Specialized Shotcrete at Malaysia's Pahang Selangor Raw Water Transfer Tunnels

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ABSTRACT: Tunnel Boring Machines typically have several types of conventional ground support equipment installed at the front of the machine. These systems allow contractors to adequately support ground as the machine advances. Tunnel excavation mainly through granites is currently underway on a 35 kilometer section of the Pahang Selangor Raw Water Transfer Tunnel project in Malaysia utilizing three (3) 5.2meter (17.06ft) hard rock Tunnel Boring Machines. This paper will discuss an alternative method to ground support and tunnel lining consisting of mainly a fiber mortar application and ring beams as the primary methods of ground support.

OVERVIEW

Mechanized main beam or gripper type hard rock tunnel boring machines (TBMs) more often than not achieve significantly better production results than traditional drill and blast methods of excavating tunnels. However, to a large degree this depends upon the ground conditions encountered at the project. How many times have we heard 'good ground, good men, good machine', or the complete opposite 'bad ground, bad men, bad machine'?

When it comes to ground support on hard rock boring machines there are several obstacles to overcome, the main one being the lack of space at the front of the machine in the area directly behind the cutterhead support. This area, commonly known as the L1 ground support zone, reaches as far back as the area in which the gripper pads are extended to the bored tunnel.

It is also fair to say that for the most part when it comes to ground support on hard rock machines manufacturers and contractors nearly always revert to the more traditional methods of ground support. These include but are not limited to:

- Rock Bolting
- Installation of mesh
- Ring beams
- Shotcreting (either wet type or dry type shotcrete)
- Steel Ribs with timber lagging

More recently the introduction of the 'McNally' system that provides continuous tunnel crown support in the form of re-bar or wooden lagging boards being fed out from the roof support of a TBM is becoming more popular.

We could actually conclude that mechanized tunnel boring is in fact a hybrid system whereby a TBM allows for higher rates of advance than conventional tunneling but has installed on it systems that allow for the more traditional methods of rock support when poorer ground conditions are encountered.

In some cases, it might actually be hard for an owner of a project, whether it be a local authority or private concern, to justify the cost of procuring a hard rock boring machine. After all should the machine need to bore through poorer ground conditions then we revert to traditional ground support methods-- resulting more often than not in noticeable drops in rates of advance. Why not simply use conventional tunneling on several fronts rather than purchase what can be a very expensive machine?

HISTORY

There are basically two types of shotcrete mix delivered to a tunnel boring machine: dry mix and wet mix. The dry mix can be brought into the machine in bags or containers and sometimes in pressurized vessels. Wet mix shotcrete is brought into the machine in an agitator car and transferred to a storage tank located on the back-up of the machine.

The dry mix method involves placing the dry ingredients into a hopper and then conveying them pneumatically through a hose to the nozzle. The nozzleman is the person controlling the nozzle that delivers the shotcrete to the surface. The nozzle can be controlled by hand—for smaller applications this is usually a one man operation. However for tunneling applications it usually requires a two or three man team to ensure that the shotcrete is applied in the desired area. In a drill and blast type tunnel there is typically sufficient space for this team to move around without hindrance. However on Main Beam TBMs the space for movement is much more limited. On larger machines the nozzle can sometimes be held by mechanical arms or ‘robots’, where the nozzleman controls the operation by a hand-held remote control.

The nozzleman controls the addition of water at the nozzle. The water and the dry mixture is not completely mixed, but is completed as the mixture hits the receiving surface. This requires a skilled nozzleman, especially in the case of thick or heavily reinforced sections. The main advantage of the dry mix process is that the water content can be adjusted instantaneously by the nozzleman, allowing more effective placement in overhead and vertical applications without using accelerators. The dry mix process is useful in repair applications when it is necessary to stop frequently, as the dry material is easily discharged from the hose. The disadvantage of this system is that it can and does create a lot of rebound waste (when material falls to the floor). This means that before it is used on a TBM, personnel must provide adequate protection to sensitive equipment on the boring machine in the area where the shotcrete is going to be sprayed. Hydraulic cylinders, electrical and hydraulic equipment all need protecting prior to the application of shotcrete. This, along with the cleaning of rebound, results in further delays to production.

