PAPER NO.604

# CRITERIA FOR SELECTION AND APPLICATION OF TBMs IN TUNNELING PROJECTS

BY

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## ABSTRACT

With the recent technological advances, Tunnel Boring Machines (TBM) have become a viable economic alternative to drill and blast in hard rock excavation. These machines are finding increasing use in tunnel development due to the potential benefits they offer. The successful application of TBM technology to tunneling depends on the selection of the most suitable equipment and cutting tools for the rock and ground conditions to be encountered. In addition to required testing and geotechnical investigations, cutterhead design optimization is an integral part of the machine selection to assure a successful application of the machines in a specific project. This paper presents and discusses the criteria for TBM application in typical tunnel projects, the process of conducting site investigation and the necessary laboratory testing together with machine selection and performance estimation for TBM use in underground development.

## INTRODUCTION:

Mechanical rock excavation offers many advantages over the conventional drill and blast techniques. They include improved safety, minimal ground disturbances and reduced support requirements. It eliminates the vibrations generated by blasting, reduces ventilation requirement and the uniform muck size allows for the implementation of continuous haulage systems, such as belt conveyor to attain high rates of advance and possibility of automation.

Tunnel boring machines are used for boring tunnels. This takes place in an almost continuous process, as opposed to the cyclic nature of drilling and blasting. A primitive compressed air driven TBM was developed in 1881 and was used to drive two early pilot tunnels under the English Channel, the era of the modern TBM did not start until 1950s, when a machine developed by James Robbins and Associates was put to work in excavation of a diversion tunnel for the Oahe Dam Project in South Dakota, USA. Since then, TBM development has progressed in two directions to:

- ☐ Enable the machines to tackle ever harder and more abrasive rock formations.
- ☐ Make the machine capable of operating in both stable, competent rock and in ground so unstable that it requires the tunnel to be lined concurrently with excavation.

## TBM SELECTION:

The selection of type and design of a TBM to be used on a particular tunneling project is invariably governed by the following two main characteristics of the project:

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- ☐ The geological conditions expected to be met along the tunnel length.
- ☐ The overall design of the tunnel and any specific peculiarity of the project as a whole.

## Geological Considerations:

The main geological parameters always to be taken into account in the selection of a TBM for a particular project are the borability and the stability of the ground. The former will determine what type of boring tools will be used and how much power should be available to obtain a certain boring speed for a certain diameter of the tunnel. The later controls the type of ground support to be used and thus determines whether the TBM must take an active part in supporting the tunnel and ultimately integrated with the tunnel lining and ground support. This is for the case where it is necessary to use that type of support to keep the tunnel from collapsing during drivage.

### Borability.

The types of tools used for TBMs are either drag bits (or so called picks) or roller cutters. In both cases, the designation indicates the mode of operation:

Drag bits loosen the material to be excavated by being dragged through it in circular paths and dislodging the material in between the kerfs they cut.

Roller cutters roll over the surface of the rock - i.e. the face of the tunnel - under a high thrust load, establishing kerfs by crushing the rock underneath their cutting edges and spalling out larger chips of rock from the area between two neighboring kerfs.

The dragging action of the drag tools leads to friction between the bit and the rock surface and thus to heat development which combines with the strength and abrasivity of the material to cause tool wear. Drag bit equipped TBMs therefore cannot be used with economically acceptable results in any but the soft ground. TBMs for all other types of ground are fitted with roller cutters which are much less wear sensitive, as they roll over the rock instead of being dragged through it. The most popular type of roller cutter and the most efficient one is the Disc cutter.

### Stability.

In stable, competent rock, there is no need to support the tunnel by more than an sporadic rock bolt to secure blocks of rock delineated by local cracks. As structural features in the rock, in the form of bedding planes, cracks and fissures or faults increases, rock support measures will increase to a regular rock bolting pattern, possibly with wire mesh, shotcreting, the installation of concrete segments or steel sets or combinations of these and ultimately to a partial or a full lining.

