TUNNEL CONSTRUCTION GUIDELINES
01 – TBM SELECTION

INTRODUCTION

This guideline is intended to provide a general overview of the criteria that may be considered when making the selection of Tunnel Boring Machine (TBM) at the commencement of a Project. The TBM and it's suitability for a particular project have tremendous potential cost and schedule impacts and hence can pose a significant risk. TBM selection is therefore one of the most important choices to be made by the project procurement team whether this role falls to Client, Consultant or Contractor.

This guideline should be read in conjunction with related GIGs 04.6 Soft Ground Tunnelling and 04.4 Hard Rock Tunnelling.

BACKGROUND

There is an increasing trend throughout the tunnelling industry, particularly characterised in Hong Kong, towards fully mechanised tunnelling with appropriate use of TBMs across the whole range of ground conditions from hard rock to soft ground. This trend has been fuelled mainly by the advances in the technology of tunnelling machines which have in turn increased the economic efficiency of tunnelling projects. Tunnels are now being driven longer, in more diverse ground conditions and with far greater expediency than ever before and TBM manufacturers are increasingly able and willing to provide a more specialised product, in many cases customised to the specific requirements of a particular project. Whilst there was previously a clear distinction between machines for hard rock and soft ground, there is now a full range of machines that blur the intermediate divide of mixed ground conditions.

TBM OR OTHER METHOD?

Although this is not the primary subject of this TCG, it may be of benefit to outline the general criteria for TBM use over other methods such as Drill & Blast, Roadheader or hand excavation.

Generally, TBMs will be used where tunnels are to be long in length and of uniform cross-section and profile. They may also be used where environmental or political factors prohibit the use of Drill & Blast.

SELECTION CRITERIA

- **Geology** – the anticipated ground conditions along the proposed alignment of the tunnel are critical to the selection process. The type of soil, rock and the presence or otherwise of water are fundamental criteria and for this reason the more extensive the ground investigation prior to TBM selection the better. Investigation of sub-soils may be by;

1. Exploratory or pilot tunnels;
2. Geophysical investigation
3. Dynamic penetration tests, pressure probes;
4. Borehole expansion tests, pressiometer;
5. Hydraulic injection tests;
6. Boreholes to obtain samples and cores;

For tunnels to be driven in rock it is important to know;

- the compressive, tensile, shearing and cleavage strength of the rock;
- the nature of bedding planes and fault zones;
- the degree of decomposition and weathering;
- the mineralogy and petrology;
- the abrasiveness of the rock and
- the nature of the hydrological conditions.

In soft ground the following are important parameters;

- grain distribution curves
- angle of friction
- cohesion
- deposit thickness

(Special thanks to Mr. Andy Westmoreland for his preparation of this guideline)

Advantages of EPBM

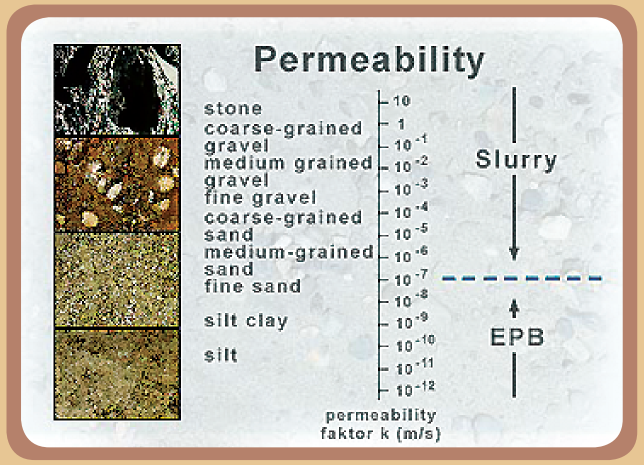
- In the event of face collapse, ground loss is limited
- Able to operate in open mode in firm ground
- Better production rates are possible
- Lower capital cost
- Smaller work site and launch shaft

Advantages of SPBM

- Working pressure control is systematic
- Muck is only evident at the surface – cleaner tunnel, less dust, etc
- Less power requirement at cutterhead
- Less torque required
- Easier to understand and operate
- Reduced cutter wear, less frequent interventions

A slurry TBM is ideal in loose water-bearing granular soils which are easily separated at surface. By contrast, silts and clays are difficult to separate and can be extremely problematic for slurry recirculation. This is particularly the case if the amount of fines (particles smaller the 60μm) is greater than 20%. For an EPBM, the higher percentage (>10%) of fines, or a predominance of silt, will make it easier to form a plug in the mucking screw and thus control the earth pressure in the chamber. Clays with a high plasticity index (PI) can be problematic to both of these types of TBM.

