The advantages of tunnel boring : a qualitative/quantitative comparison of D&B and TBM excavation

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Introduction

Historical perspectives

TUNNEL boring was originally attempted over 150 years ago, simultaneously yet independently in England, Europe and North America. The original attempts are generally considered failures, except for the 1.5km Shakespeare tunnel in Dover, a part of the original Channel tunnel, bored over 100 years ago. The imagination of scientists and engineers were far ahead of the technology necessary to turn their concepts into practical reality.

Another major attempt to establish tunnel boring was made in the United States during the early 1950s and continuing into the 1960s with some success in very soft rocks. With advances in technology and a desire to excavate harder and harder rock, success was not always realized. Nevertheless, the use of Tunnel Boring Machines (TBMs) increased into the 1960s and 1970s with technological advances that allowed successful tunnel boring in harder as well as less competent rock. With each advance in technology and success in the field, unsuccessful projects were not uncommon.

As the use of TBMs increased worldwide, they were also used in labour-rich and capital-poor countries because of inherent advantages and because overseas TBM contractors became very competitive with local D&B excavation. In the late 1960s and early 1970s, the question often 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 remain impartial, TBMs cannot alone be considered a solution for concerns or problems of tunnel excavation, overbreak, support, dealing with difficult ground or timely completion. Avoidance of problems can only be accomplished with project coordination, management and planning while using the most suitable methods and equipment. That the most appropriate methods most often consist of tunnel boring, does not in itself guarantee successful tunnel boring.

With this in mind, let us look at the qualitative and quantitative advantages of tunnel boring.

Recent developments

Tunnelling and especially tunnel boring has had a particular fascination for engineers and contractors alike. The use of tunnel boring has increased through the last two decades to the extent that more than 20 tunnel projects are begun each year by new and used TBMs worldwide (Fig 1).

Although tunnel boring accounts for 80 to 90% of all civil tunnel excavation in North America and an ever increasing portion of tunnels worldwide, tunnel boring has not been the method of choice in many parts of the world. For example, in Hong Kong, reasons that have prevented the implementation of tunnel boring, until recently, were:

- the existence of hard granitic and volcanic rock
- plentiful and low cost labour

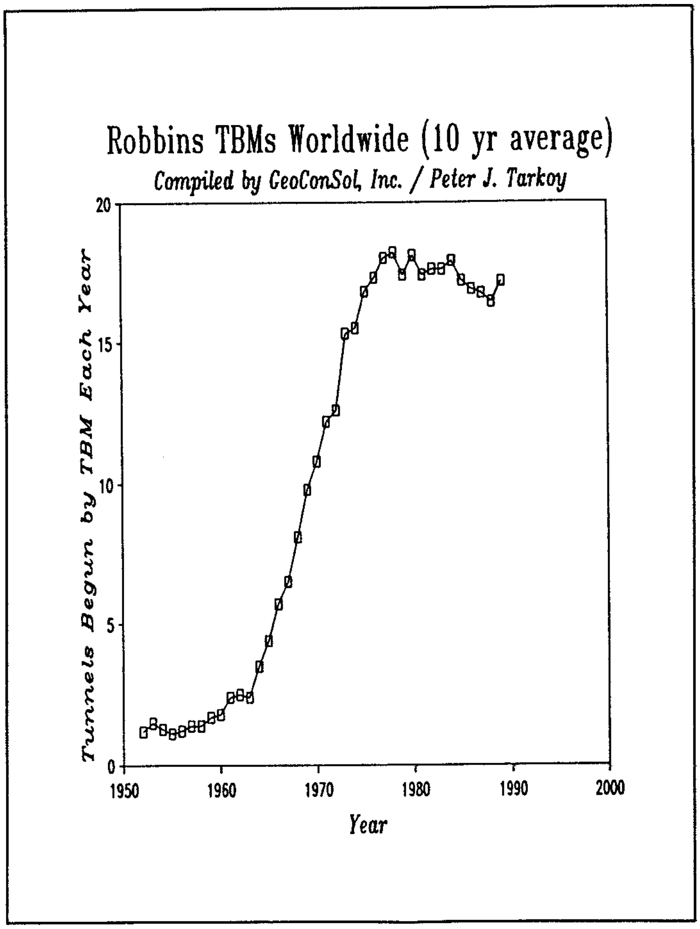

Fig 1 Tunnels begun each year by Robbins TBMs

- short lead times available for beginning conventional (drill and blast) tunnelling

As we speak, a new TBM is being built and a used TBM is being re-furbished to begin excavation in Hong Kong in less than *six* months.