Wet-mix shotcrete involves pumping of a previously prepared concrete, typically ready-mixed concrete, to the nozzle. Compressed air is introduced at the nozzle to impel the mixture onto the receiving surface. The wet mix procedure generally produces less rebound and dust compared to the dry-mix procedure. The greatest advantage of the wet-mix process is that larger volumes can be placed in less time. Again this is offset by the need to protect sensitive equipment in the area that the shotcrete is being sprayed and by the fact that in most cases the system pumps can be up to 100 m from the front of the TBM. This setup can and does result in high pressure pumping and blockages in the wet shotcrete pipeline.

Technological developments in sprayed concrete technology have resulted in steel and polypropylene fibers being added to the concrete mix to improve lining strength. This creates a natural load-bearing ring, which minimizes the rock's deformation.

FIBER MORTAR SHOTCRETE

The concept of using fibers as reinforcement is not new. Fibers in the form of horsehair, straw and to some extent asbestos have been used as reinforcement since the earliest times. More recently steel and polypropylene fibers have been introduced to replace the earlier fibers. Fibers are usually used in concrete to control cracking due to both plastic shrinkage and drying shrinkage. They also reduce the permeability of concrete and thus reduce bleeding of water. Some types of fibers produce greater impact, abrasion and shatter resistance in concrete. Generally fibers do not increase the flexural strength (also known as modulus of rupture) of concrete, and so cannot replace moment resisting or structural steel reinforcement.

In some sections of the Channel Tunnel Rail Link (CTRL) the tunnel lining incorporated concrete containing 1 kg/m³ of polypropylene fibers, of diameter 18 & 32 µm, giving the benefits noted below:

- Improved mix cohesion,
- Improved pumpability over long distances
- Improved freeze-thaw resistance
- Improved resistance to explosive spalling in case of a severe fire
- Improved impact resistance

- Increased resistance to plastic shrinkage during curing

Another advantage of steel fibers relates to segment production for lined tunnels. Recently we have seen a shift away from regular steel cage reinforcement with manufacturers of segments now using precast lining segments reinforced with steel fibers only.

PAHANG SELANGOR RAW WATER TRANSFER TUNNELS

The Pahang Selangor Raw Water Tunnel, for the Malaysian Ministry of Energy, Green Technology, and Water, will convey raw water from the Semantan River in Pahang to the South Klang Valley area of Selangor state. The three tunnels, totaling 44.6 km (27.7 mi), will address projected water shortages due to the region's rapidly growing population. Once completed, the tunnel will transfer 27.6 cubic meters (7,300 gallons) of water per second to a new treatment plant. The drinking water will supply about 7.2 million people by 2013.

The contract was signed on 25th May 2009 and the first tunnel boring machine arrived on site in August 2010.

The deliveries of the three machines where staggered so that each machine arrived at site approx. 1 month after the previous machine was delivered. This gave the assembly crew time to complete the main component assembly of each machine and commence walking the machine to the starting position before delivery of the subsequent TBM.

Initial assembly of each boring machine was completed on the surface. The machine was then 'walked' down declined adits of varying lengths & gradients using a specialized hydraulic walking system . The TBMs then turned around a corner and were walked into the final assembly position in the starting chamber.

The use of continuous tunnel conveyors for muck removal as opposed to muck skips or other methods over this length of tunnel further improves the chances of sustaining higher rates of production. This is because the time waiting for skips to arrive at the boring machine is eliminated. Downtime for extension of the conveyor belt is approx 12 hours when it occurs. The capacity of the conveyor storage cassette allows for 300m of boring without stoppage. Usually, the conveyor extensions are planned events enabling the contractor to carry out other essential maintenance.