In terms of permeability, Slurry TBMs will be the better choice in ground permeability is greater than 1 x 10^{-7} m/s, whilst EPBMs are more applicable where permeability is lower. These considerations have to also consider the hydrostatic head. Higher water pressures will favour the use of slurry TBMs, as the seal to the face provided by the bentonite slurry will aid compressed air interventions to the cutterhead.



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Both types of TBM have the ability to control surface settlement if operated correctly, however, the opportunities to operate an EPBM incorrectly are greater than those provided by a slurry TBM. When ground conditions make plug formation in a EPBM difficult, the temptation exists for the operator to advance the TBM in open mode, thus risking over excavation and inevitably, settlement. These same temptations towards incorrect TBM operation, whilst present, are significantly reduced with a slurry TBM. Conversely, control of overexcavation is easier to monitor in an EPBM where muck quantities are immediately evident in the muck skips, whereas measurement of muck in the slurry system relies on more intricate density and flow measurements in the out-flow pipeline.

OTHER FACTORS FOR TBM DESIGN

The type of shield and more particularly the type of features incorporated into a particular TBM will depend on many factors, but principally these are;

- Type of temporary support to be installed;
- Type of permanent tunnel lining to be constructed;
- Tunnel alignment.

If the tunnel is to be lined concurrently with the TBM advance by the construction of a prefabricated, segmental, concrete lining, this will require the incorporation of a segment erector. In a soft-ground shield the erector would normally be sited immediately behind, or within the tailskin of, the shield. In the absence of a tailskin, trailing fingers may be installed to provide some protection from the exposed excavation. On an unshielded hard rock TBM, an erector may be incorporated as an add-on at some point further back from the face, and to a limited extent, advance of the lining construction is independent of the TBM advance. Segments may not be constructed close to the face due to the passage and operation of the grippers.

A telescopic shield may be used in soft ground to allow the lining to be constructed concurrently with the excavation; the front and rear shields move independently thus allowing some overlap between the principal operations in the tunnelling cycle.

Articulated shields may be used to improve TBM steerability, particularly where a tunnel alignment includes very tight radius curves.

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- compressive and shearing strengths
- pore volume
- plasticity
- swelling behaviour
- permeability
- the nature of hydrological conditions

From knowledge of the above parameters it is possible to ascertain technical criteria for your choice of TBM, these include;

- face stability
- sub-soil stability
- face support measures
- influence of groundwater
- ease of break-out of the sub-soil
- potential for surface settlement
- deformation behaviour of the sub-soil
- abrasiveness of sub-soil on cutters and the TBM structure
- separability of spoil from slurry
- suitability of spoil for landfill

- **Tunnel Alignment** – The selected TBM must be designed and built to negotiate both the vertical and horizontal alignment proposed, taking particular account of the minimum curve radius and maximum grade. Most TBMs are able to negotiate curves of greater than 300m radius but anything smaller would require a more custom-made machine.

- **Tunnel Diameter** – Whilst most types of TBM are available for larger size tunnels, TBM selection may be limited in small diameter tunnels. Most commonly, tunnels of diameters 0.6m to 2.0m, are constructed using pipe-jacking TBMs for which slurry is the preferred means of both face support and muck extraction. Size prohibits segmental lining construction, thus concrete jacking pipes provide both, immediate, and permanent support. Alternatively, in soft, and more recently hard rock conditions, Auger Boring Machines (ABMs) may be combined with pipe-jacking methods, in an increasingly diverse mix of tunnelling applications.

- **Site Restrictions** – Many work sites particularly in congested urban areas such as Hong Kong have limitations on both area and access. The mechanisms involved to deliver, assemble and launch the TBM, as well as extract it from the completed tunnel, will impact on the type of TBM employed. Whether or not a TBM can be recovered from a project for resale or re-use will have a significant influence on the economics of TBM selection. In addition, particular types of TBM such as Slurry Pressure Machines require a large site area for the slurry support back-up system and in such cases this may be the overriding selection criteria.