Former advantages of D&B excavation

Rock hardness greater than that found in Hong Kong and up to 400 MPa has been successfully bored in other parts of the world in the past 10-15 years. Hard rock boring has become more and more economical as a result of the increase 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), and improvements in cutter metallurgy.

The availability of labour has dwindled in many countries. In Hong Kong the shortage of labour may be attributable to the many public works projects currently underway. Consequently, the cost and scarcity of skilled labour has dramatically increased. Furthermore, with the increase in the number of ongoing projects, Castle Peak Tunnel (9km), Hong Kong Electric's Second Cable Tunnel (5km), Tolo Harbour Effluent Export

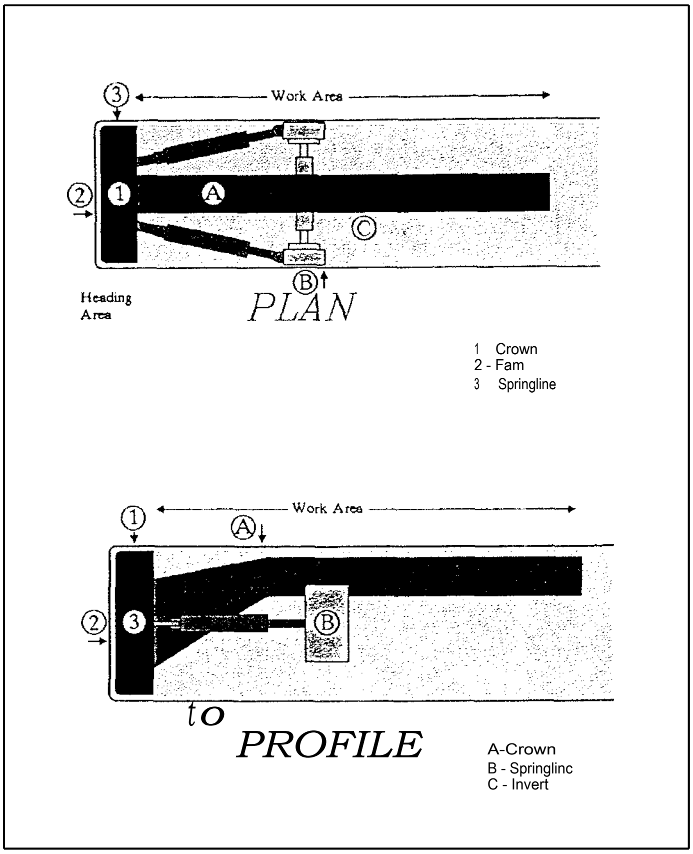

Fig 2 Face and work area stability considerations

Scheme (7.5km), Highway 3 (20km), the Master Sewerage Scheme (total of 30km of tunnels), it is expected that labour shortages, particularly skilled labour necessary for D&B excavation, will become crucial. A summary of anticipated projects have been summarized by Wallis (1989).

The short lead times can be dealt with in the following ways:

- use of reconditioned machines (short refurbishment time)
- early order of new machines
- partial pre-order of major machine components by the contractor

A study of TBM excavation rates will reveal that excavation by machine may allow time for the manufacture of the TBM, a delayed start of excavation, while still maintaining a timely project completion with less risk.

Basis *of comparison*

A simple comparison intended to identify the major cost considerations associated with drill and blast excavation and mechanical tunnel boring will be the subject of this paper. The comparison of conventional (D&B) and mechanical ('113M) excavation will be made on the basis of similar physical, labour, level of skill, mechanical and other conditions. Wherever possible, assumptions will reflect appropriate conditions and localexperience will be used for construction performance, excavation rates and workmanship.