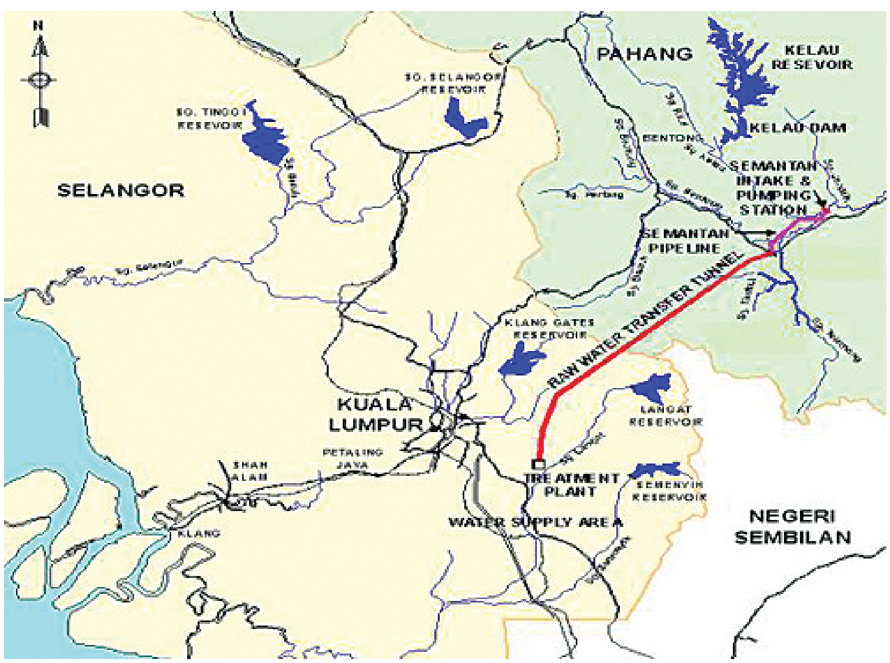

Figure 1. Project location in Malaysia

GEOLOGICAL DATA

Tunneling is taking place in high overburden conditions. In some areas the machines will bore through sections of tunnel up to 1,200 m (3,900 ft) below the Titiwangsa mountain range.

The geology for most of the length of the tunnel consists of hard, abrasive granitic rock up to 200 MPa (29,000 psi) UCS. The tunnels are being supported with ring beams, and fiber mortar shotcrete depending on the conditions encountered. Other ground support measures are being taken according to the rock conditions. Table 1 shows the project rock classification and ground support measures required in each rock class.

TABLE 1. ROCK CLASS & SUPPORT REQUIRED AT THE PROJECT

Rock Class	*Rock Bolts*	*Mesh*	*Steel Sets (Channels, ribs or panels)*	*Fiber Mortar*	*Grouting*	*Segment*	*Other*
Type A-T Rock Class A:- RMR : 81-100 (Very Good Rock)	None needed	None needed	None needed	None needed	None needed	Invert segment	
Type B-T Rock Class B:- RMR: 61-80 (Good Rock)	Localized bolts	Occasional as needed	Channel as needed	Localized as required to 20mm thickness	None needed	Invert segment	
Type CI-T Rock Class CI:- RMR: 41-60 (Fair Rock)	None needed	None Needed	None needed	20mm thickness on top 180º of tunnel Followed by steel fiber final lining 100mm nominal thickness	None needed	Invert Segment	
Type CII-T Rock Class CII RMR: 41-60 (Fair to Poor Rock)	None needed	None needed	Steel rib100mm 'H" Beam at 1.5m center	20mm thickness on top 180º of tunnel Followed by steel fiber final lining 100mm nominal thickness	Install grout pipe for backfilling if required	Invert Segment	Steel lagging between steel ribs
Type D-T (Rock Class D) RMR: 21-40 (Poor Rock)	None needed	None needed	Steel rib125mm 'H" Beam at 1.0m center	30mm thickness on for 270º of tunnel Followed by steel fiber final lining 250mm nominal thickness	Install grout pipe for backfilling if required	Invert Segment	Steel lagging between steel ribs
Type E-T (Rock Class E) RMR: <20 (Very Poor Rock)	None needed	None needed	Steel rib 125mm 'H" Beam at 0.5m centers	30mm thickness on for 270º of tunnel 130mm thickness at in area where gripper pads touch the tunnel wall Followed by steel fiber final lining 250mm nominal thickness	Install grout pipe for backfilling if required	Invert Segment	Steel lagging between steel ribs

