Chapter 25

Tunnel Boring Machines in Hong Kong

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Introduction

Given the mountainous nature of the local igneous terrain, hard rock tunnelling plays an important role in the development of Hong Kong's infrastructure.

In 1990, tenderers for two tunnel projects were encouraged to consider using hard rock TBMs, the territories' first. As a result the 7.5km long, 3.56m diameter Tolo Effluent Tunnel and the 5.3km long, 4.8m diameter Hong Kong Electric Cable Tunnel were excavated by hard rock TBMs. The successful completion of both projects in 1992 should make the TBM method an attractive construction alternative for planned, upcoming projects in Hong Kong.

Tunnelling Conditions

Tunnelling solutions are frequently adopted in Hong Kong due to the intensity of development, lack of flat landscape and proximity of mountainous terrain to the main centers of population. This is carried out primarily in granites or granitic-type rocks which surround Victoria harbour, and to a lesser extent in the outlying volcanic rocks which include extremely hard tuffs and lavas.

Tunnelling will generally take place in granitic rocks, normally about 100-250 MPa in strength, and with an average joint spacing of 0.3m and a quartz content of 30-

46%. In some locations the rocks are deeply weathered leaving zones of large core boulders. The volcanic rocks are more varied in nature with strengths commonly varying from 80-200 MPa with zones of eutazitic tuffs up to 400 MPa. These rocks have an average joint spacing of 0.25m but are occasionally highly fractured with spacings as low as 0.01m. They are more consistently weathered, have quartz contents in the range of 40-46% and occasional sedimentary inclusions which can be preferentially fractured.

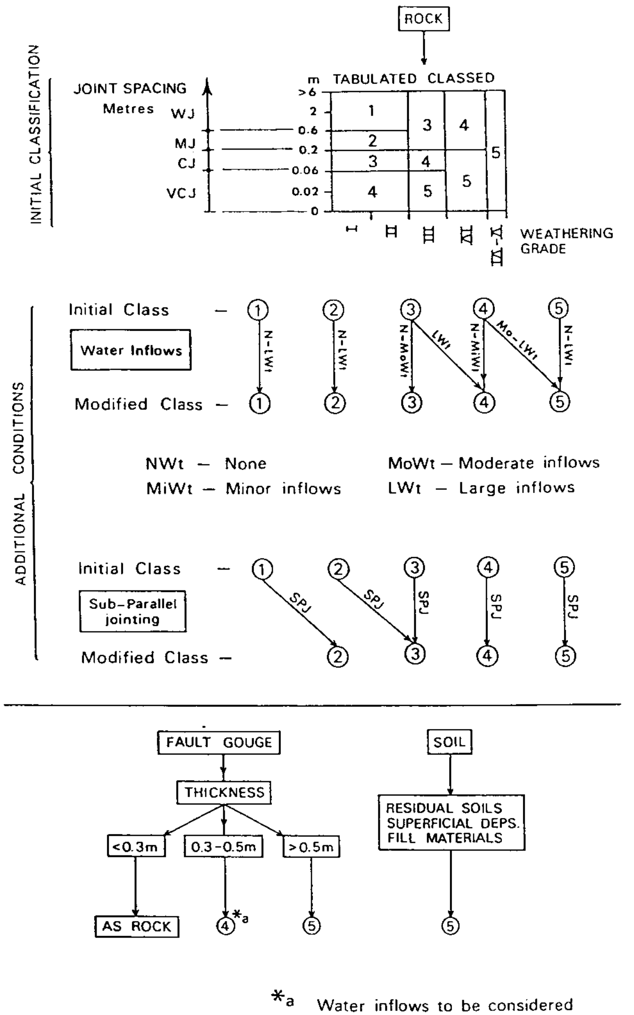
Rock data and tunnel experience show that Hong Kong's rocks are amongst the hardest in the world. TBMs employed in such conditions must be designed to cut hard abrasive rock with high capacity, rotary disc cutters. High cutter costs must generally be expected.

