Hybrid TBM Excavation in Challenging Mixed Ground Conditions at the Mumbai Metro

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ABSTRACT: Excavation in mixed ground conditions is always a challenge, but under a densely urban environment the stakes become even higher. At India's Mumbai Metro, two 6.65 m hybrid-type rock/soft ground Single Shield TBMs are successfully boring parallel 2.8 km tunnels in basalt rock with transition zones of shale, tuff, and breccia below the city. They have made intermediate breakthroughs at the 1.2 km mark and overcome rock strengths up to 125 MPa UCS with significant water ingress, all just one year after factory acceptance, shipping, site assembly, and launch. The hybrid machines are optimized for abrasive rock geology using a robust cutterhead mounted with disc cutters and a reinforced screw conveyor at the centerline. The machines can also operate in closed or semi-closed mode using features designed to advance in soft ground with water inflows: dual ratio gearboxes to adjust cutterhead speed and torque to the geology, screw conveyors with bulkhead gates and discharge gates, ground conditioning with foam and polymers, and probe drills for pre-excavation grouting. This paper will examine the good excavation rates of the uniquely designed machines, as well as the logistics of tunneling in changing geology, adjustments to cutterhead and screw conveyor RPM, ground conditioning, and other factors that have made mixed ground tunneling more efficient.

KEYWORDS: Tunneling, Mumbai Metro, TBM, mixed ground conditions

1. INTRODUCTION

Mumbai, financial capital of India and one the most populated cities in the world with over 23 million people in the metropolitan region, is facing growing traffic congestion. The number of vehicles on the roads has increased by 360% in the last 20 years. Air pollution associated with road traffic has become a major concern for the residents of Mumbai. In 2014, the first line of the metro system opened to curb the growth of road traffic. Seven additional lines for a total of 235 km are under construction with an overall project completion expected in 2025. The 33.5 km of the underground metro line 3 will span from the south end of Mumbai in the business district of Cuffe Parade to the SEEPZ district and will serve the Chhatrapati Shivaji international airport. Metro line 3 is expected to initially decrease road traffic in the area by 35%, reducing fuel consumption by 460,000 liters every day. It takes today up to 2 hours on the road to cover the 25 km separating Cuffe Parade to the airport. The same trip with the metro will take 50 minutes.

The metro line 3 project is divided into seven packages. Package 1 was awarded to the joint venture between Larsen & Toubro and the Shanghai Tunnel Engineering Company (L&T – STEC) and consists of two 2.8 km parallel tunnels between the Cuffe Parade station and the Hutatma Chowk station. Two 6.65m Robbins hybrid or Crossover TBMs are currently boring these two tunnels and are the subject of this paper. Robbins also supplied two slurry TBMs for package 3 that are boring the 3.5 km section of tunnels between the stations of Mumbai Central and Worli. The location of packages 1 and 3 are shown in Figure 1.

The two TBMs on package 1 started boring in August 2018 and November 2018. They broke through at Vidhan Bhavan, the first of two intermediate stations, in April 2019 and they resumed boring towards the Churchgate station in July 2019. They passed the halfway mark of their journey in August 2019.

Overall, the tunnel excavation on Mumbai metro line 3 was 54% complete as of August 2019.

