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Tunnels and Underground Spaces: Sustainability and Innovations

CHOICE BETWEEN TUNNEL BORING MACHINE AND DRILL & BLAST SYSTEM

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ABSTRACT

Traditionally, tunnels have been excavated by drilling and blasting method, but now with the advent of road headers and Tunnel Boring Machines (TBMs), there has been a significant increase in the rate of excavation and improved safety record. Often in problematic reaches, drill and blast methods come to the rescue and are handy (Ramamurthy, 2008). When unfavourable or changed conditions are encountered without warning, it has a far greater impact on the rate of advance, construction costs and schedule delays in a TBM driven tunnel than in a drill and blast tunnelling.

The choice between TBM and drill and blast is an often faced dilemma. It is not surprising as these two methods have been competing for more than thirty years (Nord, 2006). During this time period both methods have made major technical advances. The main difference between conventional mechanized drill and blast and TBM tunnelling is related to the process cycle and operational continuity. There are only a few tunnelling projects where the excavation method can be selected before a proper investigation and estimations have been made. The choice between the two methods is an open question before the bottom line on risks, time and cost is arrived at.

In this paper, the conditions for the judicious selection of the excavation method have been highlighted and discussed considering the following factors:

A. Tunnel Design Parameters: Diameter, length, inclination and shape.
B. Rock Mass Characteristics: Strength, geological features, abrasiveness, hydrogeology and rock mass rating.
C. Performance Factors: Rate of advance, boreability, over-break, support requirements and skill of the available labour.
D. Contract Related Factors: Environmental and safety constraints, cost and quality.

RÉSUMÉ

Traditionnellement, les tunnels ont été creusé en entraînant et exploser la méthode, mais maintenant avec la venue d'en-têtes de route et de Tunnel Ennuyant des Machines (TBMs), il y a eu une augmentation significative dans le taux d'excavation et de rapport de sécurité amélioré. Souvent dans les portées problématiques, les méthodes d'exercice et explosion viennent au secours et sont pratique (Ramamurthy, 2008). Quand les conditions défavorables ou changées sont rencontrées sans l'avertissement, il a un plus grand impact éloigné sur le taux d'avance, les coûts de construction et les retards de plan dans un TBM le tunnel motivé que dans un exercice et une explosion qui creuse un tunnel.

Le choix entre TBM et l'exercice et l'explosion est un dilemme souvent fait face à. Il n'étonne pas comme ces deux méthodes ont concouru pour plus de trente ans (Nord, 2006). Pendant cette période que les deux méthodes ont fait des avances techniques majeures. La différence principale entre l'exercice et creuser un tunnel d'explosion et TBM mécanisé conventionnel est relatée au cycle de processus et à la continuité opérationnelle. Il y a peu de creusant un tunnel des projets où la méthode d'excavation peut être avant choisie qu'une investigation et les jugements corrects ont été faits. Le choix entre les deux méthodes est une question ouverte avant le résultat sur les risques, le temps et le coût sont arrivés à.

Dans ce papier, les conditions pour la sélection judicieuse de la méthode d'excavation ont été soulignées et ont été discutées in Vu les facteurs suivants :

A. Paramètres de Conception de Tunnel d'a.: Le diamètre, la longueur, l'inclination et forme.
B. Caractéristiques de Masse de Rocher : de la force, les caractéristiques géologiques, la rudesse, la masse de hydrogeology et rocher qui évalue.

C. L'Exécution de c. Factorise: Le taux d'avance, boreability, la sur-coupure, soutenir des conditions et la compétence du travail disponible.

D. Le Contrat de d. A Relaté des Facteurs: Contraintes écologique et de sécurité, le coût et la qualité.

1 INTRODUCTION

Traditionally, tunnels have been excavated by drilling and blasting method, but now with the advent of road headers and Tunnel Boring Machines (TBMs), there has been a significant increase in the rate of excavation and improved safety record. Often in problematic reaches, drill and blast methods come to the rescue and are handy (Ramamurthy, 2008). When unfavourable or changed conditions are encountered without warning, it has a far greater impact on the rate of advance, construction costs and schedule delays in a TBM driven tunnel than in a drill and blast tunnelling.

