# EPB Technology opens up the soft ground Tunnelling Range

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**Continual improvement in TBM design resulting in a safer work environment, more effective excavation of a wider range of geology, more reliable machines and higher rates of excavation is the target where TBM Technology is going on. The following article shows some solutions.**

EPB design and assembly are governed by multiple variables, no matter the machine diameter – a sentiment that rings true for a large Robbins EPB TBM currently being assembled at Mexico City's new metro Line 12. The 6.2 km long machine-bored tunnel will cut commute times in the southeast area of the city, reducing a 3-hour public bus ride to just 25 minutes on the subway.

Due to launch in late 2009, the 10.2 m diameter behemoth will be Mexico's largest-ever TBM, dwarfing a 6.5 m machine used several years prior. A specially designed cutterhead can handle boulders up to 800 mm in diameter, while an articulated shield body can guide the TBM through curves as small as 250 m radius. The two-stage screw conveyor will handle unique conditions only seen in several areas around the world.

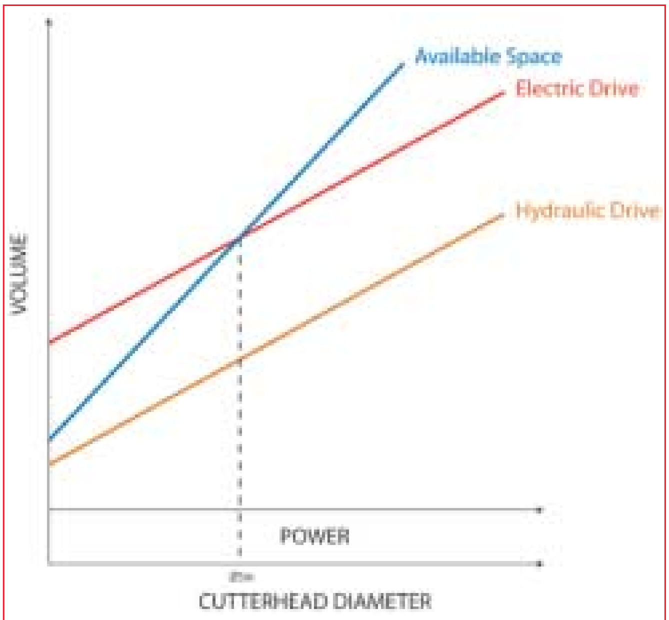
The configuration is one of many possible for soft ground TBMs. But what factors influence the design of this and other EPB machines? Variables include geological conditions, level of ground water, tunnel alignment, and proposed diameter.

## Cutterhead Design

Proper cutterhead design is critical for the variable ground present in many EPB tunnels. Whether boulders or significant ground water are present, optimal cutting tools, cutterhead configuration, and opening ratio can all increase efficiency, equipment life and control possible subsidence.

### Soft Ground Conditions

In soft ground, a large cutterhead opening ratio with spoke-type cutterhead is ideal to ensure a smooth flow of muck from the tunnel face to the mixing chamber. A range of soft ground tools, from drag bits to various types of knife-edge bits, can be mounted in the cutterhead. The bits scrape away at the tunnel face and are not typically used for ground over 20 MPa UCS.




1 EPB Drives: The Power to Volume Ratio. While less compact, electric (VFD) drives offer much higher efficiency that makes them advantagous on TBMs over 5 m in diameter

The overall design of a spoke-type cutterhead allows for less abrasive wear and faster excavation than breasting plate cutterheads. Past projects, such as the Sapporo Metro Project in Sapporo/J, have proven the relative efficiency of spoke-type versus breasting plate designs. The metro project consisted of parallel rail tunnels in identical geology under separate contracts. One contract opted for an EPB with a breasting plate cutterhead, while the other chose an EPB with a spoke-type cutterhead. While both machines successfully excavated the project, it was shown that the breasting plate cutterhead had higher cutter consumption and required both higher thrust and higher torque throughout the bore.

### Mixed Ground Conditions

Mixed ground cutterheads often require disc cutters, including multi-row tungsten carbide disc cutters and single disc cutters, to excavate harder rock and boulders.

