Logistics of Limited Space Urban Tunnelling at Singapore's Mega Metro

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ABSTRACT: Today's mega metro projects are using multiple TBMs in difficult ground, short tunnels, and in urban settings: Factors that create unique challenges. At Singapore's metro construction, 21 km of tunnel for the Downtown Line 3 are underway using 29 TBMs boring between 16 station sites in short bores often less than 1.5 km each. By 2017, 39 km of new construction will cut commute times in half in one of the world's most densely populated locales.

This paper will detail six earth pressure balance machines on the project, analyzing the challenges of boring in a highly urban setting through rock and soft ground under water pressure. Machine performance at the Singapore Downtown Line will be analyzed with a discussion of the challenges involved.

1 INTRODUCTION

Singapore's Downtown Line is one of the most extensive projects in the tunneling industry today, using more than 50 TBMs in three phases. The machines, all designed for soft and mixed ground conditions, are required to be new and most of themwill bore short distances of 1.5 km or less, due to contractual stipulations. This unique arrangement has both positive and negative effects on the tunneling industry. Both phases two and three are under construction, while phase one has been completed.

Other unique factors include the project location, in one of the world's most densely populated cities. Jobsites are often small and located in close proximity to high rise buildings with limited space to launch a TBM—a machine that with its fully assembled back-up system can exceed 100 m in length.

Ground conditions in Singapore are yet another challenge for both equipment manufacturer and contractor. Geology ranges from clay, mudstone, and sand to complex boulder fields.
For the purposes of this paper, the remainder of the discussion will focus on three contracts and six TBMs: contracts C925, C927, and C937.

1.1 *Downtown Line Construction*

Singapore's downtown line is the fifth rapid transit route to be built in the country. The entire Downtown Line including phases 1 and 2, for Singapore's Land Transportation Authority (LTA), will consist of 42 km of new track with 34 stations. Once complete in 2017, the DTL is estimated to serve half a million commuters daily (see Figure 1).

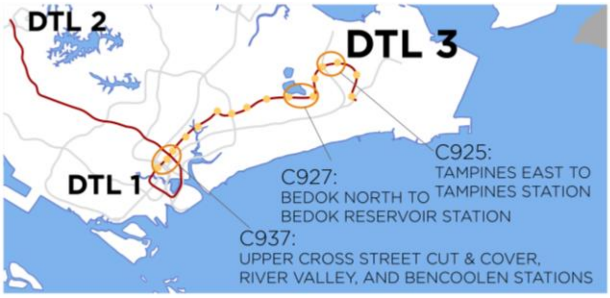

Figure 1.Current three phases of the Singapore Downtown Line (DTL) with a focus on three contracts.

In January 2013, the LTA announced a Downtown Line extension, which will be completed by 2025. Other metro plans in the country include the Thompson Line, which will involve an additional 30 km running from North to South, and employ a further 32 TBMs.

1.2 *Contracts*

As noted, this paper focuses on three contracts: C925, C927, and C937. Each contract was awarded by the LTA in 2011, and required the use of 6.60 m diameter Earth Pressure Balance (EPB) TBMs. Contract C925, for an 800 m long section of parallel tunnels running between Tampines and Tampines East Station sites, was awarded to Korean contractor GS Engineering & Construction Corporation. Similarly, parallel 1.4 km lines on the C927 contract running between Bedok Park and Bedok Reservoir Stations were awarded to Italian contractor CMC di Ravenna. C937, consisting of two 780 m tunnels driven between River Valley station and Bencoolen station and two 560 m long tunnels between River Valley station and Upper Cross Street, was awarded to GS Engineering & Construction Corporation. All contracts require building of the station sites and metro tunnels—C925 required one TBM, C927 two TBMs, and C937 three TBMs. At contract Two eastbound tunnels, each 780m long, are being bored by one machine each. Westbound, there are two tunnels about 560 m long each. Here only one TBM is used, which will be dismantled after the first drive and transported on the surface back to the launch shaft to begin the second drive. GS contract C925 is additionally two parallel tunnels bored with one machine. The GS machine must come back to the launch shaft through the tunnel to be launched on the second drive.

1.3 *Implications for the Tunnelling Industry*

It is the goal of the LTA to finish the entire project as soon as possible, including all phases of the Downtown Line. Ultimately, the LTA's goal is that Singaporeans are never more than 400 m from a station. The multiple contracts at short tunnel lengths with large amounts of machines are the LTA's bid to keep construction times short.

