Comparing TBMs with drill+blast excavation

Comparisons between these two construction methods can be made both on qualitative and quantitative grounds, and both determine excavation costs. Geotechnical and Tunnel Boring Consultant Peter J Tarkoy *assesses both methods, drawing on historical and current practice.*

Tunnel boring began in the latter half of the 19th century, simultaneously yet independently in England, Europe and North America. Original attempts were not on the whole successful, except for the Shakespeare Tunnel in Dover, UK, which was part of the original Channel Tunnel in the last century. The imagination of scientists and engineers was far ahead of the technology required to turn concepts into practical reality.

A second generation of tunnel boring started in North America during the early 1950s, continuing into the 1960s with considerable success. Records achieved in soft rocks in the 1960s stand even today. Technological advance coupled with occasionally overzealous desire for wider application of TBMs, made consistent success elusive. Nevertheless, the total average length of tunnels begun annually by TBMs has consistently increased into the 1970s and 1980s.

Tunnelling, especially tunnel boring, has had a particular fascination for engineers and contractors alike. The use of tunnel boring has increased in the last two decades to the extent that more than 200km of tunnels are begun each year by new and used TBMs worldwide (Fig 1).

Technological advances in the 1980s permitted successful tunnel boring in harder intact rock and in less competent rock masses. But these machines were more commonly refurbished and deployed with greater longevity. Used machines had the inherent disadvantage of not being specifically designed for project conditions and thus more often prone to produce less than successful results.

As the use of TBMs increased worldwide, they found favour even in labour rich countries due to considerable and inherent advantages. International TBM contractors started to compete with local drill +blast excavation. In the 1960s and 1970s, the question asked was: "Can the tunnel be excavated by TBM?" Today the question has become: "Can you afford not to excavate with a TBM?"

Yet, to be realistic, TBMs cannot alone deliver economic tunnel excavation, reduce overbreak and support, deal with difficult ground and complete on time. Avoiding problems can only be accomplished with project coordination, management and planning while using the most suitable methods and equipment. Even though the most appropriate method of excavation may consist of tunnel boring, it does not guarantee successful results. With this in mind, let us look at the qualitative and quantitative advantages of tunnel boring.

Although tunnel boring accounts for over 90 per cent of all civil tunnel excavation in North America and an ever increasing proportion of tunnels worldwide, tunnel boring has not been the method of choice in many parts of the world. More extensive implementation of tunnel boring has been prevented by:

- the presence of hard rock;
- low quality rock masses and soil conditions in a rock tunnel;
- plentiful and low cost labour; and
- short lead times necessary for beginning conventional (drill+blast) tunnelling.

Technological advances

Recently, TBMs have been operating in places previously considered unlikely such as the hard granites of formerly labour rich Hong Kong, poor rock mass conditions in Taiwan, basalt flows intermixed with soil conditions in California, and sand intermixed with 'arenisca dura' in Colombia.

Rock hardness greater than 400MPa has been successfully bored in various parts of the world in the past 10-15 years. Hard rock boring has become more economical as a result of increases in:

- cutter diameters (by a factor of 1.5);
- cutterhead gauge velocities (by a factor of 2);
- cutter load capacity (by a factor of 7-9);
- improvements in cutter geometry; and
- improvements in cutter metallurgy.

These advances have increased TBM penetration, but overall production gains have been at the mercy of inadequate human and management technology.

A wide range of ground conditions, including blocky rock and the presence of soil, have been conquered by using:

- full recessed cutterheads;
- short, long, double, articulated shields;
- continuous boring/stroking mechanisms;
- mechanical installation of precast segments; and
- use of NATM around TBMs.

Other advances include larger diameters (10-11m) either using full face boring or achieved with pilot and reaming machines with an increase in boring inclines and declines *(T&T, Dec' 91, p51)*. Availability of skilled labour has dwindled, even in such places as Hong Kong and Taiwan. Consequently, the cost of labour has increased and excavation rates of only 3-6m/day are not surprising.

An increase in the number of new and ongoing tunnelling projects to curb pollution in Hong Kong, Taiwan and other Asian countries will make labour shortages for drill+blast excavation crucial. Anticipated projects in Hong Kong and Taiwan have been summarised[13,15].

The short lead times have been accommodated by:

- using reconditioned machines (short refurbishment time);
- placing an early order for the new machines (as for Hong Kong's second electric cable tunnel; and
- pre-ordering major machine components or the TBM by the contractor.

