Proceedings of the World Tunnel Congress 2014 – Tunnels for a better Life. Foz do Iguaçu, Brazil.

Rock Tunneling Machines: Options and Methods for Variable Geology

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ABSTRACT: Modern tunnel boring machines come in a variety of designs that use different excavation methods to address a wide variation of geology seen during tunneling operations. Invariably tunnels of any length run into varying geology, some of which will fall outside the traditional range of any one machine type. On projects where the majority of the drive is rock with a short percentage of a softer formation, selection of a hard rock machine with maximized advance rates, minimized operating cost and wear would be desirable. However, when there are concerns associated with risks of the machine getting stuck, of high water inflow and of subsidence in soft ground, the contractor may be driven towards the choice of a soft ground machine. This paper will review the additional features and ground treatment options that could expand the spectrum of projects benefitting from a hard rock type machine, even when sections of soft ground are present.

1 INTRODUCTION

Since the advent of the Tunnel Boring Machine (TBM) an ever increasing percentage of underground projects are using the technology to great success. Several styles of machines have been developed to excavate differing geologic conditions ranging from competent hard rock to soft ground under water pressure. Each machine type is specialized for a certain geology making consistency of geology along the entire tunnel alignment desirable for the best performance. If possible a slight change in alignment may allow for more consistent geology, making machine selection straight forward. If it is not possible to find an alignment with uniform geology then the best option from a machine perspective would be to split each drive into sections using different machine types. This is very often not possible due to location, access and length of the different sections of geology as well as cost associated with the use of two separate machines. The selection of one machine type over another then becomes a tradeoff, particularly in variable ground—one machine type will have obvious advantages in one condition but many disadvantages in another condition. One approach is to use hybrid TBM, which are designed to incorporate the most favorable attributes of different types of machines in order to excavate mixed geology in a more efficient manner. For the purpose of this paper, hybrid TBMs will be defined as machines fitted with more than one muck handling system, or with the capability of applying multiple combinations of ground support systems. Because the designs of the muck handling systems are very different, hybrid TBM design often requires a compromise to achieve the best machine performance throughout the drive. To reduce the level of inefficiencies associated with the different muck handling systems, varying degrees of conversion are required when changing from one method to another. If the geology is disparate, a hybrid machine may the best solution, but this is certainly not always the case depending on the degree of geological variation and length of each type.

It is not uncommon to see rock geology for the majority of the drive with a small percentage of a softer formation. Concerns over settlement and possible risk of the machine getting stuck in the soft ground drive the choice towards an EPB or Slurry type machine. A solution could also involve a Hybrid TBM despite of lower advance rates and higher operating cost that would be achieved with that of hard rock TBM.

The focus of this paper is on hard rock machine design and the implementation of several different machine features allowing them to excavate sections of soft ground.

2 TBM SELECTION

2.1 Hard Rock TBM boring

Hard rock TBMs are designed to excavate hard rock of varying quality and can be Open-type, Single Shielded or Double Shielded. (see Figures 1-3). These are listed in the order of traditional selection criteria of decreasing rock quality (see Figures 1-3):

Figure 1. Main Beam or Open-Type TBM for competent rock

Figure 2. Double Shield TBM for somewhat fractured rock

Figure 3. Single Shield TBM for very fractured rock

All types use the same basic method for excavating and removing the bored ground. The front of the machine has a rotating cutterhead dressed with disc cutters that fracture the rock at the tunnel face. Chips fall to the bottom of the tunnel and are then scooped into the cutterhead buckets and delivered to a belt conveyor at the center of the machine for removal from the tunnel (see figure 4). The figure shows a pile of muck at the bottom of the head for clarity of operation, but it is worth noting that a hard rock cutterhead is designed to keep the invert clear of muck. This greatly reduces the amount of wear on the cutterhead and cutting tools.

