Tunneling in Mixed Face Conditions: An Enduring Challenge for EPB TBM Excavation

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ABSTRACT

EPB TBM tunneling in mixed face conditions—partially in both rock and soil—is inherently problematic for even the most experienced crews. Over-excavation, excessive damage to cutter tools and regular cutterhead interventions are major challenges when negotiating mixed face geology.

This paper will draw from real field experiences, including successful bores in abrasive rock and soil at India's Chennai and Bangalore metro projects, to determine the optimal operational parameters for TBMs in such conditions. It will also address reduction of air losses to facilitate cutterhead interventions under hyperbaric conditions when installation of safe-haven grout blocks is not an option due to surface structures.

INTRODUCTION: CHENNAI METRO

Contract UAA-01 is part of the Chennai metro line 1, which runs from the Washermanpet area of the city to the airport. It consists of 5500 meters of twin tunnels, five stations and 17 cross passages. AFCONS was awarded the contract and subsequently chose The Robbins Company to supply a TBM to bore the Chennai Central Station to Mayday Park station section of the project. This section consists of two tunnels: an up line and a down line of approximately 1032 meters each. The works schedule was for the machine to be launched from Mayday Park station, disassembled and retrieved at central station, then relaunched at Mayday park to complete the second drive. The machine was actually used to complete a third drive but that is not in the scope of this paper as the geology did not contain mixed face conditions.

Geological/Hydrological

The entire area of the project is situated within a flood plain, with relatively minor deviations in surface levels. The geology along the alignment of the Chennai Central Station to Mayday Park station section is made up of dense silty sands interbedded with layers of clay and silt and granite with weathering grades varying from highly fractured and weathered (Grade V) to fresh rock (Grade I). The water table varies seasonally but remains above the tunnel alignment all year round. The overburden along the alignment ranged between approximately 11 meters and 16 meters (see Figure 1).

TBM Selection

Based on the geological information and discussions with AFCONS, The Robbins company supplied a mixed face EPB machine fitted with active articulation. The cutterhead was designed with the option of changing out soft ground tools to hard rock tools for excavation in weathered granite, sand, silt, and clay, and to cope with boulders up to 300 mm in diameter. The TBM was equipped with small grippers to allow for cutterhead stabilization in harder ground and to provide the reaction forces required to