It appears that TBMs and drill and blast method (DBM) are expected to provide constructability options for contractors to be competitive. In the tunnelling industry, where market conditions continue to demand higher advance rates and lower costs, TBMs offer numerous benefits, including higher advance rates, continuous operation, less rock damage, uniform muck characteristics, greater safety and potential for remote automated operation. On the other hand, the drill and blast method is very flexible and adaptable. The definite answer to which tunnelling method should be chosen is always a tough question.

Proper choice of the tunnelling method is crucial for the engineers and contractors, as mistakes or misjudgements can have serious consequences, both for the economic viability and the overall success of the project. Tunnelling engineers have to make judicious choices on a case-by-case basis considering the site conditions and expected outcome. When both TBM and DBM are feasible, a careful assessment of the risks must be made, particularly, in terms of safety, economy and productivity.

1.1 Factors Affecting the Choice of Tunnel Method

A. Tunnel Design Parameters: Diameter, length, inclination and shape.

B. Rock Mass Characteristics: Strength, geological features, abrasiveness, hydrogeology and rock mass rating.

C. Performance Factors: Rate of advance, boreability, over-break, support requirements and skill of the available labour.

D. Contract Related Factors: Environmental and safety constraints, cost and quality.

1.2 Tunnel Parameters

1.2.1 Diameter

Although TBMs have excavated tunnels more than 15m diameter, yet it is better to limit the size of the tunnel due to the following reasons:

- The success potential of a TBM in hard rock decreases with increasing diameter (Kovari et al., 1993; Bruland, 1998).
- There are technological limits for the maximum dimensions of some major TBM components e.g. the bearing and the head (Nord,2006).
- The intensities of both the instability phenomena and the induced convergence also increase with increasing diameter of excavation (Tseng at al., 1998; Barla G. and Barla M., 1998)

A TBM drive requires a pre-determined (fixed) tunnel diameter but it can excavate a circular profile with a high degree of accuracy. However with the drill and blast system, the tunnel cross-section can be driven to any required size or shape and most importantly the tunnel size and shape can be changed along the length of the drive.

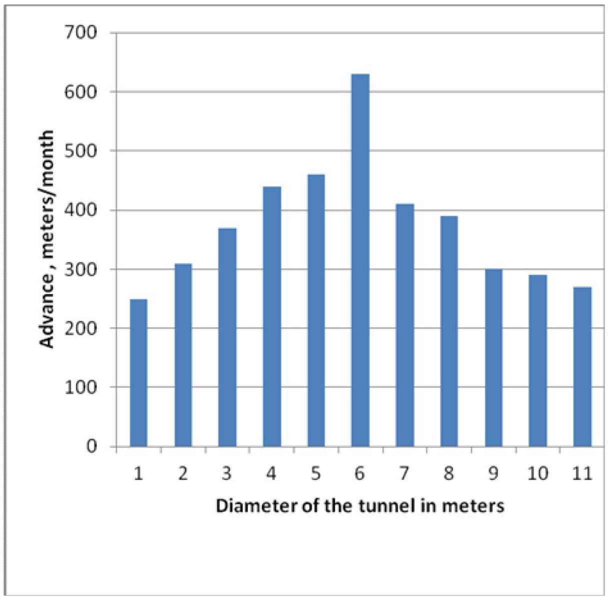

Figure 1. Diameter of the tunnel vs. Average Advance / month

1.2.2 Length

Since the mobilization cost of TBM is high, it requires a long tunnel to justify a large capital investment. Therefore TBMs will be used where tunnels are to be long and of uniform cross-section and profile.

The conventional drill and blast method is therefore most often used on shorter tunnels.

In the case of long tunnels with favourable geology, relatively high advance rates can be achieved with a TBM. However as soon as the geology becomes complex and there are zones of disturbance, drill and blast performance can become significantly better as compared with a TBM.