The downside from the machine manufacturing perspective is the glut of used machines on the world market that will result after the project. At the same time, this may benefit contractors in terms of lower cost machine prices for projects elsewhere in the world. Because the LTA has so far required TBMs to be new for all contracts, none of these machines will be allowed on future projects in Singapore. Furthermore, the machines should be in relatively good condition because of the short drives. As of October 2013 there are about 50 machines operating in Singapore, not including future projects like the Thomson Line.

2 GEOLOGY

The geology in Singapore is very complex and can vary radically even along the relatively short contractual tunnel lengths. Multiple core drills were conducted along the alignments, resulting in a detailed listing (see Table 1).

Table 1. Singapore Geology.

Geological Conditions in Singapore				
Formation	**Designation**	**Rock or Soil**	**Rock/Soil Types**	**Projects that encounter this geology**
Jurong	SI	Rock	Mudstone, Siltstone, Sandstone	C937
Jurong	SII	Rock	Mudstone, Siltstone, Sandstone	C937
Jurong	SIII	Rock	Mudstone, Siltstone, Sandstone	C937
Jurong	SIV	Rock	Mudstone, Siltstone, Sandstone	C937
Jurong	SV	Soil	Sand, Silt, Clay	C937
Jurong	SVI	Soil	Sand, Silt, Clay	C937
Kallang	M	Soil	Marine Clay	C937, C927, C925

Kallang	F2	Soil	Fluvial Clay	C937, C927, C925
Kallang	F1	Soil	Fluvial Sand	C937, C927, C925
Kallang	E	Soil	Estuarine Clay	C937, C927, C925
Fort Canning Boulder Bed	FCBB	Soil w/ Rock Boulders	Sandy Clay Silt, SandySilty Clay, Sandstone	C937
Old Alluvium	OA	Soils with varying degrees of weathering	Sand,gravel, sandstone conglomerate	C925, C927

The Fort Canning Boulder Bed (FCBB) in particular poses challenges to the machinery. While no machine on the C937 contract has yet passed through the boulder field, the following observations are based on previous machines that have excavated in the area:

Since the FCBB has relatively strong boulders located in a clay matrix, the cutting action of the disc cutters on the TBM cutterheads is hindered. Before the pressure required to chip the boulders into fragments is reached, the boulder moves in the clay matrix. When these boulders move, they can bang against other parts of the cutterhead, such as scrapers and bits, and damage them as well. In addition, the boulders and clay matrix have different hardness, so that the cutters are exposed to many shock loads in a short time. This reduces the life of the cutter and creates more interventions to replace the cutters. Boring through this boulder field is a slow ordeal as the TBM must go slow enough to avoid moving the boulders, but still push hard enough to break the boulders. This cannot always be achieved. If the boulders will not break, divers must go in front of the cutterhead to manually break up the boulders before the machine can advance (see Figure 2—a section of the contract C937 requiring excavation through the boulder field).

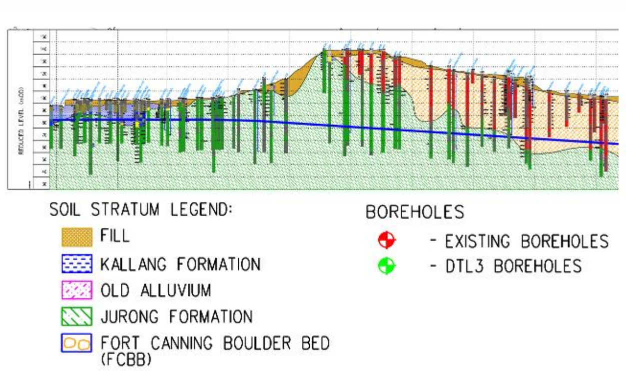

Figure 2. Portion of the C937 contract in the Fort Canning Boulder Bed (orang) and Jurong formation.

3 MACHINE DESIGN

Each of the six 6.60 m diameter Earth Pressure Balance Machines (EPBs) designed for the three contracts was built by The Robbins Company in their Chinese manufacturing facilities. The TBMs were engineered to cope with both rock and soft ground under water pressure up to 3.0 bars as well as rock and boulders (see Table 2).

