Selecting used tunnel boring machines: the pros and cons

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The cost of tunnel excavation can be minimised and bidding for such work may be much more competitive with the utilisation of used TBMs. An increasing number of tunnels have been excavated with used machines, although occasionally with disastrous results. Based on past experience, methods will be suggested to evaluate the condition and suitability of used machines on a given project.

The limit of rock hardness that could be excavated by tunnel boring machines has increased continually during the last decade and has resulted in much more extensive use of TBMs throughout the world. As the cost of these machines has increased, the number of used machines advertised for re-sale on the market after project completion has increased as well. The result has been that projects which were considered economically marginal for TBM excavation have a better chance of being excavated by a used machine.

Often, local, urban, or other physical restrictions dictate the use of TBMs, regardless of tunnel length, economic considerations or advantages of mechanical excavation. On other projects where TBMs are the obvious prerequisite, the contractor may have a competitive edge simply by bidding with a used machine.

In the past, rock hardness and associated performance have been the primary consideration. Other major considerations are: lag time for machine delivery, up to 12 months; machine cost ($US500 000 per metre of diameter); economy of mechanical excavation as a function of tunnel length.

A used machine can be on site in a fraction of the time and at a fraction of the cost it takes to have a new machine ready to bore. However, there are limitations and disadvantages in the utilisation of used machines. TBMs are generally designed and manufactured for a specific project and known type of geology with limited flexibility and range, or reserve power and ability. Therefore, it is essential to determine if a used TBM, designed for anticipated geology, diameter and conditions of another project, can in fact excavate the anticipated material of the tunnel project being considered.

The factors which most directly affect the performance of a used TBM are the anticipated geological conditions, adequacy of available mechanical forces, mechanical design and fabrication, structural design and fabrication, backup system and condition of the TBM.

Used machines should always be evaluated to determine if they can provide the cutter forces necessary for efficient rock breakage for the anticipated rock; checked for mechanical design and fabrication adequate for efficient rock breakage; checked for structural design and fabrication adequate to sustain any required increase in mechanical forces; evaluated for compatibility with and adequacy of the backup system (mucking and support) for anticipated rates and conditions; and surveyed to reveal any of the following: structural damage, structural integrity, excessive wear and poor tolerances, condition of the hydraulic and electrical systems, history of actual repair and maintenance performed, and proper protective storage.

Recommendations for inspection and evaluation of used TBMs will be given and a number of case histories will illustrate common problems, precautions, or solutions.

Anticipated geotechnical conditions

The decision whether or not to use a TBM (new or used) is based on the anticipated geology, geotechnical conditions (stability and support requirements), mechanical rock properties (particularly rock hardness, strength and abrasiveness) and excavation performance (Tarkoy and Hendron, 1975). TBMs are designed and manufactured for a specific project and geology with some reserve power and ability for a margin of safety.

Accurate evaluation of anticipated conditions for new machines is essential for successful excavation (Tarkoy, 1979). For used machines it is even more critical because mechanical design and available forces are already fixed on a used machine and can be changed only minimally, and then only prior to placement of the machine in the tunnel.

The effect of the ground conditions, especially rock hardness and strength, on evaluating the feasibility of a used TBM is directly related to the adequacy of available cutter forces for efficient rock breakage. Therefore, appraisal of a used TBM relies on the accuracy of anticipated geotechnical conditions.

TBM forces

The disintegration of rock is achieved by the application of forces to the rock through the cutter/rock interface. The disc cutter on TBMs sustains a normal load (F_n) against the face for penetration and a tangential load (F_t) (rolling force) which moves it through the rock.

Thrust and normal cutter load (F_n)

The available thrust and the number of cutters determine the normal cutter load (F_n) which may be applied to the rock surface. The load acting on the cutter/rock interface determines the ability and efficiency of the cutter to disintegrate rock. The relationship between required forces and the rock strength is complex. For simplicity and as a rough estimate, the static normal cutter load (F_n) should have the following relationship with the anticipated unconfined compressive strength (q_u) of the rock for efficient cutting:

$$F_n(kg) = K_1 \times q_u(Mpa)$$

or

$$F_n(kg) = K_2 \times H_1$$

where: F_n = normal cutter load
q_u = unconfined compressive strength
$K_1 > 70$
$K_2 \doteq 100$ to 500
(After Tarkoy, 1983).