Ground suspected of being in need of more elaborate support or of containing local fault zones can be investigated in advance by probe drilling ahead of the TBM and reinforcing it by grout injection, when the probe holes indicate the need thereof. Methods using micro-seismic and ground penetrating radar's have also been proposed and utilized for identification of anomalies along the tunnel alignment and taking precautions.

The more elaborate the ground support and reinforcement or sealing measures become, the more they will influence the selection of the type of TBM for a particular project and the detailed design of the machine. While the simpler types of support can be handled in conjunction with the use of a so called open type hard rock TBM, support in the form of a full concrete segments lining installed during drivage invariably calls for some type of shielded TBM. However for the ground conditions between these two and various other ground support methods, there are specially designed systems that have to be ordered and integrated into the machine design.

No matter which type is selected, the occurrence of methane will always influence the design of the machine, either by the installation of a methane warning system or additionally the explosion proof instrumentation of the total electrical system.

Tunnel design and project specifics:

The following parameters will influence the design of the TBM, once the basic machine type to be used has been selected by using the available geological information.

Tunnel design.

The shape and the dimensions of the tunnel cross section are the first parameters which characterize tunnel design. To lend itself to excavation by TBM, a tunnel must in general have a circular cross section, though special types of machines have been developed to accommodate non-circular, most often horseshoe-shaped cross sections. It is obvious that a TBM's mechanical design and its installed power are directly related to the diameter of the cross section.

In the case of a very large diameter, it may be better to excavate the tunnel by first boring a pilot tunnel by a smaller diameter, standard TBM and to ream the pilot bore with a special "reamer TBM". Amongst others, this offers the opportunity of locating any "geological anomalies" and dealing with them before the large size opening is created.

If the tunnel is not to be straight from start to finish, the radius of the curves to be bored will influence the design of the TBM and perhaps even more so that of the Back Up system which houses all the auxiliary gear a TBM needs for its operation. Most TBMs will cope with curve radii down to some 250 m without any problems. For tighter curves, special layouts may become necessary, especially in small diameter tunnels.

The dip and the incline of the tunnel in the direction of drivage will influence the design of the boring machine when they exceed approximately 1:10. If the choice exists

whether to drive a tunnel going down or up, one will normally select the latter, as this provides a natural drainage. If the tunnel has to be driven downwards, a sump pump must be installed at the front end of the machine to cope with the inflow of water. At declines steeper than 1: 4 normal belt conveyors become unsuitable for muck removal and need to be equipped with special belting or exchanged for a different type of conveyor.

Boring upwards poses its problems, specially when the incline becomes so steep that the machine gets a tendency to slide backwards, when it is not gripped in. This usually occurs at grades steeper than 1: 5, depending on the surface conditions of the tunnel invert. Also, the muck may present problems, in that it starts to roll on a moving belt. In such cases TBMs operating on an incline will have to be provided with a safety grippers to stop it, and the Back Up from sliding down. Special muck removal systems must be considered as well. In addition machine must be capable of high thrust to overcome the gravity and the weight of the machine and the Back Up system. Inclines of up to 1 : 1 have been bored success-fully by TBMs thus modified on a number of occasions.

Project specifics.

The following items will influence TBM design to a greater or lesser degree:

- ☐ The location of the site

Here one meets such aspects as: access, altitude above sea level, climatic conditions (ambient temperature range, rain/snow falls, humidity), the availability of water for cooling, the availability of skilled personnel to operate and maintain the machine, the availability of maintenance facilities and a reliable spare parts delivery, etc. The absence of electricians with experience in electronics, for instance, makes it less advisable to base the TBM's control system on a Programmable Logic Controller.

- ☐ Access to the starting point of the bore

Complicated access may necessitate a special machine configuration, for instance if the components have to be taken up a winding mountain road or lowered down a shaft before they can be assembled near the actual starting point of the tunnel.

- ☐ Muck transport and dumping possibilities

These factors may influence perhaps not so much the machine itself as its Back Up.

- ☐ Environmental aspects

To quote but one instance: if the avoidance of oil spills is of special importance, the use of a hydraulic cutterhead drive system should be ruled out, due to the risk of hose ruptures. Contaminated muck has to be contained.

