Microtunneling in Mixed Face/Mixed Reach Hard Rock

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Bradshaw Construction Corporation recently completed a microtunnel drive that crossed the Schuylkill River in Reading, Pennsylvania. The project consisted of 436 feet of 60 inch steel casing with an average depth of 35 feet at the shafts. Ground cover under the river was as little as 5 feet. Mining conditions began with a mixed face of non-cohesive gravel in the top of the heading overlaying fractured dolomitic rock at the bottom. The heading transitioned to a full face of fractured dolomitic rock approximately half way in to the drive. The rock had unconfined compressive strength (UCS) values of up to 34,300 psi. This paper discusses the challenges associated with the project, including limited work space, rock excavation in the shaft and tunnel, disc cutter wear and changes, managing the water table, and receiving the MTBM in a 9 foot ID drilled shaft.

1. INTRODUCTION

The City of Reading, Pennsylvania, determined that a portion of their sewer system required the installation of approximately 7,000 lineal feet of 42 inch diameter ductile iron force main paralleling an existing 42 inch force main (see Figure 1). This alignment at the south end of the City provided numerous benefits and challenges. The benefits were: 1) it allowed for the shutdown of one force main while repairs or maintenance could be completed on the other; 2) it allowed for lower velocities through the force main when both were in operation; and 3) it provided additional capacity for projected future growth. The majority of the new force main was installed by trenching methods. However, the position of the existing pump station at 6th Street and Canal Street would require the force main to cross the Schuylkill River from north to south before paralleling it in a southeast direction. To install the 42 inch ductile iron pipe (DIP) force main under the river in 60 inch steel casing (two pass method), pipe jacking using either a slurry or earth pressure balance (EPB) microtunnel boring machine (MTBM) was required.

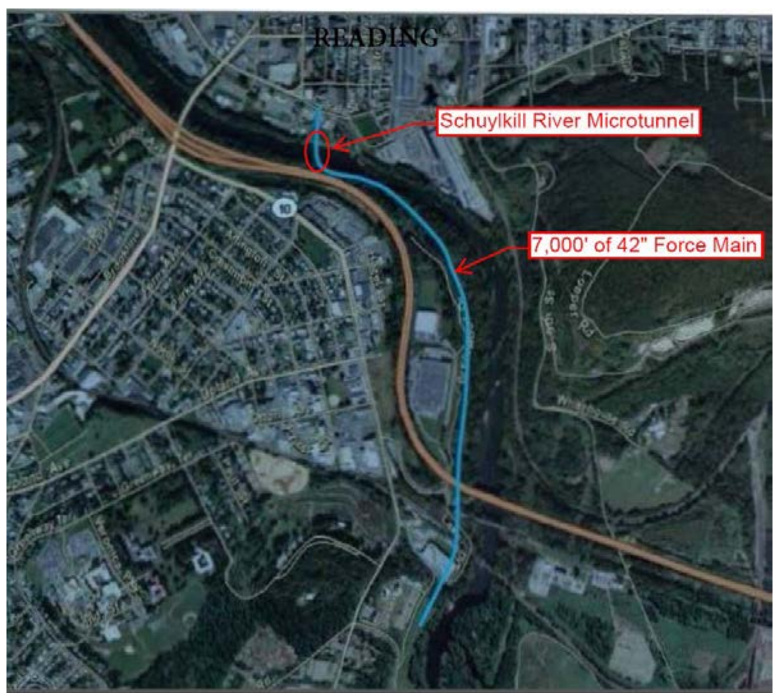

Figure 1: Project Location Map

Numerous challenges existed with the alignment as well, including: 1) contaminated groundwater at the 6th Street and Canal Street pump station on the north side of river, limiting jacking shaft dewatering; 2) deteriorated conditions of the existing parallel force main, which prevented blasting from being used to excavate rock; 3) the alignment positioning was susceptible to flooding from the river; 4) the work could not impact normal operations of the existing pump station, wastewater treatment plant and force main, including restrictions on plant traffic and construction site access; and 5) the rocky geologic conditions at the jacking shaft limited support options.

