Brightwater Conveyance Tunnel, West Contract (BT-4), King County, Seattle, Washington, USA; TBM System Design to Facilitate Cuttinghead Maintenance in Adverse Conditions.

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1.0 INTRODUCTION

The Brightwater Conveyance Project (Figure 1) is being constructed as a regional wastewater treatment facility, to cope with the growth of the greater Seattle region. It consists of a series of tunnels and associated structures; which include a new treatment plant, 21.7 kilometers of conveyance lines (influent and effluent) and five portals. Construction was divided into three main contracts: the East, Central, and West.

The Brightwater West Tunnel Contract was awarded to the joint venture group of Jay Dee Contractors/Frank Coluccio Construction/Taisei Corporation (JCT). This tunnel (BT-4) is 6.4 km (21,000 ft) long and is lined with 4m (13ft) internal diameter concrete segments. The machine chosen for the project was a LOVAT RME184SE Series 23600 Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). The tunnel was driven up gradient in an easterly direction, extending from the Point Wells Portal Structure to the Ballinger Way Portal, which is the terminus for the BT-4 TBM. The west tunnel is the longest single heading on the project. Traversing glacially deposited outwash and tills, under hydrostatic heads exceeding 5 bar pressure, with no intermediate access points from the surface, making cuttinghead inspections/maintenance a challenge.

Figure 1 - Map view of the overall Brightwater Conveyance Project

2.0 GEOLOGIC CONDITIONS

The Geotechnical Baseline Report (GBR) establishes a baseline for various geotechnical conditions that the owner and contractor use to plan the work. Based on the GBR, the Brightwater West tunnel will be constructed through glacial and non-glacial sediments. The first half of the alignment was expected to encounter non-glacial sediments, and the second half was expected
to encounter glacial deposits. However, this distinction in depositional environment did not have much effect in the baseline description of the soil types expected to be encountered by the TBM.

The abrasive natures of the glacial and non-glacial deposits were highlighted in the GBR. It was important to provide a clear indication of the abrasiveness of the geology, as the contractor and TBM manufacturer would need to be prepared to handle it; especially with respect to the length of this tunnel and that this was a single heading with no intermediate shafts for maintenance work.

2.1 SOIL ABRASIVITY

The GBR did provide some guidance concerning the abrasive nature of the soil using x-ray diffraction methods to estimate the mineralogy composition of the soils, as well as slurry abrasivity (Miller Number) tests, and abrasivity results from the Norwegian University of Science and Technology performance prediction model (AVS). The two relevant statements in the Brightwater West GBR are as follows:

"Based on the AVS values, the quartz content and soil gradation along the alignment the abrasiveness of the soil will be higher at the western end of the project and be less abrasive toward the east."

"Due to the abrasive nature of the soils, attempting to excavate through any portion of BT4 alignment using a pressurized-face TBM without the use of the proper soil conditioners may (JCT assumed "will") result in severe wear of the TBM and associated cutting tools."

2.2 HIGH GROUND WATER HEAD

The entire West Tunnel alignment is below the groundwater surface. Groundwater heights above tunnel invert vary from 9 m – 49 m (29 to 161 ft). Because of the presence of the aquitard and the elevation of the discharge points, there is considerable difference in the head levels between the east and west portions of the tunnel alignment. Hydrostatic heads in the western portion of the West contract range from about 1 to 2 bar, and hydrostatic heads in the eastern portion range from 3 to 5 bar. This high hydrostatic head will require hyperbaric interventions to perform cutter changes, inspections, and maintenance.

2.3 BOULDERS

Boulders are present in glacial deposits and were expected on the BT-4 tunnel; ranging in size from .457 to .914 m (1.5 to 3 ft), and some greater than .914 m (3 ft) were expected to be encountered during excavation. Nested boulders are likely to be encountered twice in BT-4 tunnel. The max UCS of the boulders is expected to be approximately 290 MPa (42,000 psi).