Basic assumptions

When comparing D&B and' IBM excavation costs, project assumptions will be the same, namely in terms of tunnel length and diameter. The only differences will be in terms of:

- number of working headings
- the excavation advance rate (per working heading)
- qualitative differences between D&B and TBM excavation

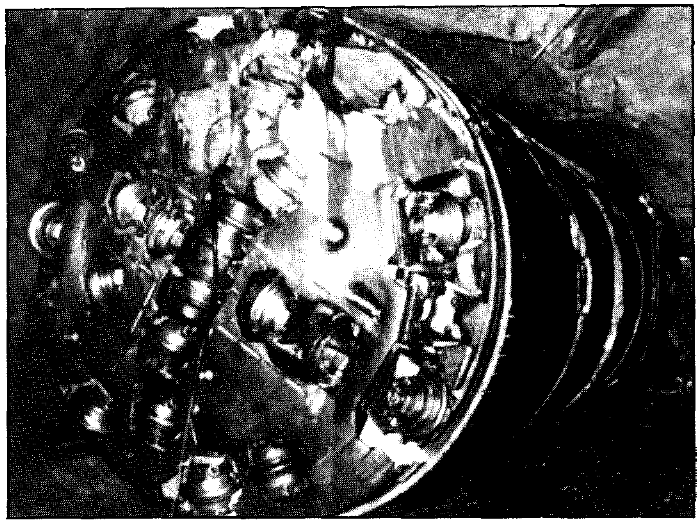

Fig 3 Recessed cutterhead and fully shielded TBM

- access structures (as needed only)

Case history data utilized

D&B advance rate experience is based on average Hong Kong excavation rates. The TBM advance rate is based on two reported case histories (Tarkoy, 1988; Tarkoy, 1989) and one recently visited site. Case history "TLHP" and "SRT" (Tarkoy, 1989) represent easily attainable advance rates possible under geological conditions similar to Hong Kong. Case "TLHP" represents advance rates without effective and ambitious project management, whereas, project "SRT" represents effective planning, rigorous project management and ambitious construction excavation. Similarly, the "SHEP" project is averaging nearly lkm per month.

Major cost items

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

- cost savings resulting from qualitative advantages of mechanical excavation
- l'BM excavation rates four to six times higher than D&B 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
- elimination of temporary construction structures (access adits and/or shafts)

The cost comparison has been prepared to be applicable only in Hong Kong. A full and realistic construction estimate should be prepared for establishing the method of excavation and support.

Operational advantages

There are a number of inherent advantages to tunnel boring which are difficult to quantify yet have a considerable impact on the outcome of excavation rates and costs. These are difficult to value in a tender. These advantages cannot fully be appreciated except from firsthand tunnel boring excavation experience. Some of these are:

- structural stability and safety at the face and work area
- continuous (non-cyclic) operation

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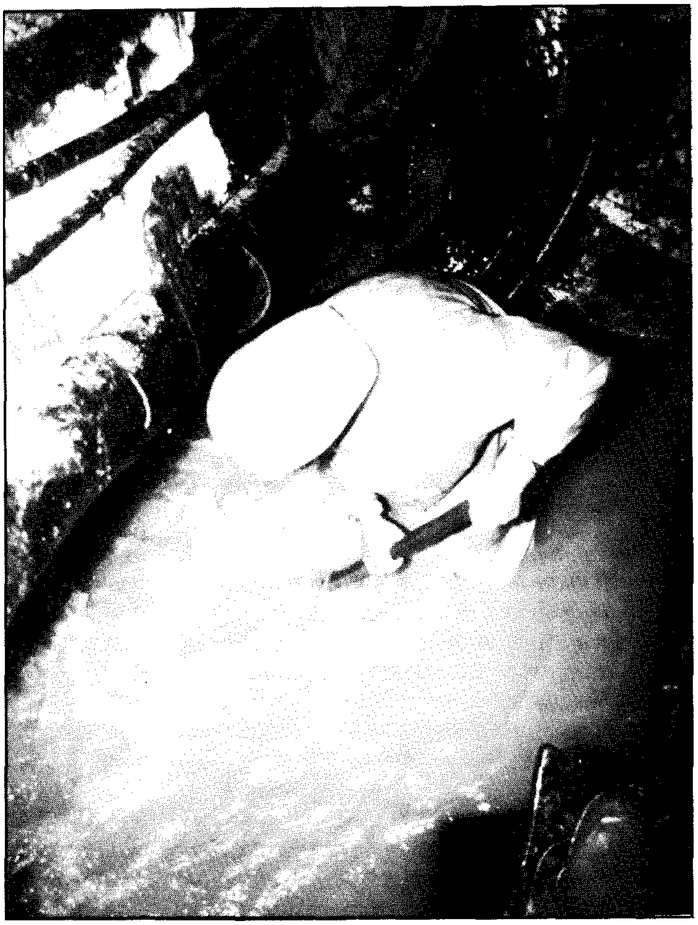

Fig 4 Stability in work **area (water inflow)**

- consistent, 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)
- safer and more pleasant working environment than in D&B

Structural stability and safety

The stability and safety at the excavation face, heading, work area and the lifeline out of the tunnel has always been of great concern in tunnelling. Current technology and tunnelling techniques provide the ability to provide safe and stable conditions in all areas illustrated in Fig 2.