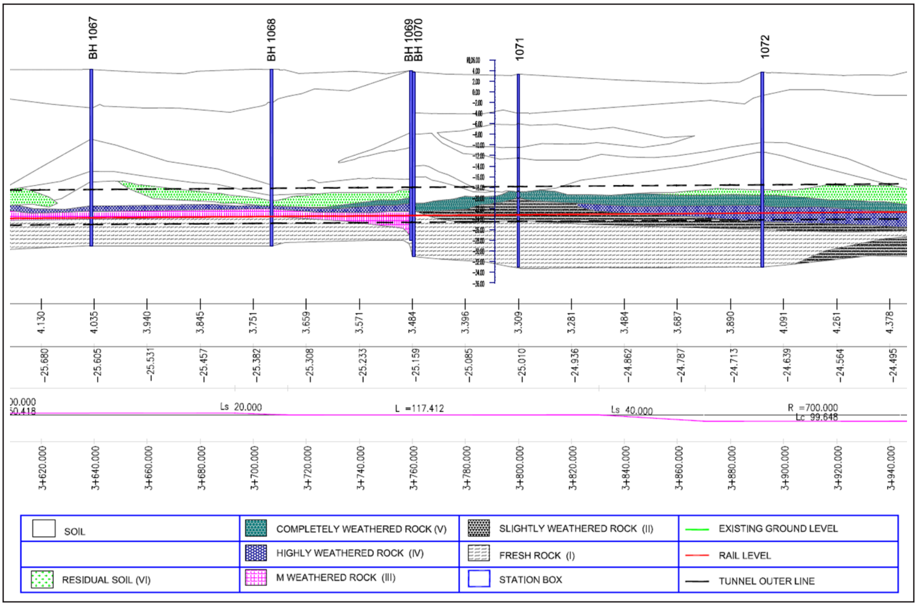

Figure 1. Geological section showing mixed face in the tunnel cross section

Table 1. Key machine specifications

Machine Type	**Mixed Face EPB**
Design Parameters	
Shield Diameter Bore diameter (Soft ground tools) Bore diameter (Hard rock tools)	6.6 m 6.63 m 6.65 m
Disc cutters	17," back-loading
Cutterhead power	6 x 210 kW = 1,260 kW
Cutterhead speed Cutterhead working torque	0–4.5 RPM 7,038 kNm
Maximum starting torque	9,149 kNm
Maximum main thrust Articulation type Trust cylinder stroke length	45,000 kN Active 2.2 m
Screw conveyor diameter Screw conveyor speed	0.9 m 0–22 rpm
Segment Backfill	Bi-component grout

pull the cutterhead back from the face in difficult conditions. The key technical specifications of the machine can be seen in Table 1.

TBM Launch

The machine was launched into a full face of silty sands/silty clays in January 2012. It completed the initial drive with a short start-up procedure utilizing umbilical cables without any problems. After completion of the initial drive the machine was stopped, the remaining gantries installed, the temporary rings and reaction frame removed, and the shaft bottom rail system installed. Boring operations then recommenced. Upon completing 160 m of boring (ring No. 109) granite was encountered in the invert of the bore. This was much sooner than expected but the rock was highly weathered and


Figure 2. Damaged cutter worn flat


Figure 3. Damaged cutter ring

estimated to be weathering grade IV or V, so it didn't pose a significant challenge to the boring operations. The level of the weathered granite gradually increased in the face until 188 m of boring had been completed (Ring No. 125). At this point the whole of the lower 30% of the face was made up of weathered granites, and furthermore, fresh granites were now present in the invert of the alignment. It was not possible to access/assess the strength of the rock in the invert as interventions were being carried out under hyperbaric conditions and site experience dictated that at least 40% of the chamber needed to remain filled with material to hold hyperbaric pressure.

Increase in Cutter Consumption

After encountering the fresh rock in the invert, operations were adversely affected by excessive cutter damage. Production time was lost carrying out cutterhead interventions to facilitate cutter changes. A total of five cutterhead interventions were undertaken between ring No. 134 and ring No. 259 (187 m of boring). During these interventions 144 cutters needed replacing. These interventions were all carried out under hyperbaric conditions. A substantial percentage of the damaged cutters were deformed and jammed into the housings; therefore, major difficulties were faced during the removal process. The total time taken to complete these interventions was over 90 days. The impact on the project schedule was significant so AFCONS requested that Robbins investigate the reason for the damage and offer a solution.

Analysis of Cutter Failure Mode and Boring Parameters

Analysis of the mode of cutter failure revealed that almost 90% of the cutter consumption was due to abnormal wear. A significant percentage of cutters that had been replaced had either chipping or radial cracks in the cutter discs. Many of the cracked discs had been displaced completely either by cracking or worn flat, leaving the cutter hubs exposed to the rock and resulting in the hubs being worn through to the bearings and shaft (see Figure 2 and Figure 3).

To further understand the reason for this damage the historical information on boring parameters was downloaded from the machine's data logger. Comprehensive information was available for each ring that had been bored since the machine was launched. Table 2 shows the typical boring parameters that had been used while boring in the silty sands and clays up until around ring No. 109. No major problems were faced during this time but the information is useful as a baseline for analysis.

Table 3 shows the typical boring parameters that had been used from ring 109 through to ring 125 while boring through a mixed face of soils and weathered granites.