2. BID REQUIREMENTS

The project was designed by Entech Engineering, Inc. of Reading, PA, and the project manager was Hill International, Inc. of Philadelphia, PA. Given the challenge of a major river crossing in both soft and rock ground conditions, the engineer determined that pipe jacking subcontractors with extensive microtunneling experience had to be pre-qualified. This required interested “microtunneling” contractors or subcontractors to submit extensive information, such as: 1) resumes of managerial, supervisory and operational key personnel; 2) experience qualifications, including detailed descriptions of a minimum of five previous microtunneling projects of similar size and scope; 3) the listing of five separate projects completed that used either a Slurry or Auger (Earth Pressure Balance) based system, etc. The engineer determined that three microtunnel subcontractors were qualified to submit bids to the prime (general) contractors. The contractor had to name all significant subcontractors and suppliers including the microtunneling subcontractor in their bid submission. Pact Construction of Ringoes, NJ was the low bidder and they submitted Bradshaw Construction Corporation as their microtunneling subcontractor.

3. PROJECT GEOLOGY

While the geology found throughout the entire project was complex, this paper will focus only on the geology at the microtunnel drive under the Schuylkill River. Fill, sand, silt and gravel (alluvial deposits) overlaid rock which consisted of moderately to highly weathered limestone and slightly weathered, hard, strong dolomite (see Figure 2 for typical surface rock outcrop). The UCS peaked at 34,300 psi in the dolomite. The rock quality designations (RQDs) ranged from 0 to 17 percent in the limestone and 22 to 100 percent in the dolomite. The rock Cerchar abrasivity values averaged a moderate 2.6 on a scale of 1 to 6. Based on the MTBM behavior during mining, we believe that core stones were encountered in the highly weathered limestone where alluvial soils had been expected.

Figure 2: Representative Rock Outcrop

The jacking shaft on the north side of the Schuylkill River was shown to be in fill and alluvial deposits, well above the underlying weathered limestone. The receiving shaft on the south side of the Schuylkill River was shown to be in alluvial deposits to slightly weathered, strong, hard dolomite. The microtunnel drive was expected to start out in a full face of alluvial deposits then transition into a full face of rock under the river which resulted in both a mixed face and mixed reach tunnel alignment. Twelve (12) soil borings were taken along the 436 foot tunnel alignment from the jacking to the receiving shaft. There were nine (9) within the banks of the Schuylkill River alone. Therefore, soil borings were spaced approximately every 40 feet. In spite of this substantial effort, top of rock requiring mechanical excavation was actually found up to 12 feet higher than expected at the jacking shaft and in the first half of the microtunnel drive. The mixed face transition zone where the ground was expected to change from alluvial soils to full face rock was considerably longer as well. Obviously, attempting to create a profile of the rock elevation in weathered limestone and dolomite adjacent to and under a river is a very difficult undertaking even when a large number of soil borings are taken. Figure 3 below shows the rock profile at the shafts and microtunnel drive assumed at bid time (solid red line) versus the actual rock profile encountered during construction (dotted red line where it deviates).