Figure 1: Robbins TBMs at the Mumbai Metro line 3 project

2. GEOLOGY

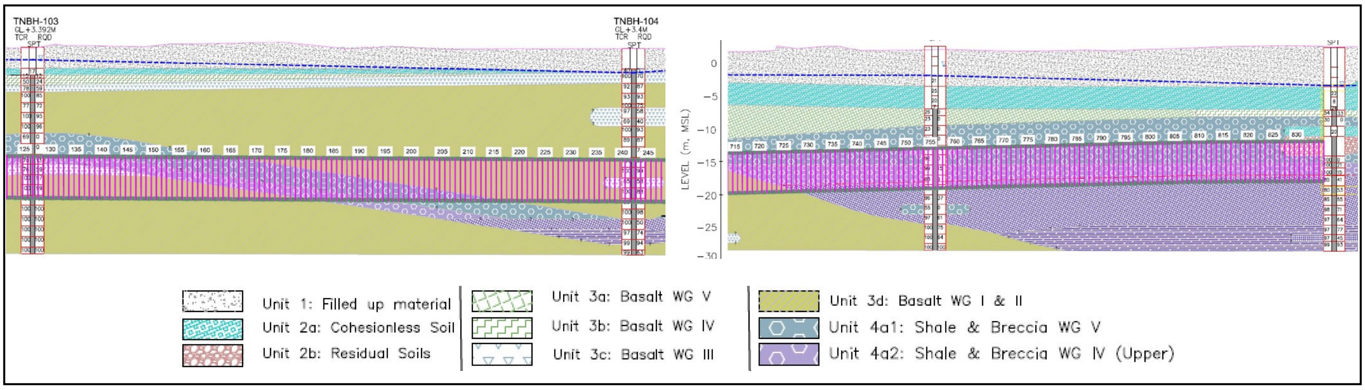

Figure 2: Extracts of the geological profile of package 1 showing the variety of terrains

The geology of package 1 consists of fresh greyish basalt, soft volcanic tuffs, shale, and breccias which are consolidated rocks of angular fragments of disintegrated volcanic rock.

As shown on Figure 2, the tunnels transition between these rock formations several times:

- Full tunnel face of fresh to slightly weathered Basalt with UCS up to 125 MPa
- Full tunnel face of weak to completely weathered Shale and Breccia with UCS in the 10 to 15 MPa range
- Mixed tunnel face while transitioning between a fresh Basalt layer and a weak layer of Shale and Breccia.

The TBMs on Line 3 excavate with only 15 to 20 meters of cover above the tunnel. At the surface, some structures such as the Mittal towers and the historic Bhikha Behram Well have been instrumented to monitor vibrations, movements, and potential settlement.

As expected, the TBMs has been going through significant amounts of groundwater with up to 300 l/min between Cuffe Parade and Vidhan Bhavan. Water pressure of up to 2 bar is foreseen.

3. TBM DESIGN

3.1. TBM General specifications

Engineers from L&T were heavily involved with the specification and design of the TBM which was critical for the success of the project and the good excavation rates currently being seen on both machines. Specifications of the Robbins Crossover TBM are listed in Table 1 and the TBM general layout is shown in Figure 4.

Table 1: TBM specifications

Bore diameter	6650mm
Tunnel lining	5 reinforced concrete segments + 1 key
Tunnel curve	Turn radius: 200 m
Ground water pressure	TBM designed for 3 bar of external water pressure
Cutterhead	• 8 variable freq. drive motors, 210 kW each • Speed: ○ 0-8.8rpm in hard rock mode (high speed) ○ 0-4.5rpm in soft ground mode (high torque) • 42 x 17" disc cutters
Hydraulic system	• Installed power: 420 kW • Working pressure: 345 bar
Screw conveyor	• Speed: 0-19 rpm • Torque: 100 kNm
Segment erector	• Radio controlled • Mechanical pickup
Ground conditioning	Foam injection via nozzles in the cutterhead and in the screw conveyor
Ground exploration	Probe drill mounted on segment erector ring

3.2. TBM special features

The expected geology and the presence of ground water required the use of a TBM with the ability to excavate effectively in continuously changing conditions.

3.2.1. Adaptable Cutterhead

The two-speed gearboxes installed on each of the eight drive motors allows for a quick adaptation of the cutterhead torque and speed to the type of ground. The high speed ratio is used in full face hard rock, whereas the high torque ratio, which increases the available torque by a factor of 2.5, allows for operation in soft ground or mixed face. The extra torque is required to start the cutterhead should there be a face collapse, or to bore when the cutterhead is full of excavated material.

The cutterhead design is optimized for hard rock with six peripheral bidirectional muck buckets as shown in Figure 3. In extreme soft and running ground conditions, the opening ratio of the cutterhead can be increased by removing part of the face plates and installing soft ground cutting tools.