The precise calculation of the required cutter loads may be determined from empirical relationships developed be-

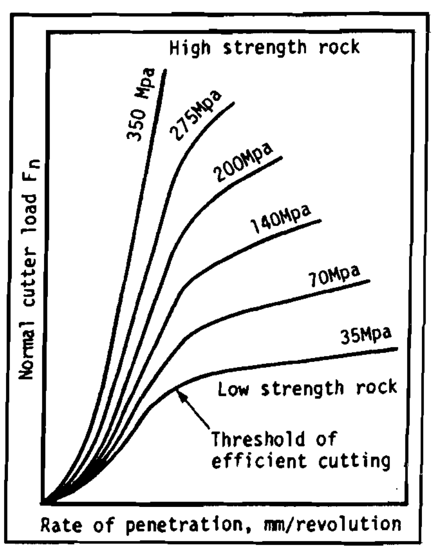

Fig 1. Threshold of efficient cutting (after Robbins, 1970).

tween Total Hardness (H_T) and the normal cutter load (F_n) while taking into account the nature of the rock and the characteristics of the TBM. The thresholds illustrated in the curves in Fig 1 must be exceeded for efficient cutting.

Torque and tangential cutter load (F_t)

The torque is the force required to turn the cutterhead and move the cutters through the rock with an applied tangential force (F_t) at the cutter/rock interface. The tangential force (F_t) is a dependent variable which is a function of the normal force (F_n), rock hardness, depth of penetration and cutter geometry. The depth of penetration (with everything else being equal) has the greatest effect on the required tangential forces (F_t). Therefore, a softer rock will require a higher torque than a harder rock.

Cutting coefficient

The cutting coefficient is the relationship between the normal (F_n) and tangential forces (F_t) and is calculated as follows:

$$\text{Cutting coefficient} = \frac{F_t}{F_n}$$

where: F_t = tangential cutter load
F_n = normal cutter load

Past experience indicates that for general purposes, cutting coefficients of 0.15 and 0.10 are adequate in soft and hard rock respectively (Tarkoy, 1983).

Analysis of forces

The analysis of forces is simple and straightforward. The first calculation requires some knowledge of the maximum anticipated rock properties. All subsequent calculations (tangential cutter load and torque) depend indirectly on the rock strength and directly on the normal cutter load.

The required normal cutter load may be determined by first establishing the maximum unconfined compressive strength (q_u) or Total Hardness (H_T) of the anticipated rock. The following relationship should be maintained for the maximum strength or hardness of the rock:

$$F_n(\text{kg}) = K_1 \times q_u(\text{Mpa})$$

or

$$F_n(\text{kg}) = K_2 \times H_T$$

where: F_n = normal cutter load
q_u = unconfined compressive strength
$K_1 > 70$
$K_2 = 100$ to 500
(After Tarkoy, 1983).

It must be kept in mind, that for some rock types which have inherent discontinuities (such as foliation, jointing, bedding, fracturing, crystal and grain boundaries, etc) which affect their uniaxial strength, the test results may not reflect the highest rock strength or the behaviour of the material in situ. This is most common with foliated metamorphic rock. It is not uncommon for samples to have the same Total Hardness (H_T) while the strength of rock having well developed foliation may be half that of an unfoliated sample with similar composition. Furthermore, field experience indicates that the existence of these discontinuities, especially in a confined face, does not assist the rock excavation process and more often becomes a problem when blocks (6 to 18in) break from the face (Tarkoy, 1983).

The required total thrust may be determined from the normal load (F_n) required on each cutter and the number of cutters on the cutterhead as follows:

$$T = F_n \times n$$

where: T = thrust
F_n = normal cutter load
n = number of cutters

Once the maximum normal cutter load (F_n) is known, the tangential cutter load is determined with the aid of the cutting coefficient as follows:

$$F_t = \text{cutting coefficient} \times F_n$$

where: cutting coefficient
= 0.10 for hard rock
= 0.15 for soft rock
F_t = tangential cutter force
F_n = normal cutter force
(After Tarkoy, 1983).

The torque is determined as follows:

$$t = \sum_{i=1}^{n} (F_t \times R_i)$$

where: t = torque
F_t = tangential cutter force
R_i = radius or moment arm of each cutter

Mechanical design

Some mechanical design criteria affect penetration without having critical effects on the feasibility of using a TBM. Those that have important effects on performance, other than the TBM forces, are cutterhead rotational rate and cutter spacing.