Historical TBM excavation rates suggest

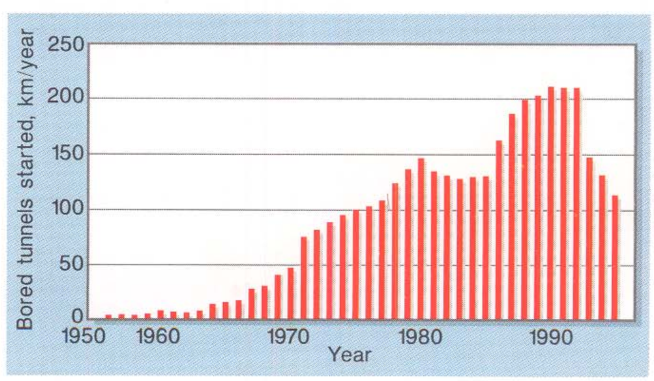


Fig 1. TBM tunnels built annually.

Table1. Advantages of tunnel boring.

Feature	D+B	TBM
Stability		Mechanical solutions for temporary stabilisation of: The face area; Around work area; The tunnel behind the work area
Shape	Any shape is possible; however, overbreak is inevitable	Naturally stable; Ideal for: mass transit, pilot tunnelling, unlined hydro and water conveyance tunnels; Superior flow characteristics may eliminate lining requirement
Overbreak		Nearly total elimination of overbreak
Support		Tunnel support may be reduced by 90%
Operating	Very cyclic; dangerous and unpleasant working environment	Continuous (non-cyclic), repetitive operation; safer and more pleasant working environment than in D+B
Blasting	Increased support requirement; Increased water inflow; Increased overbreak	
Overbreak	Costly filling with concrete	Eliminated
Support		Mechanical solutions available for stability and temporary support at the face, work area, and permanently behind the excavation operation
Crews	All skills required	Consistent, repetitive, less skilled, and easily trained operations (labour is assigned to limited tasks that are repetitive, become routine, and may even produce competition among the labourers
Access structure	Shafts and adits necessary to open multiple headings;	Can eliminate all temporary access structures, particularly if the project is well laid out

that delays in excavation due to TBM manufacture can be made up with higher excavation rates and less risk than drill+blast excavation which started earlier.

Comparison with drill+blast

Comparisons can be made on two grounds: one is purely economic while the other is qualitative, both having considerable impact on overall economy of the project. Intangible benefits can be attributed to operational advantages; the economic advantages will be compared quantitatively.

Inherent advantages of tunnel boring may be difficult to quantify yet have a considerable impact on the outcome of excavation costs. These are difficult to value in a tender and cannot fully be appreciated except from firsthand tunnel boring excavation experience. Some of these are summarised in Table 1.

Stability and safety at the excavation face, in the heading, in the work area and behind the excavation system have always been of great concern in tunnelling. Current technologies provide for much safer and more stable conditions in previously hazardous areas such as at the face ahead of and around the cutterhead and in and behind the work areas.

There is an inherent level of stability in having a TBM at the heading, supporting the face and work area or blocking possible inrush of materials into the work area. In contrast, many sudden failures at the heading, typical in many fault zones, occur as a result of an excavation blast which initially took place in competent rock and travelled into unstable material, or a fault zone. A full blown collapse or tunnel inrush may occur, even under the watchful eye of the Engineer. The stabilising effect of a full face machine is striking but impossible to measure.

Recent TBM designs, such as the double shielded machines, have maximised safety in the heading and work area. These machines have negotiated some of the most adverse ground conditions successfully, as in the Los Rosales Tunnel, Colombia (*T&T, Summer '92, p41*) and Hong Kong (*T&T, Jan '89, p23*). The most common solution developed for very difficult rock conditions such as flowing sand, swelling claystones, or squeezing rock and a mixture of volcanic clay and basalt has been the use of various types of recessed cutterhead and shielded machines.

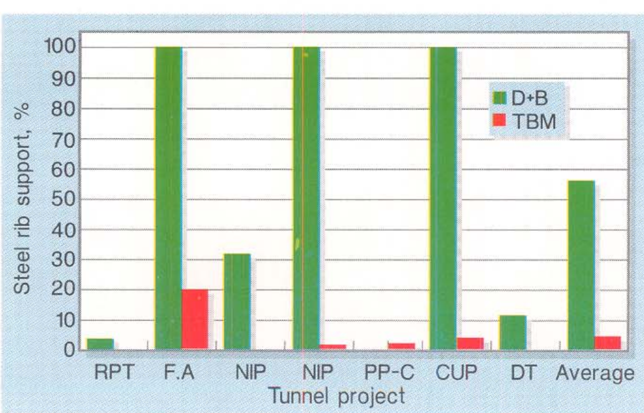


Fig 2. Drill+blast and TBM steel rib support experience.