In the worst conditions (Rock Type E-T (Rock Class E)) the contract requires ground support with additional shotcrete mainly to allow the TBM gripper pads to react on the tunnel wall. If this was not possible the manufacturer of the TBM supplied an 'invert thrust' system that allows the TBM to push forward by reacting against the installed invert segment

From the preliminary geological investigation it was understood that the percentage of each rock class encountered would be as given in Table 2:

TABLE 2. PERCENTAGES OF EXPECTED ROCK CLASSES

Rock Class	*TBM 1*	*TBM II*	*TBM III*
A & B	91%	87.5%	84.8%
CI	4.5%	6.2%	8.7%
CII	2.4%	3.2%	3.4%
D	1.5%	2.1%	2.2%
E	0.6%	0.9%	0.9%

Table 2 shows that in the main, the machines will be boring through Class A & B rock and good rates of production are expected with rock support being minimal in these areas.

As can be seen from the chart Class CI or CII rock will be the majority of the 'poorer' ground experienced and it is in these conditions that the contractor expects to see benefits from the use of fiber mortar shotcrete. For more information on the rock mass rating system refer to Hoek - Practical Rock Engineering or Bieniawski's *Rock Mass Rating* (1976, 1989).

The reality to date is that the project has actually seen worse ground conditions on two of the sections of bored tunnel than anticipated. Table 3 shows encountered conditions as of October 2011:

TABLE 3. SUMMARY OF ROCK SUPPORT AS PERCENTAGE OF TUNNEL LENGTH TO 31 OCT 2011

TBM1(L=2,895.3m/11,671m)		**TBM2(L=2,217.8m/11,671m)**	**TBM3(L=4,080.4m/11,218m)**	**TBM(All)**
Class	**Actual**	**Actual**	**Actual**	**Actual**
A/B	**97%**	**52%**	**62%**	**71%**
CI	**2%**	**38%**	**39%**	**25%**
CII	**1%**	**6%**	**0%**	**2%**
D	**0%**	**2%**	**2%**	**1%**
E	**0%**	**1%**	**1%**	**1%**

PROJECT FIBER MORTAR SYSTEM

The system chosen by the contractor was proven on the New Tomei Highway in Japan. Due to the success of the system on this project it then became the standard method of shotcreting for tunnels on Japanese highways.

The main reasons the contractor chose fiber mortar shotcrete and this particular system are:

I. Full strength of the fiber mortar can be attained in 24 hours and can be up to 15MPa.
II. With additives, this strength can be attained sooner if required especially in wet conditions or exceptionally bad ground.
III. The fiber mortar can be applied successfully in wet conditions.
IV. Studies have proved beyond doubt that there is less rebound and therefore less downtime with fiber mortar than more conventional wet or dry mix shotcrete.
V. The uses of this system allowed the contractor to eliminate the use of wire mesh in Class CI or CII rock conditions. The use of mesh, if not tied down properly, can result in more rebound.
VI. Fiber mortar can be applied more safely than conventional shotcrete in a confined area as there is less application pressure required to achieve adhesion.
VII. The transportation method into the TBM (pressure vessel) and transfer to spraying equipment has proved safer and better for the tunnel environment than wet or dry mix shotcrete transfer. This is evidenced by the fact that we see a significant reduction in dust in the tunnel.
VIII. The contractor believes there is less maintenance of the equipment required.
IX. The material inside the tunnel is transported by compressed air from the pressure vessel transport car to the equipment. When other methods of transfer are used such as auger screws, high wear and jamming will occur.

CYCLE TIMES

By the replacement of regular ground support systems with fiber mortar shotcrete can we prove that there are time savings to be taken advantage over machines that utilize traditional ground support system?

In Rock Class 'C' conditions or Type III rock conditions as they are also known with a rock mass rating (RMR) of 41-60, and with conditions that could be described as 'fair', predicted TBM production would be expected to be in the order of 1.1 to 1.5 meters per hour.