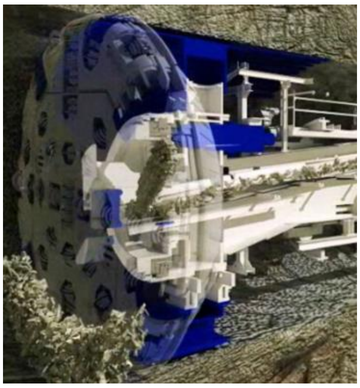

Figure 4. Cutterhead Muck handling

While very efficient at excavating rock, Hard Rock TBMs require a self-supporting face. The distance between the cutter tips and cutterhead is varied to offer some additional support in blocky ground while still allowing muck to fall to the invert, but there is a limit to the support that can be provided to the face. As the stability of the face decreases and the geology moves away from rock there are several issues that will cause the machine to become stuck or unable to continue to advance. The primary issue is the inability to control the flow of material into the cutterhead. This will have the effect of overloading the cutterhead where it is unable to rotate, thus stopping the machine. Ground with a high percentage of adhesive clay will build up in the buckets and is unlikely to empty by gravity alone. This can stop machine advance by blocking the buckets and preventing material from entering the cutterhead or by increasing the torque requirements to a point that the cutterhead is no longer able to rotate. The belt conveyor may also get overloaded in the event that material is entering the cutterhead faster than the belt is able to remove it. The presence of water exacerbates the issue of face stability by washing away the small particles that allow progressively large sections of the face to become unstable. Water inflows add fluidity to in situ ground and excavated muck, making it more difficult to control the flow into the head.

Once the machine becomes stuck it can be costly in both time and money to make it operational and the difficulty rises as the quality of the ground decreases. These events may negate all the machine benefits that were realized in the excavation of the better rock sections of the tunnel.

2.2 EPB and Slurry Machines

Machines that offer face support are sometimes selected because of the unknowns associated with navigating difficult ground. In the case of an EPB the face support is provided by the conditioned muck or a pressurized fluid; in slurry machines this would be provided by Bentonite slurry. In both cases the muck flows through the head instead of dropping to the invert with the cutting tools in constant contact with the abrasive muck. Aside from cutterhead and tool wear, a slurry machine requires a more involved muck transport system that is subject to high wear, especially with rock chips. An EPB requires that the excavated muck have a plastic impermeable consistency, which may involve substantial chemical costs as well as a screw conveyor will see high wear in rock. And, an EPB requires some face pressure in order to force material into the screw conveyor. In hard, impermeable rock, water, chemicals and air pressure are all required in order to make the excavated rock flow into the screw.

1.1 *2.3 Summary of Features and Methods*

The risks associated with a rock machine becoming stuck in a section of bad ground often lead to soft ground shielded machines being selected, which are really only suitable for a short section of the drive.. In order for a rock machine to be an effective solution for a mostly rock project with some soft ground, it must be designed with features that allow it to quickly recover and continue boring. This paper discusses methods or features that occur in front of the machine and progresses back though the machine. It starts with an overview of grout consolidation followed by use of forepoling, both of which occur in front of the machine. We will then review the use of foam in hard rock machines to treat the ground at the face of the machine followed by the drive of the cutterhead itself. On the cutterhead we will look at the use of closable muck buckets and a closable muck chute to control the flow of material into the head. Finally we will review the system of sequential mining using some of the features discussed previously.

3 OPTIMAL MACHINE DESIGN

3.1 Grout Consolidation

Treatment of the ground in front of the machine that stabilizes the ground so that it may be more easily excavated is one method that will allow a machine to advance. It is important that this is done ahead of the machine where it is most effective. Continuous probe drilling ahead of the machine is also important so that difficult ground is detected in advance and grouting is done at the optimal time.

Probe drilling and grouting ahead of the tunnel face are commonly used techniques in drill and blast (D&B) tunneling to control water leakages, consolidate the rock mass and as a continuous pre-investigation during tunneling (NFF, 2011). In tunneling applications, top hammer drill equipment is needed to drill long holes (18 – 30 m). During drilling, it is important to apply sufficient water pressure (>15 bars) to keep cuttings from clogging up in cracks along the drilling hole. The typical diameter for probe drilling and pre-grouting holes is from 45 to 64 mm, and depending on the rock mass properties net penetration rates of 1.5 – 3 m/min can be achieved (NTNU, 2005).