- **Local Experience and Availability** – Selection of a TBM may be significantly influenced by the availability of a particular TBM in a particular vicinity, in fact the availability of a particular TBM may itself influence the timing, implementation and design of a particular tunnelling project. In many geographic areas of the tunnelling industry, TBM selection is inhibited by the lack of an experienced workforce to operate the more advanced TBMs. This lag between advancing technology and appropriate expertise may be circumvented in some cases by the increasing mobility of experienced TBM operators.

- **Project Time-frame** – In large projects of considerable lead-in time it may be highly beneficial to select, design and commission the TBM at a very early stage (possibly by the Client in conjunction with a reputable TBM manufacturer, this is nowadays referred to as the Owner Procurement Process or OPP, and is used extensively in USA although is not common in Hong Kong). In this way the TBM can be customised exactly in accordance with the projects specifications. It is, however, generally the case in Hong Kong that the TBM is procured by the Contractor only after award of Contract.

A smaller, more expedient project, may dictate the use of a readily available second-hand TBM in which case the limits of the TBM market will, to a large extent, dictate the type of TBM selected. The project time-frame will also dictate the required rate of advance and thus the number and type of TBMs to be selected. If, for example, multiple slurry machines are to be selected, it must also be considered that these will require multiple large working site areas.

PRINCIPLE TYPES OF TBM

1. 'Open' Hard Rock TBMs – These generally have a circular cutter-head equipped with disc-cutters spaced in spiral fashion from the centre to the periphery. The machine is held in place during excavation by grippers extended laterally against the

tunnel walls, any decomposition [RQD < 50%] of the rock will restrict gripper forces and inhibit effective TBM utilisation. The excavation is generally not supported immediately, although fingers may extend behind the cutterhead to provide some initial protection. Such a TBM would be selected for tunnels in solid rock (UCS of 50-300MPa) with medium or high face stability. The TBM provides no means of preventing groundwater entering the excavation other than by separate pre- or postgrouting operations. The degree of cutter wear and the extent of groundwater control grouting, are principal economic factors in the selection of this type of TBM.

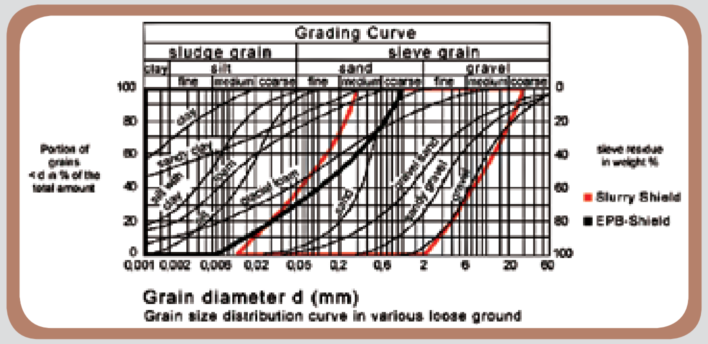
2.Shielded TBMs – In ground with low stability, TBMs are equipped with a closed shield body immediately behind the cutterhead and support, usually pre-cast concrete segmental lining or concrete pipe, is constructed directly behind the shield. The TBM then propels itself by shoving off the newly constructed support. There are a number of different types of TBM Shields to suit different ground conditions i.e. Earth Pressure Balance Machines, Slurry Machines, Mixed Shields and Open Shields. Depending on whether the ground is hard or soft the cutterhead may be equipped with Cutter discs or soft-ground picks and scrapers.

SLURRY OR EARTH PRESSURE BALANCE?

In soft-ground tunnelling, pressurised face support may be provided by two distinct methods; slurry and earth pressure balance. Use of compressed air (applied to the whole tunnel or restrained by a bulkhead within the TBM) as the principal means of support is diminishing, although it is still used as a composite in Mixed Shields. The choice between slurry or EPB is both complex and critical.

Generally EPB machines will be used in finer grained soils whilst SPB machines are preferred in coarser materials. This criteria has been made more vague in recent years by the development of improved soil-conditioning additives and additive injection systems, which broaden the range of ground conditions that each type is able to operate in.

For projects where the geology is spread across the full range of the grading curve it may be necessary to develop a dual slurry/EPB system. The two types of TBM have the following comparative advantages;



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