Achieving Fast EPB Advance in Mixed Ground: A Study of Contributing Factors

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ABSTRACT: Earth Pressure Balance (EPB) tunneling in mixed ground conditions is a challenging prospect, as it often includes excavation in boulder fields, sections of rock, and/or sticky clay, under high water pressure or changing water pressure. Maintaining a rapid advance rate in such conditions is a function of many factors—from adequate cutting tools to cutterhead design, pre-planning and execution of an appropriate ground conditioning regime as well as proper maintenance and operation of the TBM. This paper will analyze recent record-breaking and high-performing projects seeking to identify factors that contribute to fast machine advance. These factors will then be discussed and an effort made to form simple, high level guidelines for optimal TBM excavation in mixed ground conditions.

INTRODUCTION

Labor costs for tunnels excavated with hard rock TBM and soft ground EPB machines (EPBMs) typically are 30 to 50 plus percent of total project cost. Reduction of the time for tunnel construction without increasing staffing results in a substantial savings in total project cost. Finding methods by which we can safely reduce total tunnel construction time has a clear cost benefit to project owners and generally to the tax paying public. It also has the benefit of bringing needed infrastructure online sooner, which never meets with public disapproval.

In this paper the authors attempt to find commonalities among EPBMs operating in mixed ground conditions that achieved higher than average advance rates within a given sample of projects. By mixed ground we mean that the tunnel alignment contains some fairly easy to excavate material for an EPBM, which typically implies soils, sands, gravel & clays in some combination, as well as material that is not easily excavated by an EPB machine, which typically implies:

- Coarse sands and gravels, below the water table, with insufficient fines to form a plug in the screw conveyor
- Large boulders requiring disc cutters to break
- Competent rock
  - Above the water table
  - Impermeable rock below the water table
  - Permeable rock below the water table

Each of these geological types imposes somewhat unique challenges when excavated with an EPBM.

MIXED GROUND CHALLENGES

Following is a brief discussion of some of the challenges each of the above mentioned geological types presents when excavation is attempted with an EPB machine.

Coarse Sand and Gravels

When EPBs are below the water table and contain insufficient fines to form a plug in the screw, it is necessary to add foams, polymers or fine material to form the plug.

In addition, sands and gravels can be extremely abrasive and it is usually prudent to add friction-reducing foams and polymers. This addition reduces the rate of wear on the cutterhead, screw conveyor and other components. Reducing wear is essential to high performance because it reduces the number of interventions likely to be required for maintenance of cutters, cutterhead and other wearing components forward of the pressure bulkhead. In all of the mixed ground conditions we are discussing, the importance of reducing wear is paramount.

Large Boulders

When large boulders are expected the cutterhead is typically fitted with disc cutters. However, when the tunnel also passes through more traditional EPB materials, it is important to maintain the cutterhead face opening ratio. Disc cutters take up a lot of precious cutterhead space compared to EPB picks and bits. The design of the cutters and cutterhead take on great importance for mixed ground tunnels with a probability of large boulders, as the appropriate EPB cutterhead opening ratio for excavating traditional EPB materials must still be maintained. Restricting the size of rock pieces that may pass through the cutterhead is important to reducing the risk of blockage of the screw conveyor. Also, in such situations, minimizing wear is imperative.

Competent Rock

Competent Rock Above the Water Table

Generally, in this condition, we have the same concern as mentioned above for large boulders. In addition, we have a muck flow issue and a potentially extreme EPB wear issue. EPBs depend upon a combination of face pressure and the always full mixing chamber to charge the screw conveyor with muck. When cutting solid rock above the water table, there is no face pressure and so the mixing chamber will not naturally fill, meaning the screw conveyor will also not fill naturally. In practice, if no extraordinary measures are taken, the flow of material through the screw happens cyclically:

- Machine bores rock until a sufficient amount of material is in the mixing chamber
- The rock in the mixing chamber, finally at sufficient height, under its own weight, will flow into the screw conveyor
- The screw conveyor will then discharge the muck, and the cycle repeats.

Of course, with practice, it is sometimes possible to balance the screw conveyor drive speed to the EPBM advance speed to maintain a charged mixing chamber to maintain flow to the screw. However, this requires the rock to break in consistent ways to provide a smooth, almost fluid flow of the excavated material, which rarely happens.

In reality, machine operators generally must resort to injecting material into the chamber to mix with the cut rock in order to create a mix of materials that will flow in a more fluid-like manner. Generally, the material injected into the mixing chamber includes a volume of water along with foams, polymers or other materials. Often, the mixing chamber may have to be artificially pressurized with compressed air in order to help the material flow into the screw conveyor.

Depending on the abrasivity of the rock being excavated, anti-wear, torque-reducing foams and polymers will likely be required.

Competent, Impermeable Rock Below the Water Table

The challenges of this condition are essentially the same as described above, for solid rock above the water table.

Competent, Permeable Rock Below the Water Table

This situation is essentially the same as that described for the previously mentioned two solid rock sections, except that the rate of water injection into the mixing chamber to achieve a properly flowing material will be affected by the natural flow rate of water into the cutting chamber. It remains highly likely that it will require the injection of foams, polymers or other fines in order to form a plug in the screw conveyor.

Again, depending on on the abrasivity of the rock being excavated, anti-wear, torque-reducing foams and polymers will likely be required. In addition abrasive wear on the cutters due to water injection and the presence of rock is a challenge.