Probe drilling is typically done with 1-6 holes in zones where the need has been identified in the geological pre-investigations. A grouting pattern typically consists of 20-60 holes, depending on the size of the cross section and the permeability of the rock mass. The holes are then injected with grout at pressures that are significantly higher than the ground water pressure. This is in order to fill, consolidate and shut off any water-bearing planes in the rock mass. A typical plan/layout for grouting in D&B tunneling is shown in 5.

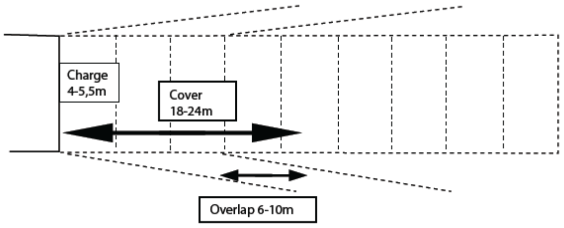

Figure 5: Typical layout of grout curtain in D&B tunneling (NFF, 2011)

Grouting is done with cement, micro cements or chemical additives through packers. Typical grouting pressures range from 30-100 bar, depending on the rock mass and the requirements from the project owners. The criteria to stop grouting a hole are typically related to achieving grouting pressure and/or grout volume (NFF, 2011).

Desirable capacity for the grouting pumps is about 100 liters per minute at approximately 80% of maximum applied pressure (NFF, 2011).

Probe drilling and pre-grouting in TBM tunneling is done with customized rock drills mounted as close to the tunnel face as practically possible to avoid additional boring up to the face. The distance between the entry points of the drill string and the cutterhead is dependent on the type of TBM chosen. The drilling is done through preset guide holes through the cutterhead support or the gripper shield, depending on the machine type. The collaring angle is typically 7 degrees.

There has traditionally been a reluctance to probe drill through the cutterhead, due to problems related to loss of the drill string. The improvement in drilling equipment has reduced this problem as well as other risks significantly and probe drilling through the cutterhead should be considered a possibility when the TBM is not boring.

The methodology is in principle the same as in D&B tunneling with:

- Probe drilling holes from 20-40 m with 5-10 m overlap
- Grouting holes from 18-24 m with an overlap of 5-10 m
- Grouting through packers installed in the bore hole

The grouting umbrella is designed, drilled and grouted on the basis of the results from the probe holes and a general geological evaluation. The grouting is performed from stationary platforms located close to the drill hammer positions.

The distance from the entry point of the boring string to the tunnel face requires the packer rods to be longer than in D&B applications to keep the high pressure grout from escaping into the tunnel. As a general rule the packer should be installed 1-3 meters in front of the tunnel face if possible.

The most important steps to be able to efficiently probe drill and pre-grout are done prior to the project, during the planning and investigation stages. The need for probing/grouting should be identified in the geological pre-investigations and the TBM should be designed to do this task efficiently.

The following machine aspects should be considered when designing: :

- TBM Type
- Major rock support types
- Location of drill hammers
- Number of drill hammers
- Location of preset probing holes
- Systems for analyzing drilling parameters

Planning in the construction phase is also an essential part of efficient probe drilling and pre-grouting on projects. A typical utilization rate of a large diameter TBM is 35-40% (See figure 6). This leaves sufficient time to do systematic probe drilling without impeding the TBM operation, if processes are planned simultaneously.

However experience from projects shows that this recommendation is rarely followed.