Table 2. Typical boring parameters in silty sands/clays

TBM Operational Parameters in Full Face of Silty Sands/Clays	
Cutterhead Speed Main Thrust pressure CHD torque	1.0–1.4 RPM 19,000 kN 3,500 kNm
Earth pressure (centre of face) Advance rate	2.0 Bar 25 mm/min

Table 3. Typical boring parameters in mixed face of soils and weathered granite

TBM Operational Parameters in Mixed Face of Silty Sands/Clays and Weathered Granite	
Cutterhead Speed Main Thrust pressure CHD torque	1.7–2.0 RPM 21,000 kN 3,800 kNm
Earth pressure (centre of face) Advance rate	2.0 Bar 12 mm/min

Table 4. Typical boring parameters in a mixed face of soils and weathered to fresh granite

TBM Operational Parameters in Mixed Face of Silty Sands/Clays, Weathered & Fresh Granite	
Cutterhead Speed Main Thrust pressure CHD torque	1.7–2.6 RPM 24,000 kN 3,600 kNm
Earth pressure (centre of face) Advance rate	2.0 Bar 5–9 mm/min

It was observed that the penetration rate was reduced by over 50% despite the cutterhead speed being increased by 35%, thrust increased by 22% and a minor increase in cutterhead torque; however, this was within acceptable ranges when boring through mixed face conditions with highly weathered, low-strength rock. Cutter consumption was within original estimations at this point, hence, there was no concern regarding these operating parameters.

Table 4 shows the typical boring parameters that were used from ring 125 through to ring 138. The geology through this stretch was made up of a mixed face including soils in the upper 60% of the face, weathered granite below this and fresh granite in the invert. These parameters needed to be carefully analysed as an intervention was carried out at this point and 33 cutters needed replacing. Also, similar boring parameters had been used from ring No. 138 to ring No. 259 resulting in a further 111 cutters needing replacement.

The initial observations and analysis of the chipping and radial cracks pointed to the failure mode of the cutters being caused by impact damage. Impact damage is caused when disc cutters are rotating through soft material or voids in the geology before coming into contact with hard rock. In general terms, the higher the cutterhead speed and the smaller the percentage of rock in the face, the more likelihood there is of impact damage to the cutters. However reasonably hard rock is usually present when impact damage occurs, so to confirm this theory Robbins deputed a geologist to site. The mixing chamber of the machine was emptied as low as possible to enable face mapping and rock identification was carried out. The granite in the invert was found to be fresh with weathering grade I and an estimated UCS value of 180 mPa (see Figure 4).

The information from the face mapping along with data showing that the cutterhead had been rotating at speeds of up to 2.6 rpm confirmed beyond any reasonable doubt

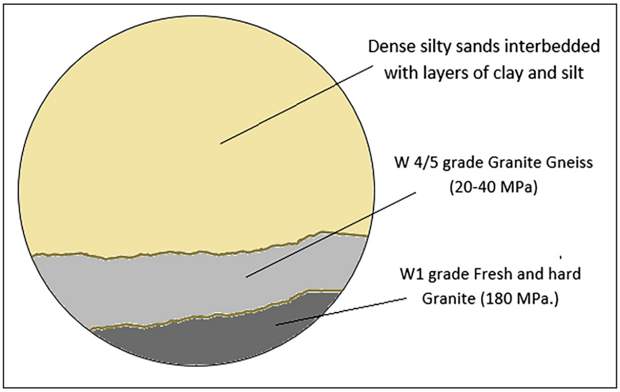

Figure 4. Face map showing mixed face conditions

that impact damage was the cause of many of the cutter failures. However, it was not the cause of all cutter failures.

The reason that 33 cutters needed replacing in a single intervention was most certainly caused by the failure of a single cutter initially, which then resulted in a cascade type wipe-out of adjacent cutters. When failure of a single cutter was not immediately identified it caused the adjacent cutters to take more load, ultimately causing failing due to overload. The overload situation is especially critical in the centre cutter positions, as their cutter tracks overlap. When failure of a centre cutter occurs, it is almost a certainty that a cascading failure will continue until the machine is stopped.

