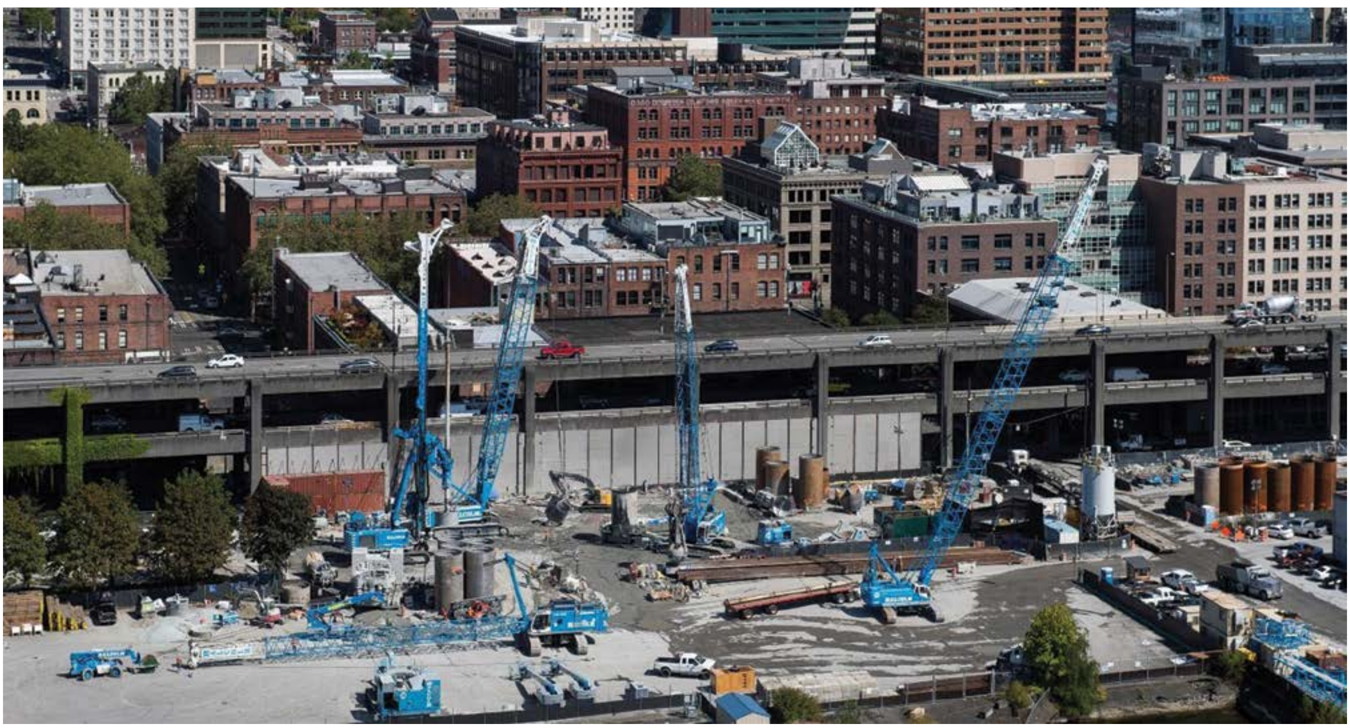
FEATURE ARTICLE

Construction of the SR-99 recovery shaft

FIG. 1

Site layout/access constraints - Note existing SR-99 behind work area, and pile-supported structure above Puget Sound in foreground, just out of view.



Mining on Seattle's SR99 tunnel began in July of 2013. Initial mining progressed slowly through a 4.5 m (14.9-ft) thick fiber-reinforced concrete headwall before immediately entering the first of three planned safe havens. Once through the headwall and safe haven the machine would move through roughly 122 lineal m (400 ft) of jet grout improved soil at a rate of slightly more than 1.6 m/d (5.3 ftpd). It was anticipated that once mining has passed through the improved area, "Bertha" – now the world's second largest tunnel boring machine (TBM), would be moving at a rate of almost 11 m/d (36 ftpd). By the end of October 2013, Bertha had mined roughly 131 m (430 ft), averaging 1.4 m/d (4.7 ftpd), and had begun mining within native soils. By the start of December 2013, tunneling had reached the 244 m (800 ft) mark and Bertha was averaging 3.6 m/d (11.9 ftpd), achieving as much as 12.8 m (42 ft) of progress on given days. Unfortunately, on Dec. 6th, 2013, Bertha began to stumble and all progress quickly came to a halt.