THE PROJECT DATABASE

For this paper the authors reviewed 25 projects in 10 different countries which employed 40 different EPBMs on projects for which we deemed the geology to be "mixed." Obviously, the geology of some of these projects was decidedly more challenging than others but all contained at least some sections of geology that included coarse sands and gravels that wouldn't form a plug, or they contained large boulders or hard rock. Many of the tunnels contained some combination of these "difficult to excavate with an EPB" geologies.

We were looking for machines that had achieved high advance rates relative to the other machines in our sample. But, it would not be sufficient to have merely had a world record "best day" or "best month." We were looking for projects on which the EPBM performance over the entire tunnel excavation was significantly better than others operating in similarly difficult geology. For this purpose, we elected to use "average weekly meterage" as our measure of total productivity. One caveat to the reader: contractors and consultants are loathe to share complete information on their projects because it is hard-won intellectual property that enables them to more accurately tender future work. In some cases, we were not given accurate data regarding total working hours per week, holidays and other information which would have allowed us to normalize the data completely (i.e., providing an average advance per working hour). We were forced to look at the total length of the tunnel versus the weeks required for excavation and assume that a similar number of hours were worked each week on average. Of course, in industry publications and on the internet we also sought and found additional data regarding each project (e.g., confirmed dates, additional geological data, additional EPBM specifications, etc.) These data helped to ensure a more complete and objective data set.

The basic data set for each project / EPBM included:

- Project name
- Country
- Length of tunnel
- Average weekly advance in meters
- Geological description
- Water / face pressure
- Diameter of machine
- Cutterhead drive type (e.g., hydraulic, VFD electric)
- Cutterhead power
- Cutting tools fitted to cutterhead and quantity
- Muck removal system (e.g., muck cars / rail, conveyor)
- Ground conditioning (e.g., existence of pre-project ground conditioning planning and coordination with machine manufacturer and chemical supplier and/or near continuous use of ground conditioning agents, and a list of chemicals employed)

THE PROJECTS, THE EPBMs, AND THEIR PERFORMANCE

For the 40 EPBMs reviewed the diameter ranged from 5.9 to 10.2 meters, though the vast majority were in the 6 to 6.5 m range. Thirty-one of the machines were employed on metro projects, eight on sewerage projects and one on a train tunnel. They were supplied by three different manufacturers. The face pressure under which they worked ranged from 0 to 13.5 bar with an average of 3.6 bar, with seven projects not reporting the ground pressure. Forty-seven percent of the machines were fitted with variable frequency electric cutterhead drives and the balance were driven hydraulically. The geology on which the machines operated varied widely from sedimentary rock and weathered rock through glacial till, gravel, sands, soils and clays, however all had encountered mixed conditions.

Fifty-four percent of the projects gave information regarding ground conditioning employed. Several projects gave detailed information regarding ground conditioning, or that information is publicly available in articles published in industry periodicals and conference papers. Unfortunately, no ground conditioning information was forthcoming or could be found in searches for nearly 40% of the projects. Given the apparent importance of this subject, and the currently fast growing knowledge on the subject of ground conditioning and its importance, it would be beneficial to have more details in this area for better statistical analysis of performance between machines employing state of the art ground conditioning and those that do not.

Thirty percent (12 machines) had average weekly advance rates exceeding 100m/week. Forty-five percent or 18 projects had average weekly advance rates exceeding the average of 85m/week (see Table 1, a summary of EPB data set).

Table 1. EPB data set summary

Number of EPBMs	40
Diameter range	5.9 to 10.2m
Face pressure range	0 to 13.5 bar, 3.6 bar average
Average weekly advance rate	85.4m/week
Maximum advance rate	178.5m/week
Minimum advance rate	32.6m/week
Standard deviation	36.0m/week

WHAT DID THE HIGH-PERFORMING EPBMs HAVE IN COMMON?

We sorted the data several ways looking for data which had a close correlation with high average weekly advance. Against the following data we found only weak correlation:

- Machine diameter
- Cutter configuration
- Cutterhead drive type (electric and hydraulic)
- Face pressure
- Mucking system
- Tunnel length
- Country of project, and developed / developing nations

For example, Canada had two of the top 10 performers, but it also had 2 of the bottom 10 performers. The top 10 performers were about equally divided between developed and developing countries with the top performer being on the Moscow Metro Line 3 project.

There was no correlation between performance and face pressure and, in fact, four machines with very high average weekly advances of 120 to 179m/week were working at 6 to 8 bar on the Abu Dhabi STEP project.

Perhaps not surprisingly, contractor experience does have some correlation with machine performance. All of the contractors operating machines that had average weekly advance rates in excess of 100m/week had previously excavated at least three prior EPB tunnels with some of them having excavated many. With one exception, the bottom 40% of performers was operated by contractors very new to EPB operations.

Conveyor mucking systems were used on seven of the projects, but there was no correlation with performance with conveyors being used on top, mid and bottom performers. Obviously perhaps, conveyors can help set the stage for high performance but are not alone sufficient to guarantee high performance. Neither did tunnel length strongly correlate though longer tunnels trended toward higher average weekly advance rates, as one would expect.