Table 2.Machine Specification

Specification	All Contracts
Max Thrust	48,000 kN
Drive Motors	VFD
Cutterhead Power	1,050 kW
Cutterhead Speed	0-3.5 RPM
Cutterhead Torque	5,848 kNm
Screw Conveyor	Shaft Type
TBM Weight	417 tonnes

Each machine is fitted with a mixed ground cutterhead with the possibility to install 17-inch disc cutters or tungsten carbide knife bits, or a mixture of both, depending on the ground conditions encountered. Cutting tools are categorized into two types: (1) disc cutters and knife bits that break and loosen the ground, and (2) scrapers that gather and guide the loosened material into the mixing chamber. Both knife bits and scraper bits contain tungsten carbide wear material. The opening ratio was custom configured to accommodate varying setups of disc cutters and bits. High quality wear plate was also added to increase abrasion resistance in rocky conditions. Injection ports in the cutterheads allow for a wide variety of ground conditioning materials to be injected, including foam, polymer, and Bentonite (see Figure 3).

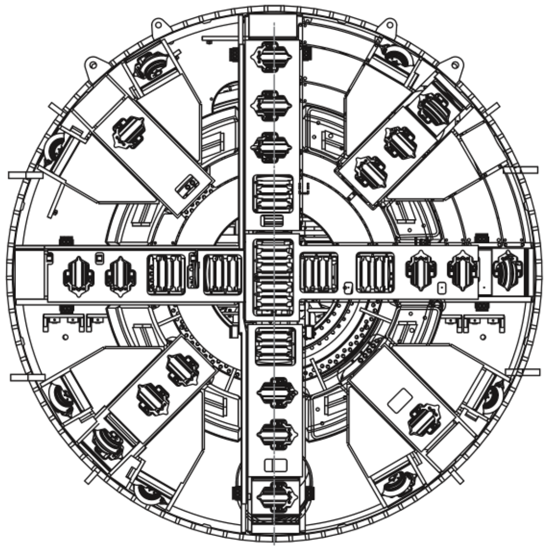

Figure 3. Mixed ground cutterhead with both disc cutters and carbide cutting tools.

As there are strict settlement limits in the contract, the machines are each using active articulation, which allows the rear and forward shields to move independently of one another in a curve. Equal thrust is reacted on all portions of the erected segment ring, reducing the risk of ring deformation that can lead to settlement. In addition, the machines are utilizing two-liquid back-filling. The “A” liquid, a cementitious grout, is combined with the “B” liquid accelerant at the nozzle, just before injection into the annulus, allowing the annular space between the ring and tunnel walls to be filled and harden in less than a minute. (see Figure 4 for the general assembly of the machines).

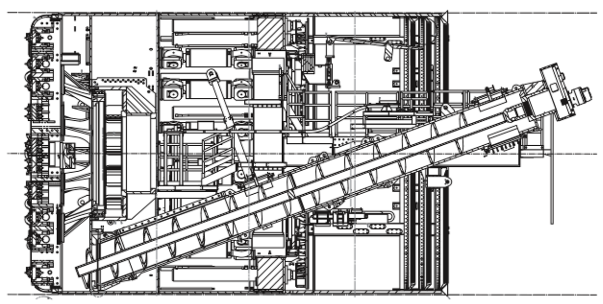

Figure 4. EPB general assembly.

A notably unique part of each machines settlement minimization program is the ring reformer—a setup used widely on Japanese tunnel boring machines but with limited use elsewhere. The device includes two hydraulic jacks that stabilize each ring during assembly, preventing vertical deformation (see Figure 5).

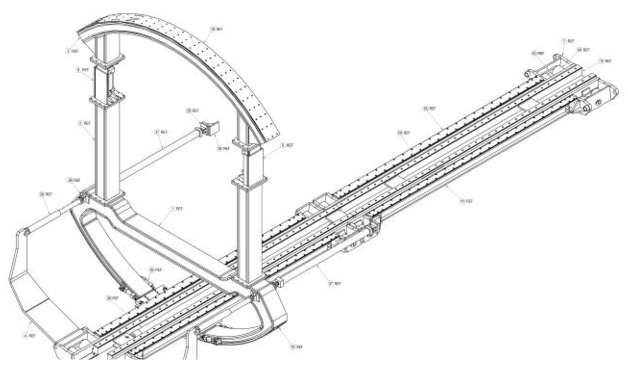

Figure 5. Ring reformer to prevent vertical deformation during ring builds.