The examples presented above clearly indicate that varying geological conditions and project dictated circumstances in combination influence the choice of TBM type to be used in general and its individual layout and detailed design to a much larger degree than what is the case for many other types of heavy construction equipment. This and the large capital expenditure for a TBM and its Back Up, most often leads to a high degree of tailoring each

machine for a specific project. The more comprehensive and the more accurate information available when selecting and designing the TBM and the back-up equipment, the greater the chances of a successful and profitable project.

## GEOTECHNICAL INVESTIGATION AND PERFORMANCE ESTIMATION

The most important key in the successful application of TBMs in tunneling environment is to learn from the past experience gained in the previous projects. Prior to application of a mechanical excavator, specially TBMs in any project there are several tasks that have to be performed to assure the success of that project. This is due to the high capital investment involved in using these machines and the sensitivity of the TBMs to the ground conditions. These tasks start with a well planned geotechnical investigation and is followed by a reliable feasibility study. The geotechnical exploration will identify the rock types and ground conditions to be encountered and allows for careful planning to avoid major problems and unnecessary delays. Feasibility study provides the means for realistic performance estimation for planning and scheduling as well as cost estimation. The following sections describe these steps in more details.

### Study of Ground Conditions.

TBMs are very sensitive to the ground conditions and it must be remembered that these machines are site specific. All the available means have to be used to provide a reliable geological map to include the major formations to be cut, potential intrusions in the tunnel alignment, fault zones specially in water bearing formations, ground water characteristics, rock mass information to include joints and discontinuities and their frequency (RQD) and surface characteristics, and in situ stresses. This type of information can be obtained form exploratory drilling and cores. Also, other means of probing and exploration have to be considered. Some examples of these techniques are the geophysical and micro-seismic investigations, satellite pictures, and even the ground penetrating radar. Often people are amazed to learn how much information were available at small costs compared to the overall scope of the project.

### Rock Mechanics Testing.

Rock mechanics or physical property testing is probably the back bone of the geotechnical investigations. This specially has to be emphasized for tunneling projects since the primary interest is to bore the tunnel economically. The most common suit of tests pertaining to application of mechanical hard rock excavators are:

- ☐ Unconfined Compressive Strength ( UCS )
- ☐ Brazilian Tensile Strength ( BTS )
- ☐ Quartz Content or Rock Abrasivity
- ☐ Cherchar Index.

Yet there are several other test and measurements that could indicate peculiar behavior in the rock cutting behavior that are not run as often as they probably should. They include:

- ☐ Measuring Grain Size, Shape

- ☐ Schistostiy and Grain Orientation
- ☐ Rock Toughness
- ☐ Rock Drillability Indices
- ☐ Rock Hardness

These parameters are essential in evaluation of the TBM specifications and performance estimation.

Full Scale Testing.

Full scale cutting test of the rock types to be encountered is the safest and the most reliable method for evaluating the rock borability and cutting behavior. These tests entail actual measurement of cutting forces and specific energy requirements for cutting the rock at the actual spacing and penetrations with a full size cutter. The results of this test will eliminate a great deal of speculations and guess work in machine design optimization and performance estimation. This is mainly because these tests inherently include all the parameters affecting the rock cutting from rock and cutter characteristics to cutting geometry. These tests combined with the results of physical property testing can provide for ability to extend the results of full scale cutting tests to other formations present at the site.

Performance and Cost Estimation.

In spite of all the great features and advantages of TBMs and record setting cutting speeds, these machines can not be used in any project unless proper justifications are made for their usage. This refers to the estimated cost of driving a unit length of drift along with the anticipated time of completion. At this stage, machine's general configuration and specifications can be estimated from the above mentioned testing and investigations. The collected data can be used towards the development of estimates for penetration and advance rates using the performance prediction models available. The models are based either on the empirical or theoretical formulas developed for this purpose over a long period of time and observation of numerous TBM projects. It is highly recommended that a combination of both models to be used for any job site to minimize the risk of under-or overestimating the machine penetration rates.