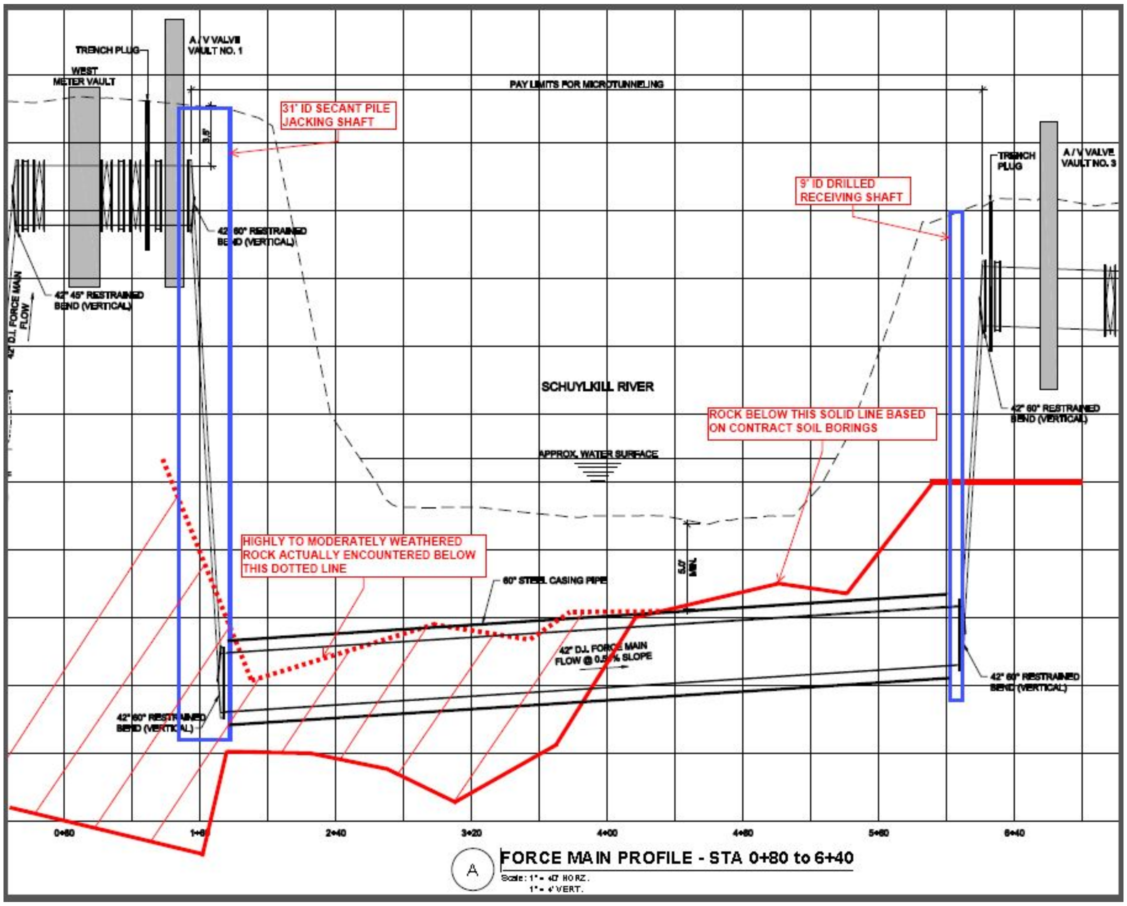

Figure 3: Rock Profile Pre & Post Construction

4. MICROTUNNELING REQUIREMENTS

Pipe jacking using a slurry or earth pressure balanced microtunnel boring machine was specified for the Schuylkill River tunnel. The following requirements were excerpted from the contract specifications:

a. Contractor responsible for selection of type of MTBM and type of cutterhead.
b. Contractor responsible for the means and methods to retrieve the microtunnel boring machine (MTBM) in the event of a stalled or failed crossing and to complete the crossing at no additional cost to the Owner.
c. Contractor to remove, clear, or otherwise make it possible for microtunneling system and casing pipe to progress past or through any obstructions encountered at no additional cost to the Owner.
d. MTBM shall have sufficient power and ability in normal operation to cut or crush hard material of sizes up to 1/3 internal diameter of pipe and up to 30,000 psi compressive strength.
e. Casing to be installed within 2 inches of vertical and horizontal alignment shown on the Contract Drawings.
f. Contractor responsible for redesign of pipeline or associated structures if jacked casing pipe is off design line or grade at no additional cost to the Owner.
g. Outside diameter of MTBM not to exceed outside diameter of casing pipe by more than 1 inch (MTBM shield overcut).
h. Limit annular space between excavated material and outside diameter of casing pipe to maximum of 0.5 inch.

There were several inconsistencies and conflicts created by the specifications and the design of the microtunnel drive. First, item d) states the MTBM shall have the ability to crush rock up to 30,000 psi when the geologic report found rock strengths up to 34,300 psi. This was a crucial fact given rock of this strength approaches the rock cutting limits of most MTBMs. Second, item e) gives installation tolerances for the jacked casing, but surprisingly not for the force main installed within. We do not believe it was a critical omission given this was a pressure pipe installation. However, we normally see a specified minimum clearance between the jacked casing and carrier pipe. Finally, items g) and h) limited the annular space created outside the jacked casing by the MTBM to a maximum of 0.5 inches radially. While this would be marginally acceptable and possibly desirable in the alluvial soil and mixed face portions of the drive, particularly given the shallow 5 feet of cover (one casing diameter) under the river, our experience in microtunneling rock for the last decade has taught us that such limitations would be completely inappropriate for the portion of the drive in the full face of rock. Because this was a mixed reach tunnel, the annular space had to be adjusted to allow for the completion of the drive based on the most taxing ground condition for microtunneling, which is hard rock. Microtunneling hard rock requires substantially greater annular space for the following reasons: a) allow for MTBM steering, b) perimeter gage cutter(s) to wear as the drive progresses, and c) to allow for minimizing excessive jacking forces that build up under the MTBM and jacked casing from slurry cuttings bypassing the rock cutter wheel. As a compromise, the annular space was increased to 0.71inches radially, and if not for the shallow cover to the river bottom, it would have been as much as 1.0 inch radially, given the extent and hardness of the dolomitic rock.