Cutterhead rotational rate

The cutterhead rotational rate has a direct effect on the rate of penetration because it determines how often the cutters pass over or penetrate any portion of the rock face. However, of itself, it is not critical to the feasibility except as it affects or determines an acceptable penetration rate and cutter wear. It is limited by the maximum permissible linear velocity of the outermost gauge cutter which is specified by the manufacturer. Simple calculations to determine the rotational rate are as follows:

$$RPM = \frac{V_l}{D \times Pi}$$

where: RPM = cutterhead rotational rate
V_l = maximum linear cutter velocity
D = cutterhead diameter
Pi = 3.14

Cutter spacing

The cutter spacing is kept within a relatively limited range (6 to 10cm) for most rock types. The cutter spacing becomes important in hard rock where maximum penetration (depth and width) may not occur because the effects of adjacent cutter paths do not interact adequately. In order to maintain the maximum cutter penetration, it is essential to have the optimal spacing (which normally yields some overlap).

With existing used TBMs, the cutter spacing has already been fixed for the original project and rock for which the machine was designed. However, if there is a substantial change in rock hardness between the original and current (proposed) rocks to be bored, it is essential that the cutter saddles be remounted for appropriate cutter spacing determined from empirical relationships developed between Total Hardness (H_T) and kerf spacing.

The cutter spacing is best determined by an engineer experienced with TBMs and geotechnical materials. For a rough estimate only, however, the following equation may be used:

$$s = -0.013H_T + 9$$

where s = cutter spacing (cm)
H_T = Total Hardness
(After Tarkoy, 1983).

Structural design

The structural design of the TBM limits the forces which it can sustain. In other words, it may not be possible to increase the forces applied at the cutter/rock interface unless the structural framework, gears, hydraulic systems and bearings can sustain the increased loads. The mechanical and functional limitations of the TBM mechanism can easily be overlooked with severe and costly consequences.

Backup system

The TBM cannot outrun the backup system, most particularly the mucking system (including the cutterhead muck buckets, the muck chute, TBM conveyor, the gantry conveyor and the muck train scheme), utility (air, water, drainage, ventilation and electric), installation scheme and the primary support installation system.

The general rule of thumb dictates that these systems be designed to accommodate in excess of the average anticipated penetration rate.

Condition of TBM

Downtime to repair direct damage or damage caused by poor maintenance can seriously affect utilisation and the daily advance rate. In addition, a larger spare parts inventory should normally be considered for a used machine. One cannot forego taking the precaution of a detailed inspection and accurate evaluation of a used TBM. The inspection and evaluation should include consideration of the following: possible damage to the structure or components; critical tolerances; repair and maintenance record; storage conditions; and machine history and contractor reputation.

Damage

The most important consideration is to determine if the TBM has undergone structural damage. It is important to investigate and yet it may be the most difficult to discover. The most important components to check are: the cutterhead, the main bearing and seal, the cutter saddles, the beam, the conveyor supports, the grippers and all hydraulic cylinders.

The cutterhead and main bearings and seals are some of the most critical and costly components to repair, particularly in the tunnel. Therefore, they should receive the closest scrutiny. Examination should discover breaks of welds or steel plate on the cutterhead and scoring to machined surfaces.

Tolerances

A check of important tolerances will provide more accurate information on the degree of wear than the machine's history. A check of tolerances can be carried out with the help of templates or movement of the components by jacking and checking with manufacturer specified permissible values. These tests are considered reliable as an indicator of the degree of wear for essential components, particularly for the main bearing.

The most important component to check for wear is the main bearing. At the same time it is essential that the condition of the main seal be checked because it may provide some clues to the condition or protection of the main bearing. If the main seal is damaged, broken, or leaking, the main bearing may have been or will be damaged, if not remedied.

Repair and maintenance

Painted components should be inspected to determine if sandblasting was done prior to painting. This may indicate that good care had been taken with the machine and the paint job was not just a cosmetic camouflage of poor underlying conditions. The machined surfaces, particularly those of the main bearing housing, should be protected by cosmolene or other similar material. The presence of protective sealer is an indication of conscientious maintenance.

After completion of tunnel excavation, main bearings should be dissassembled for inspection, cleaning and applying protective grease. Space permitting, the cutterhead should be stored separately to facilitate inspection of the main bearing and bearing surfaces by a potential purchaser. The existence of accurate and detailed field and shop records for all servicing, repair, and maintenance will reflect the condition of the TBM.