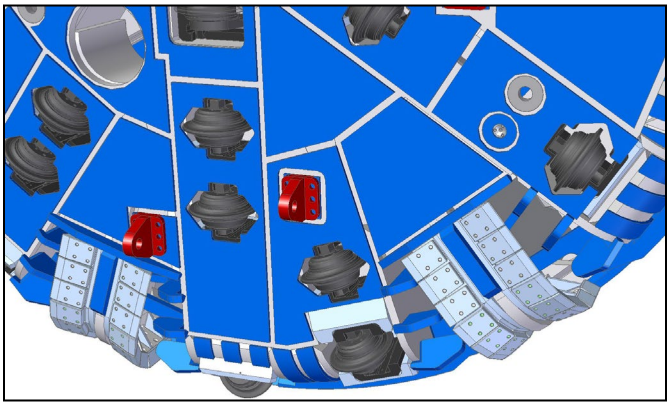

Figure 3: Bidirectional muck buckets

The roll angle of the TBM is maintained by alternating the direction of rotation of the cutterhead at each TBM stroke. This allows for a simpler thrust system, eliminating the need for a skew ring.

As in an EPB machine, disc cutter maintenance is made possible by a manlock for hyperbaric interventions inside the cutterhead chamber up to 3 bar. All cutters are replaceable from the cutterhead chamber.

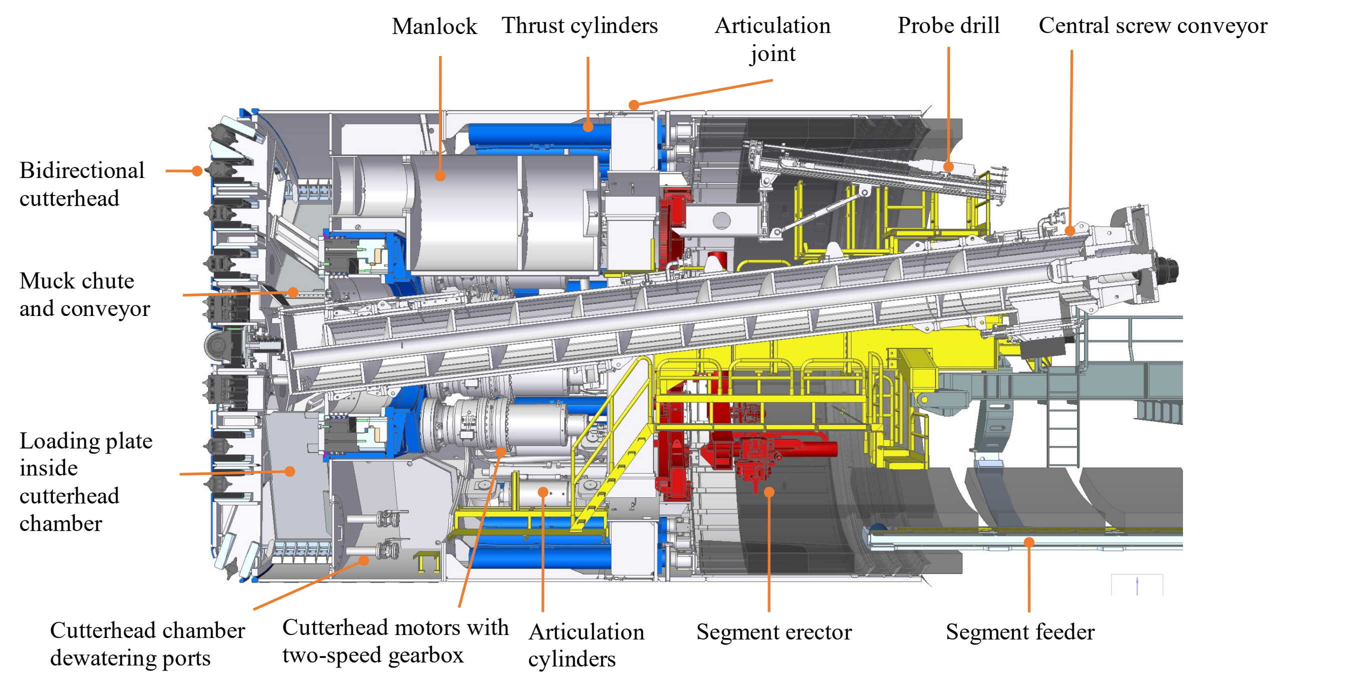

Figure 4: TBM general layout

3.2.2. Central screw conveyor

Dedicated hard rock TBMs generally use a belt conveyor located in the center of the machine as a means to convey muck out of the cutterhead chamber. Pure EPB TBMs on the other hand use a screw conveyor most often located at the bottom of the excavation chamber. By using a screw conveyor in the center of the machine, the Crossover TBMs used in Mumbai offer the advantages of both designs:

- Full mucking of the cutterhead chamber in rock mode thanks to the six loading plates that continuously scoop excavated material from the invert and dump it in the screw conveyor inlet. This design allows for minimal wear by keeping the amount of rocks inside the chamber to the minimum.
- Ability to work in pressurized terrains and to control ground water with the cutterhead chamber full of material and using the screw conveyor as a plug to maintain pressure at the excavation face, thus avoiding ground settlement at the surface.