One recent example is that of two 6.3 m diameter Robbins EPBs at China's Guangzhou Metro project. Geology on the metro's Lot 12 consists of a complex layered profile, ranging from highly weathered to slightly weathered granite, coarse to fine sand, and silt; all formations

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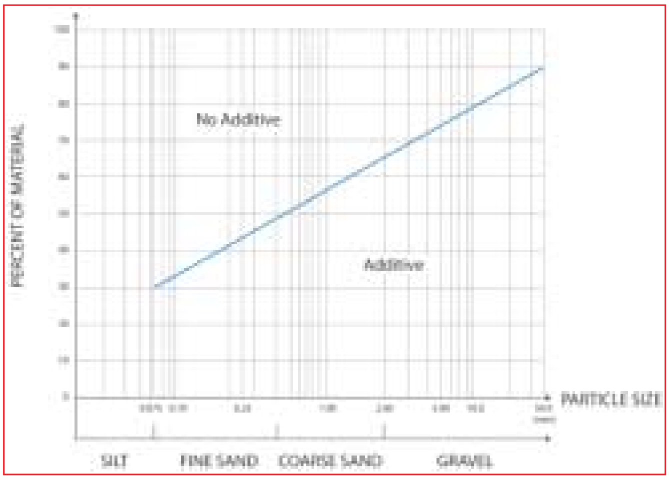
subject to pressures up to 4 bar water pressure. About 70 % of the tunneling is through a mixed face, with the alignment above the spring line in soft soils and the bottom half of the tunnel in rock of at least 50 MPa UCS. The remaining 30 % consists of flowing sand with high water content. The resulting cutterhead design had to address the sticky clay-like consistency of highly weathered rock, as well as soft soils and harder rock conditions.

The Guangzhou machines were designed with spoke-type cutterheads and a large opening ratio of 37 %. Both carbide bits and 432 mm (17 inch) hard rock single disc cutters were used in anticipation of both clay-like and rocky conditions. In soft ground, knife-edge bits scrape away at soils, while disc cutters break away rock at the face by creating a crush zone through which fractures propagate.

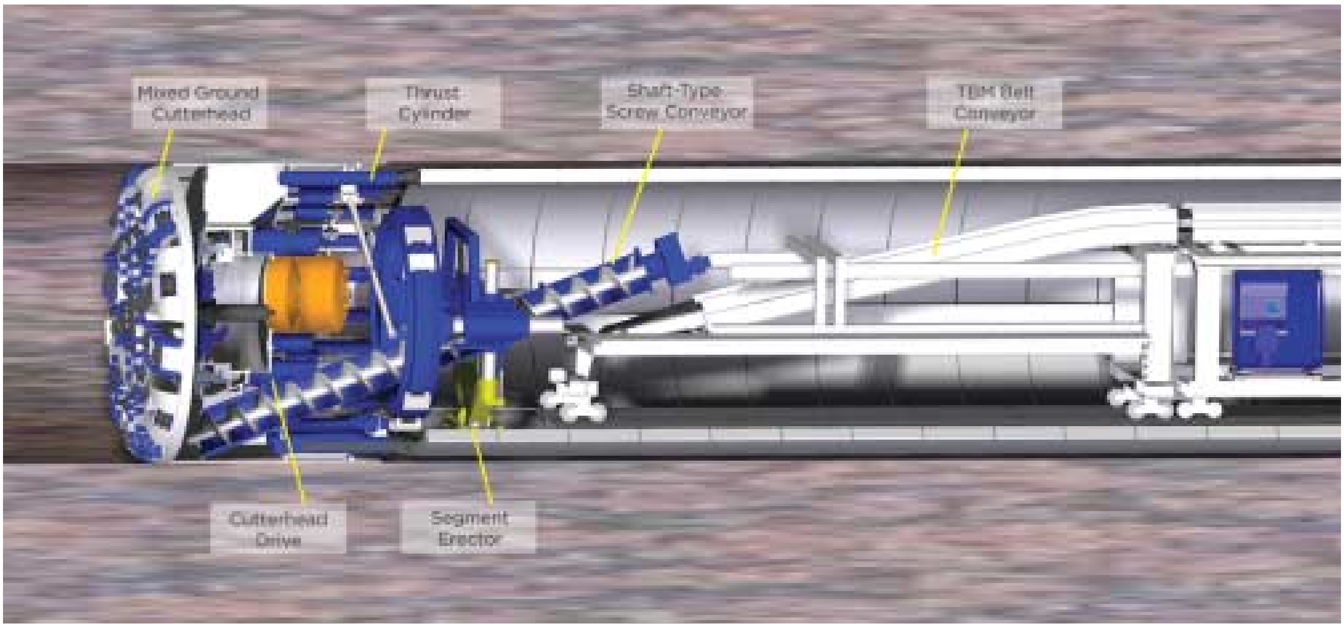
The machines have since gone on to achieve 16 project records, including a record for 377 m in 1 month. "We are quite satisfied with the excavation speed of these machines. We believe the high rates can be attributed in part to fewer equipment failures and efficient cutterhead design that has limited tool wear," said Ju Yicheng, Vice Chief Engineer for project contractor China Communication Construction Corp., 2nd Navigation Engineering Bureau Ltd. (CCCC).