In spite of the substantial experience of local contractors, the extent of overbreak encountered in drill and blast tunnels continues to be unacceptably high. This is normally about 15% of the excavated volume for most tunnels. Tunnelling in the volcanic rocks is problematic where these are highly fractured, as blasting can cause unravelling of the rock mass necessitating the rapid installation of support close to the tunnel face.

Tolo Effluent Export Scheme

This scheme has been designed by Balfours Haswell consultants for the Drainage Services Department to carry treated effluent which currently enters the Tolo Harbour from the Tai Po and Sha Tin Treatment Works. The effluent will be conveyed via transfer works into Victoria Harbour at the Kai Tak Nullah. The transfer works include a 7.4km long, 2.5m internal diameter gravity effluent tunnel terminating at an 18m deep shaft at Diamond Hill.

Constraints to the tunnelling works included a high pressure (90m) aqueduct tunnel from the High Island reservoir which was located only 3.5m above the effluent tunnel at the crossing point; the twin bore tunnels for the Tate's Cairn Highway Tunnel which were located 12m below the effluent tunnel; and a 100-200m wide zone of moderately to completely weathered granite located below the Fung Tak Estate where the overburden cover was generally about 60m. Other constraints were the limitation of 13mm/s ppv imposed by the Water Supplies Department (WSD) for blasting close to the aqueduct tunnel, and the desire to avoid complaints from residents of the estate due to blasting or settlement.



Procedure

1. Determine material type present in tunnel arch and classify as ROCK, FAULT GOUGE or SOIL.
2. For classification of ROCK monitor average conditions present in tunnel arch.
3. Use joint spacing and weathering grade as shown to determine initial classification.
4. Check for effect of additional conditions, namely water inflows and sub-parallel jointing.
5. For classification of FAULT GOUGE measure average thickness and classify as shown above.

Figure I
IMS Rock Classification System

The geology of the route consists largely of fine to coarse grained granite intersected locally by porphyritic rhyolite, syenite, and dolerite dykes. A comprehensive site investigation was carried out for this contract. This included geological mapping of the tunnel route, seismic refraction surveying, and the drilling of a 300m long horizontal borehole at the Sha Tin portal. Regular vertical drilling was carried out with inclined drilling conducted to intersect possible fault zones. Specialist machinability testing was undertaken together with other standard field and laboratory testing. The investigations provided essential details on the rock materials and rock mass both for design and tendering purposes.

In order to encourage tenderers to consider the use of TBMs, payment for excavation and support of the tunnel was based on the IMS Rock Classification System. (Figure I). The method involves tenderers pricing estimated lengths of five rock classes. Payment during construction is made according to the lengths actually encountered, hence removing some geological risk from the contractor.

Most tenderers submitted bids based on TBM excavation, including the Italian contractor, Vianini Lavori SpA, who was awarded the contract late 1990. This contractor produced the lowest bid with an alternative design substituting a precast segmental concrete lining for the insitu lining shown on the tender drawings (See Figure II).