There is an inherent level of stability in having a tunnel boring machine at the heading, supporting the work area or blocking possible inrush of materials into the work area. For example, many sudden failures at the heading (typical in fault zones in Taiwan) occur as a result of an excavation blast initially in rock, transgressing into unstable material, soil or a fault zone. The final blast in competent ground triggers the deteriorating ground conditions and a full blown collapse or tunnel inrush may occur even under the watchful eye of the engineer (eg - second Tienlun Power Tunnel).

The avoidance of blasting and the stabilizing effect of a full face machine has often been immeasurable, yet striking. The major zones of concern are at the tunnel face, ahead and around the TBM cutterhead and in the work area, as illustrated in Fig 2. These areas of concern may be summarized as follows:

- Heading
    - Face - **full** face cutterhead

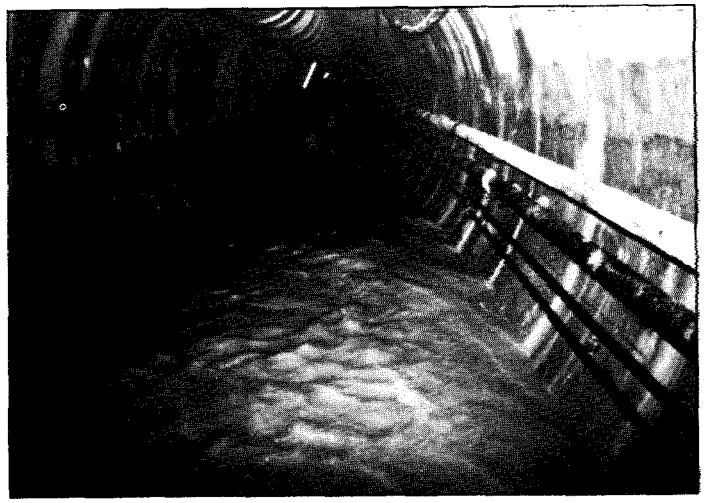

Fig 5 Stability behind work area (water inflow)

    - Crown cutterhead shield
- Work area
    - Crown finger shield, full
    - Springline arch shield, full shield
    - Invert invert shoe, full shield
- Behind the work area
    - temporary support
        - rock bolts, strapping, channels, and mesh
        - shotcrete
        - steel ribs and lagging
        - pre-cast segments (primary and/or final)
    - permanent support (pre-cast segments or cast-in-place close behind the excavation face)

Stability and safety is of particular significance in the heading and work area and recent TBM designs, such as illustrated in Fig 3 have maneuvered some of the most adverse ground conditions successfully. The most common solution developed for very difficult rock conditions such as flowing sand, swelling claystones or squeezing rock has been the use of various types of recessed cutterhead and shielded tunnel boring machines as illustrated in Fig 3. Fig 4 illustrates the same TBM having encountered 3001/sec flowing from the invert. Had the same tunnel been driven by D&B it would certainly have been impossible to work safely at the heading above voids with flowing water that were safely bridged, first by the shield and later by the pre-cast segments. 0

Fig 6 Stability behind work **area** (flowing sand)