2 Injection of EPB additive is based on a standardize graph of particle distribution through differently sized filters

## Cutterhead Drives

EPB cutterheads are driven by either hydraulic or variable frequency drive (VFD) electric motors, depending on machine diameter. Ultimately, the type of motor used depends on the so-called power to volume ratio (Fig. 1). Smaller diameter machines, less than about 5 m, must use hydraulic motors to achieve high torque, in order to take up less space on the machine. Though more compact, system availability tends to be less for hydraulic systems – about 75 %, compared to more




3 Robbins EPBs are customized to the ground conditions, and may include mixed ground or soft ground cutterheads, as well as different types of screw conveyor systems

than 90 % average availability for electric drives. Hydraulic drives are also harder to keep at maximum efficiency, as the oil often becomes contaminated, which drastically lowers efficiency. In addition, hydraulics require strict humidity control.

During excavation, EPB cutterhead rotation is kept low (around 1.5 rpm at maximum), in stark contrast to the higher speeds (around 10+ rpm maximum) used in similar diameter hard rock TBM tunneling. In hard rock, high rpm results in fast advance, while in soft ground high rotational speed often results in ground disturbance and surface settlement of non-self-supporting geology. In soft ground, the same result of high advance rates can instead be achieved by increasing the cutterhead torque and thrust, which increases the instantaneous rate of penetration.

## Moving Muck Efficiently

Once spoils have been scraped from the face, muck and additives are further mixed within the cutterhead, inside the mixing chamber. Two mixing bars fixed to the inside of the cutterhead and to the pressure bulkhead homogenize the muck as much as possible before it exits via the screw conveyor.

Screw conveyor design depends on variables including ground conditions and ground water levels. Soft, water-bearing ground is best controlled using a standard shaft-type screw conveyor to transfer muck to the hopper. At high water pressures, above about 3 bar, a two-stage shaft-type setup can be used to better regulate system pressure.

In mixed ground containing boulders with low water pressure, a two-stage ribbon-type setup is optimal. The system consists of a primary ribbon screw connected to a shaft-type

4 EPBs boring the Guangzhou Metro Project achieved 16 project records, along with rates of up to 377 m per month

conveyor. Boulders up to a specified diameter travel down a space through the middle of the screw and exit via a boulder collecting gate, while the secondary shaft-type conveyor maintains pressure.

The 10.2 m Robbins EPB for the Mexico City Metro will feature a two-stage ribbon-type screw conveyor system to handle highly variable ground and to better control discharge volume. Ground along the alignment consists of sensitive clays that can turn to slurry-type material once disturbed. A section near the end of the drive is expected to include boulders up to 800 mm in diameter, in addition to the unstable clays.

## Preventing Surface Settlement and Voids

Prevention of settlement is a function of ground control and stabilization of the surrounding soils. Additives are used to consolidate ground and maintain a smooth flow of muck through the cutterhead, thereby maintaining consistent earth pressure. Back-filling is further used to stabilize segments and prevent settlement behind the machine.

### Additives

The type of additive used is based on a standardized curve comparing particle size and distribution based on filtering samples of material through differently sized screens (Fig. 2). Ground with less than 30 % fines, or particles less than 0.2 mm in diameter, is difficult to fluidize. In this type of non-cohesive ground, bentonite is used for consolidation. For other types of ground with fewer fines, foam consisting of water, surfactant, and additive is used. If water pressure is high and small particles are present, a polymer can be injected in addition to the foam to increase cohesiveness of the material.

The use of foam reduces the required cutterhead torque and reduces overall machine wear. Insufficient foam injection has been associated with increased thrust and required power, as well as higher cutter consumption. Independent foam injection points on the cutterhead are used to consolidate the flow of muck. The independent systems also prevent clogging of multiple ports on one side of the cutterhead, which is often the case when common lines are used. Clogged ports can lead to uneven wear of the cutterhead and cutting tools.

A Programmable Logic Controller (PLC) continuously regulates the variables of the additive system to prevent surface subsidence. The air flow rate, or the amount of air mixed with foam, is kept constant by monitoring air flow and pressure. The Foam Injection Ratio (FIR), or the amount of foam injected versus the volume of muck mined, is also kept constant. The PLC controls this by calculating the TBM advance rate and adjusting the foam injection rate accordingly, thereby preventing voids.