Due to the geology being primarily rock, extra wear protection was added to the screw conveyor and includes a replaceable casing liner, replaceable flight plates and extra access doors in the casing for maintenance and replacement of the wear plates.

3.2.3. Ground conditioning, mapping, and consolidation

The TBMs are equipped with a foam plant, 6 injection nozzles on the cutterhead, and 1 at the inlet of the screw conveyor. Foam has several uses on a TBM:

- Control dust in the excavation chamber in rock mode
- Reduce friction and wear in soft ground mode when the cutterhead chamber is full of material
- Reduce the permeability of the ground in order to reduce ground water inflow.

A probe drill can be installed on the erector ring for ground mapping ahead of the excavation. Drilling is done through 12 ports located all around the TBM shield at a 7-degree angle from the TBM axis and through six ports straight forward through the cutterhead. Probe holes can be used in an umbrella pattern for pre-excavation grouting to consolidate and seal the ground in front of the cutterhead for higher boring advance rates.

Several lubrication ports are installed radially along the TBM shield for injection of bentonite to reduce friction with the tunnel wall in sticky conditions or squeezing ground.

3.2.4. Cutterhead inspection camera system

The six probing ports through the cutterhead can also be used to install a camera with LED lighting to inspect the condition of the cutters without the need for a worker to enter the cutterhead chamber (see Figure 5).

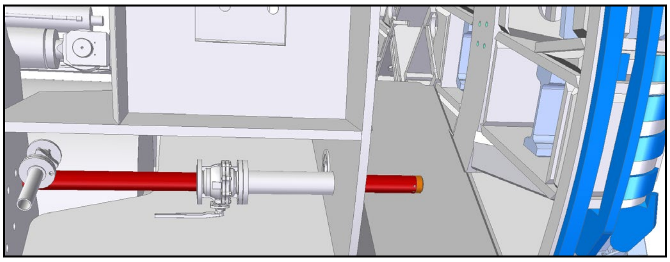

Figure 5: Cutterhead inspection camera

4. Familiarization and training

Although L&T had extensive experience in both traditional and mechanized tunnelling methodology, they had not had any hands-on experience with the design features of the crossover machine. As part of the machine supply agreement Robbins provided a team of key personnel to train and familiarize L&T's team in all aspects of the Crossover machine's design features including both technical and operational features during boring operations.

5. Site assembly and launch configuration

5.1 Transportation

The machine arrived in Mumbai June 2018; however, due to the limited space available at the Cuffe parade launch shaft a staging area located just over 1km from the site was utilized for storing the machine until the shaft excavation was completed. Vehicular access adjacent to the site for unloading the backup gantries was a major problem as it involved partial closure of the main arterial road leading from South Mumbai into the city and required authorization from the local police department. The solution was to fully equip all backup gantries at the staging area before transporting them to the jobsite. They were then lifted directly from flatbed trucks into position alongside the shaft. The TBM shields were unloaded from a side street.

5.2 Off-center assembly

The station/launch shaft excavation was supported by secant piles, frames and struts. The centerline of the tunnel and rail tracks for both drives were located beneath a series of diagonal struts as shown in Figure 6. This meant that the TBM shields could not be assembled either in their launch positions or simultaneously. The only available option was to assemble the first machine in the center of the shaft then move it into its launch position, therefore leaving the shaft center free to begin assembly of the second set of TBM shields. This procedure was achieved by decking the shaft bottom with steel sheets, assembling the machines on robust launch cradles and using hydraulic rams to move the cradles onto the tunnel alignment.