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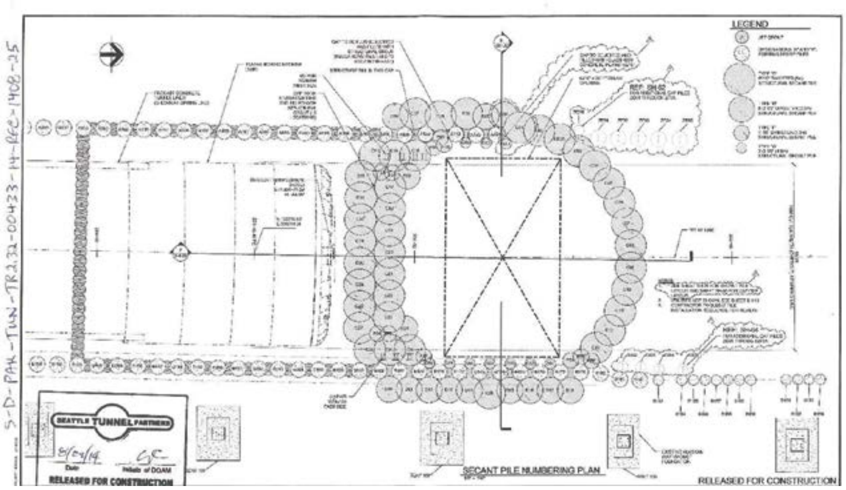
Initial reports stated an obstruction had stopped Bertha in her tracks. The preliminary investigation involved installation of 10 deep dewatering wells to reduce the hydrostatic pressure within the ground around the TBM, to allow the contractor's personnel to inspect the cutter head from within and also to investigate for the presence of obstructions at the face of the cutter head. During inspection, the contractor's crews found fragments of steel pipe entangled in the cutter head. The steel was apparently from an abandoned 254 mm (0.9 in.) diameter monitoring well casing, previously installed by the Washington State Department of Transportation (WSDOT) to monitor groundwater conditions for the

FIG. 2

Access/recovery shaft layout - Note existing SR-99 footings, near bottom edge of drawing.

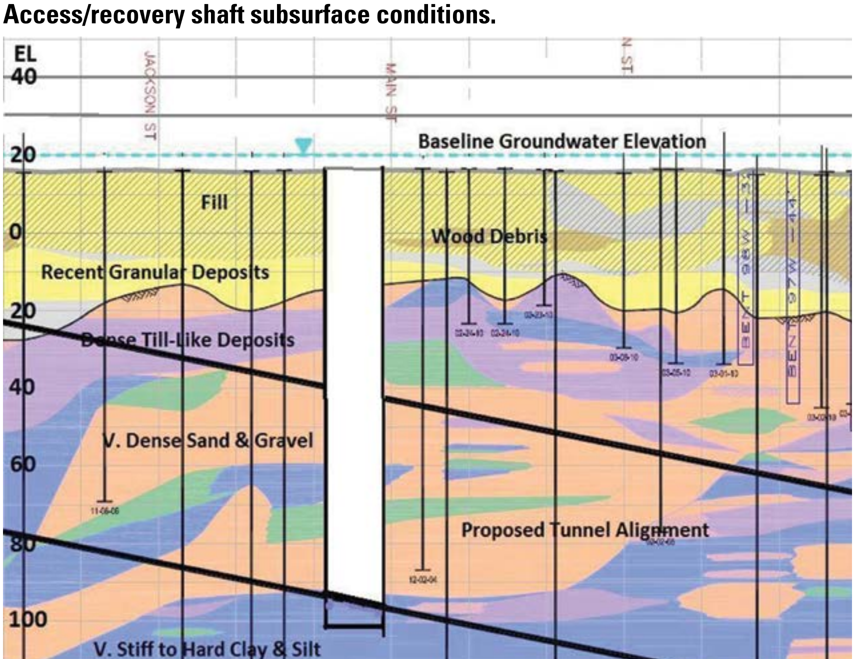


design and planning of this tunnel project. After the steel was removed from the cutter head and cleared from Bertha's path, she attempted to move forward but was only able to generate a slow crawl.