It is also possible to determine the condition of the equipment by observing the manner of machine storage as summarised in Table 1.

Therefore, a few simple case histories have been included.

Inadequate torque

A small diameter TBM was used to bore 2700m of tunnel in hard metamorphic rock at an average of 0.9-1.5m/h. Subsequently, the machine was used to bore about 6100m of soft shale. With the same thrust as in the metamorphic rock, the cutters penetrated deeper in the shale. Consequently, the required torque to turn the head with the deeper penetration at times exceeded the capacity of the machine and the cutterhead was stalled.

The simplest solution would have been: to take into account the limitation of the torque; to lower the setting on the normal operating thrust limit switch and thereby control penetration, and to estimate the performance accordingly in the bid.

Lowering the thrust limit would decrease penetration and lower the required torque. Since the lowered penetration had not been anticipated in the bid, the contractor suffered some financial loss.

Several alternatives, such as changing from multiple disc to single disc cutters or removing some of the cutters on the face could have provided a compromise solution to the problem. Such changes should always be done with caution and under strictly controlled test conditions.

Table 1. Summary of storage conditions to review for evaluation of used TBMs.

Components	Recommendations
Outside surfaces	These should be protected or painted to prevent rusting; surfaces should be sandblasted before painting to reveal cracks or other damage. Machines should be stored away from the effects of weather.
Gears, etc	These should have clean and fresh lubricants, filters and connections.
Hydraulic system	This should have all hoses repaired and connections should be capped, reservoirs cleaned, new filters installed.
Electrical equipment	These should be placed in dry storage.
Machined surfaces	These should be protected against rust or pitting with grease or appropriate material.
Main bearing	This should be disassembled for inspection, cleaning, storage, and to facilitate inspection by purchaser.

Contractor history and reputation

The history of the machine is fairly reliable in revealing both past problems and potential future problems. This history includes: the TBM's owner; associated personnel (project managers, mechanics, walkers, shifters, operators and home office shop mechanics).

Inspection

In order to determine and evaluate the foregoing conditions it is necessary to make an inspection of the TBM to check for: damage to structural members and the main components; tolerances of bearings and bearing surfaces; repairs and maintenance (verbal and written) records; storage conditions; and hydraulic leakage or malfunctioning hydraulic controls.

An inspection trip should be no less than a full day, preferably two days, and should include talking to the TBM's owner, project managers, mechanics, walkers, shifters, operators and the home office shop mechanics. All routine and unusual maintenance records should be examined. The success of an entire project may well hinge on the findings of such an inspection.

Case histories

Words of wisdom are rarely heard as receptively as horror stories of past experience and problems encountered.

Inadequate backup facilities

A small diameter TBM was used to bore 3000m of tunnel in a hard schist which required no support except for two locations where steel pans were rock bolted to the wall. The same TBM was subsequently used to bore 3000m of tunnel on each of two projects in shale. The shale was horizontally bedded with two vertical joint sets. The TBM was not designed to permit support installation close to the face and eight clamping legs prevented installation of rock bolts until the passing of the tail of the TBM. The only rock bolts that could be installed at the face were near the springline where they were generally useless, as shown in Fig 2. The results were: large fallouts behind the cutterhead; excessive downtime for clearing rock fallouts; and downtime to halt the TBM to place rock bolts behind the TBM conveyor.

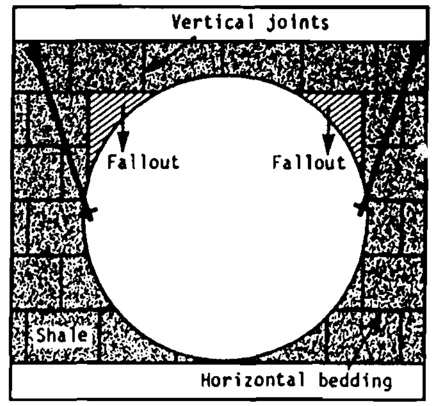

Fig 2. Geological structure and restricted inadequate rock bolt support.

The original (and unchanged) mucking capacity of this machine was adequate for hard rock at 1.5m/h. In the shale, the TBM was able to achieve and was limited by a penetration of 3m/h. At this rate, the muck buckets were too small and spilled much of the muck outside the muck chute above the conveyor. The muck fell and remained in the invert and was the cause of poor track and extensive derailments.

The consistent running of the conveyor at its limit or under an overloaded condition resulted in excessive downtime because of conveyor jams and problems with conveyor drive motors and damage to the belts.