3.0 PLANNED SOLUTION – TBM DESIGN ELEMENTS

The specifications, as outlined by the owner, were quite detailed. The TBM had to include a certain 'level' of equipment, spare parts, and had to be designed for frequent TBM inspection stops and operational requirements; some of the TBM design elements are described below.

3.1 INTEGRAL AIRLOCK / WISHA REQUIREMENTS

It was mandated in the owner’s specifications that regular inspections and interventions be performed throughout the length of the tunnel, at specific milestones during the tunnel drive.

As the tunnel alignment traversed zones of high hydrostatic pressures, it was known to the contractor that some interventions would have to be carried out under pressure; and some interventions could be planned for in areas of lower combined earth and water pressure.
The low pressure zones or ‘safe havens’ were optimized by the contractor, to perform observations/inspections of the TBM face and cutters, under free air and for extended periods of time, to determine the amount of wear experienced or for regular maintenance required.

Knowing that the TBM cuttinghead would have to be inspected / serviced in zones that would require hyperbaric interventions, as outlined in the owners’ specifications, Lovat, along with input from the contractor, designed the EPB TBM with an integral airlock for personnel access to the cuttinghead chamber. This integral airlock, designed to WISHA regulations, formed part of the TBM. The TBM airlock was developed to facilitate and expedite, efficiently and safely, the replacement of cutters and to perform general face maintenance, in zones where technicians could be working in up to 5 bar pressure, for limited time periods.

Located within the TBMs stationary shell structure, but bolted to the forward shell rear bulkhead, the TBMs airlock vessel consists of two inline airlock chambers (entry chamber and main lock) twinned-up, making the vessel a four chamber design. The inline chambers also had a throughway door which linked them to the auxiliary entry and main lock, see Figure 2.

The airlock entry and main chambers could transfer men through the airlock into the forward shell working chamber, which was also pressurized during interventions, giving the workers/technicians a safe and somewhat ‘roomier’ area to work in. This in turn simplified the passage of cutters/tools/parts/equipment and personnel adding to worker safety.

The airlock doors were designed to be large enough to pass a maindrive electric motor or gearbox should they need replacement.

Figure 2 - Isometric view of TBM w/o skins

The ‘bolted-in-place’ design meant that in the unlikely occurrence that the main bearing of the TBM failed, the airlock could be removed allowing the main bearing to be removed and replaced underground. Albeit this would be a lengthy procedure, it could still be accomplishable, and the owner and J.V. decided to mitigate any potential risk associated with this type of failure by incorporating this into the design.

The airlock system (structure, chamber dimensions, and control systems) conformed to the required regulations for compressed air work environments and pressure vessels; as per the Washington Industrial Safety and Health Act (WISHA); WAC 296-36-125; WAC 296-155-730; and manufactured to ASME PVHO-1-2002 code.

The TBMs working chamber and internal components could be pressurized to the work environment pressure, up to 5 bar.

Figure 3 – Photo of Airlock with controls

The screw conveyor passes through the airlock and forward shell, into the cuttinghead chamber. The sealing system of the screw conveyor through the bulkheads, and surrounding airlock, was a new and challenging design. It allowed the screw conveyor to articulate through the TBM while
mining and maintained a positive seal between the screw casing, the cutting head chamber and airlock, when pressurized.

The internal casing and auger flights of the screw were protected against wear by the application of chromium carbide wear resistant plating. This, along with the introduction of soil conditioning agents along the length of the screw, gave the screw a longer life in the abrasive soil conditions.

The introduction of soil conditioners also helped create ‘plugs’ along the auger flights of the screw, which were used as the control medium in the dissipation of pressures along the screws length, and in mining in earth pressure balance mode.

3.2 ROBUST, ARMORED CUTTINGHEAD DESIGN

Preventing potential wear of the TBM cuttinghead is of critical importance when mining in abrasive grounds, under high head pressures, and over long distances, especially when there is no intermediate surface access. The cuttinghead was designed to withstand the abrasive nature of the ground while maintaining the ability to effectively excavate the earth. The cuttinghead was a mixed face four spoke design, with eight face isolation doors. It could mine in both directions, powered by variable frequency electric motors capable of variable speeds and torque. The cuttinghead structure was manufactured using high strength steel and the entire face and gauge positions were covered with abrasion resistant chromium carbide plating. The face was designed with a maximum opening area of 25%.