The contractor elected to further investigate the soil located immediately in front of the TBM. At the contractor's request, Malcolm Drilling Co. mobilized a Davey Drill 725 duplex rotary drill to install 18, 152 mm (6 in.) diameter probe holes on 1.5 m (4.11 in.) centers across the face of the cutter head. Of the 18 holes drilled, six obstructions were found at depths between 17 to 24 m (55.9 to 78.8 ft) located between the top of the cutter head to near spring line). Small fragments of steel were found in several of these holes, and the drill casing was not able to be advanced beyond the obstruction. Malcolm Drilling Co. was then directed to drill 1.5 m (4.11 in.) diameter holes in four locations where the obstructions were encountered, to facilitate their removal. However, after these additional, larger exploratory holes were drilled, no additional steel fragments, nor obvious signs of apparent obstructions were encountered. All additional exploratory work was completed by late February 2014, and the alignment was then thought to be clear and ready for Bertha to continue moving forward. However, once the TBM was cleared to resume mining, and the cutter head started turning again, a much larger issue was discovered. The machine's main bearing had been damaged so severely upon encountering the obstructions, it would need to be completely replaced. This would require a monumental effort, with the fast-track design and construction of a structure more than 36.6-m (120-ft) deep and more than 24 m (78.8 ft) in diameter; that would provide access to the TBM and allow the disassembly and removal of the entire cutter head.

FIG. 3

Access/recovery shaft subsurface conditions.



Site constraints

Malcolm Drilling Co. was solicited to help with preliminary design and constructability of the access shaft required for the repair of the machine. Several obstacles had to be overcome in designing an access shaft that would work for this project. The primary constraint was space and access (Fig. 1). With the Puget Sound approximately 30.5 m (100 ft) to the west and the deteriorating Alaskan Way Viaduct (SR-99) immediately to the east within feet of the proposed access shaft location, there were severe "at grade" access restrictions. Also, previously installed under the main tunneling contract, 1.5 m (4.11 ft) diameter tangent piles, spaced 0.46 m (1.6 ft) from each other, ran along the east and west of the tunnel alignment. These piles were required for settlement mitigation during tunneling and to protect the existing viaduct. In addition, a very high water table, only 2.4 m (7.11 ft) below grade, needed to be cut off. And last, but not least, were the schedule implications for building something effective and quickly enough to get this major project back on track.

Rescue shaft desgin

Exact reasons for Bertha's lack of progress has been the subject of much speculation, however one indisputable fact remained; the full cutter head and inner workings needed to be removed to facilitate a complete repair of the TBM. To accomplish this, a recovery shaft needed to be designed and installed immediately in front of the TBM to allow it to enter the shaft and provide access for repairs.

Having extensive experience with secant pile compression rings, Malcolm Drilling Co. recommended a circular access shaft comprised of over-lapping secant piles, which would provide excavation support, groundwater cut-off, and eliminate the need for horizontal anchors or braces thereby maximizing space for removal of the cutter head. The original design included 2.13 m (10.3 ft) diameter secant piles in a circular ring with jet grouting between the originally placed tangent piles. Moreover, jet grouting continued across the back of the machine to provide water cut-off for internal maintenance of the machine, as well as controlling water when the machine enters the access shaft.

Designed by Brierley and Associates, this option was put out to bid to select drilling contractors. Upon initial review of the design, Malcolm Drilling Co. suggested an alternate option; to install 3-m (9.84-ft) diameter drilled secant piles, thus requiring fewer secants and reducing the anticipated schedule. Once awarded the work, Malcolm Drilling Co. worked closely with Brierley in finalizing the design with the capabilities that could be brought to the project (Fig. 2).

Subsurface conditions

The south Seattle waterfront sits upon reclaimed lands comprised of decades of undocumented fills, debris, and various organic deposits. Within the upper reaches of the soil profile, numerous timber piles and railroad ties from buried trestles can be expected. The various fill deposits overlie soft and loose marine sediments that lie on top of glacial till at depths of 12 to 27 m (39 to 88 ft).

The complex glacial stratigraphy controls the nature of the groundwater flow. The permeabilities vary by orders of magnitude in adjacent stratigraphic units. Consequently, there are multiple perched groundwater-bearing layers and multiple piezometric surfaces along the proposed tunnel alignment.

Groundwater movement is governed by hydraulic

FIG. 4

Access/recovery shaft construction — confined work site.

FIG. 5

Access/recovery shaft dewatering – Horizontal drain layout.