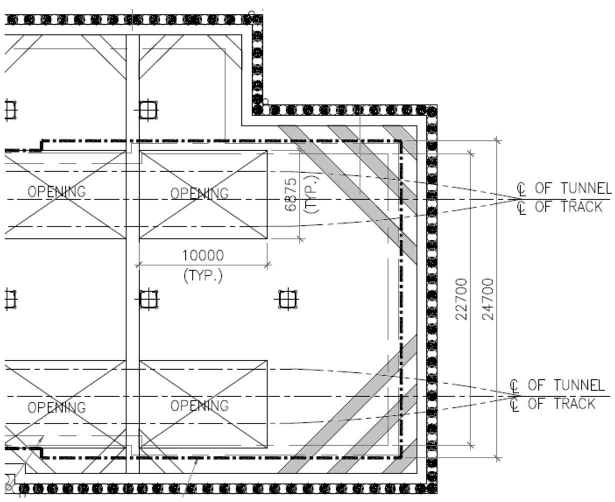

Figure 6: Shaft support struts

5.3 Initial drive machine configuration

Excavation of the launch shaft had suffered delays due to restrictions on working hours because the site was located close to several high-rise residential apartment blocks. This issue had been anticipated in advance during the site assembly planning stage, but it was not clear to what extent the excavation schedule would be impacted although it *was* clear that launching a completely assembled machine and backup system would not be possible.

Several assembly/launch configurations were prepared and it was hoped that space would be available for launching with a minimum of: machine, bridge gantry and Gantry #1. This setup would allow the segment handling system to be fully operational and facilitate the installation of a shortened conveyor system for mucking. However, at the time of launch the available space dictated that the machine was launched in a worst-case scenario, without any gantries at all. Electrical and hydraulic umbilicals had been procured to enable the initial drive of 105m to be completed, with the machine only. With this configuration, production operations would be hindered due to mucking directly from the screw conveyor into a relatively small skip rather than a muck car, and segment handling would be slow without the segment handling system. Bearing this in mind discussions took place to assess the benefits of carrying out a phased initial drive as follows:

- Machine to bore 28 meters of excavation, before lowering and connecting the bridge gantry and gantry # 1 (to allow segment handling system and shortened conveyor to be installed).
- After 60 meters of excavation, backup gantries 2, 3 and 4 to be lowered and connected (to allow complete conveyor system to be installed, facilitate use of two muck cars, free up space on the surface for the gantries of the second machine, and reduce the length of the umbilicals).
- After 105 meters of excavation, remaining backup gantries to be lowered and assembled.

Although the phased assembly sequence would substantially reduce the time taken to complete the initial drive for TBM 1, the downside would be delays to the assembly of TBM 2. There was insufficient space available to mobilize a dedicated crane for each machine, hence assembly of TBM 2 would be disrupted when the crane was being utilized for each phase of the TBM 1 assembly operations. Finally, it was decided to complete the whole of the initial TBM 1 drive utilizing the machine only. Shaft excavation would continue as a parallel activity, which would shorten the overall length of boring required to enable lowering of all gantries.

5.4 Initial drive production Rates

A couple of days before TBM 1 commenced boring, assembly operations on TBM 2 commenced. This should be considered when assessing the production rates during the initial drive. Other major factors that have already been mentioned are mucking with a single skip, which had to be transported to the shaft, lifted to the surface and tipped before being returned to the discharge point of the screw conveyor, and a makeshift segment handling system. TBM 1 completed 70 meters/42 rings of boring in 33 working days, giving an average production rate of 2.12 m per days. Only 70 meters was required for the initial drive of TBM 1 because the shaft excavation was extended during this time, which provided the space required for the back-up gantries. The initial drive of TBM 2 consisted of 97m of boring and using the same configuration as TBM 1, (machine only, fed by umbilicals) was completed in 37 days with an average production rate of 2.6 m per day. Both of the initial drives were completed on time. The geology along the alignment of both initial drives consisted of Basalt ranging from weathering grade I to weathering grade III. Water ingress was not significant, hence the machines were operated in open hard rock mode.

6. Machimar Nagar

One of the biggest concerns along the alignment of the package 1 tunnels between Cuffe Parade and Vidhan Bhavan station was that the drives ran in close proximity to the coastline of the Arabian Sea. At one point in the vicinity of Machimar Nagar TBM 1 would be little more than 25m from the coastline, with the invert level of the tunnel running approximately 22m below mean sea level (see Figure 7).