Cascade type wipe-outs are not uncommon when boring in rock or mixed face conditions containing rock. With open type hard rock machines, they are generally caused by cutter bearings failing and subsequently the cutters becoming blocked. In the case of broken discs, the damaged cutter parts are discharged almost immediately so boring is halted as soon as these parts are spotted and this prevents a wipe-out from occurring.

Wipe-outs due to broken discs are more difficult to prevent with EPB machines, as the displaced cutter discs can remain in the mixing chamber for extended periods of time before being discharged through the screw conveyor. The operator has to rely on being able to interpret changes in the operating parameters, especially cutterhead torque and TBM rate of penetration, to identify cutter damage and to cease boring before a wipe-out occurs. Interpretation of TBM parameters isn't always straightforward even when boring in a full face of relatively homogenous strata. In mixed face conditions it is far more difficult as the operating parameters can vary significantly during the length of a single stroke.

Solution

Although it was counterintuitive the solution to improving overall production was to reduce the cutterhead speed, restrict penetration per revolution and carry out interventions more frequently. The aim was to prevent or at the very least minimise impact damage to the cutters and to also reduce the risk of wipe-out failures. In the long term this would result in less time spent carrying out lengthy interventions to replace large amounts of cutters. Based on Robbins previous global experience and discussions with AFCONS It was decided that while boring through the mixed face conditions a baseline rotational speed of 15.0 meters per minute would be used for the outer

Table 5. Final operating parameters to prevent impact damage in mixed face conditions

TBM Operational Parameters, Mixed Face Rock/Soils to Prevent Impact Damage to Cutters	
Cutterhead Speed Main Thrust pressure CHD torque	0.8 RPM (Maximum) 19000 kN (Maximum) 3,600 kNm (Maximum)
Earth pressure (centre of face) Advance rate	2.0 Bar 5–7 mm/min (Maximum)

profile of the cutterhead. This equates to a cutterhead speed of around 0.75 rpm. The advance rate of the machine would also be restricted. To enable machine parameters to be refined to suit rock conditions, face mapping was carried out during every intervention. The agreed upon operating parameters are shown in Table 5.

Over the following 150 m of boring, the geology along the alignment gradually changed from a mixed face containing silty sands, clays and rock to a full face of granites. During this stretch the parameters were revised accordingly from the values detailed in Table 5.

Results

In the course of boring 187 m in mixed face conditions a total of 144 cutters needed to be changed due to impact damage and wipe outs. This equates to the consumption of a cutter for every 1.29 m of bored tunnel. From the introduction of refining boring parameters through to the breakthrough of the machine, a total of almost 650 m of boring, 253 cutters were replaced which equates to 2.57 m of boring for each cutter. This was an improvement of almost 100%. The first 388 m of boring had taken 11 months. The initial drive of 150 m, setup of the shaft and installation of the remaining TBM gantries was completed by mid-May but the following 240 m of boring was not completed until mid-December. A month was lost due to issues unrelated to the geology; this means that it took six months to complete 250 m of tunnel, an average of 40 m boring per month. From the change in operational parameters and increased interventions the machine completed the remaining 640 m in 6.5 months, an average of almost 100 m per month, which equates to an increase in production rates of 250%.

The total time taken to complete the first drive was 17 months. The lessons learned regarding the most suitable operating parameters were utilized on the second drive, the face mapping from the first drive aided better planning of interventions for the second drive, and hence less interventions were required. The second drive was completed in 12 months despite being driven in almost identical geology to that of the first drive.

BANGALORE METRO

The Chickpet to Majestic Station section of the North-south corridor of Bangalore Metro Phase I consists of 750 m of twin bored tunnels. The Two EPB TBMs that had been utilized to bore the sections leading up to Chickpet had suffered major delays mainly due to mixed face conditions on the alignment of the twin 432 m drives between City Market station and Chickpet station. The average time taken to complete these two drives was 17 months per drive, averaging only 25 m per month of boring progress. The slow progress on this section of the tunneling operations was delaying completion of the whole project so the project owner, Bangalore Metro Rail Corporation (BMRC) and its contractor JV, approached The Robbins Company with a proposal to overhaul the machines and accept a contract to bore the remaining two drives. Although Robbins had not supplied the machines, they agreed to an operational contract. The agreement covered all tunnel and site works apart from muck transportation