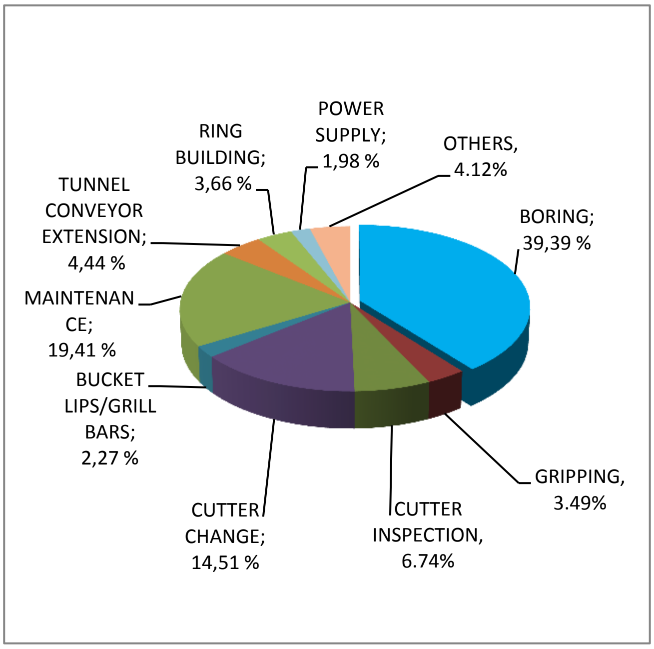

Figure 6. Typical Monthly Utilization of large diameter TBM

3.2 *Forepoles*

Forepoles, or spiles, are another ground support method that comes from conventional mining. The support elements, consisting of pipes, rods or pointed boards are driven ahead of ring beams or lattice girders. They provide temporary overhead protection during excavation for the next ring set or girder. They typically have an overlapping arrangement as seen in figure 7 so that there is never a gap in coverage. On tunnel boring machines the forepoles can be driven ahead of the machines, giving support to the ground above regardless of its ability to take grout.

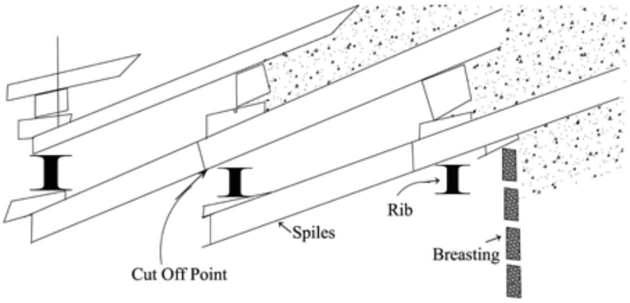

Figure 7. Typical Forepoling arrangement

On Main Beam Machines a similar arrangement is possible--Figure 8 shows the crown of the tunnel on an open Main Beam machine where the crown follows the angle of the installed pieces of grouted rebars (U.S. DOT, 2009).

Figure 8. Forepoling on Main Beam Machine

Shielded machines do not have the same access to the ground so that special openings need to be planned in the shield to allow for the installation (seefigure 9). The distance between these openings can vary depending on the geology, but a tighter spacing than is typically used for probe drilling and grouting should be planned.

Figure 9. Forepoling on Shield Machine

3.3 Foam Systems

Foam has become an integral part of modern EPB machines, expanding the range of soils and conditions where they operate, but the use on rock TBMs has been quite limited. Most rock machines are equipped with water spray nozzles on the cutterhead to assist with the suppression of dust that is created during rock fracturing. These nozzles are arranged in an even radial spacing to allow even coverage of the tunnel face. There is ongoing work studying the use of foam on hard rock TBMs looking at the issues of abrasive wear on cutting tools and higher levels of dust suppression (Grothen & Langmaack, 2010). The property of foam usually associated with EPBs is the ability to break down clays, though there are other additives that are beneficial as well for rock machines in challenging geology (seefigure 10).

Bologna cay +
water & foam

Bologna clay +
foam & Rheosoil

Figure 10. Anti-Clay Additive (courtesy of BASF)

Due to clay's adhesive properties the buckets on the machine's cutterhead can become blocked, preventing mucking and filling the buckets. A blocked cutterhead increases the torque, possibly to the point that the cutterhead is no longer able to rotate. While it is possible to modify a machine to inject foam, it can be a time consuming and difficult process in the tunnel. Foam will be destroyed if it is injected through a water spray nozzle or the smaller lines sized only for water spraying. It is much more cost effective to plumb the cutterhead to accept foam in the design stage even if a foam system is not initially supplied. Robbins offers water spray nozzles that can easily be modified to run foam, further minimizing additional required equipment.