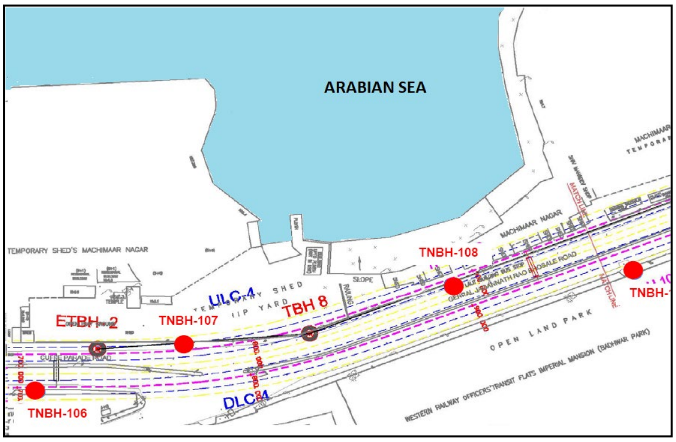

Figure 7: Machimar Nagar

Bore holes had identified that the geology along this section of the alignment consisted of Basalt with varying weathering grades up to grade IV. Lugeon values taken from the bore holes indicated low to moderate hydraulic conductivity with low to moderate rock mass discontinuities. Although the geology at the bore hole locations looked reasonably good, the geology between the bore holes was cause for concern.

Due to the relatively short length of the screw conveyor there was a risk that if the machine encountered geology with high water pressure and low fines content there would be difficulties maintaining a plug in the screw conveyor. To mitigate this risk the machine was designed with an option to operate in sequential mucking mode if required. This option is facilitated by a gate installed on the cutterhead end of the screw conveyor (in addition to the industry standard gate on the discharge end of the conveyor). This allows the screw to be filled, before the front gate is closed, the rear gate is then opened, the screw is emptied, the rear gate is then closed before the front gate is re-opened and the cycle repeated. This is a relatively slow process and feasible for short distances only.

Fortunately, the borehole information proved to be relatively accurate. Although the ground was more fractured than expected the machine was operated in closed mode through parts of this section of the alignment, and the sequential operation feature was not required. Screw conveyor speeds as low as 2 rpm were used in order to maintain a plug in the screw and maintain earth pressure.

The fractured ground did however result in the cutterhead being subjected to high torque conditions but as mentioned above the cutterhead motors are equipped with dual-speed gear boxes capable of boring in high speed - low torque rock mode, or low speed - high torque EPB mode (see Figure 8).

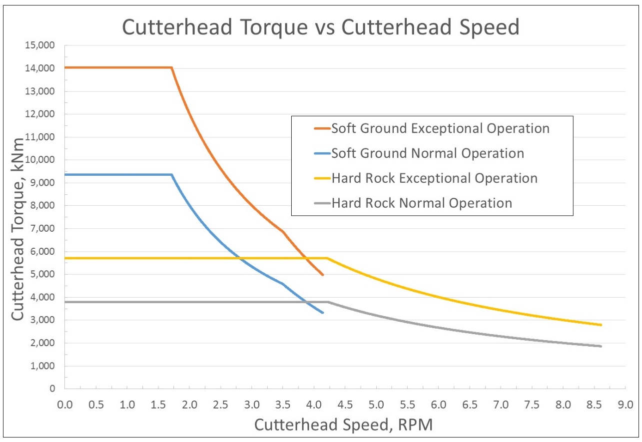

Figure 8: Cutterhead torque curves

The machine operating parameters while boring in the competent rock are detailed in Table 2.

Table 2: TBM Parameters in competent rock

Cutterhead speed	5 to 6 rpm
Cutterhead torque	1800 to 2400 kNm
Main thrust force	10,000 to 11,000 kN
Advance rate	40 to 50mm/minute

When the machine encountered the fractured ground the drive motor safe sets were blown (which prevents damage to the motors), so the low speed - high torque gears were engaged, and the machine operating parameters were changed accordingly (see Table 3). Mapei Polyfoamer FP/LL, anionic surfactant/lubricating polymer was injected into the chamber and cutterhead to reduce friction and prevent clocking of the cutterhead and muck buckets. The machine traversed this section of the alignment without any major problems.

