

MICROTUNNEL JACKING AND RECEIVING SHAFTS CONSTRUCTED USING CUTTER SOIL MIXING (CSM) TECHNOLOGY

Norman Joyal, Associate, Jacobs Associates, San Francisco, California

ABSTRACT

The cutter-soil-mixing (CSM) method, a construction technology relatively new to the United States, is being used on a Contra Costa Water District project in northern California to construct 50- and 90-ft (15- and 27-m) deep watertight shafts in difficult ground conditions. The shafts will be used for a 900-ft (275-m) long microtunnel crossing of Old River. This is the second known application of this technology in the U.S. for the construction of microtunnel shafts and the first known application using shotcrete-reinforced walls. The shafts penetrate soft saturated silts and clays and loose-to-dense sands. Existing construction techniques, such as secant piles and slurry walls, were not considered feasible for the deeper shaft due to pile drift during installation, which can result in “windows” between the panels/panels. Caissons constructed in the wet were considered the most feasible method for the ground conditions. Rather than specifying a design, however, a performance-based specification was prepared, allowing contractors to provide their own designs. The successful contractor, proposed the use of CSM. CSM was first introduced in Europe by BAUER Maschinen GmbH and has been used in Europe, Asia, and Canada. It was recently used in the U.S. to construct trench walls in Seattle, Washington, and 36- and 52-ft deep (11- and 16-m-deep) shafts near Sacramento, California. This paper will focus on the shaft design, equipment features, construction, quality control, and constructed shafts for the Contra Costa project.

1. INTRODUCTION

The Contra Costa Water District (CCWD) in Concord, California, is building a new Alternative Intake Project (AIP) near its existing pumping facilities in the Delta region east of the San Francisco Bay (Figure 1). The new AIP project will provide an alternative raw water intake facility at Victoria Canal, where the water quality is much higher than that at the current intake location on Old River. The new AIP project will pump raw water directly into the CCWD's existing Old River pipeline facilities that convey the raw water to the District's Los Vaqueros Reservoir.

This new AIP project will divert up to 250 cubic feet (7,000 L) of raw water per second from the new intake pumping plant through a new 72 in. (1,800 mm) pipeline. An approximate 900 ft (274 m) section of this new pipeline crosses under Old River at the existing Old River Intake Facility. Construction of the crossing will require the installation of a 96-in. (2,400-mm) steel casing using microtunnel pipe-jacking techniques. The crossing also required a 92-ft (28 m) deep jacking shaft and a 49-ft (15-m) deep receiving shaft. CSM panels about 105 and 92 ft (32 and 20 m) deep were constructed to embed the shaft walls below the bottom plug.