5. PROJECT CONSTRUCTION

<u>Jacking Shaft</u>

The jacking shaft was located on the north side of the Schuylkill River directly behind the 6th Street and Canal Street pump station and treatment plant. Access was through the plant property. The work to install the shaft, microtunnel drive and force main connection to the pump station could not impact normal plant operations. This included not interrupting plant traffic, which in turn limited access to the construction area. Excellent cooperation between the plant operators, the contractor, and the subcontractor prevented interruptions.

While fill had been previously added to the jacking shaft site, it was still subject to flooding from the river. Additionally, the groundwater at this location was considered contaminated. All of the groundwater from the jacking shaft required treatment or special disposal. As a result, shaft dewatering was limited by the contract to no more than 50 gallons per minute (GPM).

The alluvial soils and weathered rock geology, combined with the proximity of the jacking shaft to the river, provided an unlimited groundwater source. A water tight shaft shoring system had to be used to minimize dewatering. Steel sheeting was considered but discarded because the anticipated rocky soil conditions could prevent the sheeting toes from reaching the depth necessary to cut off the groundwater and properly support the alluvial soils. Therefore, the secant pile shaft support method was selected to address these concerns.

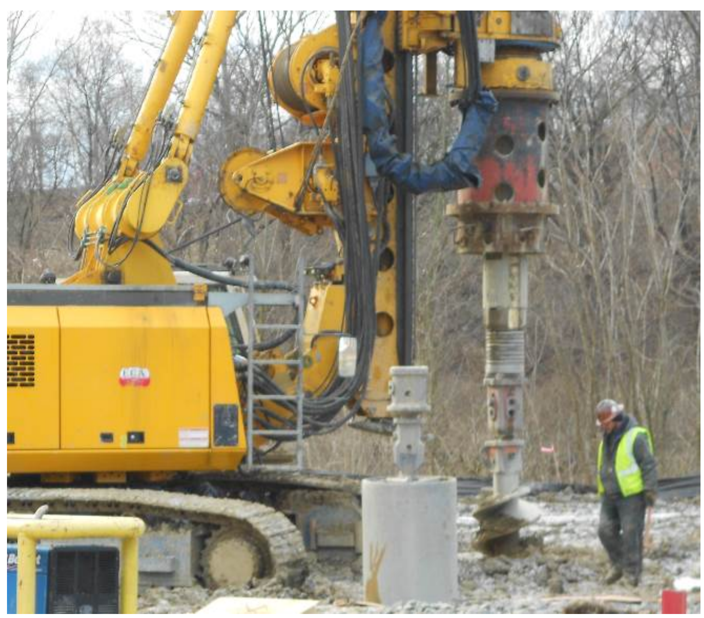

Figure 4: Secant Pile Drilling

Secant piles were designed to be drilled 15 feet below top of the invert tremie plug (see Figure 4). Excavation was planned as subaqueous. Once excavation was completed, a concrete tremie plug would be installed to resist hydrostatic uplift and the shaft would be pumped out and made ready for pipe jacking.

However, while drilling for the first secant pile, hard rock was encountered well above the level shown in the geologic report (see Figure 3 above). Substantial extra drilling efforts were required to reach the designed pile depth, resulting in work durations that took twice as long as anticipated with extraordinary equipment wear and tear. Once the secant piles were all in place, subaqueous shaft excavation was supposed to proceed, followed by sealing the shaft invert with a concrete tremie plug. However, given the obvious presence of hard rock much higher than shown, the plan was changed. A reinforced concrete slab to resist hydrostatic uplift was designed in place of the previously submitted tremie plug to minimize the amount of rock excavation necessary to secure the shaft invert (see Figure 5). Excavation had to be in the dry to allow for the removal of the rock by mechanical means (excavators with hydraulic hammers). This again took considerable extra effort and additional time.