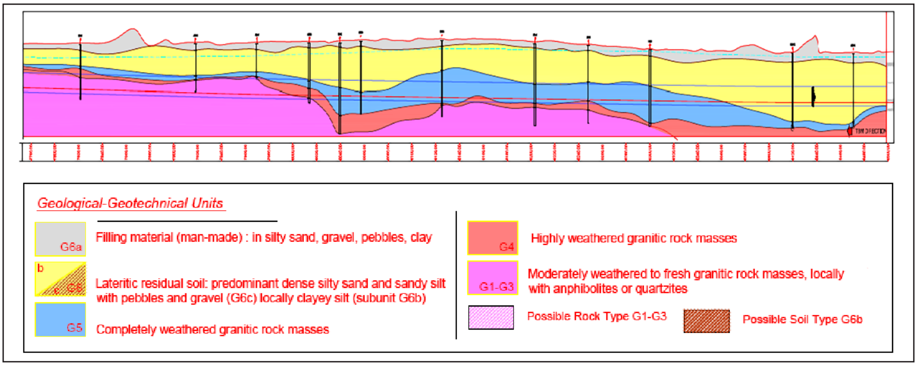

Figure 5. Geological cross section showing mixed face conditions

from site and segments casting/delivery. This was an industry first, wherein a TBM manufacturer had utilised their in-house expertise and knowledge to take on this level of responsibility for a project.

Geological/Hydrological

The geology between Chickpet and Majestic station is made up of fill material, residual soils, dense silty clay and varying grades of granite ranging from completely weathered through to fresh un-weathered rock. The piezometric level ranges from between 5 m to 10 m above the crown of the tunnel. The overburden along the alignment ranges from approximately 10–14 meters. Approximately 60% of the drives were expected to be driven through difficult mixed face conditions. In addition to the difficult geology the vast majority of the alignment ran beneath a densely populated area crammed with surface structures, many of which were poorly constructed. The geological long section can be seen in Figure 5.

Machine Launch

The first machine was launched in March 2015 into strata consisting predominantly of residual soils and dense silty sand. While boring through the residual soils over the initial 160 m the cutterhead rotational speed had ranged between 1.75 to 2.5 rpm and advance rates of up to 16 mm per evolution/40 mm per minute were achieved.

Mixed Face Conditions

From chainage 160 m weathered granite was encountered in the invert of the bore. The weathered granite acted as a conduit for water—the mixture of excavated clayey silt and water caused blockages of the cutterhead openings and a build-up of material on the plenum bulkhead. This resulted in high cutterhead torque, greatly reduced advance rates, and a substantial increase in muck temperature in the mixing chamber due to heat caused by friction. Interventions under hyperbaric conditions were undertaken to clear the choked cutterhead and material from the plenum bulkhead. Typically, an intervention needed to be carried out every 15 rings (22.5 m of boring) and each intervention would take over 24 hours. Up to 12 hours of this time was consumed waiting for the temperature in the chamber to drop from up to 65° Centigrade to below 35° Centigrade before personnel could enter. Cautious trials with various TBM operating parameters and foam injection/expansion ratios were carried out without any significant improvement. The problem was of course rooted in the ground conditioning regime. A good ground conditioning regime can be equally as important as the machine design and logistical aspects on any EPB project [Roby et al., 2014]. The ground conditioning agent that was being used up until this point was a basic foaming agent. After consulting various industry sources trials with an anionic water-soluble polymer (Mapedrill M1) were carried out. The product has an encapsulating effect on active clays, as well as acting as a lubricant. The polymer was mixed into the bentonite holding tank at a dosage of 5 kg per 1000 litres of water and pumped directly into the cutterhead and mixing chamber at a rate of 2–3 litres per cubic metre of excavated material. Cutterhead torque was reduced by approximately 40% within 20 minutes of injection. The overall effect of introducing the polymer into the ground conditioning regime was the reduction of cutterhead blockages to the point where cleaning was only carried out during standard interventions for cutter changes. It also reduced the friction and subsequent temperature in the chamber down to a maximum of 55° Centigrade.