A simple indicator on when a TBM solution might be suitable is to make a simple estimate as shown below. The formula simply says

Tunnel length (m)/Tunnel dia. (m) x (UCS in Pascals)$^{1/3}$ > 1.5 (Nord, 2006)

That if the tunnel length divided by the tunnel diameter and the unconfined compressive strength of the rock at power of one third and the result is larger than 1,5 it might be worthwhile to check the TBM alternative. The trigger value of 1.5 using the above formula is not as accurate as it might seem and perhaps it would be better to say that when the result is 3, the TBM option is definitely a viable solution and when the value is less than 1, the TBM option should be considered less favourable than the DBM. Please note that this expression has no scientific back up. Poor ground conditions are not foreseen here and nor is abrasive rock considered (Nord, 2006).

Based on the research at the Swiss Federal Institute of Technology, TBM technology shows excellent cost efficiency in the case of tunnels longer than approximately three kilometers. The exact length depends upon the rock mass characteristics, tunnel parameters, labour cost and utilization factor.

PARAMETER	RANGE	METHOD	REMARKS
Length (Km)	<0.5	DBM	Strongly recommended
	0.5-1.0	DBM	Recommended
	1.0-2.0	DBM	Preferred
	2.0-3.0	DBM or TBM	
	>3.0	TBM	Preferred
Diameter (m)	<3.0	DBM	Preferred
	3-10	TBM	Preferred
	>10	DBM	Preferred
Inclination in Degrees	<6	TBM or DBM	
	>6<30	DBM	Recommended
Curvature	<30m radius	DBM	
	>30m radius	TBM or DBM	
Shape	Circular	TBM	Preferred
	Non-circular	DBM	Strongly recommended
Cross-section	Uniform	TBM or DBM	
	Variable	DBM	Strongly recommended

Table 1. Preference of the tunnelling method based upon the tunnel parameters.

1.3 Shape

The drill and blast system is very adaptable and flexible in regards to the excavation of any tunnel cross-section (Grimscheid and Schennayder, 2002). A circular profile can be excavated with a high degree of accuracy by a TBM. However, with drill and blast system the tunnel cross-section can be created to any required shape or size and most importantly the tunnel shape and size can be changed along the length of the drive.

The suggestions for choice between tunnel boring machine and drill and blast system have been presented in table 1.

1.4 Rock Mass Characteristics

1.4.1 Strength

The TBM excavation with respect to advance rate is by far much more depending on the strength characteristics of the rock than drill and blast.

1.4.2 Geological Features

Geological conditions to be encountered such as, faults and ground water can have a major impact on machine performance, application, operation and the production rate. These parameters must be accounted for when estimating the machine utilization, which is a key parameter in scheduling. Analysis of field performance of different TBM projects is the foundation for estimating the effect of these geological features in the rock mass.

The opinion is that drill and blast method offers a higher flexibility and consequently better opportunities to cope up with unforeseen conditions. According to Nord and Stille (1988), variable rock conditions favour the choice of the blasting method. Water conditions affect both methods, but the TBM is more hampered than the drill and blast system if pre-grouting has to be done. The variation in tunnelling speed when excavating in favourable versus unfavourable ground conditions is also less for the drill and blast than the TBM method.

In the case of TBM, massive rock is unfavourable for fast penetration, while for DBM , it is obviously favourable due to the lack of tunnel support needs and can be drilled at reasonable speed despite the lack of jointing.

1.4.3 Rock Type

The overall composition of the rock mass holds a first order control on TBM penetration. The more mafic (Iron and magnesium rich) the rock mass the lower the penetration. Some rock types (such as fine grained or glassy dike rocks, amphibolites, pegmatite, intrusive, garnetiferous zones, quartz veins) have important bearing on TBM penetration and these should be identified and categorized accurately. Unique igneous and metamorphic textures can make or break a tunnelling contract (Merguerian, 2005).

1.4.4 Abrasiveness

The abrasiveness of a rock or soil is its potential to cause wear on a tool. It is an important parameter to assess the technical and economical aspects of a tunnelling method.