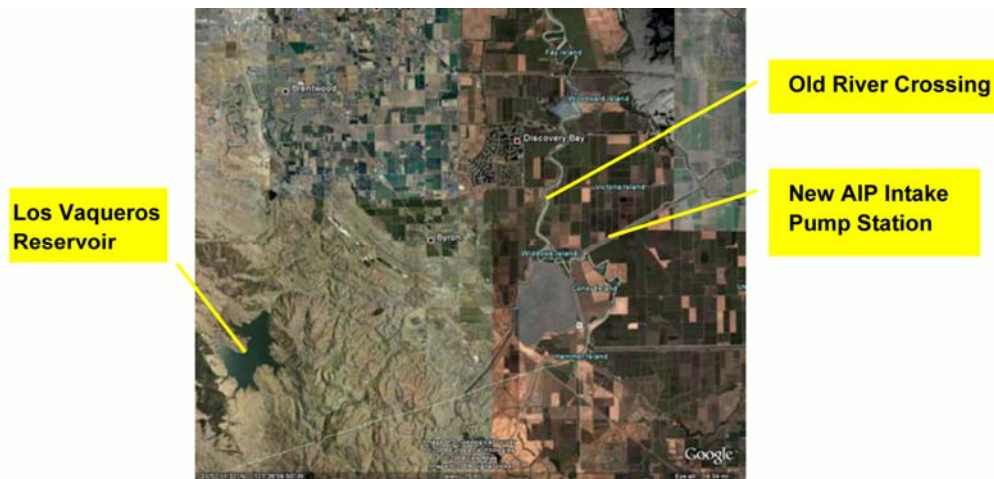


Figure 1. Project Location

2. EXISTING CONDITIONS

2.1 Geologic

The site of the microtunnel river crossing is located within the Delta region, which is part of the Central Valley geomorphic province. The Central Valley is infilled with alluvial deposits that are several kilometers thick. The upper 150 ft (50 m) or so is characterized by poorly consolidated to unconsolidated sediments. As such, the near-surface geology of the region is characterized by relatively thin deposits of peats, organic soils, and fills (typically the levee structures) that overlie the very thick alluvial soils. The Delta region is at the confluence of several major rivers that drain the Central Valley from the north, east, and south. As the rivers converged, the fine-grained materials, including silts and clays, settled out forming a complex pattern of islands and interconnecting sloughs. River and slough channels were repeatedly incised and backfilled with sediments, and the islands served as flood plains during flooding.

2.2 Geotechnical

Geotechnical borings reflect the regional depositional environment, which consists of relatively thin (fractions of meters to meters thick) and discontinuous deposits of surficial peat, clay, silt, sand, and variable mixtures thereof. The deposits have highly variable consistencies ranging from soft to stiff and loose to dense.

2.3 Groundwater and River Water

The natural groundwater level is about one meter below the ground surface. Pump testing by the California Department of Water Resources on wells located on the adjacent islands, as well as local pump testing on wells at the jacking shaft site, revealed the deeper sand layers are confined aquifers with phreatic surfaces that differ from the natural groundwater level. At the site of the jacking shaft, two distinct sand layers were encountered, each with different phreatic surfaces. The upper sand layer was encountered opposite the tunnel entrance about 85 to 98 ft (26 to 30 m) below the ground surface, and the lower aquifer was encountered about 115 to 130 ft (35 to 40 m) below the ground surface. The shaft bottom was established at approximately 90 ft (27 m) below the ground surface. Pump testing completed during the field investigation phase confirmed that the two aquifers were isolated from each other.

Another unique aspect of the site is that the land elevations are lower than the river levels by about 7 ft (2 m) on the jacking shaft side and about 15 ft (5 m) on the receiving shaft side. The river water is in direct communication with the natural groundwater level and identified aquifers. Electro piezometers were installed at the jacking shaft and set in the lower and upper aquifers, as well as in the soil profile between the ground surface and upper aquifer. Continuous long-term monitoring of the electro piezometers revealed that the aquifers, as well as the upper phreatic water level, were in direct communication with the river, as revealed by daily fluctuations in the readings that mirrored the river's daily tidal fluctuations.

2.4 Environmental Constraints

The project was not immune to environmental constraints. Of particular interest is the endangered giant garter snake, whose habitat is the small drainage channels that bisect the islands for dewatering the agricultural lands (Figure 2). The snake freeloads on the burrows made by the burrowing owl in the banks of the drainage channels. The burrowing owl is protected, but not endangered. Environmental biologists specified a 200-ft (60-m) buffer zone from their habitat during the migratory and breeding seasons of October 15 through April 15.



Figure 2. Old River Crossing

3. DESIGN CONSIDERATIONS

The levees on each side of the river are owned and maintained by different reclamation districts that imposed strict requirements on the construction. One of their biggest concerns was settlement that could potentially damage their levees. To alleviate this concern, a strict requirement was imposed limiting changes in groundwater levels to no more than 2 ft (0.6 m) below the lowest daily fluctuation. This essentially eliminated any site dewatering of the phreatic water surface in the unconfined groundwater. It also meant that the shafts had to be watertight. Watertight was defined in the specifications as 10 gal/min (40 L/min).