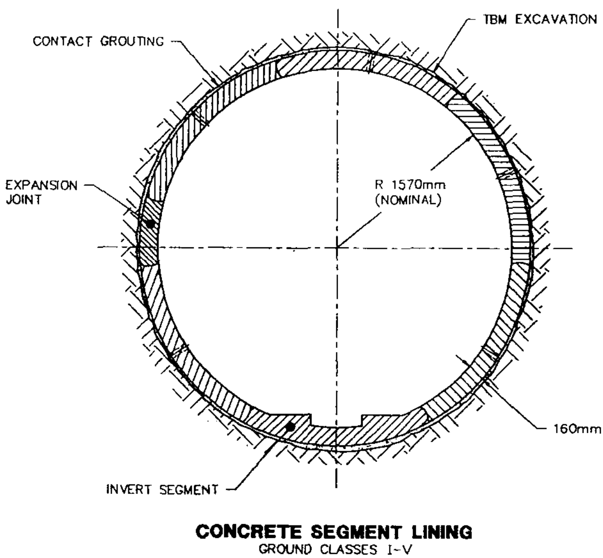


Figure II
Lining Used on Tolo Scheme

Vianini with their specialist tunnelling Italian subcontractor SELI, offered a slightly larger tunnel than was required because of the size of the TBM available. SELI's 3.56m diameter TBM is a Robbins 1111-234 Double Shield with 25 each 17 inch diameter disc cutters with an average maximum recommended thrust capacity of 222 kN per cutter (See Table I). The machine was manufactured in 1987, to a joint Robbins/SELI design, and was previously used to construct the 9km long Los Rosales Water Supply Tunnel in Bogota, Colombia.

The TBM including back-up is about 120m long. It is a shielded type machine to cope with a range of ground types including the soft ground anticipated at the southern end of the tunnel, near the Diamond Hill shaft. Open Gripper type hard rock machines might have required hand mining from the shaft to meet the TBM in hard rock and dismantling in the tunnel. A further advantage is the 160mm thick concrete segment lining being built in the tail. The one-cycle operation is quicker overall than a two-stage method using a follow up insitu lining.

The TBM was installed at the Sha Tin portal. It drove down gradient from here towards the intersection with the High Island water tunnel. Water inflows of up to 35 l/s were experienced in the drive, however, the TBMs four water pumps were capable of removing water inflows at a rate of 100 l/s. The water tunnel had previously been lined with steel for 50m to either side of the intersection and a waterproof lining was installed inside the segmental lining in the effluent tunnel for a length of 100m.

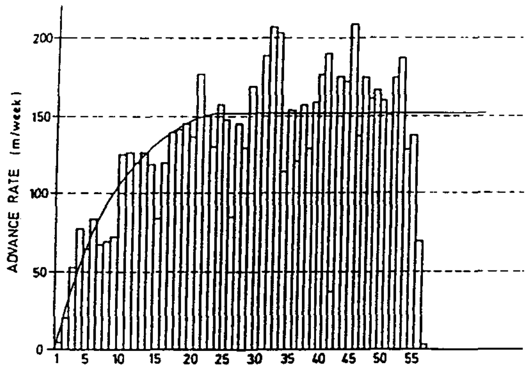


Figure III
Progress Rates for Tolo TBM

Figure III shows the weekly advance rates and learning curve. Construction was carried out largely without incident. Tunnelling through the fault zone took place in ground classes 4 and 5. This was carried out in weeks 53-54 at advance rates higher than in competent granite. The 7.4km long tunnel was excavated in about 55 full working weeks, at an average rate of 135m/week. As the Hong Kong government's first TBM drive this was an impressive performance achieved by a client willing to encourage the use of modern tunnelling techniques and by the expertise of both contractor and consultant.

Cable Tunnel

The Nam Fung to Parker 275 kV power transmission line undertaken by the Hong Kong Electric Company who was the Engineer for the project. Haswell were appointed as Consultants for the feasibility study, design and construction phases of the project. The works included a 4.8m diameter tunnel with 5.4km of rock tunnelling in granitic rock types and 120m of soft ground tunnelling.

Constraints for the tunnelling works included a WSD gravity water tunnel running from Tai Tam Reservoir located about 30m above the intersection of the two alignments; five crossings of the cable tunnel below WSD catch water facilities; known faulting at Wong Nei Chung Gap and possible faulting connecting the tunnel near the quarry with the reservoir. The WSD were particularly concerned that the tunnelling works could deplete their vital water supply at Tai Tam and applied strict limitations on the allowable water inflows into the cable tunnel as well as their normal 13mm/s ppv blasting constraints for all WSD facilities.

A comprehensive site investigation was again undertaken including geological mapping, the drilling of 200m long horizontal boreholes at both portals, seismic surveying including inter-borehole topographic surveying at the Wong Nei Chung Gap fault, rock machinability assessment, permeability testing as well as other routine drilling and testing works.