High performance appears to be at least lightly linked to a mixed ground EPBM being fitted with a cutterhead designed and fitted for mixed ground (i.e., fitted with disc cutters as well as soft ground tools). Perhaps more to the point, machines that started and had to be stopped one or more times in the tunnel to have the cutting head redressed, from soft ground tools to full disc cutters, under pressure often lost so much time for the retrofit as to make it impossible to achieve a rapid tunnel excavation. Clearly, accurate geological mapping must be made available in the tendering stage if the contractor and machine manufacturer are to agree to the correct design and cutting tool selection prior to the start of excavation.

The single factor that had the strongest correlation to machine performance appears to be ground conditioning. The best performers nearly all had soils tested in a laboratory in advance of the start of boring and had established an initial ground conditioning regime in coordination with the contractor, the machine manufacturer and the chemical supplier. Even those projects that merely brought in the chemical supplier at the start of boring had more success than those who did not employ chemicals or did so only late in the project. There seems to be sufficient evidence to support the avocation for laboratory testing and coordination between contractor, machine manufacturer and chemical supplier in order to insure the best machine design for chemical injections and provide the best basis for early high performance of the EPBM.

THE IMPORTANCE OF GROUND CONDITIONING

While perhaps such a strong correlation between EPBM performance and a quality ground conditioning regime may not have been anticipated by all, those who have been heavily involved in the EPBM excavation of difficult geological conditions may not be surprised in the least. Most of those who have been involved in the use of ground conditioning for EPBMs operating in coarse gravel have known for years about the efficacy of using foams to form a plug in the screw. This method allows EPBMs to excavate material previously considered the sole domain of the slurry TBM.

A good ground conditioning regime can be equally as important as the machine design and logistical aspects on any EPB project. Additives are used to consolidate ground and maintain a smooth flow of muck through the cutterhead, thereby maintaining consistent earth pressure.

The use of ground conditioning at the cutterhead has further been shown to reduce wear and increase advance rates. The type of additive used, and indeed whether or not additive is needed at all, is determined by soil permeability, ground water pressure, and the risk of clogging/adhesion (Langmaack, 2006).

Japan, the country that truly created the modern EPBM, has been well aware of the importance of ground conditioning additives for many years and is a leader in the development of foam additives. Table 2 is a 1996 recommendation on the use of additives for EPBMs from the Japanese Society of Civil Engineers. According to the Shield Tunneling Association of Japan (established in 1985), the first EPB with a foam GC system was delivered in 1980 and a total of 431 EPBs fitted with foam GC systems have been delivered in Japan through 2007.

Over the decades we have seen the use and function of ground conditioning additives broaden substantially. From providing a method to form a plug in the screw conveyor in coarse materials, ground conditioning additives now provide a method by which to increase the cohesiveness of material, reduce the adhesiveness of material, reduce the friction of material (i.e., reduce the torque on cutterheads and screw conveyors) and more.

Soil consistence is described in 4 states: solid, semi-solid, plastic and liquid. To this standard description of "soil," on a mixed ground project we add the possibility of boulders, hard rock above and below the water table, etc. EPBMs are not capable of safely, efficiently and economically excavating materials at the extremes of these states, especially so when under the water table. However, when we change the characteristics of these materials through the use of ground conditioning agents, and when the EPBM design has been done with full knowledge of the ground conditions, we substantially broaden the range of materials that can successfully excavated by EPBMs.

ESTABLISHING A GROUND CONDITIONING REGIME

A good place to start an understanding of the basics of ground conditioning is the *Specifications and Guidelines for the Use of Specialist Products for Mechanised Tunnelling* published in 2001 by EFNARC, the European federation focused on specialist construction chemicals and concrete systems. In 2005 the document was updated to include hard rock TBMs as well. EFNARC engages with the European Commission and the CEN technical committees as well as other groups participating in the European Harmonization of Specifications and Standards. We recommend the EFNARC document to our readers for its considerable valuable information (see Figure 1).

Geotechnical Baseline Reports (GBRs) for most projects will define the geological and hydrological conditions anticipated along the tunnel

Table 2. Table from Japanese Society of Civil Engineers (1996) with recommendations regarding use of additives for EPB applications

Shield Type			EPBM		
	Soil Type	SPT N	Without Additives	With Additives	Slurry
Alluvial cohesive soil	Silk and clay	0–2	Y	Y	Y
	Sandy silt, sandy clay	0–5	Y	Y	Y
	Sandy silt, sandy clay	5–10	Y	Y	Y
Pleistocene cohesive soil	Loam and clay	10–20	N	Y	Y
	Sandy loam, sandy clay	15–25	N	Y	Y
	Sandy loam, sandy clay	over 25	N	Y	Y
Sandy soil	Sandy with silty clay	10–15	Y	Y	Y
	Loose sandy soil	10–30	N	Y	Y
	Consolidated sand	over 30	N	Y	Y
Gravel with boulders	Loose gravel	10–40	N	Y	Y
	Consolidated gravel	over 40	N	Y	Y
	Gravel with boulders	—	N	Y	N
	Boulder gravel, boulders	—	N	N	N

alignment including photographs, in situ test results and laboratory test results including particle size distributions, presence of boulders, rock types and strengths, ground water information, permeability, moisture content of clays, etc. With the GBR information and the EFNARC recommendations one can form a very rough idea of the ground conditioning that might be appropriate. Further consultation with the ground conditioning chemical supplier will result in a more well-defined initial ground conditioning plan. Further coordination with the EPBM supplier will insure that the EPBM is delivered with foam, polymer and other systems designed for the best implementation of the ground conditioning regime immediately upon launch of the EPBM. It is, however, recommended to take the ground conditioning planning a step further, to the laboratory.