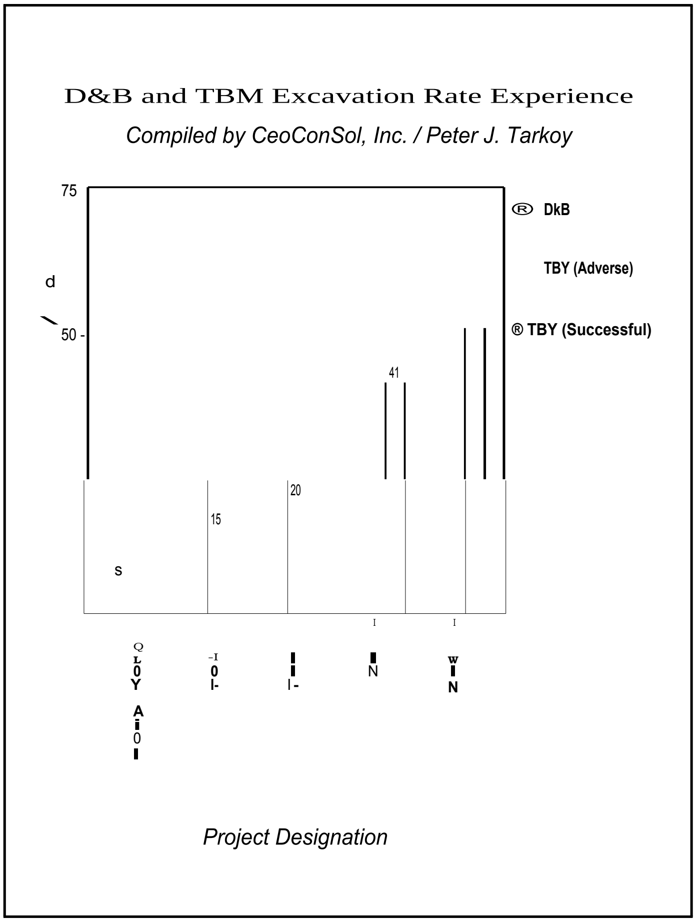

Fig 7 D&B and TBM excavation rate experience

Shielded machines as illustrated in Fig 3 have also been used, with and without temporary and final continuous pre-cast concrete lining, to protect against damage by water inflow (Fig 5) and support totally decomposed sandstone, some of which has entered the tunnel through grout holes (Fig 6).

Continuity of operation

Tunnel excavation is linear and TBM work crews perform consistent activities. For example, in conventional excavation, the entire crew generally performs cyclical operations including the drilling, loading, wiring, blasting, venting, scaling, installing support and mucking. This requires a variety of well developed competences and skills. In comparison, TBM crew members are generally assigned a much more limited and consistent set of tasks or responsibilities, such as:

- TBM operator
- mechanics and electricians
- general labour
  - installation of rail, utilities and support
  - maintenance
- train operation

All require fewer skills that are performed repetitively.

An added benefit of TBM excavation is that it does not interfere or conflict with installation of support or mucking.

Advantages in terms of skilled labour requirements

There are unique advantages and a lower labour skill requirements for TBM excavation because of its continuous nature and assignment of crew members to specific and limited responsibilities. First, the training of unskilled labour is easier than for comparative conventional excavation for the following reasons:

- each crew member has limited responsibilities and therefore is required to learn fewer skills
- since the operation is continuous and the activities of crew members repetitive, learning is continually reinforced and accelerated
- fewer high skill level tasks (machine operator, mechanic, electrician)

Fig 8 Illustration of overbreak (TDLR)

Performance advantages

TBM performance advantages can be directly related to quantitative benefits and differences which 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
- elimination of temporary structures

High excavation rates

One of the most significant advantages of tunnel boring are the high excavation rates which can be attained (four to six times higher than local D&B advance rates). D&B experience in

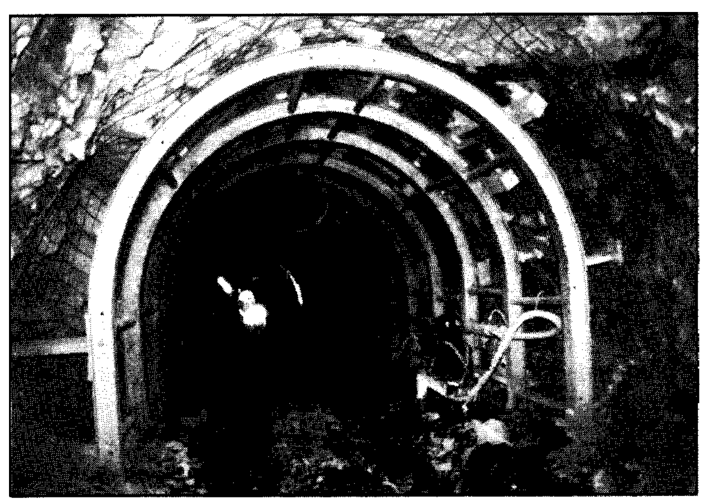

Fig 9 Illustration of overbreak (LD&T)

