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# King County Uses Trenchless Methods to Construct a Large Siphon Under Seattle's Ship Canal

Kimberlie Staheli, Ph.D., P.E., Staheli Trenchless Consultants, Seattle, WA
Doug Genzlinger, P.E. Tetra Tech, Seattle, WA
Ade Franklin, King County, Seattle, WA
Marty Nobel, King County, Seattle, WA
Jeremy Johnson, P.E., Jacobs Associates, Seattle, WA

**ABSTRACT:** King County in Seattle, WA is constructing a larger diameter siphon to convey sewer flows beneath the Ship Canal to the West Point Treatment Plant. The siphon was designed with pre-cast concrete segments with a 128-inch OD to accommodate a curved alignment. The contractor chose to use a Herrenknecht EPB machine that could be converted between segment and pipe jacking modes. The 1,980 foot tunnel begins in a shaft that is 138 feet deep and terminates in a shaft that is 80 feet deep on the far side of the canal. Upon completion of the tunnel, an 85.5 inch diameter pipeline was installed within the tunnel to provide critical velocities within the siphon. The 1,980-ft tunnel started in stiff to hard silty clays and transitioned to medium dense sands beneath the canal. A geotechnical baseline report was written for the project and used during construction to evaluate potential differing site condition claims. This paper details the construction of the EPB tunnel and provides lessons learned during the construction, along with insight into the use of the GBR on the project, and offers recommendations for future designs.

## 1. INTRODUCTION

King County originally started the design work for the Ballard Siphon Replacement Project in 2006. The Ballard Siphon originally consisted of two 36-inch diameter wood stave siphons that were 1,365 feet long and connected the Ballard Regulator to a 72-inch diameter pipeline that continued to the West Point Treatment Plant. One of the 36-inch siphons served normal flow and the second served as an overflow siphon. However, due to growth in the region, there was a need to upsize the capacity of the siphon to eliminate overflows. The Ballard Siphon Replacement Project was designed to correct the capacity problems by replacing the existing Ballard Siphon system with additional pipelines to transport wastewater under the Ship Canal and Salmon Bay.

Based on an extensive hydraulic analysis and the development of a number of possible flow configurations that could accommodate that need, the preferred configuration was determined to be two 26.5-inch pipelines, to serve low flow and a single 84-inch overflow siphon.

## 2. CONSTRUCTION METHODS

For the low flow siphons, it was decided to maximize the use of the existing facility by sliplining the 36-inch wood stave pipes with 30-inch HDPE, resulting in a 26.5-inch inner diameter. During design the existing siphons were pigged in a three stage process, increasing the outer diameter of the pig with each step, to ensure that the 30-inch HDPE would easily fit within the existing siphons. Based on those findings, installation of the sliplining was specified with the use of a HDD rig, where the drill pipe would be threaded through the existing siphon to an exit area where it would be attached to the HDPE pipe. The HDD rig would then pull the HDPE pipe inside the existing wood stave pipe.

For the construction of the 84-inch tunnel, microtunneling was initially evaluated for construction. However, the tunnel length was over 2,000 feet and at the time of the design there was only a single microtunnel longer than 2,000 feet in the United States. Due to the potential risks associated with the length of the microtunnel drive from deep shafts, the recommendations from a peer review panel, and the inability to construct access shafts from within the Ship Canal, the tunnel was specified for construction with a Earth-Pressure Balance Machine (EPBM) with a segmental liner.

## 3. USE OF AN EARTH PRESSURE BALANCE MACHINE

An EPBM controls the stability of the excavated face by adjusting pressure inside the cutting head chamber to balance the pressure of the soil and groundwater outside the cutting head. The shield of an EPBM is specially designed and sealed to operate in soils with high groundwater head (up to 10 Bar or 145 psi). The cutting head chamber is located outside the sealed portion of the EPBM. A screw conveyor removes the excavated material from the EPBM's pressurized chamber. The screw conveyor controls the pressure at the tunnel face by matching the speed and discharge rate of muck to the pressure in front of the "pressure bulkhead." Conditioners are often added to the excavated material to create "earth paste" that is removed through the augers. Once removed from the face, the muck is conveyed to the launch shaft using rail cars. Figure 1 shows the key components of an EPBM.