SPECIAL LABORATORY TESTING FOR EPB SOIL CONDITIONING SPECIFICATION

Today there are a growing number of laboratories, in private companies and at universities, which can perform a number of tests aimed specifically at defining a ground conditioning regime for an EPB project. Typically, these laboratories mix actual soil samples from the job site, at their in situ moisture content, with various foams and polymers and then test the treated samples (see Figure 2). One such simple test is a slump test, such as is typically performed on wet concrete to determine its workability. (This test can also be done on the job site, if the correct equipment is made available at the site). As written in the paper *Characterization of Soil Conditioning for Mechanized Tunneling:* "…the carried out tests show that the slump test is a good indicator to define the global behavior of a conditioned soil and due to its simplicity, can be used in the preliminary design stage but in particular on the job site to keep the conditioning development under control during excavation" (Borio 2007).

Other tests include permeability testing of the sample to determine the probability of the material forming a plug in the screw conveyor. Other lab testing done today includes wear testing and even scale model screw conveyance of the material under pressure.

Professionally performed specialist laboratory testing can give us a much better recommendation for an initial soil conditioning regime to be employed at EPBM launch, including recommended foam and polymer types along with specifying the important parameters for use, including:

- **Cf**—the concentration of foam product in water. Generally this will be in the 0.1 to 4.0% range, though it is dependent upon the ground condition and the specific foam product selected.
- **FER**—the Foam Expansion Ratio. Values are typically ×5 to ×30, being expressed as the ratio of air to foam, where ×18 will be 17 parts air and 1 part foam/water solution. The larger the expansion ratio the dryer the foam. Generally, the wetter the soil is, the dryer the foam should be.
- **FIR**—the Foam Injection Ratio. This is the ratio of foam injected into the cutting head and the in situ volume of soil being excavated. This is typically in the range of 30 to 60% per EFNARC guidelines, but in the Japanese standard goes beyond 100% up to 130% foam/insitu soil volume. (The reader should bear in mind that the actual ratio of

foam to soil in the chamber will be dependent upon the pressure in the chamber, as the air in the foam compresses under pressure, hence the ability to go above 100% and still excavate material.)

- **Cp**—the concentration of Polymer product in water, typically in the 0.1 to 2.0% range, but can go to 5% according to EFNARC.

Many foam products are provided with polymers so that only the foam guidelines need be followed.

If wear tests are provided they can aid the contractor in making a better estimate of wear of the EPBM and cutting elements thereby assisting with both the cost estimate and estimation of down time for interventions for repairs. While the wear tests won't provide definitive numbers, if the wear tests

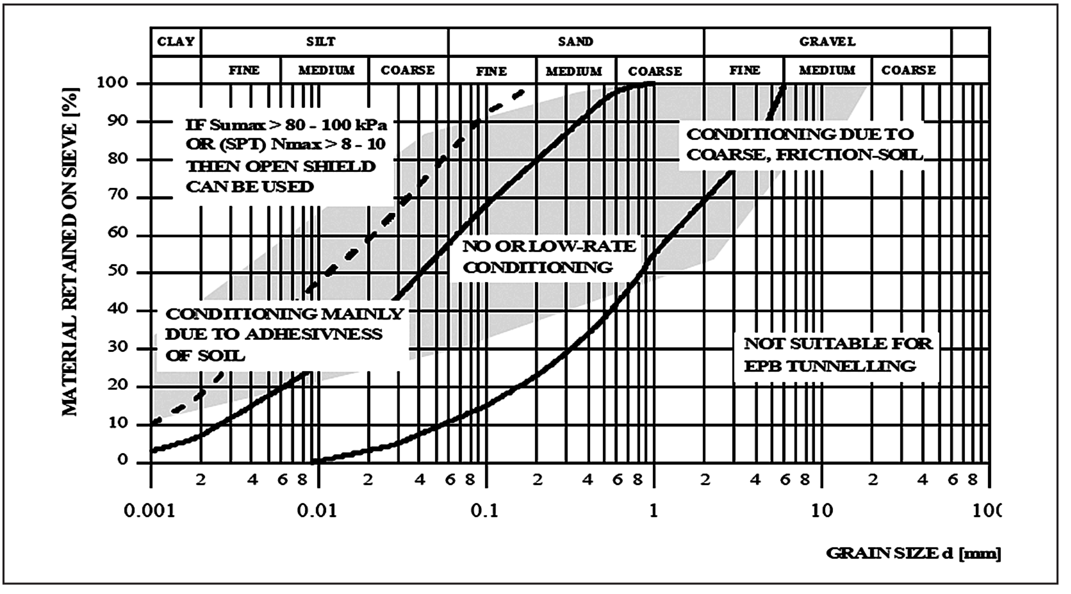

Figure 1. EFNARC guideline for particle size distribution in which EPBs can be employed, as well as soil conditioning needs in different ground types (boundaries are only indicative)

Figure 2. Testing fixture. Treated sample is placed in barrel on left and subjected to pressure and extracted from barrel through screw conveyor on right (Photo courtesy of Mapei-UTT).

show a reduction in wear of 25% with the use of additives, it provides some indication of the savings one might reasonably expect to see in the field. Given the danger, downtime and cost of hyperbaric interventions, reduction in wear may well prove to be one of the higher motivations for the use of ground conditioning / wear reduction agents.