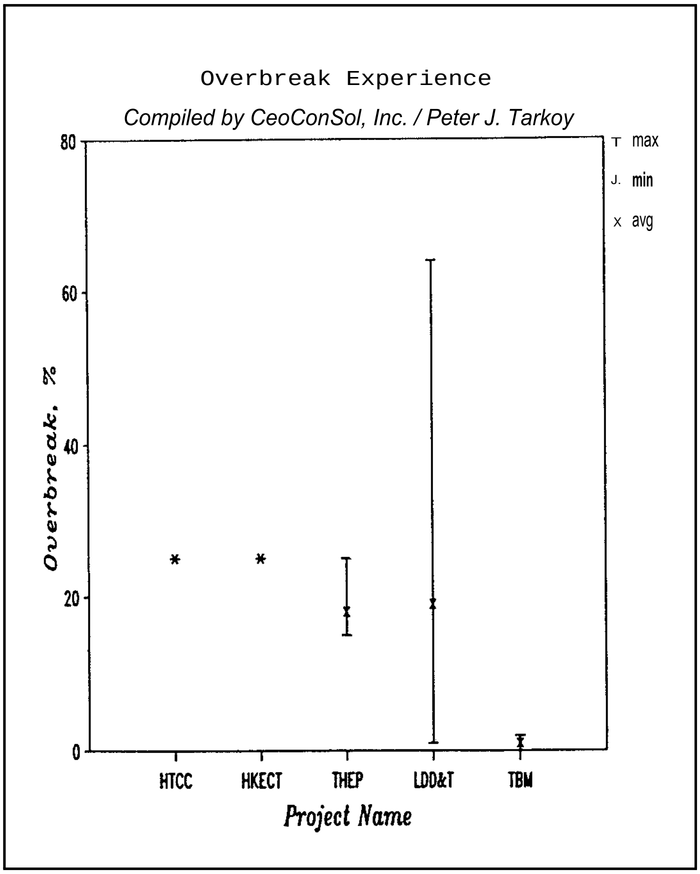

Fig 10 **Overbreak experience**

Hong Kong and TBM experience under similar conditions in other parts of the world are illustrated in Fig 7.

Overbreak

Overbreak is generally influenced by the following factors:

- lithology
- rock (intact and mass) properties
- quality of the blasting practices

Typically, no less than 10% overbreak should be anticipated in drill and blast excavation. However, in ideal conditions, using controlled blasting practices, a lower percentage of overbreak can be attained. Most commonly, however, the overbreak in Hong Kong, Taiwan, and where poor blasting practices are used, is quite high. Comparative illustrations between overbreak sustained in D&B and TBM tunnels is shown in Figs 8 and 9. Fig 8 illustrates a transition from good rock excavated by drill and blast and weak rock excavated by TBM and lined by pre-cast segments. Fig 9 illustrates a D&B tunnel excavation where in some cases the overbreak exceeded 60% of the face area.

This overbreak will eventually have to be filled with concrete, require building of special bulkheads, result in additional concrete wastage, and sustain a greater wastage, leading to substantial additional costs. Overbreak experience for several projects is illustrated in Fig 10.

Support costs

Tunnels excavated through similar geological conditions (portals starting from opposite sides of a river valley) have consistently required much more support when excavated by D&B than by TBM as illustrated in Fig 11. A study of seven sites where excavations by D&B and TBM encountered similar geological conditions, revealed that the average steel rib support in TBM excavated tunnels is 1/12 that of D&B tunnels as illustrated in Fig 12.

Since there is generally 90-95% less steel rib support required for mechanically excavated tunnels, a considerable cost saving can be realized with mechanical excavation. The cost saving thus calculated will be for the steel ribs only, however, similar reduction of rock-bolt, shotcrete, NATM and other types of support can also be realized. 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