Figure 5: Secant Pile Shaft Invert Pour

Receiving Shaft

The receiving shaft was located on the south side of the Schuylkill River with the ground surface 6 feet below the surface elevation of the jacking shaft. This significantly increased the chances of flooding. It was accessed by a haul road used to inspect the existing 42inch force main along the river bottom approximately 4,000 feet from the project's southern entrance. The receiving shaft was installed approximately 50 feet away from the existing 42inch force main at a depth of 34 feet. No blasting was allowed, yet 17 feet of hard dolomite rock at the bottom of the shaft had to be excavated. Mechanical excavation was the only method allowed for excavating the rock at the receiving shaft because of concern for the decayed existing steel force main. Drilling the shaft in place was chosen for economic

Figure 6: Drilling the Receiving Shaft

reasons. However, the hard dolomite (peak UCS = 34,300 psi) limited drilling the shaft to a finished diameter of 9 feet (see Figure 6). Bradshaw's specialized 60 inch MTBM was capable of being recovered from this extremely limited diameter shaft. It was drilled using slurry and steel casing shaft supports installed to the full depth and grouted in place. While drilling the hard rock was slow, the shaft was installed to depth without incident.

Microtunneling

Figure 7: Rock Cutter Wheel

With the jacking and receiving shafts in place, preparations were made to begin the slurry microtunnel pipe jacking drive. First, a concrete entrance wall was formed and poured and an entrance seal attached. Next, a concrete thrust block was poured and a 520 metric ton jacking frame was set to line and grade. The specially fabricated 60 inch OD MTBM was configured with a rock cutter wheel using 280 mm disk cutters as shown in Figure 7.

The MTBM has an internal porthole to access the back of the cutter wheel. This allows cutting tool changes from within the MTBM during the microtunnel drive. This access is a critical requirement for any MTBM when microtunneling through hard rock. A telescopic tail can (telecan), which is essentially a recoverable intermediate jacking station (IJS), was fabricated by Bradshaw and installed behind the MTBM and trailing tube. The telecan was necessary to efficiently mine the rock portion of the drive and yet had to be recovered through the same 9 foot ID receiving shaft as the MTBM, so it too was specifically fabricated.

The MTBM was set in the jacking frame, pushed through the entrance seal and began mining through the secant pile wall. The secant piles at the entrance eye were reinforced with fiberglass instead of steel reinforcing rods to allow the MTBM to mine through it. The MTBM, trailing tube and telecan were launched before the first 20 foot joint of Permalok steel casing was set and jacked in place. The actual microtunneling operations in the jacking shaft are pictured in Figure 8.

The slurry microtunnel method for this drive had three key challenges. They are listed below in order of occurrence and not in order of their relative critical nature:

1) Small Diameter Receiving shaft: A typical receiving shaft for a 60 inch MTBM has a 16 foot ID. With only a 9 foot ID shaft, the accuracy of the microtunnel drive was critical. The installed alignment had to be within ± 1.5 inches to allow MTBM recovery. While this may seem reasonable given the 436 foot drive length, one has to take into account the exceptionally challenging mixed face and mixed reach ground conditions for this drive. There was the potential for significant deflection of the MTBM that would have made recovery extremely difficult and costly.

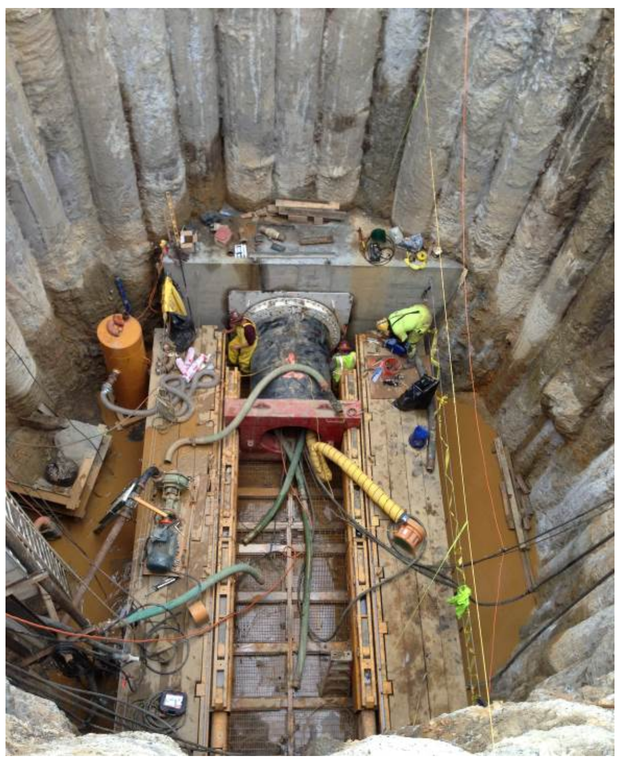

Figure 8: Microtunneling Operation

2) Limited Cover: The design elevation and grade of the force main showed the jacked casing with at least 5 feet (one tunnel diameter) below the anticipated river bottom. For bidding purposes, this established the depth of shafts and resulted in microtunneling through a mixed face and mixed reach subsurface profile.