Ground support in type C conditions might consist of rock bolts of around 2.5 m length, installed in a 4 or 5 bolt pattern at 1.5 m spacing between each row of rock bolts, plus wire mesh installed for at least the top 120º of the tunnel crown. The bolts would more than likely be resin anchored bolts and the time taken to install each bolt would be in the order of 5 minutes. Add to this the time taken to rotate the rock drills into the correct position for the correct bolt pattern (made even more difficult in the L1 zone on smaller diameter machines with space limitations) and the time taken to install the mesh and we soon find ourselves on the lower side of our predicted advance rates. With advances in TBM technology today we see rock bolting systems on machines that to a certain degree allow for continuous ground support and boring, but more often than not, we find the machine stopped waiting for bolting or ground support. The total cycle time for boring, re-gripping and ground support could take around two hours before the machine is ready to commence the next boring cycle.

As the fiber mortar system is installed on the machine and there is enough storage capacity within the system for fiber mortar to be sprayed over the top 180º degrees of the crown for two full boring strokes, preparation time for shotcreting is kept to a minimum. Furthermore, as the contractor is required to install an invert segments on this project, the fiber mortar storage hopper is replenished in a timely manner. This setup means that there are fewer delays in waiting for materials. Add to this the fact that lower pressure is required to apply the fiber mortar shotcrete than conventional shotcrete, a feature that results in less rebound, and overall this means that we see production rates towards the higher end of our predicted advance rates. This can also result in reductions in cycle times of approx. 30 minutes. At first glance this improvement may appear insignificant, but within a 24 hour cycle period (allowing for four hours of maintenance each day) there is the potential to excavate a further three additional meters daily using the fiber mortar system over conventional ground support systems. This becomes more even more significant when considered over the 33 km of this project.

As with all projects, cost is an integral component of any system chosen by a contractor. At first glance it would be easy to assume that the fiber mortar costs would far outweigh the cost of a regular shotcreting system. By excluding the cost of equipment and comparing the costs of the materials for the two systems on a given project over a two month period we find the following in Table 4:

TABLE 4. COST COMPARISON OF REGULAR AND FIBER MORTAR SYSTEMS

The costs shown are in US dollars. Costs shown are for comparison purposes only and are not actual costs.

	Shotcreting with conventional fresh mixed concrete
Material costs (typical costs)	Estimated typical cost per 100 linear meters Thickness of shotcrete = 10centimeters (cm) Loss ratio = 300% Qty of concrete used = 180 cubic meters (m^3)

Item	Qty		Unit cost	Total cost
Fresh mixed concrete	180	Cubic meters	735	132,300
Accelerator	4,500	Kilograms (kg)	5	22,500

ADVANTAGE	Material costs are less expensive
DISADVANTAGE	Large amounts of rebound and dust

	Shotcreting with Fiber Mortar (Sub-Shot System)
Material costs (typical costs)	Estimated typical cost per 100 linear meters Thickness of shotcrete = 5 centimeters (cm) Loss ratio= 150% Qty of Fiber Mortar used = 45 cubic meters (m^3) (45m^3 = approx 79,650 kilogram (kg) of PF-Mortar)

Item	Qty		Unit cost	Total cost
PF-Mortar	79,650	kg	6	477,360
Fibers	3,960	kg	1.3	5,148

ADVANTAGE	--Facilities are more compact --Low rebound (high efficiency and less cleaning work) --Much quicker to work with & could contribute to shorter construction & cycle times (i.e. total construction period)

DISADVANTAGE	Material costs are comparatively more expensive

Whilst the cost of fiber mortar materials is more expensive than wet or dry mix shotcrete, the cost of the equipment for fiber mortar shotcreting compared to regular shotcreting is less expensive (approx 40% less) and it is very easy to create an argument that the fiber mortar system is, on the whole, slightly more cost effective than a wet or dry shotcreting system. Combine this with the benefits mentioned earlier in this paper and the advantages explained previously, particularly with regards to omitting rock bolts and mesh in certain rock class conditions, and it becomes clear that in certain conditions the fiber mortar system is a viable option to regular shotcreting.