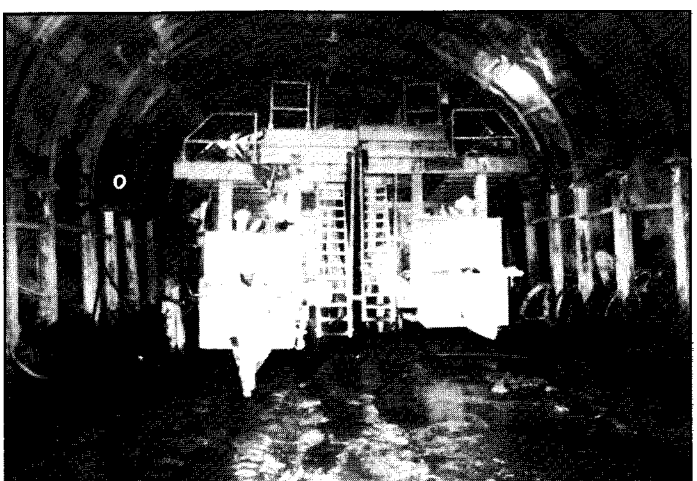

Fig 11 Illustration of D&B and TBM steel supports

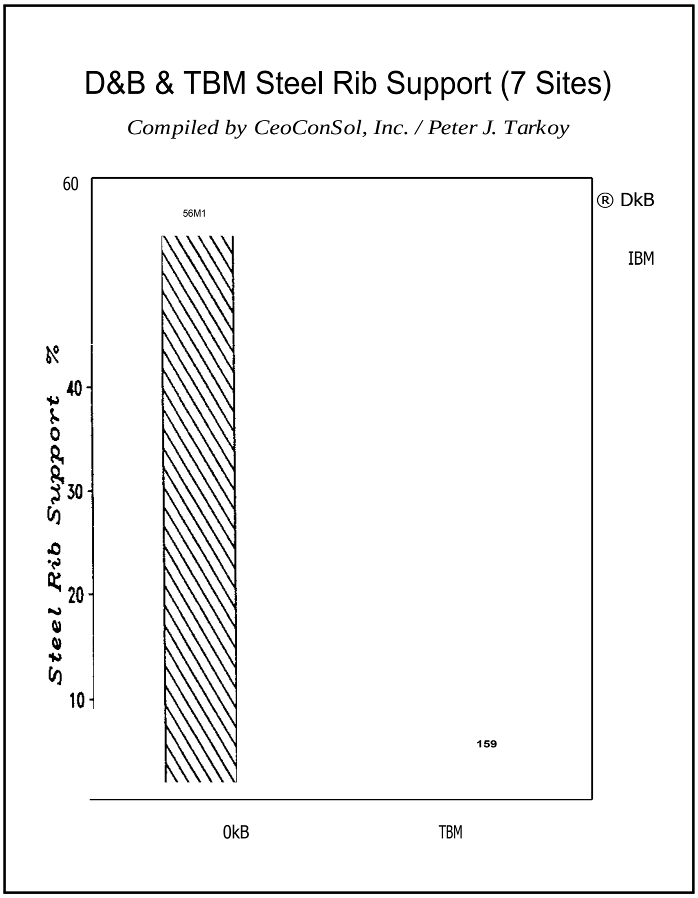

Fig 12 D&B & TBM steel rib support

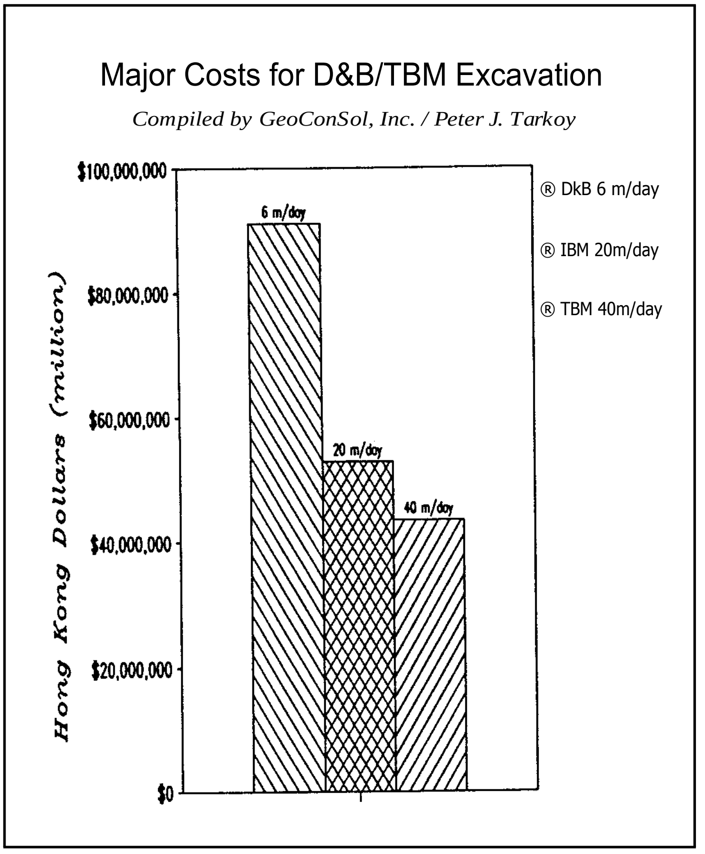

Fig 14 Major cost for D&B and TBM excavation

in crew composition.