![Mixed Face Cuttinghead](image)

Figure 4 - Mixed Face Cuttinghead

Removable grizzly bars were positioned across the face openings to restrict boulders beyond a certain size from entering into the chamber and potentially jamming the screw.

Five independently operated injection ports were located on the face, for foam or bentonite injection; an additional injection port was located on the cuttinghead rim position.

The mixed face design incorporated back-loading Ripper Teeth that were interchangeable with disc cutting tools; for maximum flexibility in varying ground types.

3.3 WEAR INDICATORS FOR CUTTERS

Tool life for TBMs and the need and frequency of tool changes, is a function of soil abrasivity, tool steel and cladding, the use of chemical additives and TBM cuttinghead speed, torque and thrust. In order to prevent critical wear from occurring, potentially damaging the TBM structure, and as an indication of cutter wear, the TBM is outfitted with 3 No. Ripper Type Wear Detectors located on gauge positions of the cuttinghead. These wear detector rippers are fitted with a pressurized hydraulic oil line that, when breached (tool worn to the point the oil line bleeds), sends a signal to the TBM operator that the tooling may need replacement.

3.4 SPECIAL CARBIDE CLAD RIPPER TEETH

To optimize excavation potential and increase tool life, heavy duty Ripper Teeth were utilized.
These teeth were fully clad with Tungsten Carbide Inserts and Chromium Carbide Plating to ensure longevity and performance require for the varying geology of the project. This was very important as the contractor tried to extend the cutter life as long as possible to reduce the number of interventions necessary, and at the same time required a cutter that would excavate efficiently. See Figure 5.

3.5 COPY CUTTERS AS EMERGENCY OVERCUTTERS

The cuttinghead was equipped with two hydraulically adjustable copy cutters. These cutters could be used to ‘over cut’ in case a need arose, and could be extended to create space to install new gage cutters when the old ones were worn down.

3.6 PERISCOPE FOR CUTTINGHEAD INSPECTIONS

The machine was equipped with a periscope camera for non intrusive, unmanned, face inspections. The system consisted of a color camera, power supply and controller, along with the feed frame and valve.

Figure 5 – Heavy Duty Ripper Teeth c/w carbide inserts and abrasion resistant plating.

3.7 ENHANCED GROUND CONDITIONING SYSTEM

The TBM was equipped with a Ground Conditioning System (GCS) to achieve a muck consistency that would enable efficient excavation and to help reduce wear. The system had an injection capacity of up to 2000 liter/min with a foam expansion ratio of 10:1. There were injection ports on the cuttinghead face and rim, in the cuttinghead chamber and along the casing of the screw conveyor. For this project, the GCS was of particular importance as the glacial and non-glacial materials being mined required careful conditioning to mechanically alter the ground characteristics and improve wear resistance and reduce torque.

4.0 PLANNED SOLUTION – OPERATIONAL ELEMENTS

During the preparation for tunneling phase of this project JCT kept two issues in mind: Successfully mining the first 200 lineal feet of tunnel without settlement; and minimizing wear on the cuttinghead. The first 200 feet of tunnel included the crossing of 2 mainline railroad tracks with less than a diameter of cover to the bottom of the ballast. These lines carry an average of 42 passenger and freight trains per day, and are the mainline between Seattle and Vancouver. Once the railroad had been successfully negotiated with no settlement, the primary technical focus was on minimizing wear.

All of the muck handling aspects of the project was set up around handling a very fluid material, since a fluid muck results in less wear on the consumable components of the TBM. This included the use of low angle belt conveyors, and specially modified muck barges capable of transporting muck that was essentially a fluid.