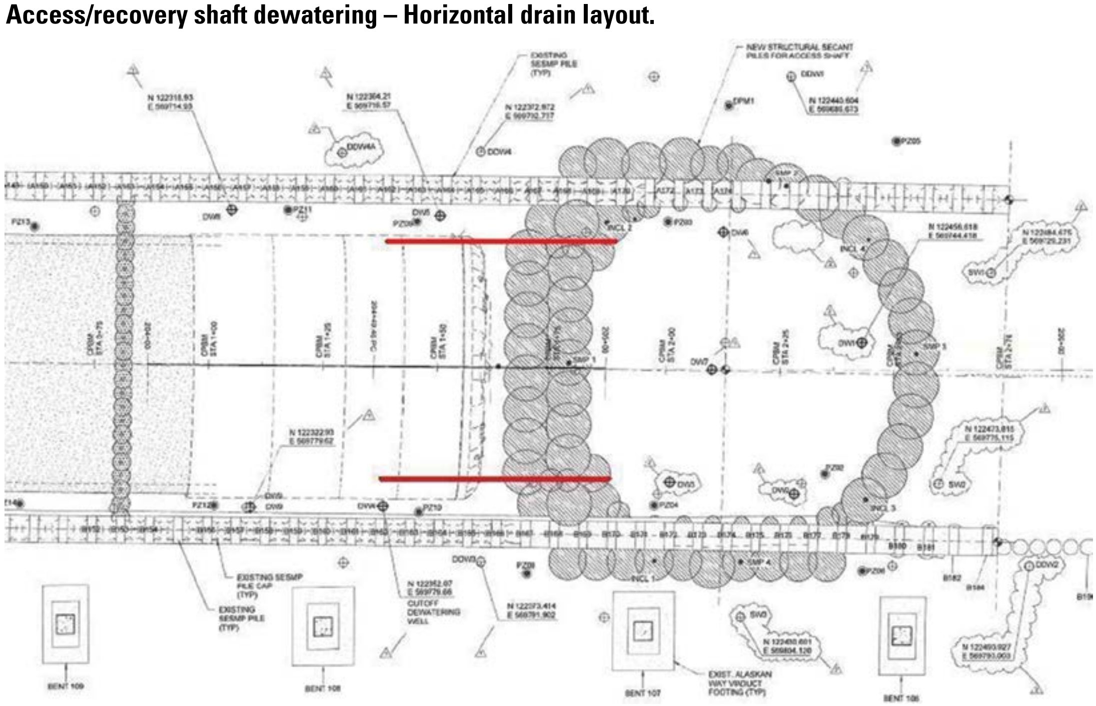


FIG. 6

Access/recovery shaft dewatering – Horizontal drain installation from within shaft.

gradients, which may increase, or decrease with depth; downward gradients typical of upland areas, and upward gradients often observed in water-bearing units close to discharge points. Soil borings near the south portal, with multiple piezometers installed, indicated multiple piezometric surfaces with variations in groundwater levels of up to 3 m (9.84 ft); some indicated artesian pressures of up to 1.5 (4.11 ft) meters above the ground surface (Fig. 3). Tidal influence was also observed to affect the groundwater level within the area of the recovery shaft, with groundwater levels observed as shallow as 1.5 m (4.11 ft) below grade.

Consistent with the known subsurface conditions at this reach of the tunnel alignment, there was an abundance of wood debris within the upper fill zone. Relic deposits of wood, pulp and decayed organic matter would be routinely encountered in vast areas where little to no natural granular soils were detected.

Additional geotechnical investigation within the vicinity of the recovery shaft revealed a deep aquifer with direct communication to, and encompassing, the silt deposit that constitutes a majority of the soil plug within and beneath the proposed access shaft. In addition, the presence of several large voids were confirmed, some that required more than 420 m^3 (459 cuft) of CDF to fill, and some that had been previously filled with large crushed rock by the contractor.

Drilled secant piles

The original design for the TBM launch pit included two parallel rows of drilled shafts, one to the east, and one to the west, of the proposed tunnel alignment. They were designed to prevent lateral soil movement adjacent to the tunnel, and mitigate potential surface settlement; they were referred to as South End Settlement Mitigation Plan (SESMP) piles. Please note, for the purpose of this discussion, the authors will use the terms “drilled shaft” and “pile” interchangeably, to refer to the deep foundation and earth support elements used to construct both the recovery shaft and the original TBM launch pit. To incorporate the existing SESMP piles into the access shaft, smaller 1-m (3.3-ft) diameter drilled shafts were constructed parallel to, and along the interior face of the existing SESMP piles. These drilled shafts help create a continuous outer wall along both the east and west sides of the access shaft, and to provide additional bearing capacity for the cap beams, required for support of the gantry crane. The work was completed with a Bauer BG-50 installing drilled shafts up to 40 m (131 ft) in depth. Once again there was difficulty with maintaining verticality that was specified to be within 152 mm at 40 m (5.9 in. at 131 ft), as checked with a SoniCaliper. The difficulty was a result of the concrete over-break of the existing SESMP piles (drilled shafts) and field adjustments had to be made to accommodate these issues. It was clear that the actual installation of the drilled shafts required to construct the access/recovery shaft was going to be significantly more challenging than designing it. Additionally, far more obstacles than anyone could have imagined during the planning and design phase were encountered. However, having the designer’s field representative on-site full-time provided the opportunity to quickly address challenges as they arose, allowing the project to move forward as quickly and efficiently as possible.