Labour costs

Cost comparisons of D&B and TBM excavation must inevitably include the following differences in labour requirements:

- only one crew is required for a single TBM working face (TBM excavation rate roughly equivalent to four D&B working faces)
  the TBM crew will be larger (1 foreman, 1 operator/mechanic, 1 electrician, 2 labourers for utilities/rails/support, 1 conveyor operator, 2 locomotive operators, 2 brakemen for a total of 10 labourers at the heading and train; on a recent project in Norway, the same crew functions were performed by only 4 men)
- less skill and more easily trainable because operations are more consistent and continuous

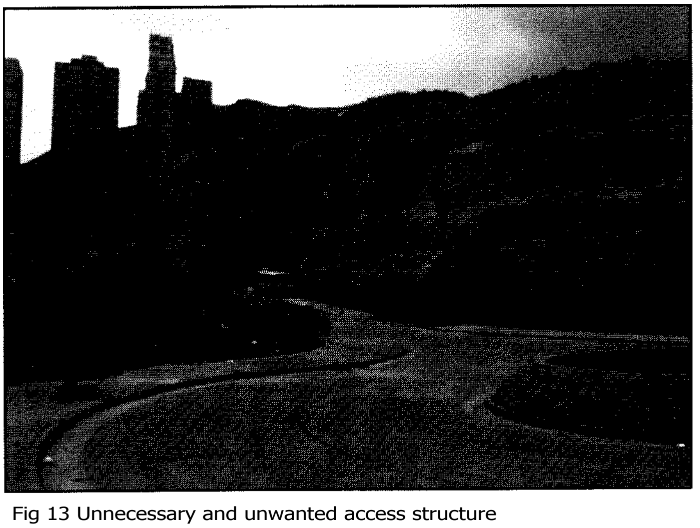

Fig 13 Unnecessary and unwanted access structure

Cost of equipment and supplies

The major equipment costs in multiple D&B headings are associated with the drilling jumbo, mucking equipment and other support plant (air, water, discharge pumps, etc). This is particularly costly when needed for isolated headings, access adits or shafts in remote areas. In addition, D&B excavation would include cost of supplies such as spares, drill bits, drill steel and blasting powder and caps.

In contrast, TBM excavation costs will be for the boring machine (partial depreciation of a new machine or leasing costs for a rebuilt machine) and the cutter costs. It is unusual that a new machine can completely be depreciated on a single project. The purchase of a TBM requires long term investment for use of a machine in more than just one project.

Elimination of temporary construction structures

The single most extraordinary saving that.can be realized with TBM excavation is in the possibility of eliminating temporary excavation structures such as access adits, tunnels and shafts. This becomes possible with a single'1 BM heading having the same rate of excavation advance as four D&B Dings.

In Hong Kong, the cost of an access adit or shaft, with associated workings, has been bid at about HK$50 million (for a 3-3.5m tunnel) recently.

Some temporary access structures and associated blasting may also be highly undesirable to local surroundings as for example in the residential neighbourhood of Hong Kong illustrated in Fig 13.

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Quantitative cost comparisons

The results of the cost comparisons are presented in Fig 14. It is evident that TBM excavation has substantial cost advantages when temporary structures are eliminated. TBM excavation costs in Fig 14 reflect a savings of nearly HK$50 million for the elimination of a temporary access structure. The initial capital investment for tunnel boring equipment 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

- TBM excavation offers major cost advantages at low progress rates with the major cost savings from the elimination of temporary construction structures.
- TBM excavation provides considerable advantages at high progress rates with some cost savings from the elimination of temporary construction structures.
- Inclusion of the cost saving associated with the elimination of temporary excavation structures provides a substantial cost advantage to TBM excavation.

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