4.1 INSPECTION AND MAINTENANCE AND THE USE OF ‘SAFE HAVENS’

During the early planning for this project Jay Dee had just finished a project in central Ohio that was similar in that it was an EPB tunnel through glacially deposited materials. During the Ohio project the TBM had gone over 1.2 km (4,000 ft) without a cuttinghead maintenance stop in an unusually uniform fine sand deposit. A portion of the muck from this section of the tunnel was stockpiled for possible use as backfill. Since the wear from the tunneling in the Ohio fine sand was well documented, a sample of the muck was sent out testing to establish the Miller Number...
(ASTM G 75 - 01) for the fine sand, and it was compared to a weighted average Miller Number of the material expected along the length of the Brightwater West alignment.

The results of this analysis was that the uniform fine sand encountered in the Ohio project was more abrasive than the average material expected along the Brightwater West alignment. Since the rippers on the Ohio project did not have embedded carbides (due to the extraordinary number of boulders expected on that project) it was anticipated that the tool life would be greater for the armored rippers in equally abrasive soil. The planning assumption was therefore made that (on average) the distance between tool changes would be greater than 1.2 km (4,000 ft) on the Brightwater West project.

Based on the comparison of the Miller Numbers and the information contained in the GBR, JCT assumed that 8 stops would be more than enough (a safety factor of approximately 1.5) for cuttinghead maintenance.

There was a contractual requirement to perform 40 cuttinghead inspections over the length of the drive. This would leave 2 maintenance stops to be performed under hyperbaric conditions and 32 inspections to be performed with the remote camera (periscope).

During the initial planning, 62 schedule days were set aside for cuttinghead inspection and maintenance. It was anticipated that the majority of the required maintenance could be performed under free air; whenever the geologic conditions favored it rather than when it was required to maintain forward advance.

4.2 REDUCING THE ABRASIVITY OF THE MUCK

The ground conditioning system ensured the TBM operator would never be limited in the amount of foam available, cushioning collisions between soil particles, tools and structure of the cuttinghead. Ensuring that the muck was properly conditioned for minimum wear was of primary importance to the set up and operation of the TBM.

4.3 REDUCING THE EXPOSURE TIME OF THE CUTTINGHEAD TO WEAR

During the TBM excavation cycle, muck is in constant contact with the tools and structure of the cuttinghead. Wear on the cuttinghead was modeled based on the following: A) Abrasiveness of the muck, as described in the GBR, and subsequently modified by the addition of conditioning agents; B) The EPB pressure which determines how hard the muck is being pressed against the moving components of the cuttinghead; C) The distance which the moving components of the cuttinghead have to travel in this abrasive environment.

The assumption that the TBM could advance at an average rate of 76 mm/min (3”/min) results in a multiplicity of requirements from the designers of the TBM, but it also results in the elimination of disc cutters as cutting tools. The machines cuttinghead rotation was in the order of 2 rpm to maintain an average advance rate of 76 mm/min (3”/min), the penetration of the cutting tools was 381 mm/rev (1.5”/rev). Disc cutters work at advance rates of 6 mm/rev (0.25”/rev), and anything greater than 12 mm/rev (0.5”/rev) destroys them almost instantly. The logical conclusion is to abandon the use of disc cutters unless a significant amount of rock is expected, or you are breaking rippers at a rate of six times as fast as you are wearing them out.

5.0 RESULTS – TBM / AIRLOCK PERFORMANCE

The TBM and the airlock performed very well during the execution of this project. The airlock was used once, during the cuttinghead maintenance performed after 3.9 km (13,000 ft) of tunneling.
5.1 REMOTE CUTTINGHEAD INSPECTIONS

Thus far on the project 30 cutting head inspection/maintenance stops have been performed. Of these, one has been under hyperbaric conditions, six have been under free-air conditions and the remaining twenty three have been remote camera (periscope) inspections (Figure 6).

Of the 23 remote camera inspections 4 showed a distinct image of a ripper and clearly indicated the condition of the cutting tools on the head. The remaining 19 attempts failed to yield video evidence of the condition of the cutters, but valuable information was typically obtained nevertheless. The activity of pushing the periscope out through the cutting head chamber and flood door served a dual purpose as both a periscope and a probe.