Once the advance rate is known, the time for excavating different portions and reaches of tunnel can be easily calculated. The generated information is then used for project planning and scheduling as well as man power and cost estimation.

## DESCRIPTION OF TBM TYPES:

As various types of ground overlap with regard to some of their characteristics, so are the TBMs used to excavate them. The two main types of ground are called *soft ground* and *hard rock,* however imprecise such names and such a division may be, it is also a coarse classification of the TBM for respective ground conditions can be illustrated by a diagram as indicated in Fig. 1. The diagram indicates that soft ground will always calls for application of a shield machine, while both types of TBMs can be utilized for boring tunnels in hard rock.

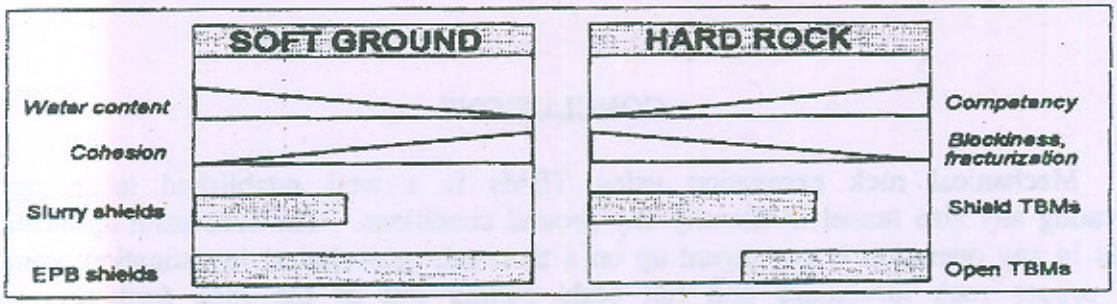



Figure. 1 Classification of TBM types with a view to ground conditions ( Atlas Copco )

Soft ground shields.

By definition, the main characteristic of soft ground is that it requires immediate support to keep it from moving into the excavated space (the tunnel). The only practical way of doing this is by enclosing the boring machinery in a shield which can prevent large movements of the ground and thus support the tunnel temporarily and protect the TBM itself. This allows for the installation of the permanent support which typically is concrete segments.

Hard rock TBMs.

The term hard rock can be defined in different ways and many controversies have been raised on this subject over the years. Still the most appropriate definition of and the best way to measure hardness and express it in a figure. However, this characteristic often is expressed in term of the uniaxial compressive strength (UCS) of the rock formation.

The samples for UCS determination are small in comparison to even the distance between neighboring cutters on a hard rock TBM, the UCS figure by itself will not determine how hard a rock may be to bore. Fractures, bedding planes and other features that do not fall within the sample volume, will influence borability. In most cases, if they are oriented favorably, they have a weakening effect on the rock, and borability increases.

Finally, another factor to be considered is the cost. Cutting the rock typically is not the main problem. This may require building a machine with enough built-in thrust capability and power. But, as tunnels in the end are to serve an economical purpose thus the cost of tunneling therefore has to be minimized. The important question is that whether it is economically feasible to use TBMs and it all boils down to "what is the costs of boring in tunneling a particular kind of rock".

Under certain conditions hard rock may require shield type of support. That is the reason why hard rock TBMs are divided into so called *open* i.e. not shielded and *shield machines,* even if they use the same type of rolling cutter tools.

## CONCLUSIONS

Mechanical rock excavation using TBMs is a well established technology for excavating any size tunnel in literally any ground conditions. The successful application of TBMs in any operation is contingent up on a thorough geotechnical investigation, combined with proper rock mechanics and full scale cutting test of the rock formations to be encountered. In addition, the machine specifications have to match the underground environments and the constraints related to tunnel design. Meanwhile, present designs and excavation methods have to be revised to facilitate utilization of the modern machine in state of the art operations. Therefore, mining and underground heavy construction industry along with research institutions and machine manufacturers have to join forces and make an attempt to revisit the issues involved and remove the roadblocks limiting the widespread application of TBMs in their operations

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