Table 3: TBM Parameters in fractured rock

Cutterhead speed	2 to 3.5 rpm
Cutterhead torque	4000 to 6000kNm
Main thrust force	13,000 to 16,000 kN
Advance rate	15 to 35 mm/minute

7. Production rates - main drives

7.1 TBM performance

Figure 9 shows the monthly production rates of TBM 1 throughout the whole of the first drive and the initial 350m of the second drive.

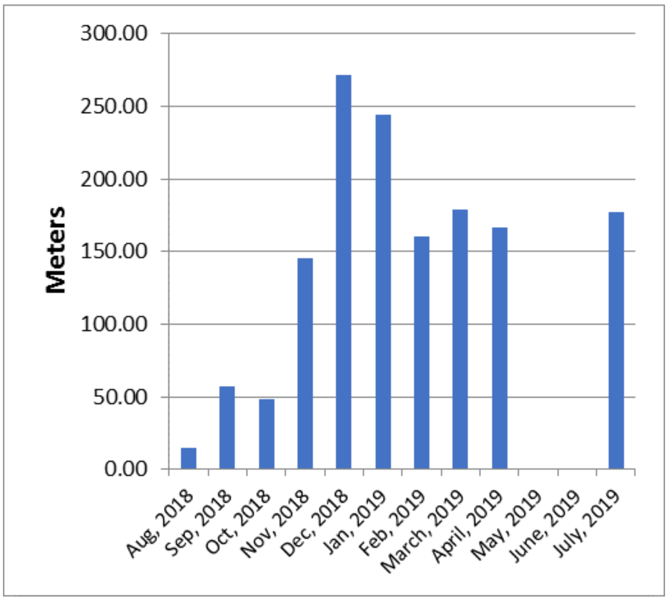

Figure 9: TBM 1 Production rates

For further analysis it should be noted that the machine was not launched until August 20th, 2018 and production rates were affected up until the end of October 2018 by the short start-up and the stoppage to complete the machine back-up gantry assembly, removal of the temporary rings/thrust frame and shaft setup. The machine completed the first drive in April 2019. May and June were taken up dragging the machine through the station box and setting up for re-launch. Taking aside the months that were affected by short start-up, shaft set up, and assembly of the backup gantries the average production rate for the first drive was 195m per month. The machine was relaunched for the second drive complete with all gantries on the 8th July 2019 and by the end of August had completed 351m of boring.

Figure 10 shows the monthly production rates of TBM 2 throughout the whole of the first drive and the initial 230m of the second drive. During the months of November and December 2018 Production rates for TBM 2 were affected by the same short start-up procedures as TBM 1. Taking aside these months the average production rate for the first drive was 220.3m per month with a best month of 278.7m. June and most of July 2019 were taken up dragging the machine through the station box. TBM 2 was relaunched on the 25th July and by the end of August had completed 230m of boring.