After the completion of the drilled shaft work, other equipment was mobilized to begin the large diameter work. Two spreads of equipment and crews began work in mid-June with Liebherr dig cranes and Leffer oscillators and rotators to start the 2.5 m and 3 m (8.2 ft and 9.11) diameter secant piles included in the final Brierley design (Fig. 2). The work proved to be very difficult due to sequencing and the tight work areas on the job site (Fig. 4). The greatest assets to the project were the two Leffer rotators. These machines proved to be the most efficient at installing the piles on location, maintaining verticality, and with the highest rate of advancement as opposed to just using casing oscillators for advancement. In the end, the shaft work was complete be the end of August 2014, leaving only the remaining grouting and dewatering work to be constructed.

FIG. 7

Success – "Bertha" within the Access/Recovery shaft.

Jet grouting

Jet grouting was an integral part of the overall access/recovery shaft design. Jet grouting was required outside of the recovery shaft to provide a level of groundwater control at the machine "breaking," the location the TBM will bore into the recovery shaft. The SESMP piles, constructed previously, as part of the work for the original launch of the TBM, were located on both the east and west sides of the tunnel alignment, and were enhanced with jet grouting to act as cutoff walls, (Fig. 2). These SESMP piles consisted of 1.5 m (4 ft) outside diameter drilled shafts, installed in two parallel lines, one to the east and one to the west of the proposed tunnel alignment. These drilled shafts were spaced approximately 1.9 m (6.3 ft) center to center, creating a gap of about 0.4 m (1.3 ft), requiring jet grouting to enclose the gap and provide groundwater cutoff. A transverse line of jet grout columns placed in secant fashion tied the two east/west cutoff walls together and encapsulated the TBM cutter head with the recovery shaft that was yet to be constructed.

Jet grouting between the existing SESMP piles would have been extremely difficult, if not impossible, due to the large amount of concrete over-break resulting from the poor soil conditions. Accordingly, each proposed jet grout column was pre-drilled with 152 mm (5.9 in.) tooling, clearing a space for the jet grout monitor and casing to reach the designed depth. Upon completion of jet grouting along the SESMP pile lines, jet grouting efforts continued with construction of a transverse grout curtain, or cutoff wall, behind the TBM tail shield. The purpose of the cutoff wall was to control groundwater during the critical phase of shaft "breaking," as the TBM enters the access/recovery shaft.

SESMP piles were located only on the east and west walls of the access shaft. The soil between them needed to be grouted in order to create a complete and continuous wall to withstand the extreme loads required throughout the various stages of the work. However, continued dewatering, pressurizing of the TBM heading, and work within the tunnel horizon caused soil loss and changes to the subsurface conditions. This was first observed when a 420 m3 (459 cuft) sinkhole appeared in front of Bertha shortly after she first stopped. This fact was further evidenced by removal of vast quantities of TBM soil conditioner during drilled shaft excavation, at horizontal distances greater than 24 m (78 ft) to the north east of the TBM cutter face. A dynamic environment materially different than the rest of the project site had been created over a very short time. Consequently, during drilled shaft construction sink holes manifested to existing grade, requiring evacuation of all heavy drilling equipment while the safety and stability of the working platform was assessed. After mass excavation and earthwork, a large volume of quarry spalls was imported to the site to create a safe and stable working platform, or mattress, for staging the drilling equipment. Subsequently, during the following drilled secant work, quarry spalls were carried deeper into the soil profile with each tooling penetration. As a result, the combined presence of a quarry spall mattress at grade along with quarry spalls throughout the vertical soil profile created an environment that was not conducive to jet grouting methods. As an alternative to jet grouting methods Malcolm Drilling Co. mobilized two Foremost DR-24 vertical drill rigs to drill out and flush these confined spaces with high strength cement grout in hopes to treat the areas needed for the shoring design.