There were no problems regarding cutter consumption while boring through the residual soils and weathered granites. At chainage 215 m the machine encountered fresh granite in the invert of the bore. Similar operating parameters to those detailed previously on the Chennai project were implemented successfully. The results were that cutter damage due to radial cracking was not excessive and consumption was close to pre-project estimates.

Charted and Uncharted Wells

At approximately the same chainage as the machine encountered fresh granites, it also encountered both charted and uncharted wells. Numerous wells had been identified in close proximity and directly along the alignment of the tunnels. The concentration of wells increased noticeably in the 140 m stretch of the alignment beginning at ring No. 215. There are 31 charted wells (Indicated by the blue and pink spots) in the vicinity of the twin drives through this stretch (see Figure 6)

All charted wells had been filled and capped to prevent loss of face pressure and/or ground conditioning foams rising to the surface. The uncharted wells were only identified by the presence of anomalies such as bottles and clay pots in the excavated material discharged through the screw conveyor (see Figures 7–8). By the time these items were discovered the machine had already passed through the wells.

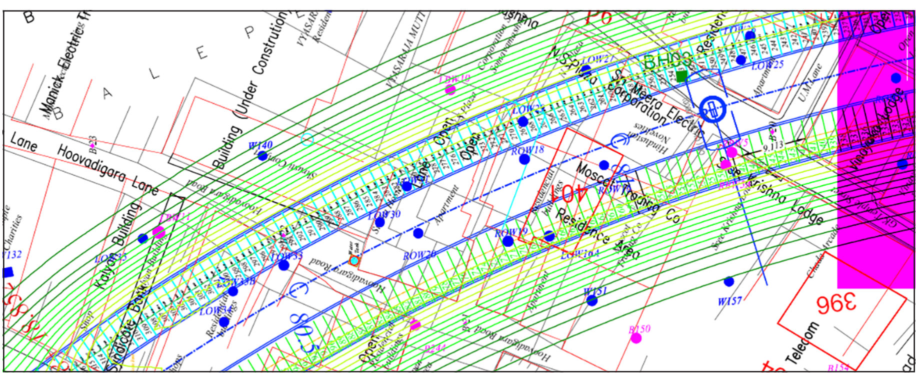

Figure 6. Charted wells in the tunnel alignment (blue and pink dots)

Figure 7. Clay pot found in excavated material

Figure 8. Bottles found in excavated material

Table 6. Final design mix

Bangalore Metro Design Mix for Cutterhead Intervention Ground consolidation	
Cement Bentonite Retarder	130 kg 50 2 litres
Sodium silicate accelerator Water Set Time	55 litres 820 litres 12–14 hours

Failed Interventions Due to Air Losses

Neither the charted nor uncharted wells produced problems with interventions while boring through the soils; however, problems with face pressure during interventions commenced along the alignment where there was rock in the face as well as wells in the vicinity. Interventions had to be aborted due to excessive air loss, although in most cases the air loss could not be located on the surface. Initially the procedure adopted was to continue boring for 3–4 rings in an attempt to reach a location were air losses were less severe. Although this proved to be effective regarding reduction of air losses and facilitation of an intervention, the continuation of boring after observation of boring parameters dictated that an intervention was necessary invariably resulted in additional cutter damage. Due to the close-packed nature of the surface structures it was not possible to install safe haven grout blocks to prevent air losses during interventions, so a procedure of pumping a weak grout mix solution through the cutterhead and mixing chamber was adopted. The grout was injected up to a predefined pressure limit of 2.5 bar before pumping was stopped. Face pressure was then monitored for 30 minutes. A reduction in pressure in excess of 0.2 bar dictated that further grout injection was required. This procedure was repeated until a steady pressure was achieved.