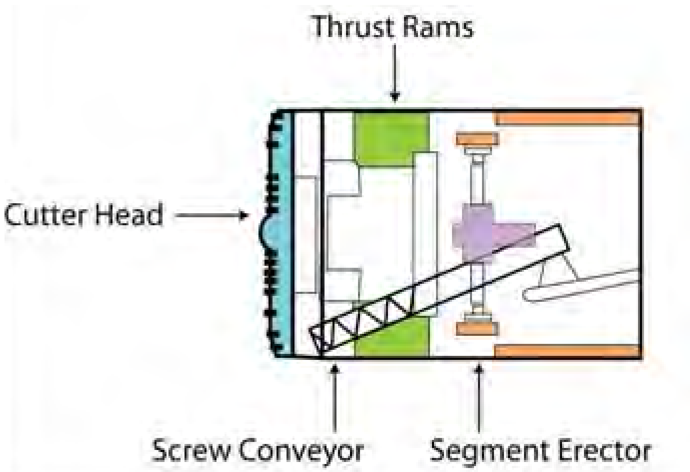


Figure 1. EPB Shield

The EPBM operator sits within the shielded portion of the machine and controls the rate of advancement and the steering by monitoring and adjusting the screw conveyor and the thrust rams. An articulated, sealed joint is located between the forward shield and the tail shield to allow steering of the EPBM. Another seal is located between the tail shield and the segmental tunnel lining. Pre-cast concrete segmental liners are erected in the EPBM's tail shield as it advances. These gasketed liners are watertight and serve as the support and final lining of the tunnel. The annular space between the over-cut of the cutter head and the tunnel liner is filled with grout.

Unlike microtunneling, the EPBM is advanced by using the previously installed tunnel ring to push against and advance the machine. Because of this, the risks associated with the length of the tunnel are eliminated. Each tunnel liner ring is comprised of a number of segments.

## 4. GEOTECHNICAL CONDITIONS

A number of project-specific soil borings were drilled to characterize the subsurface conditions at the siphon crossing location. Soil conditions along the alignment consisted of fill/alluvium over glacially consolidated silts and clays. The fill/alluvium consisted of loose to medium dense silty sand. The glacially consolidated silts and clays were very stiff to very dense clayey silt and silty clay. Groundwater was encountered at a depth of about 7 feet in the land borings and fluctuated with the level of Salmon Bay for the over-water borings. These soils did not pose significant risk for tunneling, and construction within these soils was considered favorable. However, of significance was a layer of very loose/soft soils (blow counts of less than 3 blows per foot) on the surface of the canal. These soft/loose soils presented significant challenges for tunneling as they would not provide adequate bearing capacity or steering response for the tunneling machine. Therefore, the depth and vertical alignment of the tunnel was selected to avoid these soils.

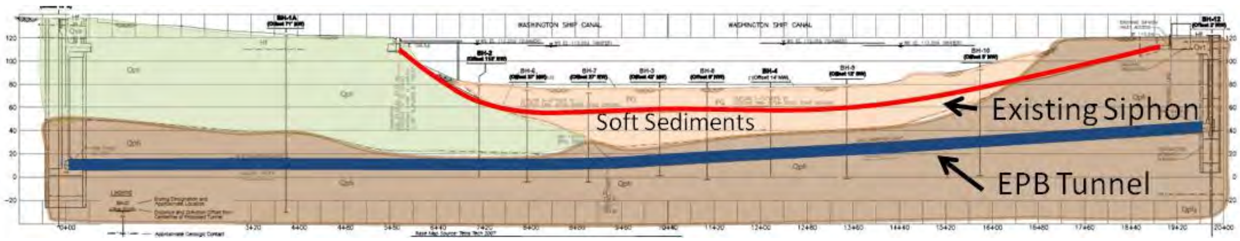


Figure 2. Geotechnical Cross Section

Although no gravel or cobbles were encountered during the geotechnical investigations, the glacial soils that were encountered at the project site have historically contained randomly distributed cobbles and boulders. As a result, the design team chose to baseline two boulders along the alignment, alerting the contractor to bring a machine capable of excavating through boulders.