PARAMETER	RANGE	METHOD
Geology	Variable	DBM
Compressive strength, MPa	<300	TBM or DBM
	>300	DBM
Strength and hardness	Variable	DBM
Rock Quality Designation	30-80	TBM Preferred
	<30 or <80	DBM Preferred
'Q' System	<0.1	DBM Preferred
	0.1-10	TBM most competitive
	10-15	TBM preferred
	100-1000	DBM recommended
RMR System	40-80	TBM Preferred
	<40 or >80	DBM Preferred
Ground water problems	Severe	DBM Preferred

Table 2. Preference of the tunnelling method based upon geological and hydrological conditions.

1.4.5 Rock Mass Rating

Nick Barton (2000) found that the TBM technique is most competitive time wise versus drill and blast when rock conditions are in the Q-range 0.1 to 10 on his rock quality scale (Figure 2).

It should be pointed out that this is a hypothetical statement but it does points on to the difficulties the TBM excavation faces when entering into a very poor ground.. Many cases have been recorded where TBM technique has to be abandoned in favour of the drill and blast technique. But also on the very end of the quality scale the TBM excavation will be difficult due to monolithic character of the rock yielding only few joints.

In low quality rock, the penetration rate can be potentially very high but the support needs, rock jams and gripper bearing failure result in slow advance rate, with utilization coefficient as low as 5 – 10% or less (Barla and Pelizza, 2000).

Grandori (1995) correlated the advance rate of the TBM with RMR value. It showed that RMR class III provided a peak in production for a double shield TBMs, while they would not be recommended for neither class V (very poor) nor class I (very good rock masses).

The choice between TBM and DBM on the basis of geological and hydrogeological considerations have been suggested in Table 2.

1.5 Performance Factors

1.5.1 Rate of Advance

In the case of drill and blast system, equipment is available in various sizes and are selected to fit the actual tunnel size. In a larger tunnel, more drilling machines can operate in parallel and larger unit can be deployed for mucking and hauling. Therefore, there is no direct relationship between tunnel size and advance rate for drill and blast operations.

Dr. Nick Barton analysed a large number of TBM driven tunnels and has concluded that there is a major variation in the rate of advance and penetration rate depending on the rock quality. He suggested a tunnel stability relationship based on Penetration Rates vs. Rock Quality Designation for TBMs. (Barton, 2000). Since the time that this was developed by Barton, we have not seen any recent research to suggest that the TBM technology has advanced in terms of penetration rates based on Barton's work.

Barton (2000) also made a comparison between advance rates of TBMs and DBM as shown in Figure 2. Although this relationship suggests a relationship based on project based information. That being said, TBM and DBM equipment improvements over the past decade have increased the equipment efficiencies and as such the relationship between Rock Quality and advance rate for TBM and DBM should be updated.

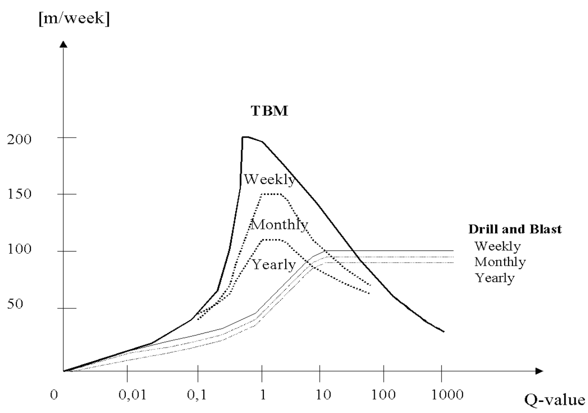

Figure 2. Comparison of advance rates for TBM and DBM (After Barton, 2000).

1.5.2 Boreability

When the TBM cannot penetrate the face to a sufficient rate and/or the wear of the cutting tools exceeds an acceptable limit, it is an indication that rock is not borable. The penetration rate per revolution of the cutter head which can be achieved under the maximum thrust is the main index describing the capacity of a TBM to excavate a given rock. A limit of penetration per revolution below which a rock shall be considered non-borable is influenced by the abrasivity of the rock, the diameter of the tunnel and the geology of the rock formation. The high abrasivity associated with low penetration dictates frequent changes of cutters, increases the cost of excavation per unit of rock, in addition to the time lost in replacing the cutters.