Various design mixes were laboratory tested and trialled during interventions before the most efficient mix was found. See Table 6 for details of final mix design.

Initially, pumping weak grout solution after an intervention failed but this involved either boring forward to fill the chamber with material or filling approximately 60% of the chamber with weak mix grout. Boring forward even if only for 600–700 mm with damaged cutters ran the risk of further damage, hence filling the chamber with weak mix grout was the option chosen. In this scenario approximately 35 m^3 of grout was required to consolidate the ground, fill the annular gap around the shields and fill the chamber. This methodology caused delays related to longer setting times for the grout plus additional time spent cleaning grout from the cutter housings and cutters. To reduce these impacts the procedure was revised to drop the level of material in the chamber by approximately 0.75 m to allow the flow of industrial compressed air into the chamber. This involved removing approximately 3–4 m^3 or 10% of the material in the chamber. The industrial air pressure was then slowly increased until it reached the design face pressure of between 1.3–1.6 bar (dependent on the overburden and water table at each specific location). If the pressure held steady for one hour without excessive air losses the chamber was emptied to below the rotary union and the intervention commenced. If air losses were excessive, weak mix grout was injected as described above. The volume of grout required for this procedure was reduced to approximately 15 m^3, a reduction of 57% compared to injecting week grout mix after a failed intervention. This methodology also drastically reduced the time spent cleaning grout from the cutter housings and cutters as they remained encased in soils, which prevented ingress of grout. The procedure was used successfully throughout areas of the alignment where excessive air losses occurred.

Surface Settlement

Another problem related to the wells along the sections of alignment consisting of mixed face of rock and soils was an increase in surface settlement. The increase in settlement occurred despite strict control and monitoring of TBM parameters and excavation volume. Face pressure had been maintained at the design value 1.8 bar, the amount of excavated material was checked using the TBM belt scales, load cell on the shaft gantry crane (when lifting muck cars), and visual inspection of each muck car during excavation. The density of the excavated material was confirmed daily and consumption of ground conditioning agents were input into the final calculations. Injection volume of the annular backfill grouting was above theoretical volume at approximately 115%. Backfill grout was also monitored closely in respect to machine advance in real time. These measures and checks confirmed that over-excavation had not occurred and that sufficient backfill grout had been injected into the annular gap.

After discussion it was agreed that the machine should continue boring, but face pressure would be increased to 2.0 bar. Additional secondary grouting would also be carried out immediately behind the tail shield of the machine. The increase in face pressure had to be aborted almost immediately due to conditioning foams being pushed through to the surface. The machine was stopped, and a weak grout mix was injected through the cutterhead and around the TBM shields to seal the leakage. The same procedure was used as described in the intervention consolidation operations. The total weak mix grout solution injected during this incident was over 60 m^3 and yet there was no sign of grout on the surface. Face mapping during cutterhead interventions confirmed that there were no existing voids in front of the machine and therefore the only viable explanation was that over decades of drawing water from the wells, the water that was recharging the wells had washed fines out of the matrix of the surrounding geology and that the vibration of the machine combined with the high-water table was causing fines to settle back into the matrix resulting in surface settlement.

As can be seen in Figure 9 the initial settlement was within acceptable limits of less than 5 mm for almost 10 days after the machine had passed. The rate of settlement then increased and continued to increase for up to 6 weeks.

Considering the time dependent nature of the settlement and the conclusion that it was being caused by vibration and infill of fines into the matrix of the strata, the preferred solution to enable continuation of boring was to revise the annular backfill grouting procedure. The parameters for primary and secondary grouting operations were changed to a system based on reaching a predefined maximum pressure rather than maximum design volume. The primary grouting cut-off pressure was defined as 2.0 bar and the secondary grouting pressure was increased to approximately 3.0 bar