The reclamation districts also expressed concern over the possibility of island flooding as a result of construction activities. Because confined and unconfined groundwater levels are in direct communication with the river water, there was concern that the microtunnel operations might lose control of the groundwater through the annular space. If that occurred, the districts were worried about shaft flooding and possible island flooding if the shaft collars were below the river flood levels. That concern was mitigated by establishing the shaft collar 1.5 ft (0.5 m) above the 100-year flood level. At the site of the jacking shaft, this was accomplished by building up a pad behind a temporary retaining wall. At the receiving shaft, an approximate 20-ft (6-m) high collar projected up in the air above the shaft collar.

4. CUTTER SOIL MIXING (CSM) METHOD

The Geotechnical Baseline Report (GBR, Jacobs 2008) originally envisioned that the shafts might be constructed with caissons using in-the-wet construction methods. However, rather than specify and provide a shaft construction method, the CCWD opted for a performance-based specification for construction of the shafts. The specified performance for the shafts consisted of the following:

- Shafts had to be watertight, defined as groundwater infiltration into the shafts of no more than 10 gal/min (40 L/min).
- Shaft tops had to be established at 1.5 ft (0.5 m) above the 100-year flood level.
- Shaft construction could not lower the groundwater table by more than 2 ft (0.6 m) below the lower-bound preconstruction levels.
- Construction vibrations could not exceed 0.5 in./sec (13 mm/sec) peak particle velocity.
- Pile foundations for existing facilities could not come under the influence of jacking loads at the jacking shaft.
- A grout prism a minimum of 5-ft (1.5-m) thick and 2 tunnel diameters centered about the vertical and horizontal axes had to be developed at the receiving shaft.

The successful contractor submitted a proposal to use the cutter soil mixing (CSM) construction method for the shafts. This method was not known to the owner or engineers, but the contractor had successfully used it to construct wall diaphragms on a project in Seattle, Washington. The specifications required a comprehensive submittal for construction of the shafts. Through the submittal process, the contractor and engineers satisfactorily demonstrated that construction of the shafts using the CSM method was feasible and that it was feasible to complete the interior excavations in the dry by limiting dewatering to the interior of the shaft.

The CSM method excavates rectangular panels by adding water to the soil to fluidize it in place to a prescribed depth. Upon retraction, the cement grout is added and mixed with the fluidized soil to form a soil cement mixture. To construct the shaft, the panels are interlocked to form a contiguous ring of panels (Figure 3).

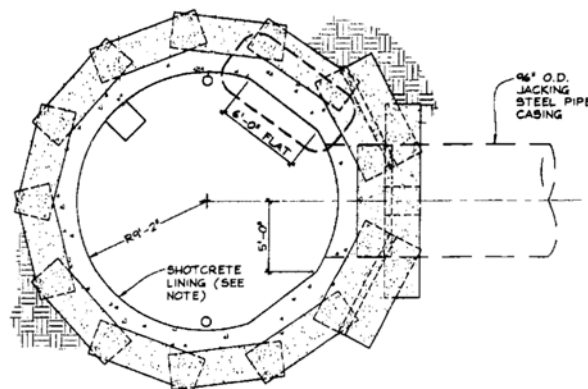


Figure 3. Interlocking Panels Form Shaft and Treated Zone at Receiving Shaft Break-in

The construction methodology is similar to that used for construction of secant piles configured in a ring and interlocked to develop water tightness. Unlike the secant pile method, which completely replaces the soil with concrete, the CSM method mixes grout with the fluidized soil to develop the cementitious soil cement panels. An appreciable amount of the

fluidized soil is displaced and must be contained and disposed of as part of the construction process.

4.1 Method Differentiation

The tooling is the primary difference between the CSM method and other traditional commonly recognized soil mixing techniques. In lieu of using tools, such as augers that are mounted in a vertical axis and turn along a horizontal axis, the cutters for the CSM method are mounted on a horizontal axis and turn on a vertical axis (Figure 4).



Figure 4. CSM Cutterhead

The cutter wheels typically counter rotate when the excavation is in process so as to bring the cuttings up to the center, where shear blades help to further break down the soil cuttings for mixing with the water that is injected at the wheel confluence. Wheel rotation can be changed to counteract deviations of the head in the plane of the cutter wheel rotation.