As for a previous 3.1km long cable tunnel, which was excavated by drill and blast for the Hong Kong Electric Company, support for the new cable tunnel was designed in accordance with the IMS Rock Classification System (Figure I).

The project was tendered in mid 1990 and awarded to Nishimatsu Construction Company who proposed the use of a new 4.8m diameter, open-type, High Performance Robbins TBM. The machine employs 32 each 19 inch cutters with thrust capacity up to 312 kN per cutter (See Table I) and incorporates facilities for advance probing in the crown through the short roof shield.

The TBM commenced excavation up gradient from the Chai Wan portal and the TBM crew included experienced operators from The Robbins Company. Initial delays at the learning curve stage were increased by the Environmental Protection Department imposing a 16 hour working day for spoil handling at the portal until suitable noise suppression facilities could be erected. Other delays were also accountable to replacement of several main motors on the TBM and to occasional water inflows on the initial sections of the tunnel, which were controlled by fissure grouting and the laying of an insitu formed concrete invert in one part of the tunnel.

The tunnel designed involved the used of 0.3 x 0.5m thick reinforced precast concrete sleepers; these were placed at the 1.0m intervals and the intervening space and invert subsequently filled with aggregate (Figure IV).

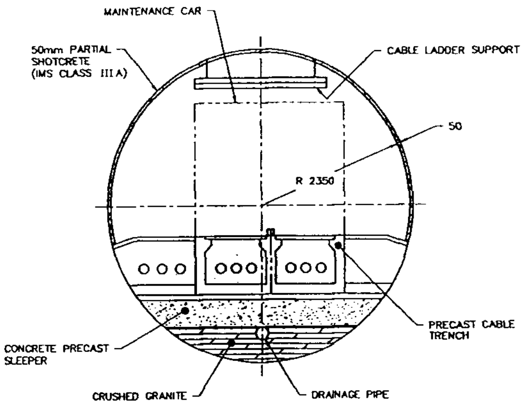


Figure IV
Lining Used on Cable Tunnel

The site investigation had revealed the existence of a 10-15m wide fault zone of shattered, to completely weathered granite at Wong Nei Chung Gap. The performance of the TBM in this zone is discussed later.

The TBM broke through some 53 (working) weeks after commencement, with an average advance rate of about 100m/week (Figure V). As Hong Kong's first TBM drive this was a creditable performance, achieved by the close co-operation of client, contractor and consultant.

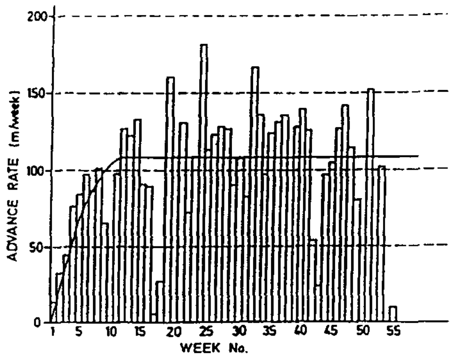


Figure V
Progress Rates for Cable Tunnel

TBM Utilization and Advance Rates

The TBM utilization diagrams of the two projects are shown on Figure VI. It may be noted that the used Tolo TBM achieved a higher machine utilization and obtained approximate the same ROP in m/machine hour as the new HP TBM. Setting aside the important issues of rock strengths and rock mass characteristics of each specific tunnel drive, the following items should be noted:

Tolo TBM:

- Machine was pushed close to or at times above maximum recommended thrust levels in order to ensure that construction programme was achieved.
- No major afterworks take place in tunnel during the excavation period to interrupt boring or mucking operations.
- Air cooled, blowing ventilation to TBM work place was provided to maintain temperature and humidity.

Cable Tunnel TBM:

- Machine was not pushed to maximum thrust level. This may mainly be caused by several reasons including, low muck train availability at the heading and chipping of cutter rings at higher load levels.

- Parallel major operations took place in the tunnel behind the back-up, including the drilling, blasting and mucking of the five tunnel enlargements. These operations created frequent interruptions of services including supply of the blowing ventilation to the heading.