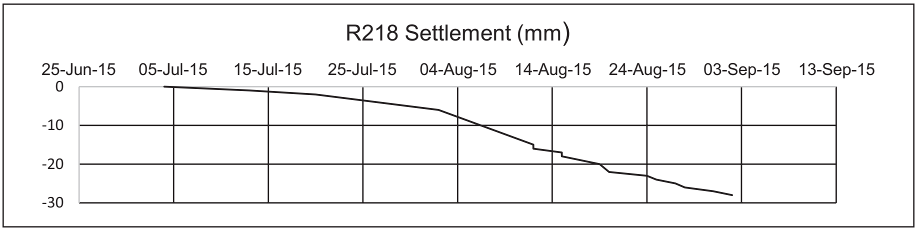

Figure 9. Measured surface settlement

depending on site conditions. An additional phase of secondary grouting approximately 30 meters behind the TBM was also introduced. This resulted in a substantial increase in grout consumption but was successful in controlling surface settlement. During the two drives the total backfill grout consumption including primary and secondary operations was over 190% of the original design volume.

Surface Vibration

As the percentage of rock in the face increased it was possible to gradually increase the cutterhead speed without risking damage to the cutters. By the time the first machine had completed almost 70% of its drive it was boring in a face consisting predominantly of rock. The cutterhead speed was operating at around 2.5 rpm, torque values were well within normal range, settlement issues and intervention problems had been resolved, and cutter consumption was not excessive; hence, the remainder of the drive was expected to be completed without any major issues. Unfortunately, this was not the case—there was one more challenge to be faced regarding machine parameters.

Up until this point there had been no complaints regarding vibration. This is probably because the alignment up until this location ran beneath small shops and other commercial buildings that had either no residential accommodation or accommodation only on the upper floors. The machine was now beneath a building that had residential accommodation on the ground floor and numerous complaints were made by panicked residents during the night shift. Due to these complaints and the possibility of further complications with local residents the boring operations had to be halted. The following day vibration monitors were utilized to determine the magnitude of the vibrations. Various cutterhead speeds between 1.0 rpm and 2.5 rpm were used during the monitoring period. Peak particle velocities were recorded ranging from at 0.3 mm/s up to 0.7 mm/s, rising steadily with a more or less constant correlation to increased cutterhead speed.

Several representatives of the residents were present during the monitoring and a comprehensive explanation of the results were conveyed to these representatives. The explanation was lengthy but conveyed in layman's terms why there was absolutely no risk of damage to the buildings. It is the unpredictability and unusual nature of a vibration rather than the level itself that is likely to result in complaints, the effect of intrusion tends to be psychological rather than physiological and is more of a problem at night when occupants of buildings expect no unusual disturbances from external sources [Schexnayder et al., 1999]. The residents remained unconvinced of the lack of risk and became irate when further discussion was attempted, so a compromise was reached wherein cutterhead speeds were restricted to 1.8 rpm during daylight hours and 1.2 rpm during the night. These speeds restricted the PPV's to less than 0.5 mm/s which was not in any way a noticeable difference to human perception, compared to PPV's of 0.7 mm/s produced at a cutterhead rpm of 2.5; however, the reduction did have a noticeable effect on production rates, reducing meters bored per day by around 40% for the following 60 m of boring.

Despite the difficult geology, charted/uncharted wells, settlement and vibration issues both drives were successfully completed by September 2016.

CONCLUSION

Mixed geology presents a multitude of challenges for mechanized tunnelling. Some but not all of these challenges are discussed in this paper. Technical advances in TBM technology have produced a generation of machines that are capable of traversing mixed geological conditions that would previously have required separate machines with different capabilities. On many projects TBMs would have been ruled out completely in favour of slower but more adaptable, traditional tunneling methods. Although the new generation of TBMs is capable of managing a wide variety of geological conditions, the technology is only a part of the equation in successfully completing a project. Baseline parameters can be pre-calculated to suit different ground conditions, but these parameters should only be used a guideline. Experienced operational personnel need to be available on site to among other things: fine tune operating parameters, decide on the frequency of interventions, and revise ground conditioning regimes. Only then will the technology be utilized to its full potential.

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