Another unique feature is that the cutterhead is mounted to a stiff Kelly that is slotted through guide sledges to maintain verticality. Mounted inside the cutterhead is an inclinometer that is used to provide the real-time location of the cutterhead. Adjustments in the longitudinal x direction can be made by simultaneously varying the wheel rotation and speed; adjustments in the short y direction can be made by slight adjustments in the tilt of the stiff Kelly. Steering control is important for all panels, but steering is especially important when panels are cut into each other side-to-side or face-to-face. Because the operator has real-time control to make corrections of the inclination and deviations in the x and y axes, the manufacturer's literature states that total panel deviation should be less than 0.5% of the panel depth.

4.2 Cutterhead

The cutter wheels are manufactured in different sizes. For this project, the receiving shaft was constructed using cutter wheels that cut a 2.5 by 7.8 ft (0.76 by 2.4 m) panel. The jacking shaft was constructed with cutter wheels that cut a 3.28 by 9.2 ft (1 by 2.8 m) panel. The cutter wheels were equipped with carbide-tipped cutters (Figure 5), which are suited for gravel, cobbles, boulders, and rock, but not well-suited for silts and clays. For this project, the bit type on the cutter wheel was dictated more by availability of the cutter wheel than soil conditions.



Figure 5. Carbide-tipped cutterhead

4.3 Vertical Control and Guidance

Vertical control and guidance are available to the operator in real time by means of a display screen (Figure 6) that monitors every facet of the panel construction. The information of greatest interest to the operator is the cutterhead deviation in the x and y axes. These are displayed on the screen in relation to a fixed vertical line that serves as the target installation line. The wavy plots on the control panel provide a visual display of the cutterhead deviations. The bar graph juxtaposed against the vertical line represents the quantity of water being injected during installation with respect to the target amount represented by the vertical line. During grouting and cutterhead extraction, the bar graph represents the amount of grout being injected relative to a predetermined injection rate represented by the vertical line.

During the CSM process, other production control parameters displayed on the operator's screens include depth vs. time, flow and total volume of slurry, slurry pressure, slurry-soil pressure in the panel, pumped slurry volume vs. time, pumped slurry volume vs. depth, inclination x and y axes, deviations x and y axes, torque output of the cutting wheels, and rotation speed of the cutting wheels. This information is stored, then used to prepare a production report that provides a visual representation of the data.



Figure 6. Guidance Control Panel

4.4 Quality Control

The contractor's quality control for this project consisted of obtaining composite samples of the materials in order to conduct a laboratory test program using grout mixes with variable cement content mixed with the composite samples. The testing program allowed the contractor's designers to select a grout strength for the structural design of the shafts.

In the field, the contractor constructed a series of full-depth test panels, whereby the grout injection quantities were varied and wet samples were obtained from within the panels for laboratory testing. Because the equipment was new and components were connected for the first time, a total of 9 test panels were constructed. The grout injection was varied between 12 ft³/yd³ (458 L/m³) to about 25 ft³/yd³ (936 L/m³). Compressive strength tests from this test panel program allowed the contractor to adjust the grout injection quantity to more closely match the grout compressive strength used in the structural designs. Following the test panel program, a grout injection rate of 13.5 ft³/yd³ (500 L/m³) was established for the shaft production panels. For the test and production panels at the receiving shaft, wet samples were obtained at depths of 26 and 52 ft (8 and 16 m). At the jacking shaft, the samples were obtained at depths of 46 and 92 ft (14 and 28 m). A sampling bucket mounted on an I-beam was used for panel sampling (Figure 7).