The foam system needed for hard rock applications is simple compared to those typically seen on EPB machines, further minimizing required capital investment (see Figure 11).

Figure 11. Manual foam system (courtesy of BASF)

3.4 High Torque Drive

As previously mentioned, a primary cause of a machine getting stuck is the inability of the machine to rotate its cutterhead. This begs the question: Why are rock cutterheads are stopped in soft geology while soft ground machines are able to keep excavating? The required torque characteristics are very different for the two machine types: EPBs require a lot of torque while much less is needed for hard rock. In short, EPBs use power to create Cutterhead torque, while hard rock machines use power to create Cutterhead speed, or RPM. There are a few contributing factors as well, the first being how the cutting tools interact with the face. A rock machine is primarily designed to heavily load rolling disc cutters onto the face, creating chips. The hard rock limits the depths that the cutter is able to penetrate; the harder the rock the lower the rate of penetration and hence the lower the torque requirements. This means that having a relatively high cutterhead speed is important as this directly affects the rate of advance through the cutter penetration per cutterhead revolution.

EPBs and slurry machines are designed for soft geology (less than 20 MPa UCS) where higher rates of penetration will not overload the cutting tools. The machines must be designed with much higher torque capabilities due to the tool penetration and torque needed to move the cutterhead through the muck, which then flows into the cutterhead and fill the mixing chamber. This makes high torque very important for the EPB machine., but cutterhead speed is not as directly tied to machine advance. At a certain point a high speed is detrimental to the flow though the cutterhead and results in higher wear on its structure rate.

In EPBs that will encounter full face rock or Hybrid machines that are weighted towards EPB operations, the variable speed properties of electrical motors are used to gain performance in rock sections of a tunnel. An electric motor can be operated faster than its base speed by using a variable frequency drive. Electric motors produce less torque at speeds higher than their base speed. The range between the based speed and the high limit of the motor speed is called the Constant Power Range. power This can be seen in figure 12 where the torque drops at a certain base speed after being constant for a range of lower speeds.

This does gain performance, though optimum speeds to excavaterock are not reached due to the relatively high gearbox ratios needed to produce the high torque required for EPB operations. It is possible depending on machine diameter to select a slightly higher ratio gear box and still be able to achieve acceptable torque for soft ground and acceptable cutterhead speeds for boring in hard rock. This will help maximize the torque that is possible, but there are limits to how much one can over speed an electric motor limiting the amount of gearbox reduction that can be achieved. If there is space it is sometimes possible to add additional drive units. Figure 12 shows such a case: a machine expected to bore only hard rock in the 10 m size range would have a base speed of about 3 ½ rpm and a torque of about 11,500 kNm. Since this machine was expected to encounter sections of very soft geology additional power was installed with ratios that provided higher torque but at a lower speed, 2 ½ rpm. In sections of hard rock sufficient torque is still available at 6 rpm, which is the limit that a machine of this diameter should operate.

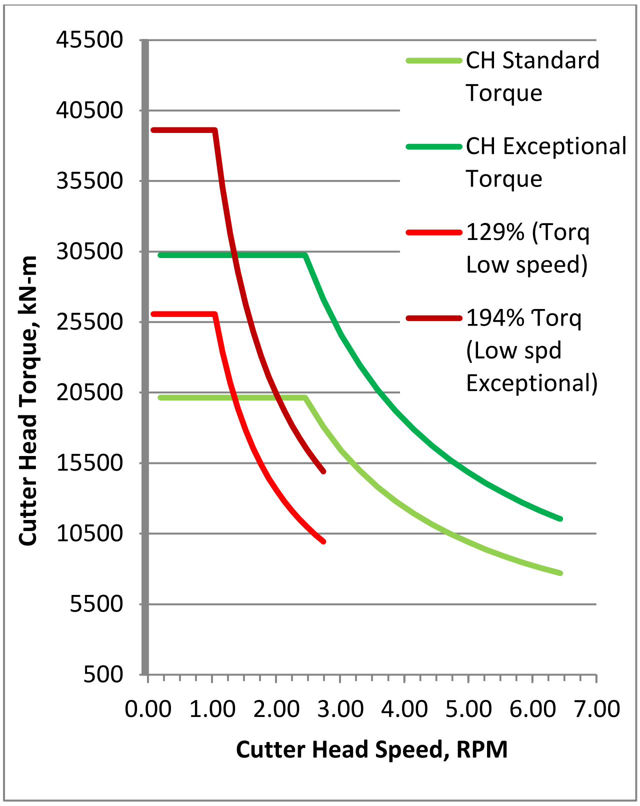

Figure 12. Torque Curves for machine for 10m DS.