- No special air cooling of the TBM work places, resulting in hot and humid conditions at the heading and the tunnel.

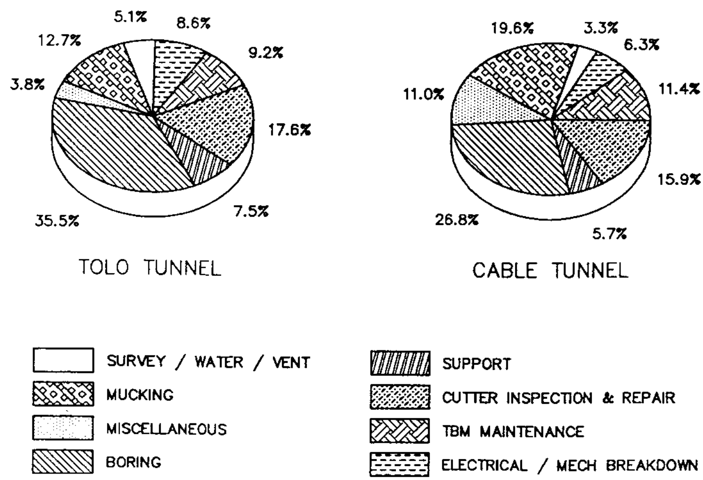


Figure VI
TBM Utilization Charts

Rate of Penetration (ROP)

The ROP for the TBMs averaged both about 2.8m/machine hour. The Tolo TBM generally ranged from about 2.6 to 3.2 m/machine hour, ROP increasing from Rock Class I to V, including with installation and expansion of concrete segments during the boring cycle.

The ROP for the Cable Tunnel TBM generally ranged from 1.7m/machine hour in no joint zones at approximately 295 kN/cutter, to more than 5m/machine hour in weathered seams and fault zones.

Actual machine tests in the various Rock Classes proved again the important relationship between cutter thrust and ROP. Assuming adequate cutters, main bearing, TBM structure and torque to withstand the high loads, the ROP will increase substantially with increased thrust levels in hard rock formations. With an increased ROP, a lower cutter cost per m^3 should also follow.

TBM Performance in Adverse Ground

Figure VII shows the Hong Kong Cable TBM's performance through the Wong Nei Chung Fault. The total measured delays are attributable to probe drilling, support and a variety of miscellaneous (unrecorded) tunnel operations. Ground treatment had been carried out from the surface prior to tunnelling and advance probing was carried out from the TBM. Overall the TBM performed well with a total delay of only 55 shift hours.

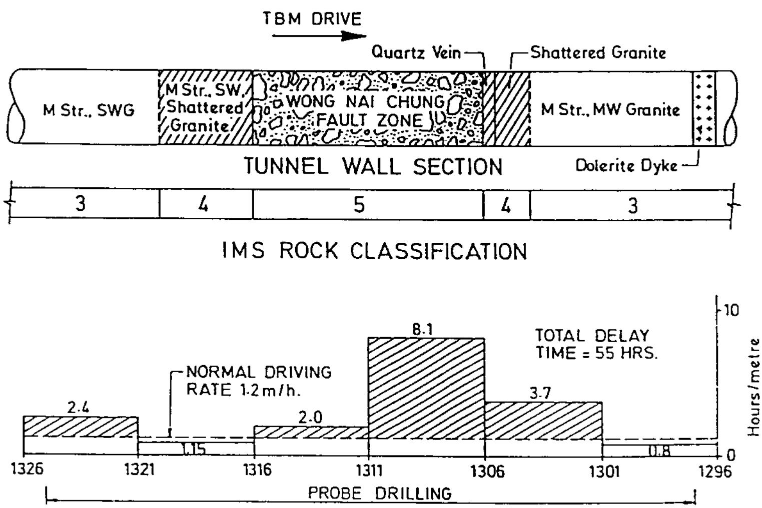


Figure VII
Performance through the Wong-Nei Chung Fault

Tunnelling Costs

For estimating and programming purposes each new tunnel project is different in terms of its unique geological conditions, layout, tunnel dimensions, access, market situation at the time of tendering and the availability of suitable plant. The following remarks are made with these aspects in mind:

Advance Rates

The advance rates gained of the case histories cited above are about four times those normally achieved by drill and blast in Hong Kong, considering the diameter of the tunnel excavated. However, a consideration for costing and programming purposes is that the delivery time and the set up time are greater for TBMs.