Figure 7. Sampler bucket at end of I-beam

4.5 Management of Excavated Slurry

The process of excavating the soil, adding water during excavation to fluidize material, and displacing fluidized material with grout means that panel construction results in excess material. The construction process results in fluidized materials that must be managed from start to finish of the panel construction. To manage the slurry, the contractor had to dig trenches, pits, and temporary holding basins to contain or pump the fluidized materials. At the receiving shaft, there was sufficient space to berm up a temporary holding basin into which the fluidized material could be pumped (Figure 8). At the jacking shaft, there was limited working space. A temporary holding basin was developed with K-rails lined with plastic into which the fluidized material was temporarily stored before being pumped and trucked away by vacuum trucks. The slurry was pumped from the work area to the holding areas by a 4-in. (102-mm) pump (Figure 9). The solids suspended in the fluidized material persistently plugged the screened inlet and proved troublesome for the contractor. The contractor adapted by constructing a screened box inlet, but the high suction force and suspended solids required persistent cleaning of the solids from the screens in order to pump the fluidized material.



Figure 8. Fluidized slurry management at the receiving shaft.



Figure 9. Fluidized slurry management at the jacking shaft

4.6 Panel Layout

Layout is critical to ensure the panels are correctly located and sufficiently overlapped for panel interlock. For this project, the contractor had the panel corners loaded into a total station survey instrument. This proved especially useful when locating the panels. The layout of new panels would have been very difficult for the contractor if he had relied upon string lines and offset measurements given the mucky condition of the ground surface following panel construction. New panel locations were established in a matter of minutes using a total station and survey brushes that protruded through the surface muck.

4.7 Work Pad Integrity

It became apparent during the test panel phase at the receiving shaft that maneuvering the CSM rig from panel to panel was very destructive to the surface grade. In anticipation of a winter construction schedule, the general contractor had developed an all-weather pad by placing an engineering fabric on the subgrade and covering it with 8 in. (200 mm) of compacted recycled aggregate material. Small radial adjustments with the track-mounted rig proved very detrimental to the all-weather pad, and in some instances the underlying fabric was almost exposed upon turning. Ultimately, pad integrity was maintained by steel plating the working area of the CSM rig. This required extra time during the panel setup to ensure that steel plates were positioned correctly to make equipment turns on the pads.

5. SHAFT CONSTRUCTION

5.1 Basis of Shaft Design

The accuracy of individual panel installation is a distinct advantage for the CSM method as it can provide a high level of confidence that individual panels are sufficiently interlocked to provide continuous straight or circular walls. Primary panels are typically constructed first and allowed to cure. Secondary overlapping or face-to-face panels are then cut into and between the primary panels to form continuously interlocking panels. The panels can be constructed straight in the case of a wall or in a circular pattern in the case of a shaft. Overlapping panels can be cut into hardened panels (hard-on-hard or cured-on-cured method) or the overlapping panels can be cut into wet or partially cured panels (fresh-on-fresh or wet-on-wet method). In the case where the application is a wall, reinforcing beams can be slotted into the panel while the soil cement is still wet. In the case of a shaft, internal panel reinforcing is not necessarily required as the design assumes hoop stress and compression.

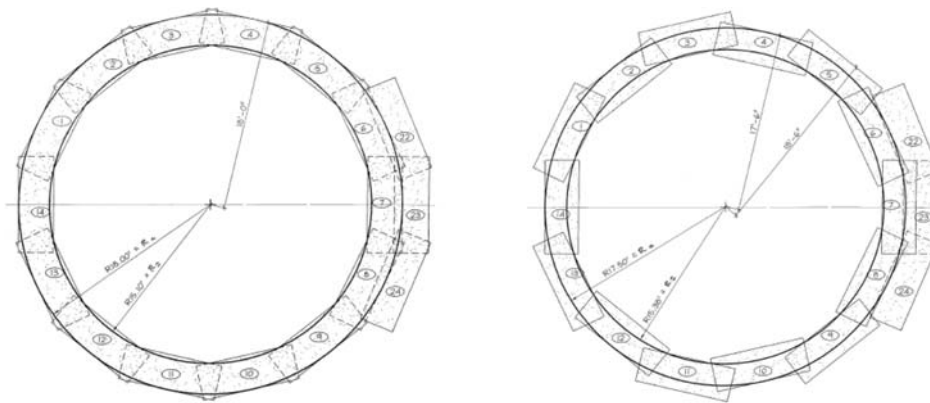


Figure 10. Theoretical Panel Width: (left) No Deviation; (right) 0.5% Alternating Panel Deviation