The penetration rates below 2-2.5 mm/rev of the cutter head is a signal of boreability problems. An excavation process starts to be efficient when the penetration rate crosses 3-4 mm/ rev.

When the diameter of the tunnel increases, three different effects make the situation worse (Barla and Pelizza, (2000):

- The rotational speed of the cutter head should decrease for an equal penetration per revolution, because the bearings and seals of the disk cutters permit only a maximum speed equivalent to 150 m/min.
- The number of cutters to be changed per meter of tunnel advance increases, therefore, increasing the stopping time required for such operations.
- The state of average wear of the cutters mounted on the head increases, thus decreasing the penetration per revolution.

Under extreme conditions, each one of the above three factors excites the other one bringing the progress rate down to unacceptable values. For these reasons, a rock type may be borable for a TBM of small diameter, but not for a TBM of large diameter.

If ROP is the average rate of penetration, then

ROP = boring length in meters/ boring time in hours

Penetration per revolution, P_r = (ROP x1000)/ (RPM x 60) mm/rev.

RPM is cutter head revolutions per minute

Field Penetration Index, FPI =F_n / P_r KN/cutter/mm/rev.

F_n is the cutter head load or normal force in KN

The choice between TBM and DBM on the basis of work done by Barla and Pellizza, (2000) and Hasanpour et al, (2011) is given in table 3.

PARAMETER	**RANGE**	**PREFERRED METHOD**
Field penetration index(FPI) (Kn/cutter/mm/revolution	7-70	TBM
	>70 and <7	DBM
Penetration per revolution (mm)	<3	DBM
	>3	TBM

Table 3. Preferred tunnelling method based upon on the boreability of rocks.

1.5.3 Support Requirements

Most tunnels will require support to ensure its long term stability. The type and magnitude of the support is determined by the rock mass characteristics, water conditions and state of stress. In general, less support is needed for a TBM than a drill and blast operation. In cases where drill and blast requires only little support, the TBM in similar conditions may require no support. In cases where heavy support is needed for drill and blast operations, the support measures and stabilization ahead of the face will not be less for TBM technology. In fact, they may be even larger and certainly take much more time due to the difficulties with installations of supports right behind and ahead of the cutter head. When heavy support is needed, TBM operations will provide lower advance rates than the DBM system (Barla and Pelizza, 2000).

1.5.4 Equipment Utilization

The TBM operations experience down time due to changes of cutters, regripping, maintenance and down time etc. All this down time adds up to 40-60% of the available operating time.

1.5.5 Skilled Labour

One crew is required for a single TBM working face but TBM crew will be larger. Crew needs higher skill level, but are easily trainable because operations are more consistent and continuous.

The suggestions for the choice between TBM and DBM on the basis of operating requirements are given in table 4.

REQUIREMENT	**PREFERRED METHOD**	**REMARKS**
Equipment mobility	DBM	
Easy housekeeping	TBM	
Short lead times	DBM	
Almost uniform muck size	TBM	Crushed fines and chips

Table 4. Preferred tunnelling method based upon the operating requirements.

2 ENVIRONMENTAL AND SAFETY CONSTRAINTS

2.1 Overbreak

Overbreak is the excavation of the rock beyond the designed profile. Overbreak increases the cost of mucking, support and concrete lining. Overbreak is generally influenced by the lithology, rock mass properties and quality of blasting. Overbreak caused by geological instabilities is generally larger when tunnelling by drill and blast than TBM. In some cases, however, it is more complicated during TBM excavation to support ahead and right behind the tunnel face and as a result of that support is installed at a very late stage resulting in larger collapses. These collapses have sometimes led to the complete burial of the TBM. Out fall behind the gripper pads of the TBM is another form of geological overbreak linked to the TBM operation. The overall experience is that TBM will generate less geological overbreak (Nord, 2006).