The double shielded TBM has successfully traversed ground conditions producing water inflows > 300litre/s from the invert. It would certainly have been impossible to work safely with drill+blast at the heading above voids with flowing water that were safely bridged first by the shield and later by the precast segments.

Shielded machines have also been used with precast concrete lining to protect against damage by water inflow and support rock that had badly decomposed.

Safety

Very little safety data are available that directly and concisely compare the safety record of drill+blast with TBM excavation. Groseclose and Tackett have examined various contracting aspects of US Bureau of Reclamation (USBR) tunnels constructed in the 1960s and 1970s[5]. It is notable that the average accident rate for TBM excavation is nearly half that of drill+blast even though 12 of the 19 projects were excavated by TBM. Average lost time is almost the same for both types of excavation. Although more accidents occur in conventional excavation, they do not translate to higher lost time than the lower accident rate in TBM excavation.

It should be noted that the USBR data represent early applications of TBMs before the workforce had extensive experience with them and before safety issues relating to TBM excavation were better understood. In addition, the statistics are too broad and do not report specific types of injuries that may or may not have been related to the excavation type, the ground conditions or project safety considerations.

Bevan and Parks[2] provide a comparison of non-mechanical and mechanical excavation (including roadheaders) accident rate. The accident frequency, without Channel Tunnel experience, appears to contradict the general perception that the environment around mechanical excavation is safer. The authors explain that mechanical excavation is prone to more accidents because of the close space around TBMs. However, that should not apply to part face machines such as roadheaders that do not fill the tunnel as do TBMs and their backup systems.

Inclusion of the Channel Tunnel TBM experience sways the data to a degree that the accident rate for mechanical excavation is a little lower than for non-mechanical excavation. The authors attribute the low accident rate in the Channel Tunnel to its length. Is it the length, the rigorous coordination or the project management? Whatever the case, it is possible to conclude from the data that mechanical excavation can produce accident statistics equal to or better than mechanical excavation. One must also wonder if the Channel

Tunnel TBM data should be compared to part face mechanical excavation (roadheaders) at all.

A greater breakdown of non-mechanical, mechanical, TBM, roadheader and accident type might have permitted a more incisive analysis. However, since the raw data were unavailable, we can only speculate on the basis of our experience.

Tunnel excavation is linear and TBM work crews perform consistent activities. For example, in conventional excavation, the entire crew generally performs cyclical operations including drilling, loading, wiring, blasting, venting, scaling, installing support and mucking. This requires a variety of well developed skills and competence. In comparison, TBM crew members are generally assigned a limited and consistent set of tasks, repeated continuously, enhancing learning, training and development of skills. Activities require fewer yet higher skill levels which are performed repetitively, and are therefore conducive to easy learning and training. An added benefit of TBM excavation is that support and mucking can be independent of the excavation and advance of the tunnel.

Major performance advantages

TBM performance advantages can be directly related to quantitative benefits and differences that easily translate into costs and are amenable to direct comparisons. Quantitative performance and cost comparisons can be made for excavation rates, overbreak, support, labour, equipment, supplies and elimination of temporary construction structures.

TBM penetration rate and cutter tool wear are easily predictable for average ranges of conditions[7] based on total hardness. Since the excavation operation is much more consistent and continuous than drill+blast excavation, predictions are easier and more reliable. The greatest uncertainty is in the prediction of TBM use. However, it is possible to design a project to minimise downtime[10].

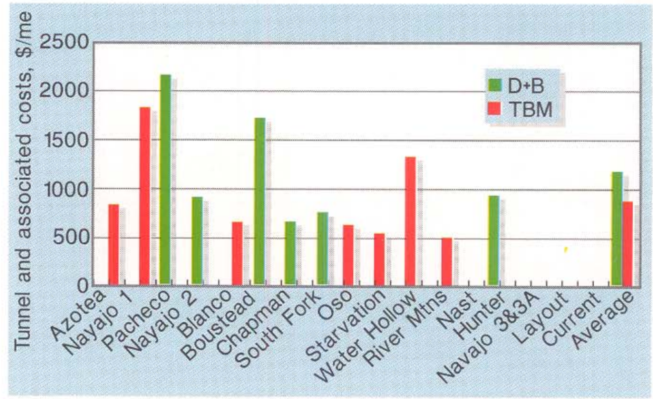
The most significant advantages of tunnel boring are the high excavation rates that can be attained (four to six times higher than local drill+blast advance rates).