Specialist laboratory testing has proven its worth. Speaking of one of the higher performing projects in our data base, it was stated, “The average ground conditioning parameters used at the job site are comparable with the values found after the laboratory tests…. This confirms the utility of making laboratory tests before the TBM launch” (Dal Negro et al. 2013).

In 2011 the Shield Tunneling Association of Japan issued a technical guideline for use of foam in EPB tunneling. The guideline includes a formula for calculating the FIR based on the results of the particle size distribution curve information and can provide a good starting point, thought the formula does not consider ground pressure, permeability or pore volume. Unfortunately, the document is currently available officially only in Japanese.

DESIGNING THE EPBM FOR THE GROUND CONDITIONING REGIME

It is imperative that the EPBM manufacturer is aware of the GC regime plan and that appropriate foam generators, polymer plant, air compressors and bentonite systems are included, as well as proper distribution and injection points on the cutterhead, into the cutting chamber and into the screw conveyor. Results from the 40 EPBMs reviewed and anecdotal evidence points to this being an area of coordination which is often overlooked or under emphasized and where a little effort early in the EPBM design can result in vastly improved performance on the project.

A properly designed EPBM GC system requires input from the contractor and the GC additives supplier (see Figure 3).

The team must agree to the GC plan and ensure that the EPBM design and GC equipment supply will fully support the GC plan. Some things that must be considered:

- Probable quantities of foam agent, polymers and bentonite (or other fine material) to be consumed, consumption rates and estimated TBM production rates
- Package sizes to be used for each GC agent
- Logistics; movement and handling of GC agents / packages into and out of the tunnel
- Specification of the dosing units
- Specification of the foam generator
- Specification of dedicated air compressor
- Specification of bentonite plants
- Locations of the above systems on the TBM and back-up
- Quantity and location of injection nozzles for all GC additives and water (cutterhead, mixing chamber and screw conveyor)
- Control systems for manual, semi-automatic and fully automatic control
- Location of system adjustment controls and ability to “lockout” to prevent unauthorized adjustments
- Quantity and placement of additional water lines into mixing chamber

Regarding this last point, yes, it is important to have the capability to inject water into the chamber in addition to GC agents. When the ground is too dry, it

Figure 3. Silty clay prior to and following GC treatment (Photo courtesy of Condat)

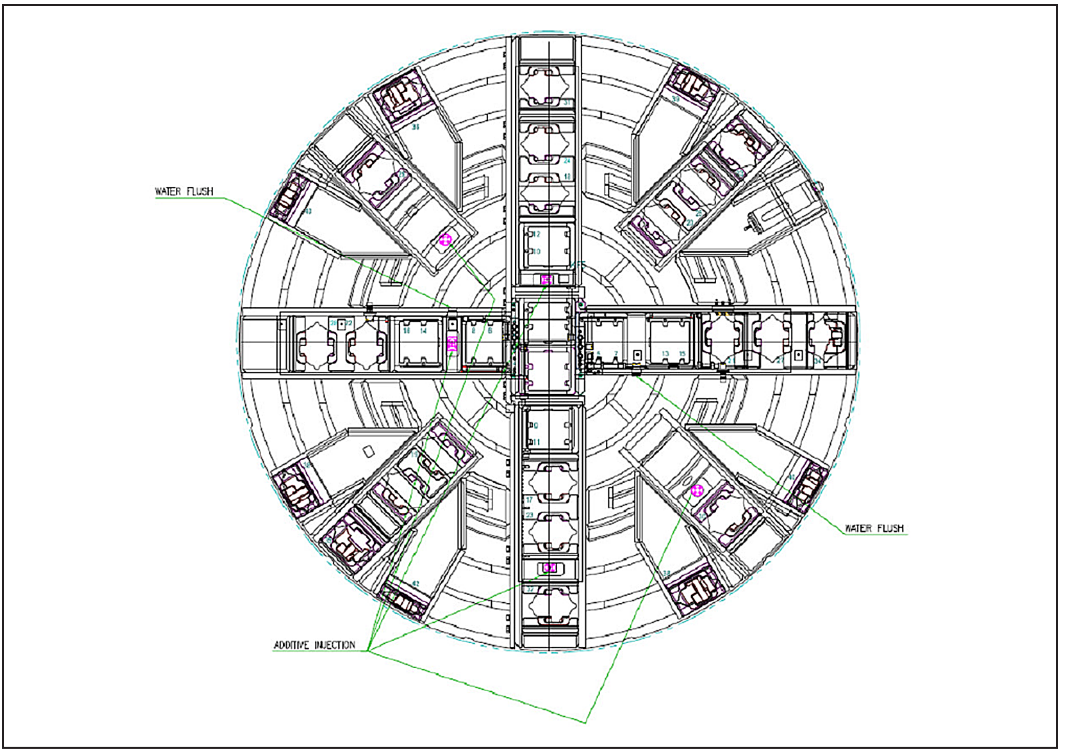

Figure 4. Ø6.6 meter EPB cutterhead with five additive injection ports and two water injection ports to prevent clogging

is most effective to use water to wet the soil and GC agents to condition the soil.