At the Guangzhou tunnels, foam injection is being used in part because it is less costly and because it reduces the required cutterhead torque. Though the ground is good quality and does not need an additive such as bentonite, neglecting to inject foam can still lead to decreased equipment life. "While the underground water was quite significant, we carried out effective measures including increased polymer injection. This worked very well," said Yicheng. "We've also controlled settlement using surface stabilization and mucking volume control to decrease the chance of voids."

**Back-filling Systems**

Back-filling systems can utilize one- or two-component grout, depending on ground conditions and risks of surface settlement. One-component grout, consisting of a concrete mixture, is used in more stable ground with a lower risk of settlement. Concrete pumps are most often used to inject grout through the segments and stabilize the surrounding geology.

Two-component backfill, made up of cement plus an accelerant, is used to harden ground rapidly. Grout is injected and the 2 separate components are mixed where the completed rings exit the tail shield. The mixture fills the annulus between the completed segment rings and surrounding soil. Volume and pressure of the backfill grout injection are constantly monitored and controlled to eliminate the risk of surface subsidence, a concern in tunnels with low cover and in urban areas. After each injection, water is forced through the pipes to prevent clogging.

## Articulation through Curves

Choice of machine articulation can be a major variable affecting project speed. Active articulation is used in curves, which engages articulation cylinders between the front and rear shields to steer the machine independently of the thrust cylinders. The process allows the thrust cylinders to react evenly against all sides of the segment ring during a TBM stroke in a curve. Typical configurations, which use flat joints to articulate the shield, are capable of making 2 to 3 degree curve adjustments over the length of the segment or stroke.

Segment deformation, or racking, is a common cause of project delays that occurs when the passive articulation system is used in curves. Passive articulation does not utilize articulation cylinders independent of the machine's thrust cylinders, so the TBM reacts against sides of the segments unevenly in curves.

## Manufacturing and Assembly

Design and planning do not stop in the initial phases; manufacturing and assembly must also be considered. Many EPBs are assembled in workshops, then disassembled, transported to the jobsite, and reassembled; though larger diameter machines and tight project schedules often require alternative methods. Assembling the machine onsite, rather than in a manufacturing facility, is one such alternative. Called Onsite First Time Assembly (OFTA), the process is capable of saving both time and money to contractors.

During the OFTA process complete assembly may range from 3 to 4 months, with an additional month often required because of the inefficiencies of working at site and any unforeseen interface problems. However, the disassembly and second shipping phase is entirely eliminated, saving several months in the overall schedule. The eliminated phases result in fewer total man-hours needed. Reductions in man-power and double shipping of large components generally add up to significant cost savings.

The 10.2 m diameter Mexico City Metro EPB will be assembled onsite beginning in late 2009, inside a 20 m deep launch shaft. The machine will be progressively assembled in a concrete 'cradle' with large components being lowered by crane. Assembly will begin by lowering the bottom shields and cutterhead support, followed by progressive sections of the machine shield and several parts of the screw conveyor, which will be welded together at the bottom of the shaft. Sub-assembly and testing of critical systems, such as the electrical and ventilation systems, will be done in facilities before shipment to the site. The assembly is expected to take about 3 months.

## Future of EPB Tunneling

Today's soft ground tunnels demand technical alignments in variable ground, often at large diameters. Current research aims to maximize efficiency in these conditions through new design concepts.

Sharp curves up to 15 degrees per segment length are a reality for many tunnels in urban environments. By using active articulation with spherical ball joints, rather than flat joints, EPB machines can make such tight turns. Also called X-type Articulation, the joints allow pivoting around the center line of the machine. Currently used in Japan, the design has applications in tunnels worldwide.

An additional Japanese development, which may hold the future for soft ground tunneling, is that of non-circular machines. Many traffic and rail tunnels bored with circular TBMs only utilize about 1/3 to 1/2 of the available cross section, leaving the bottom half of the excavation below the spring line practically useless. In these situations, non-circular or multi-face machines can maximize efficiency of the excavated tunnel while removing the minimum amount of material necessary - a design with the potential to save both time and money.

As is usual for mature products, innovation in TBM design today is incremental. However, there is continual improvement in machine design resulting in a safer work environment, more effective excavation of a wider range of geology, more reliable machines and higher rates of excavation. Much work remains to be done in the development of machines for extreme or widely ranging geological conditions, such as the 'Universal TBM', capable of changing modes from EPB to Double Shield to Slurry. The further development and acceptance of truly international standards for tunneling and TBM design will provide for more effective tunneling throughout the world.