2.2 Vibrations

This is a major concern when tunnelling by drill and blast method in an urban environment. If the surroundings are highly sensitive to vibrations, there may be constraints in the amount of explosives that can be used per delay. This may limit the progress of the DBM. However the problem is alleviated with latest advances in drill and blast technology. In case of TBMs, there are significantly less disturbances to the surroundings.

2.3 Safety and Environmental Risks

Tunnelling is not a risk free technology. Drilling and blasting system is quite challenging when tunnelling in populated areas. Not only is the work closer to people, structures and utilities, but environmental concerns about blasting effects on flora fauna and water resources need to be considered. In addition, government scrutiny of commercial explosives activities due to terrorist incidents and continuing threats have increased public fears regarding the applications of explosives in urban environment.

On the other hand, premature surrender to TBMs, sometimes becomes a costly decision. The sensitivity of TBMs to changes in actual conditions increases the probability of involved risks. During excavation, the situation can become critical at any minute, meter and under any circumstance. In some cases, the failure of a TBM necessitates the last minute switch to DBM. When blasting methods are introduced at the last minute without having proper planning and controls in place, the risks of blasting problems are increased.

During TBM excavation, the rock support in general is installed from within protected and shielded areas. Absence of blasting fumes and related problems inside the tunnel provides improved working environment.

Suggestions for the choice between TBM and DBM on the basis of environmental and safety requirements have been given in table 5.

REQUIREMENT		**METHOD**
Low vibrations		TBM
Minimum Overbreak		TBM
Low accidental risks		TBM
Low ventilation costs		TBM
Tunnel stability		TBM (except in very poor rocks)
Skill of the work force	Semi-skilled	DBM
	Highly skilled	TBM

Table 5. Preferred tunnelling method, based upon environmental and safety constraints.

2.4 Cost

Although a TBM tunnel project requires more demanding infrastructure in terms of roads, power supply, muck handling, work areas for storage and robust transportation needs, there are normally higher costs and longer times required for TBM mobilization. Transporting of the equipment to the site also needs additional time and cost. TBM tunnel projects require more electric power than DBM projects.

2.5 Tunnel Quality

During TBM excavation, it may be easier to ensure accurate alignment. The periphery of a TBM tunnel is smooth and usually has less overbreak. As such, tt is possible to maintain excavation preciseness with TBMs. Based upon the cost and quality requirements, the suggestions for the choice between a TBM or a DBM tunnel are given in table 6.

REQUIREMENT	**PREFERRED METHOD**	**REMARKS**
Low capital cost	DBM	Mobilization for DBM is much faster than TBM tunnels
Low supporting cost	TBM	Except in very poor rocks
Accurate alignment	TBM	DBM can be accurate with survey QA/QC
Smooth tunnel	TBM	
Excavation preciseness	TBM	Generally less overbreak with TBM drive

Table 6. Preferred tunnelling method based upon the costs and tunnel quality requirements.

5. CONCLUSIONS

TBM tunnel excavation represents a large investment in the decision making process with inflexibility with regard to changes in diameter and small radius curves and challenging vertical and horizontal alignments. As such, the use of TBMs for near horizontal excavation alignments can be a potentially rapid excavation and rock support method for rock tunnels.

On the other hand, DBM is very flexible and adaptable with comparatively lower advance rates. That being said, there is a need for careful planning for the optimum selection of tunnelling alternatives, because a wrong choice can lead to costly and time consuming consequences.

In this study, the suggestions for the selection of a tunnelling method based upon tunnel parameters, boreability, geological conditions, equipment operating requirements, power needs, environmental and safety constraints, costs and tunnel quality requirements have been made. The suggestions made in this paper may help facilitate the selection of the tunnelling method for a project or produce further investigation into the selection criteria and viability for each method during the design and contract bidding stages. Further research and review of project specific case studies in North America should to be investigated to determine the validity of the penetration rates when rock quality has been a factor in the tunnel equipment selection decision making process.

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