In general, it is best to inject all GC agents from the cutterhead because this provides the best possibility for GC agents to flow with and become thoroughly mixed with the excavated material. However, there are times when it might be advantageous to inject GC agents into the mixing chamber. For example it is prudent to inject bentonite during a machine stoppage because foam will collapse, eventually leaving an air bubble in the top of the chamber and water in the bottom. Under certain conditions it might be necessary to inject directly into the screw conveyor to form a plug, or to reduce friction and torque at the screw conveyor. When designing the EPBM for GC use, it is important that the systems be designed for flexibility and with redundancy. A properly designed EPBM will offer the user opportunities to employ all of the GC agents (water, foam, polymers and bentonite) in any combination and at an array of injection points on the cutterhead, into the mixing chamber and into the screw conveyor. In addition, because of the danger and difficulty associated with effecting repairs beyond the pressure bulkhead, distribution line redundancy is advisable.

Cutterhead Foam Injection Ports

EPB cutterheads should be designed with certain port sizes and locations and minimum quantities. Figure 4 shows an example of additive injection port locations on a Ø6.6m EPB cutterhead. These injection ports should be capable of injecting foam, polymer, bentonite, or any mix of these and should be located with the first port as close to the center of the cutterhead as possible. Remaining ports should be located with decreased radial spacing as they near the outer periphery of the cutterhead. It is not necessary for the ports to reach the outermost radius of the cutterhead, this being the area of fastest motion and therefore best mixing. For "metro sized" cutterheads 6 to 7m in diameter, a minimum of five injection ports is standard, with all piping having an internal diameter of about 1.5 inches (38mm). For each injection port on EPB cutterheads, protection bits with tungsten carbide inserts and hard facing should be placed on both sides of the port for protection in both directions of cutterhead rotation.

As EPB cutterheads get larger, more ports are of course needed. For example, in the Ø9m and Ø10m range EPB cutterheads, seven additive injection

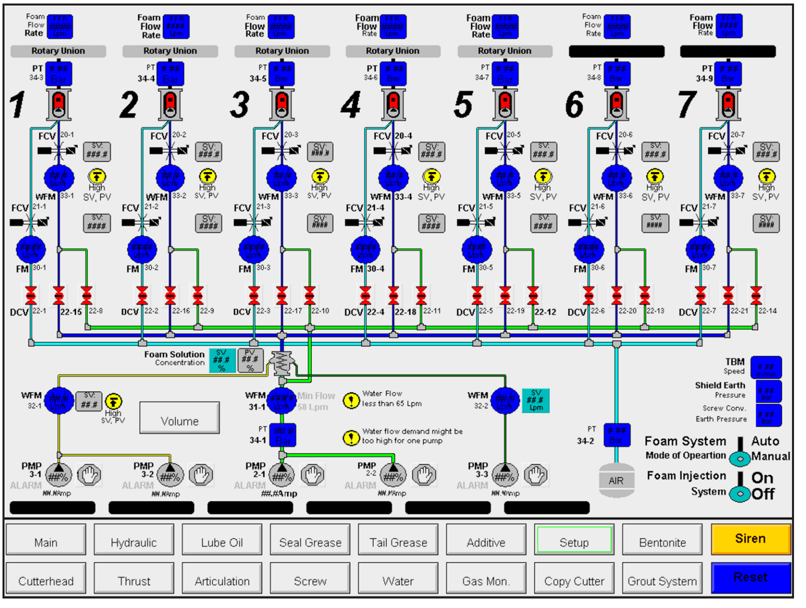

Figure 5. Foam and polymer system setup screen on EPBM operator's Human-Machine Interface

ports are used, with piping having an internal diameter of about 2 inches (50mm).

It is advisable to fit the screw conveyor with a minimum of three 50 to 100mm diameter injection ports with one located as near the pressure bulkhead as possible and the others located along the conveyor. The pressure bulkhead should have a minimum of ten 50mm diameter injection ports with at least one located immediately each side of the screw conveyor intake and the remaining distributed roughly evenly around the bulkhead.

It should be noted that GC systems (foam generators, polymer pumps, bentonite pumps and water lines) will not be connected to all of the ports fitted to the EPBM. There will be a substantial surplus of ports when the quantity is compared to the quantity of GC injection lines. What is important is, again, flexibility and redundancy so the contractor can make adjustments to the ground treatment as needed to achieve success based on actual results.

Operator Station and Software

The operator's station for the EPBM, with the usual Human Machine Interface (HMI) touch screens, typically has several screens dedicated to GC systems. The foam system will generally have one screen for setup (to set Cf, FIR and FER) and one screen for operation where the operator can monitor status in automatic mode, or control the system in manual mode.

FIR, again, is the ratio of foam injected as a percent of the in situ volume of soil being excavated. Since the rate of volume of soil being excavated is dependent upon the EPBM's advance rate, the rate at which the foam is injected must vary with the EPB advance rate in order to maintain a constant FIR, that is, the same proportion of foam to soil at all times. This being the case, it is advantageous to operate in automatic mode in order to maintain a consistent state of soil conditioning.

Of course, there are similar options on the operator's control screens for setting the parameters for polymer. The HMI may have an additional screen which shows the total volumes of air, water, foam and polymers that have been injected over some period of time which can, of course, be reset (see Figure 5).

The geology anticipated on a project affects the final design of a number of components of an EPBM: cutterhead, cutting tools, screw conveyor(s), ground conditioning systems, grout systems, etc. However, it is worth noting that if the contractor, the GC chemical supplier and TBM designers work together, the design of cutterheads and conveyors can be positively impacted for improved TBM performance and reduced component wear (see Figure 6).