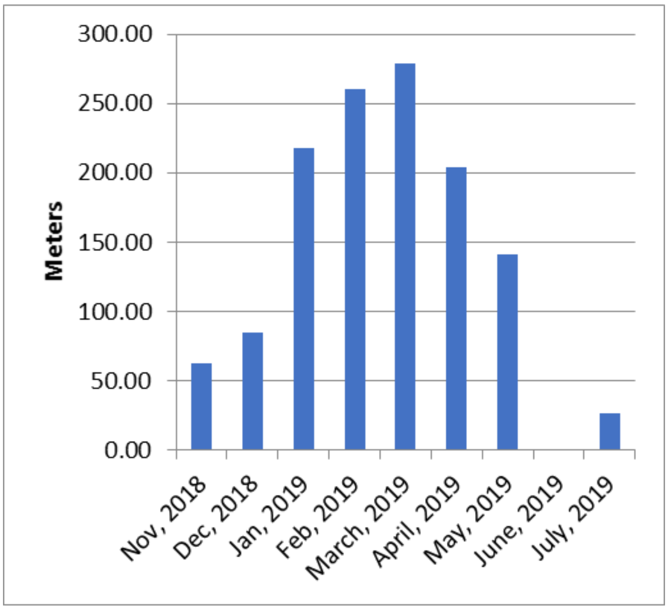

Figure 10: TBM 2 Production rates

7.2 Production restrictions

Although both machines achieved impressive production rates for TBMs with closed mode capability, boring in rock, their performance could have been far better. Substantial delays were suffered when the machines where held up due to bottlenecks in muck-shifting from site. Restrictions were imposed on heavy vehicular access to the site with access prohibited in the morning peak traffic period (6.00 am to 9.30 am) and in the evening peak traffic period (6.00 pm to 10.00 pm). Each round trip to the muck disposal area was 50km, which in Mumbai traffic could take over three hours. The restriction on the size of the site footprint dictated that the maximum capacity of the muck storage bins for each machine could not accommodate more than 4.5 meters of boring before the whole operation became muck-bound. Had there been no delays in the muck shifting operations TBM production rates would have peaked at well over 300m per month.

8. Cutter consumption

A major advantage of the centre screw and peripheral muck buckets is a substantial reduction in wear to cutter tools compared to an EPB machine boring in rock. This is especially the case when an EPB machine is operating in open mode due to the inefficiency of the standard inclined screw conveyor. We need to also consider the amount of excavated material required in the lower chamber/face of an EPB to feed the screw. This material is constantly subjecting the cutting tools and cutterhead to a re-grind wear action.

Table 4 shows the cutter consumption related to normal cutter wear of both machine after completing a combined 1,890 meters of boring. The actual number of cutters consumed was 129, but 20 cutters failed during two separate wipe-out events. This occurs when a single cutter fails and is not replaced immediately. Identifying individual damaged cutters as soon as possible is essential. When one cutter gets blocked and stops rotating, it leads to a higher load on adjacent cutters, with a possibility of a cascading failure (wipe out) of all the cutters in the worst cases (Shanahan 2010). Because wipeout failures are not considered to be normal wear and they are avoidable, only the cutters that initially failed during these two events have been included in Table 4.

Table 4: Cutter consumption

Total linear meters bored	1,890m
Cubic meters of rock cut	65,652m
Cutters/normal wear	111
Linear meters bored per cutter	17.03m
Cubic meters of rock cut per cutter	591.5m

An average of almost 600m³ of rock cut per cutter is an impressive statistic when assessing basic cutter costs. From an operational point of view, 17 linear meters of boring per cutter reduced the frequency of interventions to an average 54m of boring.

9. Conclusion

From the early stages in the design phase of metro projects worldwide, design consultants are stipulating that the tunnel boring machines must be capable of boring in closed mode and be able to maintain face pressure. This of course is to mitigate the risk of ground settlement associated with open face machines when they encounter unstable geology. The clause is also related to preventing depletion of the water table on many projects. After studying this clause in the tender documents contractors invariably start to assess the advantages and disadvantages of slurry machines versus EPB machines. The problem is that neither slurry nor EPB machines perform particularly well when boring in rock.

As already mentioned, EPB machines suffer from excessive wear to cutter tools when boring in rock. This also applies to the screw conveyor. Inefficient mucking and the time lost carrying out interventions due to high wear are major disadvantages. Another issue with EPB machines is the heat generated by friction of the material moving around in the chamber/cutterhead, which can lead to substantial delays waiting for temperatures to reduce low enough for personnel to enter the chamber and carry out interventions. Slurry machines suffer from fewer issues with wear to the cutterhead and cutter tools. Heat is not an issue as the circulation of slurry acts as an efficient heat transfer mechanism; however, production rates are restricted by the capacity of the slurry transportation and separation plant. Both the cost and the size of site footprints are major issues with slurry transportation and separation plants. Production data from projects worldwide show that the efficiency of rock machines boring in rock is far superior to either Slurry Machines or EPB machines.

The term “Hybrid machine” has been used in the industry for some time now; however, this term has often been applied to machines that require lengthy operations to change out the screw conveyer for a belt conveyor to perform efficiently in different ground conditions.

We now have a generation of machines that are truly hybrid, machines that can change from rock mode to soft ground mode almost instantly. As detailed in this paper, ‘Rock TBM’ production rates can now be achieved while still meeting the tender/design criteria of the machine being capable of operating in closed mode.

References

Shanahan, A. 2010. Cutter instrumentation system for tunnel boring machines. Proceedings North American Tunneling 2010.