4 LAUNCH AND ASSEMBLY IN LIMITED SPACE SITES

4.1 *Site Preparations*

As one of the world’s smallest nations, Singapore is necessarily densely populated, and all of the jobsites are located in close proximity to building foundations and urban structures. Interestingly, all of the jobsites are contained within station sites, and as stations, the sites tend to be quite long. But they are squeezed between existing infrastructure so they end up being very narrow. As it happens, virtually none of the surface area at the jobsite ends up being available for TBM delivery, assembly, and launching. When the TBMs are being delivered and lowered down the shaft, station and other construction activities are occurring simultaneously and consuming nearly all the available area. Because there is no room for the backup gantries at the bottom of the shaft, they are temporarily arranged on the surface in a side by side fashion. Even this small 10m x 40m area is coveted and quickly occupied as soon as the tunnel has advanced far enough for the gantries to be lowered.

At one jobsite in particular, an entire section of the Singapore River had to be moved so that a station site and tunnel could be built directly under it (see progress photos, Figures 6-10, below).

Figures 6-10. Progress photos of river diversion in order to create a jobsite.

4.2 *Machine Transport and Assembly*

Each of the six EPB TBMs was assembled in Pudong, China, and then shipped by sea to the port in Singapore (see Figure 11, assembled machine in the shop).

Figures 11. The first of six EPBS assembled in Pudong, China.

Once in Singapore, all of the machines were assembled and launched from the bottom of shafts.

Because there is no room for assembling the entire backup at the bottom of the shaft, the backup is assembled on the surface and all the services (electric supply and control, hydraulic, water, & grout, foam, Bentonite, polymer, etc. supply) are connected to the machine by a 130 m long umbilical cable/hose connection. Once the machine has bored about 80m, it is stopped and the backup is disassembled, lowered into the shaft and reassembled behind the TBM.. The tunnels are typically very short. Startup and boring under umbilical are typically slow processes, and end up comprising a significant percentage of the entire tunnel excavation schedule. For example, one tunnel under contract C937 is only 520 m long and the first 80 m or 15% of the total is being done with an umbilical connection (see Figures 12 and 13, assembly and startup using umbilical cables).

Figure 12. Assembly of one EPB on the C927 contract.

Figure 13. Umbilical hoses in shaft bottom.

5 TBM PROGRESS AND ADVANCE RATES

Each of the contracts is in various stages—the first of the C927 machines completed its drive in early November 2013, and the second machine has bored 180 m but is presently stopped while excavation of a third short "cripple tunnel" is ongoing. The cripple siding tunnel lies between the two tunnels in the launch shaft. The CMC site could not handle muck disposal for three headings, so when work on the NATM cripple tunnel began, the second TBM was stopped until the first TBM finished its drive. Now that the first TBM drive is complete, the second TBM is scheduled to resume boring in early November.

The three machines on the C937 are presently boring and are in 200 m, 195 m, & 69 m. Two of these machines must cross above the active NEL subway line with a minimum clearance of 1.2 m. One crossing has been successfully completed as of this writing. Geology so far has been as expected with the Fort Canning Boulder Bed yet to be reached

The machine for the C925 contract is scheduled to launch on its initial drive in late November.

Advance rates have been low. The C927 machines operated by CMC have had the best performance to date with 9 rings erected within a 24 hour period. At C937, the best day has seen 5 rings erected.

6 CONCLUSION

In scores of cities around the world urban density has grown far faster than have metro systems. There is immense pressure in those cities to build metro systems faster, which forces municipalities to let contracts for shorter sections of tunnel—a process which in turn forces machines to be launched from shafts between stations, rather than only from stations. While launching an EPBM from a postage stamp size job site with only a small shaft is not desirable there is no alternative when extremely rapid development of a metro system is demanded. Additional cost and time is of course required, however, with proper pre-planning and well-designed temporary equipment, such as a services umbilical and mucking devices, it is possible to successfully launch machines from such small shafts. There likely will be a growing number of metro projects which require such launches. Singapore is proving to be a city where methods for safe and efficient small shaft launches are being perfected.

REFERENCES

River Diversion photographs: GS Engineering and Construction Corporation