Overbreak is generally influenced by the following factors:

- lithology;
- intact and rock mass properties; and
- quality of blasting practices.

Typically, no less than ten per cent overbreak should be anticipated in drill +blast excavation. It may be as high as 25 per cent of the tunnel face in blocky rock with poor blasting practices. In ideal conditions using controlled blasting practices, a lower percentage of overbreak can be attained. Commonly, however, overbreak when poor blasting practices are used is quite high. This overbreak will eventually have to be filled with concrete, require building of special bulkheads and result in additional concrete wastage, leading to substantial additional costs.

Fig 3. Drill+blast and TBM excavation cost comparisons.



Tunnels excavated through similar geological conditions (e.g. portals starting from opposite sides of a river valley) have consistently required much more support when excavated by drill+blast than by TBM. A study of seven sites worldwide where excavations by drill+blast and TBM encountered similar geological conditions revealed that the average steel rib support in TBM excavated tunnel is $^1/_{12}$ that of drill+blast tunnels (Fig 2). The reduction of water inflow in bored tunnels has also been noted in like geology, even though quantitative data are scarce. A general reduction of about 50 per cent is typical. However, in some geological regimes, reductions of 75 per cent are possible.

Cost comparisons

Simple comparisons have been used to identify major cost considerations associated with drill+blast and TBM excavation and have utilised similar physical labour, skill level, mechanical and other conditions. Assumptions reflect appropriate local conditions and experience in terms of construction performance and workmanship. When comparing drill-+blast and TBM excavation costs, project assumptions will be the same in terms of tunnel length, diameter and labour requirements.

Project assumptions

- tunnel length; and
- tunnel diameter;

The only differences will be in terms of:

- number of working headings;
- the excavation advance rate (per working heading);
- qualitative differences between drill +blast and TBM excavation; and
- access structures (as needed only).

Drill+blast advance rate experience is based on average Hong Kong and Taiwan excavation rates and experience in North America. The TBM advance rate is based on two reported case histories[8,9] and one recently visited site. Case histories TLHP and SRT[9] represent easily attainable advance rates possible under geological conditions similar to Hong Kong. Case TLHP represents advance rates at the lower end of the scale while project SRT represents effective planning, rigorous project management and ambitious construction excavation. Similarly, the SHEP project is averaging nearly 1km/month.

Cost advantages are relatively easy to calculate. However, many projects could not even be considered feasible without TBM excavation. Consequently, it is too easy to overlook the qualitative and most significant advantages of tunnel boring, that is, that tunnel boring makes some projects feasible only when everything is considered. The Los Rosales Tunnel in Bogotà was designed to be excavated by drill+blast. It was the contractor's innovation, using a TBM with a fully recessed cutterhead in combination with a fully articulated double shield and a double pass lining system using initial support of precast segments and cast-in-place-concrete lining, that kept the project from turning into a major disaster.

To comprehend the potential calamity possible with drill+blast tunnelling, one has only to be told that the anticipated arenisca dura (hard sandstone) managed to flow through grout holes in the precast segments on a number of occasions. The volume of sand coming through these holes was as much as $6m^3$. In other areas, overbreak was so large that the segments had to be bolted together to keep them from collapsing into the voids.

Major cost items affected by the excavation method and considered in this analysis are:

- cost savings resulting from qualitative advantages of mechanical excavation;
- TBM excavation rates four to six times higher than drill+blast excavation;
- overbreak (cost of delivered concrete, wastage and labour to fill overbreak);
- labour crew costs;
- equipment costs (drills, jumbos, muckers, cars, trains, TBM, etc);
- associated supplies (drill bits, TBM cutters, blasting agent);
- support costs; and
- elimination of temporary construction structures (access adits and/or shafts).

Major differences in cost may be attributed to:

- cost to fill overbreak with concrete

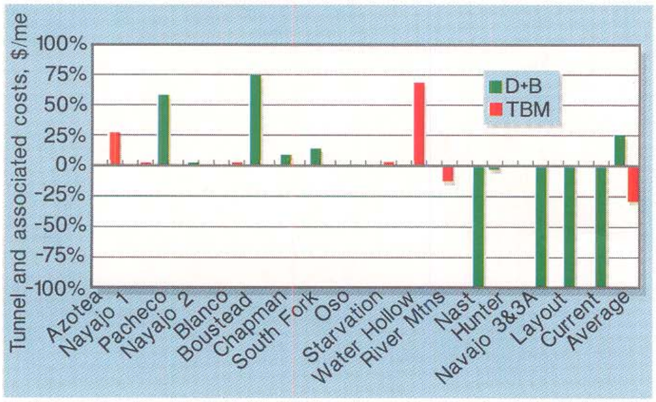


Fig 4. Drill+blast and TBM excavation cost variations.