For the jacking and receiving shaft constructed for this project, a grout strength of 450 psi (3 mPa) was used for the panel design. The receiving shaft was designed as a single panel shaft, whereas the jacking shaft was designed as a double panel shaft. For the loading conditions, a safety factor ranging from about 3.8 to over 5 was calculated for the different stress conditions evaluated. The shafts were designed on the basis that alternating panels drifted out of alignment at a rate of 0.50% of the panel depth reducing the effective width of the panel (Figure 10). The effective width was calculated at the depth of the shaft bottom slab. As an added safety factor, the shaft interiors were designed with 6 in. (150 mm) of mesh-reinforced shotcrete that increased to a 12-in. (300-mm) with depth (Figure 11).



Figure 11. Wire mesh reinforcing for shotcrete

Structural reinforcing was required to transfer loads around the tunnel eye opening and to distribute jacking loads into the shaft walls (Figure 12).



Figure 12. Structural reinforcing around the tunnel eye

Following construction of the receiving shaft panels, the grout strength achieved was considerably higher than 450 psi (3 mPa). The 14-day grout strength ranged between 1,200 and 2,600 psi (8.3 and 18 mPa). The receiving shaft design was subsequently revised to eliminate the shotcrete in the upper 30 ft (9 m) of shaft. Because of the higher than anticipated grout strengths achieved at the receiving shaft, the jacking shaft was revised from a double panel wall down to a single panel shaft with double panels opposite the microtunnel reaction wall. The shotcrete in the upper 28 ft (8.5 m) of the jacking shaft was also eliminated. However, the compressive strength of the jacking shaft panels proved to be much lower than that of the receiving shaft.

The exact cause for the lower test results at the jacking shaft has not been determined. There were a significant number of parameters that changed between the receiving and jacking shaft construction, making that determination difficult. Some of the parameters that changed included the use of a different CSM machine and cutterhead, a different higher capacity grout plant, different grout plant operators, and two different types of sampler buckets mounted on the sample beam. The parameters that stayed the same included the soil conditions, the water injection rate for fluidization, and the grout injection rate.

5.2 Break-in Panel

At the receiving shaft, the specifications required a minimum 5-ft (1.5-m) grouted zone where the microtunnel breaks into the shaft. The specified zone of improvement was two tunnel diameters centered about the horizontal and vertical axes of the tunnel with a minimum thickness of 5 ft (1.5 m). The specifications required the improved zone be constructed square

to the tunnel alignment. The improved zone was created by installing 4 outer panels, two of which were constructed wet-on-wet perpendicular to the tunnel alignment (Figure 3).

5.3 Panel Production

At the receiving shaft, seventeen 63-ft (19.2-m) long panels were constructed over a four-day period. The contractor averaged 252 linear ft (77 m) of panel production for three days. The excavation rate was set at about 4 in. (100 mm) per minute, and the rate of extraction during grouting was set at about 8 in. (200 mm) per minute. On average, from start to finish, the contractor averaged about 6.7 in. (170 mm) per minute for each panel.

At the jacking shaft, a total of seventeen 105-ft (32-m) long panels were constructed in 10 days. The jacking shaft site was much more constricted. Time was lost in the first few days managing the slurry, moving plates, and outfitting the grout plant with different pressure valves to counteract the increased height of the Kelly for the longer panels. The contractor averaged two 105-ft (33-m) long panels per day. The excavation rate was preset at about 4 in. (100 mm) per minute and the rate of extraction during grouting was set at about 8 in. (200 mm) per minute.