FIBER MORTAR SYSTEM COMPONENTS

The fiber mortar system consists of five main components (see Figure 2):

1. The loading station at the bottom of the adit
2. The transportation vessel
3. Mortar hopper and charging device for continuous charging to the mixing pump
4. Tank for liquid accelerating agent
5. Mixing pump and special nozzle for shotcreting

Figure 2. The fiber mortar system installed on TBM & the loading station at the bottom of the adit

OPERATIONS

When required, the fiber mortar is applied just behind the cutterhead support in the L1 zone within a ‘curtained’ area designed by the TBM manufacturer. This curtain greatly reduces the chances of the operators accidentally spraying sensitive equipment and reduces the downtime that would be experienced while the crew covered the sensitive equipment.

Due to the relatively low pressure required to apply the fiber mortar, the operator has that much more control over spraying, the results of which are impressive (see Figure 3).

Figure 3. The fiber mortar system applied with ring beams (left) and one man application (right)

Figure 3 shows applied fiber mortar on one of the three TBMs, with ring beams and the one man application of fiber mortar at the front of the machine. Because of the ease of operation and control the operator has over the nozzle, this makes for a very effective application with minimal rebound.

If required steel ribs are installed directly in front of the shotcrete zone either by hand (preferred at this project) or by use of a simple ring beam erector provided by the TBM manufacturer. Ring beam erection time is in the order of 11minutes.

The fiber mortar system has been used more extensively at the TBM No. 3 drive on the project. From the chart earlier it can be seen that the contractor has actually encountered three times more type Class CI conditions than predicted. The variations in ground conditions have proved to be a challenge and it is fair to say that with a daily average of some 19m, rates of production have exceeded what might be considered normal if more conventional shotcreting and ground support systems had been used.

To date over 1,770 cubic meters (m^3) of fiber mortar shotcrete has been sprayed on the bored tunnels with good results (see Figure 4). This does not include 5% accelerator for a total of 1858.5m^3. The contractor, while unfortunately having no data to prove otherwise, estimates that there has been significant time savings by using this system as compared to the installation of mesh and rock bolts in similar ground conditions. The main reason is that in its current configuration the fiber mortar system allows for some 2.2m^3 to be sprayed per hour. This is more than enough to allow continuous boring and ground support operations.

Figure 4. A section of completed tunnel looking outbye (away from the machine) in poorer ground conditions with ring beams and fiber mortar completed. Note the continuous conveyor to the left of the photo and segment installation in the invert.

CONCLUSIONS

As of December 2011, the first TBM (TBM No.3) to start boring on the project has completed 5.4 km of tunnel. The average advance rate for this tunnel equates to 450 meters per month. Some 39% of this or 2.1 km has been in type C (CI or CII) ground conditions.

Undoubtedly there are other factors, which include different types of ground conditions encountered along the length of the current drive, and the learning curve of personnel in system operations. These factors must be taken into account when considering the advance rate; however, based on the cycle times stated in this paper we can conclude the following: at the estimated advance rate of 2 hours of work per excavated meter with conventional ground support methods, the contractor would have taken 210 days to excavate and support the type C ground. With the fiber mortar system this has been reduced to 158 days—a time savings of 52days which by any standard is significant.

The preliminary evidence would suggest that the application of this method of ground support at the Pahang Selangor tunnels (while still in its infancy related to bored tunnel projects worldwide and applicable rock conditions) is so far proving to be an effective alternative system to conventional ground support methods.

It is also relevant to note that as ground conditions deteriorate, conventional 'tried and trusted' methods of support are still applicable. Only with continuing development will we be able to use newer or alternative methods for supporting ground in the worst conditions encountered on open type tunnel boring machines. The application of any system of ground support must, above anything else, be proven to be a safe method of support compared with traditional ground support methods.

It is also clear that tunnel designers, engineers, contractors & TBM manufacturers must work together to overcome the difficulties of providing acceptable ground support systems for a TBM, or look for safe, workable, alternative solutions that enable us to keep production rates at optimum levels.

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