OTHER CONTRIBUTING FACTORS

Other factors contributing to high advance rate in mixed ground are many, yet one of the most compelling is proper cutterhead and screw conveyor design. In mixed ground conditions, EPB cutterheads must balance an optimal cutterhead opening ratio for smooth muck flow with a robust cutterhead structure and the adequate number of disc cutters and cutting

Figure 6. Well-conditioned clay leaving the screw conveyor onto the belt conveyor (photo courtesy of Mapei UTT)

tools. Screw conveyors must be designed with the knowledge of the maximum face pressure to be encountered, the probable presence of boulders and the maximum boulder size which will be allowed to pass through the cutterhead.

Cutting Tools

The optimal primary protection for EPB cutterheads is the replaceable knife bit. These come in standard duty and heavy duty, but standard duty is only recommended for geology that is very easy to excavate. In a mixed face application, these bits are interchangeable with disc cutters. Cutterhead spokes are designed to alternate between primary and secondary cutting tools. It has been found that a radial spacing of these primary cutting tools at about 3.5 in (89mm) apart is efficient in the breaking up of soft ground. When hard rock or boulders are encountered and these tools are replaced by disc cutters, this same spacing allows the discs to break up the rock and allows the cracked rock in-between cutters to fall out.

Abrasion-Resistant Wear Plate

The optimal design for EPB cutterheads includes full protection with an outer cladding of abrasion resistant wear plate. There are greatly varying grades of abrasion resistant wear plate available, and the selection of this plate is usually project specific, based on balancing cost with sufficient hardness and wear resistance. There is wear plate available that can resist the wear of nearly all types of ground conditions, including very abrasive rock and long tunnels, but the cost and workability varies quite considerably.

Wear plate should cover the entire exposed front surface of the cutterhead that is not shared with a cutting tool location or a chemical injection port. Figure 7 gives an example of the type of coverage that should be given by cutterhead wear plates.

Screw Conveyors

Screw conveyors can be designed with replaceable bolt on sections and hard facing on each turn of the screw to withstand abrasive ground. The screw conveyor casings can be lined with abrasion resistant plate as well. Again, the actual abrasion resistant material selected can have a dramatic impact on cost.

Screws may have a shaft or no shaft (a "ribbon" conveyor). Shafted screws have a greater pressure drop across each flight and therefore can be made shorter than a ribbon screw to achieve the same total pressure drop across the conveyor. However, ribbon screws can pass a larger boulder within the same casing diameter compared to a shafted screw. Often times two screw conveyors are used in series to achieve the required pressure drop and these are often a combination of a ribbon screw for the first conveyor and a shafted screw for the second conveyor.

Screw conveyors can also be designed to be disassembled within the tunnel, even with the face under pressure, to make it possible to more safely

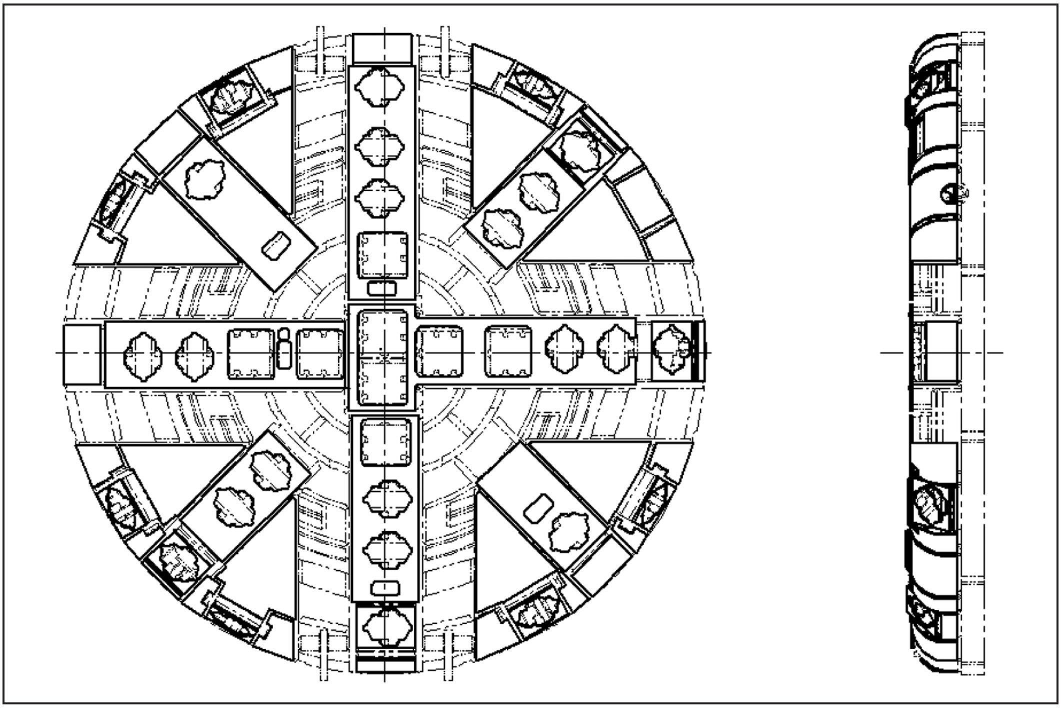

Figure 7. Drawing showing coverage of wear plate material, which is not always obvious on the EPB as wear plate and structure are often the same color

and rapidly repair and maintain worn screw flights and casings. However, this necessarily requires dividing the casing and screws into smaller pieces with bolted joints, etc., all of which increases the manufacturing complexity and cost but saves time in the tunnel.

