Because of wet conditions and environmental concerns, MJC is freezing the ground around the shaft. The shaft will be driven into the frozen ground and lined with concrete. When the TBM arrives, a large steel sleeve with an elastomeric gasket seal will connect it to the shaft and provide a dry work environment. The TBM will punch into the sleeve, and then an inflatable bladder will release the gasket and seal the machine to the sleeve. Once the seal is fully applied to the outer skin of the TBM, crews will take the TBM apart and lift it out of the receiving shaft.

From five miles away, the sleeve is a tiny target. The clearance between the TBM and seals is just 4 inches (10 centimeters), and the grinding face of the machine must not be allowed to contact the seals. Yet neither Whitman nor Fitzpatrick is visibly nervous about guiding the TBM to the required location. Fitzpatrick expects to slow the TBM as it approaches the sleeve, and possibly take additional gyro and total station measurements to confirm any final adjustments to the TBM's trajectory. When the machine reaches the Newark shaft in late 2012, Fitzpatrick expects it to end up within 2.5 inches (6 centimeters) of the center axis of the sleeve.

Fitzpatrick looks at the project as a very precise traverse. While it has a number of similar aspects to aboveground surveying, the costs and limited access demand constant attention to detail. He's designed the work keeping in mind the distance and geometry, and is keenly tuned in to the capabilities of his instruments and procedures. Everything is designed to reduce or trap blunders, and all equipment is field calibrated once per week. The Towill team has developed specific procedures to handle the TBM and its guidance system, and Whitman notes that Towill went so far as to design specialized brackets for the instrument mounts.

But even with all the checks and precision, it's possible to lose sleep over the project. "I trust my math, adjustments and measurements--it's the best you can do," Fitzpatrick says. "You've got to have a certain amount of confidence. You can't be a cowboy, but you've got to have a little bit of that risk-taking gene in you. It's not for every surveyor."

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