Comparison of a used and a new TBM

A contractor had a used TBM of the diameter required for a job being bid. The TBM had been used on three jobs for a total of about 22km of tunnel. The contractor was interested in comparing the cost of driving the tunnel with an older machine or a new state-of-the-art machine. The analyses, described by Tarkoy (1979), took into account all the aspects which are relevant and affect performance and cost as summarised in Table 2.

The qualitative review of the advantages and disadvantages illustrated in Table 2, however, does not give results which can be used to make a choice which is supported by quantitative estimates of cost. The analyses showed that, considering all factors, the purchase of a new machine was more economical overall. However, the controlling factor here was the length of the tunnel and the outcome often is in favour of a used machine for short tunnels.

Based on the analysis described by Tarkoy (1979), a new TBM was chosen. The actual TBM performance was within several per cent of the predicted values.

Cutter selection

A number of machines with various designs and cutter geometries have been used in the same type of rock. On a recent project, an experimental cutter was tested and found to last much longer than those having a sharper profile. However, the cutter profile which was used lowered the penetration rate to the extent that the job took several months longer than a comparable TBM with the sharper cutters. The extra labour cost far exceeded any savings on the cutter costs.

Similarly, experience in hard metamorphic rock with tungsten carbide insert cutters showed that they lasted twice as long as hardened steel cutters, with no effect or difference in penetration. However, the cost of tungsten carbide insert cutters was twice that of the hardened steel cutters. Therefore, the only saving was the extra labour to change the steel cutters twice as often as the tungsten carbide cutters.

Main bearing problems

A small diameter (2.6m) TBM used on five different jobs was installed to bore 2400ft of hard crystalline rock. The machine was worn and had been installed without any knowledge of its condition. Although there were no serious consequences, there was some difficulty with the loss of lubrication and vibration because of the severe wear of the main shaft and bearing.

Inadequate thrust

A used 5.6m diameter TBM was utilised to excavate a second tunnel in hard rock having a maximum reported compressive strength of about 20 000psi. The thrust capability of the TBM permitted an application of normal cutter load in excess of 20 000lb.

The excavation progressed as anticipated until harder than anticipated rock was encountered and the average penetration rate and cutter consumption decreased proportionally. As the rock hardness and strength doubled, the penetration rate dropped to less than half and cutter wear quadrupled. It became apparent that the TBM cutters were below the threshold of efficient cutting. The contractor proceeded to continue boring at very low penetration rates and with high cutter consumption.

The ultimate effect of encountering a higher strength rock was greater than a direct linear relationship would indicate because the change in rock properties went well beyond the capability of efficient cutting by the TBM. In the process of completing the tunnel, the contractor applied the maximum possible thrust to maintain the penetration of the rock, thus damaging the cutterhead structure, cutters and hydraulic system components.

A differing site condition claim was filed by the contractor for a difference in rock hardness (double), which appeared to be related to a higher than anticipated quartz content (double), which resulted in sustaining a lower (half) than anticipated penetration rate and more than (double) the anticipated cutter costs.

Conclusions

Based on experience in the industry, the following conclusions may be drawn: the use of TBMs is increasings; more used TBMs are available; estimating and bidding for tunnel excavation with used machines is becoming more common and more competitive; difficulties with used machines have beome more commonplace and have accounted for differing site condition claims; the selection of used machines to excavate a tunnel is more critical than for a new machine; and systematic evaluation of used machines is possible to minimise and almost eliminate potential risks. □

References

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Table 2. Comparative advantages of used and new tunnel boring machines.

	New	Used	Reason for used
Cost		Less	Previously depreciated; repairs and rebuilding costs are a fraction of a new machine cost.
Lead time		Short	Time to re-build if not already done is a fraction of new machine lead time (8-12 months).
Penetration	Higher	Lower	Older machine is based on an older state-of-the-art design and performance; high penetration of a new machine is the result of advances in the technology of bearings, cutters, maximum cutter loads and TBM design.
Utilisation	Lower	Higher	Higher utilisation of an older machine is possible because of an extensive (multiple job) learning curve; particularly true if the same management and crew have operated the TBM on previous jobs.
Cutter costs	Lower	Higher	Older technology; cutter size and saddles may not be optimum for current conditions; the lower cutter consumption of newer machine is possible with the use of larger diameter cutters which can sustain higher loads and penetrate the rock at a higher rate.