3) Ground Conditions: The geotechnical report indicated that the drive would be mixed face and mixed reach rather than the more traditional uniform soil conditions that are desired for pipe jacking, especially those requiring microtunneling. A full rock disk cutter wheel was the only option to excavate the portion of the tunnel in a mixed or full face of hard rock. The rock disk cutter wheel, however, had to be tolerated in the soft ground where it would hinder excavation because of its small face openings. Using the nine (9) test borings taken within the banks of the river, an estimate of the mixed face and mixed reach transition zones was determined as follows:

- ± 220 feet of alluvial soils (silts, sands and gravel)
- ± 40 feet of alluvial soil over weathered to sound rock (mixed face)
- ± 176 feet of hard rock (full face)

Consistent with shaft excavation, the MTBM mining did not begin in the expected alluvium, but rather in moderately to highly weathered rock, slowing production and greatly increasing steering difficulties. The weathered rock did not follow any clean or straight lines as depicted in the simple profile view shown in Figure 3. In fact, the MTBM behavior during mining of the first 112 feet of the drive indicated that the rock weathering created mixed face conditions. Surprisingly, while the mixed face contained conventional soft-top and hard-bottom, conditions also varied between the left and right side of the face. The MTBM experienced difficulty maintaining both alignment (side to side mixed face) and grade (top to bottom mixed face) because the MTBM cutter wheel kept encountering less than a full face of consistent-strength weathered rock. Mining production averaged only 10 feet through this zone.

Conventional mixed face conditions of alluvial soil deposits with core stones (essentially boulders) over weathered rock were encountered over the next 84 feet. This was twice the expected length of mixed face conditions assumed from the original borings. It proved a serious challenge to MTBM mining rates and alignment control as the core stones and weathered rock caused steering deflections. Nearing the middle of the river, a substantial amount of loose, poorly sorted round gravel over weathered rock created a particularly difficult mixed face condition. This highly unstable ground condition led to over-excavation and caused the MTBM cutter wheel to stall and slurry lines and pumps to clog. Mining production through the mixed face averaged 14 feet. This included the area where the MTBM advance rate had to be slowed considerably to hold alignment while it finally cut into a full face of rock. Slowing the MTBM advance rate exacerbated the over-excavation of the gravel and increased difficulties with the MTBM operation. A full face of rock was finally reached 196 feet into the drive where the rock disk cutter wheel proved its worth.

Bentonite was added to the drilling fluid from the beginning of the drive. Its density was substantially increased in what turned out to be a rather futile effort to: 1) lubricate the cutter wheel and slurry system to prevent cutter wheel stalls and clogging of the slurry lines by the gravel runs, and 2) to create a filter cake to support the tunnel crown and face in the gravel portion of the mixed face. Regardless of these efforts, some inadvertent surface return of drilling fluid and/or lubricant was observed when the drive encountered gravel over rock mixed face conditions and the shallowest cover over the MTBM and casing.

Rock microtunneling continued without incident until approximately 40 feet from the receiving shaft (nearly 400 feet into the drive). The MTBM ceased cutting and jacking pressures increased substantially. An intervention into the cutting chamber of the MTBM was necessary to determine if the MTBM cutting tools had been worn or damaged. Before attempting the intervention, the tunnel face was tested for water infiltration by disconnecting the return slurry line at the jacking shaft and opening the valve to the MTBM cutting chamber. Water was found to be free flowing into the cutterhead as if directly from the river above. We surmised the river water was in fact following the overcut annulus around the casing and into the cutterhead. This happened in spite of the use of extremely thick polymer bentonite lubricant and almost as thick bentonite drilling fluid (slurry). The only solution was to grout the annulus around the MTBM in multiple locations and also around the first joint of casing pipe behind the MTBM to cut off the water. This took several shifts but ultimately reduced the inflow of water enough to allow for a safe MTBM cutting chamber intervention. We had correctly assumed that no water was coming from the rock face. The intervention revealed the perimeter gage disk cutter had only nominal wear and was not the problem. The number two disk cutter in from the perimeter was found to be flat spotted due to bearing failure (see Figure 9). It was replaced and mining continued until the drive was complete. Mining in the final 240 feet was in a full face of rock and averaged 12 feet.