Additional torque can be realized while still achieving cutterhead speeds for rock boring with installation of a two-speed gearbox installed between the drive motor and the primary two-stage planetary gearbox (see Figure 13). During most of the drive this additional gearbox operates at a ratio of 1:1 offering no additional reduction and allows the cutterhead to reach optimal hard rock speeds. In the event that bad ground is encountered the second gear boxes can be engaged. If the second gearbox has a ratio of 2:1 then the amount of torque at the cutterhead is doubled and the speed halved. The increased torque must be fully considered during the design and specification of the primary gearbox and final drive elements. ,It may be difficult or impossible to take full advantage of this option after delivery of the machine.

Figure 13. Two-speed gearboxes (red) installed on a Robbins Double Shield TBM

3.4 Closable Muck Buckets

Closable muck buckets allow the bucket opening to be closed, controlling the flow of material through them and speeding cleaning of the head, all while leading to a shorter down time after encountering flowing materials unexpectedly.(see Figure 14). In the event that the machine does become stuck it becomes imperative that it is able to start boring again as soon as possible. Even if ground improvement is carried out in front of the machine, be it grouting, forepoling or the use of Urethanes, getting a cutterhead cleaned out and freed is no small task. This is especially true when it is not possible to keep the ground from coming in though the buckets.

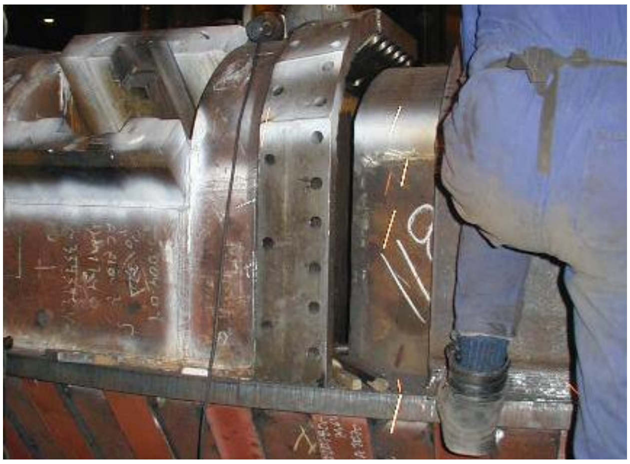

Figure 14. Muck Bucket Gate Closed for Double Shield TBM.

3.5 Closable Muck Chute

Another tool to assist in cleaning the cutterhead in the event that it fills with material is a closable muck chute (see Figure 15). As the cutterhead fills with material the machine conveyor will take ever increasing amounts of material until it is overloaded. Even if the ground is stabilized or the muck buckets are closed the material must be removed from the cutterhead. With no way to control the flow of material into the open muck chute of the conveyor this can be a slow process--something that needs to be avoided. By installing a gate above the muck chute the conveyor can be cleared without new material being introduced. Once the TBM is running again material can be removed to clear the cutterhead.

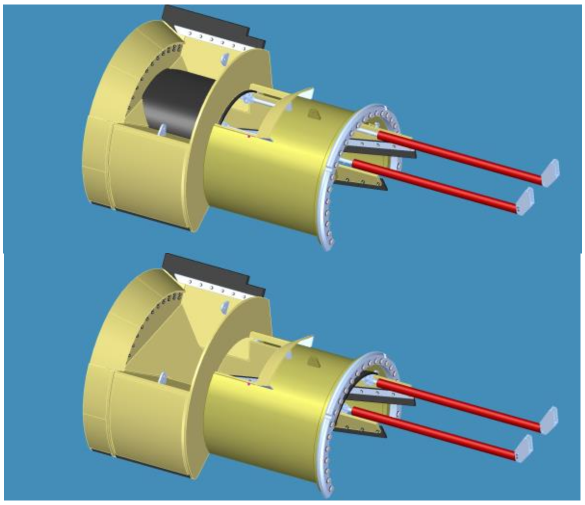

Figure 15. Muck Chute Gate Closed (above) and Open (Below).