Dewatering

Once the grouting work was completed the installation of the remaining dewatering wells commenced in addition to further geotechnical investigations and installation of instrumentation. The geotechnical investigation showed that the silt plug in the bottom of the excavation, previously assumed impermeable and to function as an aquiclude, actually had vertical silty sand seams thereby raising concern that the shaft bottom had potential to heave. This new obstacle was overcome by enhancing the current dewatering design. The current design was limited to eight wells at 47 m (154 ft) in depth. To eliminate this potential bottom heave condition, eight more wells, four at 47 m (154 ft) in depth and four more at 62.5 m (205 ft) in depth, were installed to depressurize the bottom plug for the final state of the excavation.

Prior to advancing the TBM into the access/recovery shaft, Malcolm was asked to install two horizontal drains, from within the access shaft, to relieve hydrostatic pressure behind the secant pile wall. The 15.25-m (50-ft) long drains were installed working from on top of the upper horizontal surface of the concrete cradle that was constructed in the bottom of the shaft to support Bertha upon entry, (Fig. 6). The horizontal drains were comprised of 7.6 m (24.11 ft) of pre-pack PVC well screen, and 7.6 m (24.11 ft) of solid PVC pipe. The pre-pack well screen consists of a 152 mm (5.9 in.) diameter outer and 51 mm (2 in.) diameter inner slotted PVC well screen with filter sand in the annular space. One drain was located on each side of the TBM, at roughly the lower quarter-points of the tunnel, extending parallel with the alignment (Fig. 5). An approximately 305 mm (12 in.) diameter hole was drilled through the secants and a 254 mm (10 in.) diameter pipe with a blow-out preventer (BOP) was installed at each location. The drains were installed within a 203 mm (8 in.) diameter borehole and equipped with a PVC ball valve to control flow.

Once the hydrostatic pressure surrounding the TBM was reduced to Elevation -85 (ft), essentially the elevation at which the horizontal drains were installed, the tunnel crew was given the approval to advance the damaged TBM forward, into the recovery shaft. However, prior to advancing into the recovery shaft, the perimeter of the anticipated penetration through the wall (of the recovery shaft) was pre-split with a long-reach, excavator-mounted hydraulic concrete breaker to minimize the efforts of the TBM.

TABLE 1

Construction summary. Maclcolm Drilling Co. installed the following work to the complete the access shaft.

NO.	
17	1 m (3.28 ft) diameter drilled shafts 40 m (131 ft) deep.
14	1.5 m (4.92 ft) diameter drilled shafts 40 m (131 ft) deep.
16	2.5 m (8.2 ft) diameter drilled shafts 40 m (131 ft) deep.
25	3 m (9.84 ft) diameter drilled shafts 40 m (131 ft) deep.
16	Dewatering wells up to 62.5 m (205 ft) deep
2	Horizontal drains 152 mm (5.9 in.) diameter by 15.25 m (0.6 in.) long
1,951 m (6,400 ft) of jet grout column	

Summary

The work to create this access/recovery shaft was a monumental effort requiring precise coordination from the best in all disciplines and utilization of the most state-of-the-art foundation drilling equipment. There were many obstacles to overcome, as is the case in most emergency jobs, which required problem-solving "on the fly" to accomplish this monumental task within the extremely limited time available.

A broad range of geotechnical construction techniques were required for the construction of the TBM recovery shaft on the SR 99 tunnel. Difficult ground conditions along with a condensed work schedule contributed to the complexity of the work. Moreover, a highly "dynamic" underground environment created by TBM operation and maintenance, site preparation work and maintenance, and dewatering, added unforeseen challenges. State-of-the-art specialty foundation equipment was mobilized, which worked concurrently with Leffer casing rotators and oscillators, and Liebherr duty cycle dig cranes. Other applications included various jet grouting and dewatering scopes completed both at grade and from within the shaft excavation. This work tested the capabilities of existing equipment, pushing them to (and beyond) their previous benchmarks, and in doing so has defined new limits for secant shaft construction.

At the current time, repairs to "Bertha" are complete, she has been reassembled within the recovery shaft, and has advanced a few feet, to allow for evaluation of her recent repairs and ensure no further repairs are required. The present schedule calls for her to re-commence mining operations within the coming days and potentially complete the 2.4 km drive by January 2017. ■