6. LESSONS LEARNED

6.1 Slurry Control and Management

One aspect of the CSM method to consider for future projects is slurry control and management. These need to be addressed during the project design phase as they will impact temporary construction easements for handling, storage, and disposal. Slurry management was certainly at the forefront of this project. Because there was no method-specific specification to dictate how the contractor controlled the fluidized materials, the underground contractor had lots of latitude. He was also fortunate that the shafts were being constructed in relatively uncongested areas that lent themselves to temporary development of storage basins constructed with berms and lined K-rail. Recessed channels leading to collection pits facilitated the containment and collection of the fluidized materials, but constant plugging of the slurry pump inlets with clay lumps caused the channels and pits to become overwhelmed.

In a congested urban environment, where open areas are not available, there must be an aggressive and comprehensive program to manage and dispose of the fluidized material. This would certainly have an impact on the production rates. Specifications for use of the CSM method would need to address slurry containment within the immediate vicinity of the drill site (an approximate containment area of 5 to 8 ft [1.5 to 2.5 m] outside the limits of the individual panels would suffice). This could be accomplished with hay bales or another type of flexible or articulating containment system that would provide at least 18 to 24 in. (0.5 to 0.6 m) of freeboard. Recessed pits could be constructed at the panel sites to assist in containment, but such pits tend to hamper the locating of panel corners for cutterhead alignment. In congested urban environments, slurry management might have to include the use of a slurry separation plant.

6.2 Panel Layout Using Total Station

The underground contractor was very conscientious about making sure the panels were accurately located to ensure panel interlock to satisfy the watertight performance criteria of 10 gal/min (40 L/min). In a previous project where CSM panels were laid out with control points,

offsets, and string lines, some of the panels lacked adequate interlock, resulting in “windows” between some of the panels. The lesson learned on that project is that panels on future projects should be accurately located by survey methods like that used on this project.

6.3 Cutter Wheel Tooling

Production rates could be improved by matching cutter wheel tooling to the soil conditions. The carbide bits used for this project tended to rip and tear the clayier materials into gravel to fist-sized chunks, and this hampered plugging of the slurry pump screens. Adapting clay spades to the cutter wheels could be more efficient in cutting the clay soils into smaller particle sizes to minimize plugging of the screens.

6.4 MTBM Exit of Shaft Wall

In the course of excavating through the shaft walls with the MTBM, the tunnel contractor increased the MTBM slurry pressures to match the ambient external pressure of about 30 psi (2 bar). Upon reaching about 15 psi (1 bar) water began leaking through the shaft walls via the cold joints between the CSM panels and the shotcrete. The leakage necessitated an extensive grouting program to inject a hydrophobic material into the cold joints to seal off the slurry.



Figure 13. Water leakage through a shotcrete cold joint above the tunnel



Figure 14. Hydrophobic grout injection in progress

7. CONCLUSIONS

The shafts constructed by the CSM method were successful in satisfying the project specifications. The receiving shaft was excavated in the dry, whereas the jacking shaft was excavated in the dry to a depth of about 75 ft (23 m). The low panel strengths and one panel joint deviation resulted in the contractor using in-the-wet construction methods to finish the

last 15 ft (4.5 m) of the jacking shaft excavation. After the shaft plug was constructed and the shaft was unwatered, the shaft interior remained dry with no visible signs of water. Shafts constructed using the CSM method must include:

- Construction of in-the-field test panels to validate the design assumptions in the design and to determine the grout injection rates.
- Panel locations (corners) set by survey methods using a total station survey method.
- Wet samples of constructed panels must be taken and tested—preferably 6 x 12 in. (150 x 300 mm) samples to minimize the influence of soil pockets on the overall sample size.
- Comprehensive slurry management plan to contain, collect, and dispose of the fluidized materials.
- Consideration of the disturbance to the shaft area during equipment relocation for panel construction.
- If shotcrete is used as structural reinforcing around the tunnel eye and the exit slurry pressures are in excess of about 10-15 psi (0.7-1.0 bar) to counterbalance ambient external pressures, consideration must be given to incorporating a positive seal between the shotcrete and CSM walls.

Equipment refinements in cooperation with the manufacturer could include assessments of the use of different cutters on the wheels where soil conditions are predominantly silts, clays and sands.

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