![Figure 6](image)

**Figure 6** - Figure showing the remote camera probe (periscope) within the cutting head.

The periscope had a camera on the end of it, which was used to record video and was successful in capturing images of the rippers about 20% of the time. As the probe was extended, the amount of force required to push it out, coupled with the length it was extended allowed the personnel to determine whether the cutters were at full length or not. Figure 7 illustrates the information that the remote camera could provide given the right conditions at the face.

![Figure 7](image)

**Figure 7** - Screen shot image of a ripper.

5.2 CUTTINGHEAD MAINTENANCE INTERVALS

The distance between cutting tool inspections has averaged 190 m (622.5 ft). The longest interval between inspections was 731 m (2,398 ft) and occurred during the time when the EPB pressure required for face stability averaged over 4.1 bar (60 psi). The distance between man-entry cutting tool maintenance stops has averaged 761 m (2,496 ft), with a maximum length of 1,490 m (4,888 ft) just prior to the hyperbaric man-entry. These lengths match up very closely to what was anticipated during the planning stages of this project.

5.3 FREE AIR MAINTENANCE WORK

The ground during the initial portion of the drive proved to be very unstable. While multiple remote inspections were attempted, very little information about the condition of the cutting tools was obtained until the ground conditions allowed for the first free-air inspection (Jan 21, 2009).
Very high thrust forces had led to some concern that the gauge cutters had been worn and the TBM was shielding; this proved not to be the case. The wear accrued over the initial 1,158 m (3,800 ft) of tunneling, primarily in flowing sand at pressures from 1 to 2 bar, was minimal.

The next opportunity for a free-air inspection occurred after 1.6 km (5,250 ft) of tunneling. The EPB pressure had been steadily dropping from a high of about 2 bar (30 psi) down to .7 bar (10 psi) and the ground conditions were improving from a stability standpoint. The running sands were giving way to much more stable deposits of fissured clay.

The majority of the work done on the cuttinghead during this project was done under free air, despite the fact that ground conditions required the use of a TBM capable of advancing at EPB pressures above 5 bar. This has included some limited welding and torching as well as the removal and replacement of the cutting tools and center nose cutter.

Accurately estimating the amount of cuttinghead maintenance required, using the best practices to reduce it, and accurately estimating the amount of the maintenance that could be performed under free-air was critical in completing this project; although, the hyperbaric system specified was required, and utilized in completion of the tunnel.

5.4 HYPERBARIC MAINTENANCE WORK

As anticipated, the ground conditions became extremely unstable at 3,350 m (11,000 ft) into the alignment and continued for approximately 610 m (2,000 ft) during which the minimum EPB required for controlled mining was 4 to 4.5 bar (60 to 65 psi). There was no chance of a free-air maintenance stop and the wear on the cuttinghead had started to slow the advance rate by minimizing the penetration rate per revolution. It was anticipated that significantly better geologic conditions (a safe haven) would be encountered if the TBM could be advance several hundred more feet but the advance rate was greatly reduced, and the decision was made to stop and prepare for a hyperbaric maintenance stop. The ambient static pressure was 3.5 bar (50 psi), which resulted in very short working times for the personnel. The minimum work required to get back under way was carried out in an efficient manner, as it was anticipated that only about 152 m (500 ft) of advance would be required to reach a safe haven.

The TBM advance rate reduction was due to wear to about 85% of the face cutters. The rippers were worn down to the scrapers, which were bearing directly on the unexcavated formation.

6.0 CONCLUSIONS

Brightwater West was a challenging project, with a stringent specification, developed by an informed and experienced owner. Recognizing that, proper planning, TBM design elements, along with innovation and collaboration between the contractor and TBM manufacturer ensured that the projects challenges such as cuttinghead wear reduction, tool life, interventions under high head pressures and were overcome.

7.0 REFERENCES

[1] LOVAT Archives (Drawings and Airlock Manual)
[6] Nowlin; Graphic from Seattle Times; 2009