## 5. BIDDING THE PROJECT

When the project initially went to bid only two bidders provided bids for the project and a bid protest was filed due to a bid irregularity. The bid protest resulted in the Owner deciding to rebid the project. Again, only two bidders provided bids for the project and another bid protest was filed due to questions on bidder qualifications. After a significant delay, King County awarded the project to the low bidder, JW Fowler Company of Dallas, Oregon.

## 6. EARTH PRESSURE BALANCE TUNNELING

The contractor purchased a new Herrenknecht EPB 2850 Earth Pressure Balance Tunnel Boring Machine with a 138.2 inch outer diameter shield and a cutting head with a 139.6 inch excavated diameter, resulting in a 1.4 inch overcut. The machine was fitted with a combination of 12-inch cutter discs and 3.93 inch drag picks capable of excavating through the baselined geotechnical conditions. The cutterhead was manufactured with back-loaded cutters to allow changing the cutters mid-drive should cutter wear warrant new cutters. Since the tunnel length was not considered long, cutterhead inspections and tool replacements were not planned for during the drive. A front view of the EPBM is shown in Figure 2.

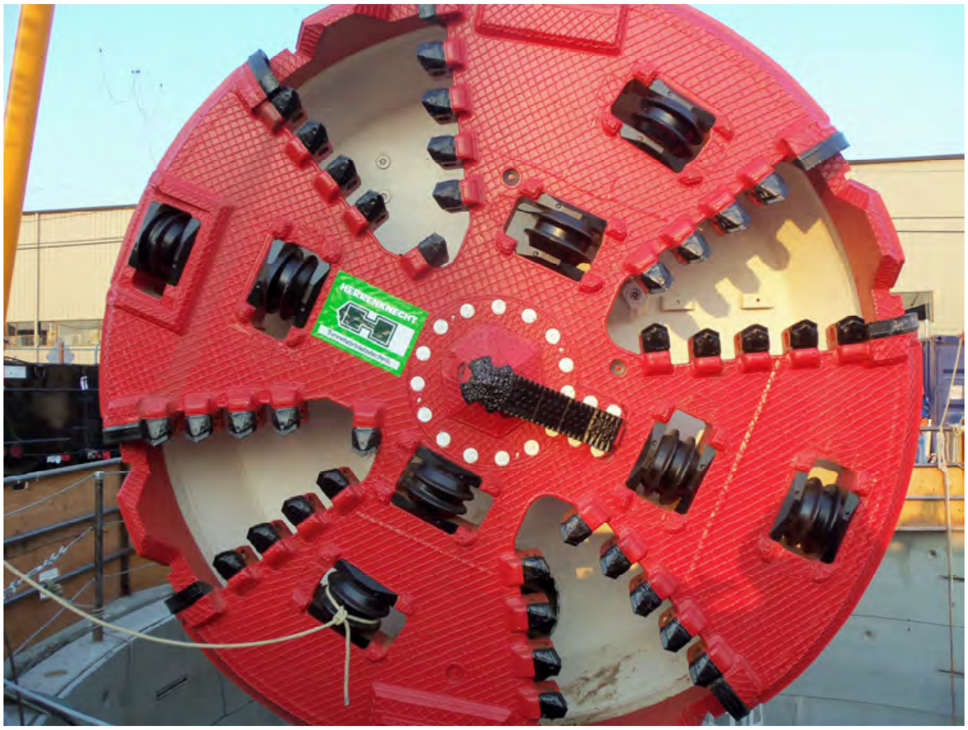

**Figure 3. EPBM Used for Excavating Beneath the Ship Canal**

The machine was used to excavate and support the tunnel face for the 1,980 foot tunnel. The tunnel was launched from a shaft approximately 115 feet deep with approximately 100 feet of groundwater head to a reception shaft approximately 83 feet deep. Entry and exit seals were incorporated into the shaft walls to provide a groundwater cutoff as shown in Figure 3. These seals were mounted to a section of the shaft that was poured square to the alignment. The square section allowed enough room for the seal to engage to the forward section of the machine and adjust to prevent leakage. Water Stop was then placed between the shaft wall and the square section to prevent water migration into the shaft. A temporary launch frame was set to the proper line and grade at the bottom of the shaft and temporary thrust supports and spacers were used to span the distance between the back of the EPB and the back wall of the shaft. Thrust cylinders were then used to advance the machine forward. Once a full stroke was completed, additional spacers were added to push the machine further forward. Once the machine was sufficiently buried, the temporary supports were removed.