With all of the variables available in selecting a properly designed screw conveyor, or conveyors, for the EPBM it is again imperative to have good information on the full range of geology, hydrology and pressures to be encountered in the tunnel.

As important as a well planned and executed ground condition conditioning regime is, in most cases the best GC plan cannot overcome a poorly designed EPBM.

CONCLUSIONS

It was our intention at the outset to attempt to derive some simple, high-level guidelines that if followed would provide the highest probability of an EPBM reaching the best possible performance in a mixed ground tunnel. Following are those guidelines, some of which are simply common sense, known already by experienced EPBM users and some of which have been suggested by several other recent authors on the subject of ground conditioning:

1. **Geological samples:** Prior to tendering, the project owner should engage an experienced geological / hydrological testing firm to perform as many hydrological tests and obtain test samples from as many points as reasonably possible along the tunnel alignment, and if possible from the actually tunnel depth. Sufficient sample quantities should be obtained to provide the tendering contractors to perform laboratory testing on the samples prior to bid. If that is not possible, then the owner or their consultants should have such laboratory testing performed, which can establish a base-line initial ground conditioning recommendation by one or several chemical suppliers. This will allow the tendering contractors to make adjustments in their commercial budgets and schedules for the improvement in performance they may reasonably expect to see on the project with the proper use of ground conditioning.
2. **Laboratory testing for ground conditioning specification:** Should the owner not provide the contractors with laboratory test results of the geological sample testing, then the contractor would be well advised to have such tests carried out at their own expense in

order to obtain a recommended ground conditioning regime from an experienced EPB chemicals supplier. The results of such tests will go far toward providing the best possibility of high performance on the project, as well as giving the tendering contractor much information regarding probable costs for ground conditioning agents.

3. **EPBM design:** Though ground conditioning is extremely important, it is equally important on mixed ground projects that the contractor and machine manufacturer review the probable geology, hydrology and face pressures of the project in detail and discuss the impact on the EPBM design, which might include:
   - Dress of cutterhead: disc cutters, scrapers, picks, bits, etc.
   - Opening ratio of cutterhead
   - Type of screw conveyors: ribbon or shafted
   - Quantity and length of screw conveyors
   - Abrasion-resistant cladding requirements: cutterhead, mixing chamber, mixing bars, screw conveyor flights and casing, etc.
   - Face pressure related design: pressure bulkhead, thrust ram sizing, articulation ram sizing, tail shield seals, main bearing seals, man-lock and tool-lock, breathable air design, air compressors, etc.
   - Ground conditioning foam, polymer and bentonite systems, air compressors, etc.
4. **Coordination and equipment specification for ground conditioning:** Early in the EPBM procurement / design phase, the contractor, chemical supplier and EPBM supplier should meet and discuss the results of the ground conditioning laboratory results. There should be agreement regarding the systems required on the EPBM to properly inject the agreed upon chemicals into the proper locations on the EPBM (e.g., cutterhead, pressure bulkhead / mixing chamber, screw conveyor points, etc.). There should be agreement on foam generation plant specifications, probable ranges for Cf, Cp, FER, FIR, and it should be ensured that those calculations for the sizing of plants (e.g., air compressors) consider the likely face pressures under which the EPBM will be working.
5. **On-site ground conditioning testing:** The job site should have the ability to do on-site testing of ground conditioning agents in order to make adjustments throughout the tunnel drive without undue downtime for the machine. At minimum this should include:
   - A laboratory scale foam generator
   - A 5 liter heavy duty mixer with 3 speeds and standard paddles
   - DIN flow table (30cm table) with standard mortar cone (slump test)
   - A graduated container of 1 or 2 liters capacity (plastic or non-breaking)
   - Weighing balance accurate to 0.1 gram
   - Stop watch
   - Calibrated glass or clear plastic cylinder, with perforated base, 1 liter capacity
   - Various calibrated plastic containers up to 2 liters
   - A 50ml graduated cylinder
   - A filter–funnel of 1 liter capacity with non-absorbent filter
6. **EPBM launch, ground conditioning adjustment and site lab setup:** At the start of boring, on the job site, there should be representatives from the chemical supplier and the EPBM supplier to work with the contractor to make any adjustments to the ground conditioning regime to obtain optimal EPBM performance. In addition, this time can be used to ensure that the ground conditioning testing that is done on site is done properly, including the training of personnel as may be required.

Ground conditioning, as the main factor explored here affecting advance rate, is the first line of influence for the contractor/additive supplier/equipment supplier to influence how material is excavated. The GC plan, implemented in front of the cutterhead, impacts the entire operation as the material must flow through the machine, out the heading, over the surface and off the site. It affects every part of the job from the number of tool changes required to the amount of cleanup in the heading and on the surface due to spillage. When this global impact of ground conditioning is taken into account, it makes good sense that advance rates are closely correlated. The authors believe that it is this overarching influence that makes a good GC plan, in combination with an EPBM properly designed for executing the plan, one of the most powerful tools available in achieving good project success.

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