3.6 Sequential Boring

As the geology moves farther from rock, greater numbers of modifications are needed. A sealed bulkhead and conveyor can be installed on the machine with the conveyor in-feed (muck chute) and discharge having gates designed to hold pressure. During the majority of the drive the gates are kept open and the cutterhead drops muck into the conveyor as on a standard hard rock machine. When bad ground is encountered the gates are shut and the ground treated as reviewed above. If this is not successful then the bad section of ground can be sequentially mined where the forward gate is opened and the conveyor takes in material until it is full to the second gate. The first gate is then closed and the second gate opened and the conveyor is allowed to discharge. The process is repeated until normal boring can continue. A screw conveyor can be installed instead of a belt conveyor as it will be better able to manage the in-feed of soft ground and take a greater amount of material for any given length, allowing for greater advance with each cycle. It is worth highlighting that this is not operating as an EPB as the head is in its original hard rock configuration. The screw can be used during hard rock mining, but as with an EPB there will be very high wear, which will need to be managed.

4 SAMPLE MACHINE DESIGN

A machine was proposed recently for multiple bores 18.5 km in length and 16.5 km with 6 m finished diameter. The vast majority of construction is located in a mix of water-bearing hard rock with some EPB conditions. Geology is abrasive granite with high quartz content (35-40%) and UCS is up to 250 MPa. The remaining ground is soft alluvium with the possibility of thermal water up to 100 degrees Celsius.

In order to excavate in these conditions, the proposed TBM was a rock machine with several special features included. The machine could excavate the majority of the tunnel as a Single Shield TBM with a closed center screw. Instead of utilizing a Slurry TBM in rock, the modified Rock machine is optimized for systematic probing and pre-grouting 30 to 50 m ahead of the machine.

If sections of soft ground are detected, the machine can withstand 10 bars pressure using flood gates and closure doors that prevent inrush of water into the machine area. Muck would then be removed using the screw conveyor in a pressurized environment.

Such a design offers benefits over standard Slurry TBMs, as the cost associated with pre-grouting is far less than that associated with interventions for cutter changes or ground conditioning for the entire tunnel route. In addition a single-direction rotating cutterhead with 20-inch cutters will cut down on abrasive wear, as compared with bi-directional cutterheads where regrinding of the material on the cutters and cutterhead structure can occur (see Figure 16).

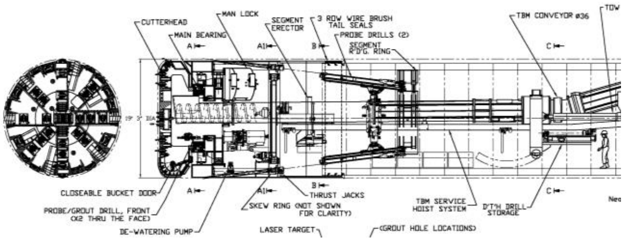

Figure 16. Rock TBM proposed for granite and alluvium tunnel.

5 CONCLUSION

Selection of the proper machine when highly variable ground is expected involves the weighing of a series of trade-offs in performance, risk, time and cost. In cases where the primary geology is rock with short sections of soft ground, machines optimized for rock can be equipped with features to better address the short sections of soft geology. This makes hard rock machines a viable option by offering higher advance rates, and lower operating and initial investment costs compared with other TBM types for the majority of the tunnel. Risk in the shorter sections of soft ground can be effectively managed. The better the geology is known from the onset, the greater understanding of the risks involved: this allows contractors and equipment manufacturers to plan for and address the adequate tunneling solution in the most efficient manner possible.

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