Plant, labour and access

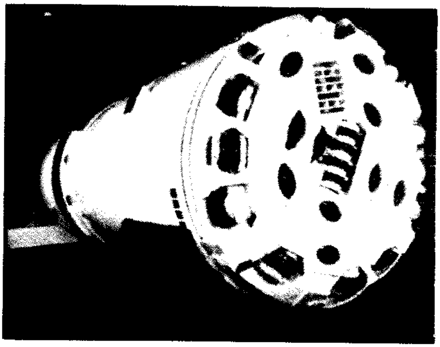
For tunnels in excess of approximately 4km in length, in order to achieve the same programme (which is inevitably tight in Hong Kong) contractors only have to employ one TBM drive, as opposed to three drill and blast drives. This results in similar plant costs and a reduction in overall staff costs for TBM excavation to about 40-60% of that required for drill and blast excavation. Further savings arise from there being no need for intermediate access shafts or adits, although in some cases, such as for subaqueous tunnelling, this may not be possible, i.e., the same programme may not be achievable by drill and blast.

Overbreak

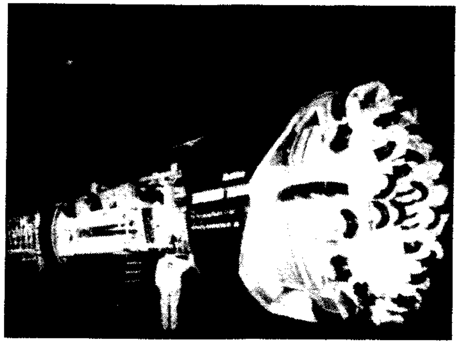
The substantial overbreak figures referenced above are to be compared with effectively nil overbreak from TBM drives in the local igneous rocks. In the event that a slightly oversized TBM is employed, as in the case of the Tolo tunnel, the contractor may absorb the cost of the additional mucking, although the larger sized tunnel and additional m^3 muck may be beneficial to some clients.

Support

For savings in support costs, which are considered additional to those for overbreak costs, a comparison was made of the supports actually installed in two cable tunnel projects in Hong Kong. These were excavated by drill and blast and TBM and installed relative to the IMS Rock Classification System. Results demonstrated that very substantial overall savings in the order of 50-100%, depending upon rock class, were achieved by the use of a TBM.



Tolo TBM
Robbins 1111-234



Cable Tunnel TBM
Robbins 152-261

	Tolo Effluent Export Tunnel	Cable Tunnel
Owner	Drainage Services Department, HK Government	Hong Kong Electric Co.
Consultant	Balfours Haswell	Haswell
Contractor	Vianoni Lavori/SELI	Nishimatsu Const. Co.
Machine Type	Double Shield	Open Gripper Type, HP
Diameter	3.56m	4.8m
Cutter Type	17" (432mm)	19" (483mm)
Number of Cutters	25	32
Max Recommended Average Cutterload	222 kN	311 kN
Cutterhead Drive	671 kW	2275 kW
Cutterhead RPM	11.7	11.5
Approx. TBM Weight	160 t	285 t

Table I

Conclusion

It is evident that TBM technology has come to Hong Kong and must be given due consideration for each new project to come. The first two applications of TBMs in Hong Kong have involved state-of-the-art plant and have been successful.

The key to achieving such success lies in tunnel owners adopting a sufficiently flexible approach for payment purposes and recognizing the need for consulting engineers, and contractors with TBM experience using modern hard rock machines with high thrust capacities and adequate torque characteristics.

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