**Figure 4. Entry Seal Mounted to Shaft Wall for Launch**

The EPB 2850 machine utilized a soil conditioning foam and earth pressure balance to maintain the necessary pressure to prevent uncontrolled loss of stability at the tunnel face. Prior to tunneling, soil samples retrieved during shaft excavation were tested with a variety of soil conditioners to determine the best conditioner for the project. The tunnel spoil was removed from the cutter chamber via a screw conveyor in the excavation chamber. The EPB TBM was equipped with three pressure transducers capable of reading pressures from 0 to 6 bar. These transducers were located in the excavation chamber (at centerline), in the excavation chamber access door, and at the forward end of the muck removal screw. A readout was provided at the Operator's control panel. During excavation, the operator attempted to keep a constant pressure at the tunnel face by controlling the rate of excavated material removal and the rate of penetration. The earth paste formed at the face was carried into muck carts and carried by a locomotive on a set of tracks to the launch shaft for removal and disposal.

Among other features of the machine was a remote monitoring station that allowed the project team to view the tunneling at all times. The machine was assigned an IP address. The tunneling design and construction inspection team had the ability to access a web site and monitor tunneling operations on a real-time basis during tunnel construction. During tunneling, web site relayed in real time steering cylinder position, installed tunnel length, horizontal and vertical deviation, steering head roll and grade, machine position, thrust force, cutter torque, RPM, cutter chamber pressure, face pressure, advance rates, air monitoring, tail shield grease pumping and tail void grout pumping.

## 7. TUNNEL LINING AND SUPPORT

The initial tunnel support was bolted and gasketed reinforced concrete segments as shown in Figure 4. Concrete segments were hauled into the tunnel on a segment car that was attached to the front of the locomotive. Once at the heading, the segments were lifted off the car and placed on a segment feeder for holding until they were placed into position. The segment erector would then lift the segments, one at a time, into the final position. Once the segment was in the final position, the bolts were installed, fastening the segment to the adjacent segment. Pressure would be applied to the segment with the thrust shoe, helping to secure the segment until the full ring was installed.

**Figure 5. Tunnel Segments used as the Initial Lining**

The EPB was fitted with grout tubes at the end of the tail shield. As the tunnel machine advanced, tail void grout was pumped into the space between the outside of the segments and the excavated diameter. The grout pressures were measured continuously to ensure that the void space outside of the segments was completely filled. The machine was fitted with a double row of wire brush tail shield seals to ensure that the grout was isolated from the machine. Heavy grease was pumped into the wire brush seals to help isolate the grout from the machine. Proof grouting was performed periodically along the tunnel alignment to ensure that the grouting was consistent.

Upon completion of the tunnel, an 85.5 inch pipe will be placed within the segments as the final liner. The annular space between the initial tunnel supports and the final liner will be grouted with 150 psi cellular grout.

## 7. SURVEY AND GUIDANCE

Line and grade was maintained by using a Universal Navigation System (UNS) Module GNS, which is a gyro navigation system. The navigation module incorporated the ring building system allowing for correction of ring orientation to the position of the machine. A tunnel surveyor was present at all time during the tunneling operations to ensure that the specified tunnel line and grade were being met.

## 7. CONCLUSION

At the time this paper was completed, the tunnel is under construction beneath the Ship Canal and excavation of the clay soils is progressing extremely well. The EPB shield is operating in open mode as the permeability of the slicken-sided clays is very low. The tunnel will be completed by the time the of the No-Dig conference and the details of the tunnel construction will be presented at the conference.

## 8. REFERENCES

Staheli, K. and Ramos, M (2008). Earth Pressure Balance Machine Tunneling. 30% Design Recommendations. Ballard Siphon Replacement Project. Technical Memorandum to Tetra Tech dated October 25, 2007, revised January 8, 2008.