Figure 9: Disk Cutter with Bearing Failure

While the full face of hard, strong dolomitic rock slowed our excavation rate, it did not present any MTBM steering challenges. In spite of concerns expressed somewhat jokingly by the Owner that we might miss the receiving shaft entirely, we actually hit the shaft dead center (See Figure 10). To minimize river water infiltration during MTBM recovery, grouting outside of the MTBM and casing was carried out again. Once the MTBM center was located, the receiving shaft steel casing wall was cut out and a rubber exit seal installed. The MTBM was jacked into the receiving shaft and disassembled into pieces and hoisted to the surface. The casing was jacked into its final position within specified alignment and grade tolerance, then contact grouted with an emphasis on the entrance and exit eyes to seal off river water infiltration.

Figure 110: MTBM Recovery in 9' ID Caisson

Carrier Pipe

The force main carrier pipe was 42 inch DIP with restrained joints in 20 foot lengths. The DIP was jacked into the microtunneled 60 inch steel casing. Three (3) casing spacers were used to support each 20 foot joint of pipe. Once the pipe was installed and pressure tested (see Figure 11), the annular space between the pipe and the jacked steel casing was filled with a flyash grout, completing the microtunnel drive under the Schuylkill River.

Figure 12: Force Main Carrier Pipe Testing

6. LESSONS LEARNED

Geotechnical Exploration

Despite taking an extraordinary number of soil borings for a 436 foot long microtunnel drive, it is hard to determine the elevation of top of rock requiring mechanical excavation in weathered formations. Since the rock elevation and consistency can vary so significantly in such formations, yet still be incredibly difficult to determine, we recommend a geologic baseline report (GBR) be prepared before the bid, defining realistic expectations for the owner and contractor to bid and build the project.

Shafts

Secant pile shafts make excellent microtunneling shafts for several reasons:

- They provide a water tight shaft support system.
- Internal bracing is generally not required, which minimizes shaft excavation time and maximizes work space.
- The secant piles provide a soft tunnel eye reducing the size of the concrete entrance headwall.
- The secant piles provide an excellent bearing surface, thus minimizing the size of the jacking thrust block.

- The secant piles provide an excellent foundation for the MTBM during launch and therefore can minimize if not eliminate the need for ground stabilization outside of the shaft.

Drilled shafts are acceptable as microtunneling receiving shafts for many reasons:

- They are often the most cost-effective shaft installation method.
- They provide efficient mechanical excavation of some types of rock.
- While drilled shafts in hard rock are generally limited to a 9 foot ID finish, they can be used as recovery shafts for properly modified MTBMs.

Microtunneling

- With an experienced rock microtunnel contractor, pipe jacking using the slurry microtunneling method can be accomplished in mixed face, mixed reach alluvial soil and weathered rock formations.
- With a full face of rock, MTBM face intervention is possible under normal atmospheric conditions if water infiltration along the casing annulus is controlled and there is no significant ground water coming through the rock face into the cutter wheel.
- Accuracy of the microtunnel installation was required by specification. However, the use of a small diameter drilled receiving shaft made it critical to achieve even tighter accuracy. Over the 436 foot drive length, the MTBM operators (most mining done with two shift operations) achieved this greater accuracy in spite of the complex mixed-face, mixed-reach ground conditions.
- A slurry MTBM's ability to complete a drive in highly abrasive rock is normally limited by the wear of the perimeter gage disk cutter. In rock that has low abrasivity or is highly weathered, total drive length is often limited by potential failure of the face disk cutters. The face disk cutters have bearing covers on their sides that can wear rapidly in the slurry laden with rock cuttings. This leads to bearing exposure and failure, which prevents the disk cutter from turning. The disk cutter then wears away, creating a flat spot in the cutter kerf which eventually stops MTBM forward progress and requires disk cutter replacement to complete the drive. Therefore, access to the MTBM cutter wheel for tool changes is critical to successful rock microtunneling.