(delivered concrete, wastage and labour);
- crew labour costs;
- equipment costs for each heading (drills, jumbos, muckers, trains, TBM, etc);
- associated heading supplies (drill bits, TBM cutters, blasting agent);
- support costs;
- elimination of temporary construction structures (access adits and/or shafts); and
- intangible cost savings resulting from the smoothness of operation in excavation as well as final cast-in-place lining.

The cost comparison has been based on Hong Kong and Taiwan conditions to establish applicability and consistency of conclusions. A full and realistic construction estimate should be prepared for all projects during feasibility, design, construction tendering, and establishing the methods of excavation and support.

Cost comparisons of drill+blast and TBM excavation must inevitably include the following differences in labour requirements:
- fewer crews required for a single TBM working face (TBM excavation rate roughly equivalent to four to six drill+blast working faces);
- TBM crew may be larger (a foreman, an operator/mechanic, an electrician, two labourers for utilities, rails and support, a conveyor operator, two locomotive operators, two brakemen for a total of ten labourers at the heading and train. Recently in Norway, the same crew functions were performed by only four men);
- less skill and more easily trainable because operations are more consistent and continuous.

Since there is generally 90-95 per cent less steel rib support required for mechanically excavated tunnels, a considerable cost saving can be realised. The savings were calculated only for the steel ribs. Similar reduction in rockbolts and shotcrete and other types of support can also be realised. Labour cost savings associated with differences in support will not be included, since they will be taken into account in advance rate comparisons and differences in crew composition.

Equipment costs in multiple drill+blast headings include drilling jumbo, mucking equipment and other support plant (air, water, discharge pumps, etc). It is particularly costly for headings, access adits or shafts in remote areas. In addition, drill +blast excavation would include cost of supplies such as spares, drill bits, drill steel, blasting powder and caps.

In contrast, TBM excavation costs will include the TBM (partial depreciation of a new machine or leasing costs for a rebuilt one) and cutter costs. Purchase of a TBM requires long term investment for use of a machine in more than just one project.

The single most extraordinary saving that can be realised with TBM excavation is the possibility of eliminating temporary excavation structures such as access adits, tunnels and shafts. This becomes possible with a single TBM heading having the same rate of excavation advance as four drill+blast headings. The cost of an access adit or shaft in Hong Kong is about US$6.5m - US$7.7m (for a 3-3.5m tunnel).

Some temporary access structures and associated blasting may also be highly undesirable for the local population. In remote areas, temporary access structures may be difficult, costly and unnecessary.

Historical cost comparisons

Some general cost comparisons may be made for conventionally and mechanically excavated tunnels. Groseclose and Tackett[5] provided comparative data of this nature. However, it note that contract terms varied (lump sum and unit price); total cost included over/underruns; total contract cost included associated structures. A simple comparison to be used with caution does confirm the greater economy of mechanical excavation (Figs 3 and 4).

Data presented by Groseclose and Tackett[5] also make it possible to compare cost over/underruns for each tunnel. Cost over/underrun data is presented in Fig 4. It is apparent that tunnel boring is less likely to produce cost overruns and may even produce cost underruns.

It is evident that TBM excavation has substantial cost advantages when temporary structures are eliminated. Initial capital investment for a TBM and its backup system is sizable. The cost comparisons were based on partial depreciation of a new TBM or alternatively on the full leasing cost of a refurbished TBM.

Conclusions

- A major cost saving associated with TBM excavation is the possibility of eliminating temporary construction structures as a consequence of high excavation rates;
- TBM excavation provides only marginal tangible advantages at low progress rates without considering cost savings from eliminating temporary structures;
- TBM excavation provides significant advantages at high progress rates without considering cost savings provided by elimination of temporary structures. ■

Acknowledgement

The material contained in this paper is a response to our client's concerns regarding the use of TBMs in Hong Kong and Taiwan. Two TBMs have completed excavation in Hong Kong and TBMs for the Pinglin Tunnel in Taiwan and will be operational at the time of publication.

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