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A tale of two tunnel bores

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ABSTRACT: Substantial improvements in the state-of-the-art of Tunnel Boring Machine (TBM) technology have been made over the last decade. Attaining predicted penetration rates require little more than turning on the switch, particularly with the newer machines that are computer controlled for startup and operation.

Improvements in geotechnical prediction and TBM performance have resulted in reliable estimates of penetration rates and cutter costs for construction estimating. Consequently, the emphasis on TBM performance has shifted from attaining higher penetration to sustaining lower downtime, higher utilization, and consequently greater daily advance.

More recently, there has been concern for reasonable penetration rates only in very hard rock. Technology has outrun (for the most part) the only remaining component of intervention through planning, design, management, and selection of a backup system capable of fully utilizing the capability of the machine to cut the rock. Managerial intervention is the only means to redesign the otherwise inevitable effect (TBM performance) that is caused the anticipated geological conditions.

1 INTRODUCTION

What produces a successful project when excavated by TBM ?

How is the highest TBM performance obtained ?

Why do some TBM projects sustain double the performance of others even though machines and geological conditions are for all practical purposes the same ?

How can the owner/engineer assure that their projects sustain the highest TBM performance possible (with associated savings) ? How can they get the most for their money and still allow the contractor a fair profit ?

What can a contractor, interested in high excavation rates, do to increase daily TBM advance ? As a contractor, how can the greatest performance be sustained for successful completion and profit with minimal risk ?

The answer to these questions is essentially the same, however, they answers must be implemented differently by owners, engineers, and contractors. Rather than suggest a cook book list of theoretical innovations, two case histories will be described. These two tunnel projects, bored with similar machines, in similar geology and under similar conditions, have been studied and compared to illustrate the impact of backup system selection and project management. They will provide some measure of practical possibilities available through rigorous planning and effective project management.

It is generally known that utilization decreases with increasing penetration rates due to the increase in length dependent downtime (support, volume of muck, installation of utilities and rail, cutter changes, travel time for laborers and muck, etc.).

Sine an increase in penetration rate will decrease utilization, it is counterproductive to attempt to affect substantial improvements in penetration. Maintaining a level of penetration rate while improving the utilization can produce much more effective and dramatic results.

Similarly, the concern for cost of cutter wear, can often be outweighed by the cost of labor associated with minor changes in the overall operation. In a project about ten years ago, two similar machines, in identical geology, utilized different cutter designs. The project with the longer lasting cutters sustained a lower penetration resulted in two months of additional excavation time than the TBM that used sharper cutters. It is obvious that the saving on cost of cutter hardware and labor to change them, was lost on an extended excavation time.

2 PROJECT DESCRIPTION

1.1 Geology

The pertinent geotechnical conditions are summarized in Table 1.

Table 1. Geotechnical conditions.

Condition	PROJECT A	PROJECT B.
Lithology	Granite	greywacke, argillite, diorite, diabase, & greenstone;
Structure	Massive, sparsely jointed, with 21 lineations or faults;	Highly jointed, with major shear zones;
max q_u, Mpa	~206	~10-115
Total Hardness	150	150
Supported	<10%	100%
rock bolts		71%
ribs		29%
Water Inflow	major	minor

1.2 Tunnel and Equipment

Pertinent project and TBM details are summarized in Table 2.

Table 2. Project and equipment details.

Project	A	B
Bored, km	7.3	6.3
Diameter, m	3.35	4.32
Head RPM	13.2	7.5
TBM	New	Used

Project B utilized a rebuilt TBM, whereas TBM A was designed specifically for this project.

The machines used to excavate the tunnel of Projects A & B are illustrated in Figures 1 and 2. They were of similar design except for the protection of some components against the anticipated heavy water inflows (max 1700 liters / second) in tunnel A.

The tunnel bores were close to the same length with tunnel B being one meter larger in diameter.

Figure 1. TBM used on project A.

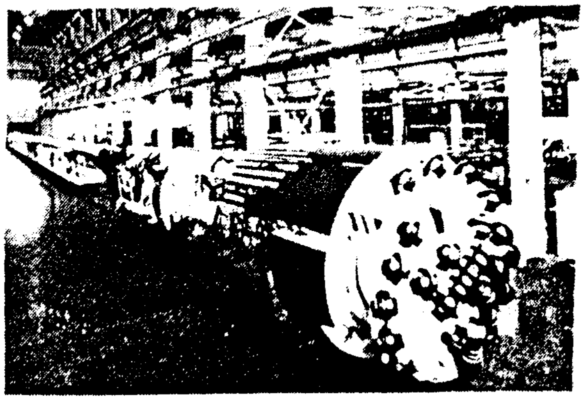
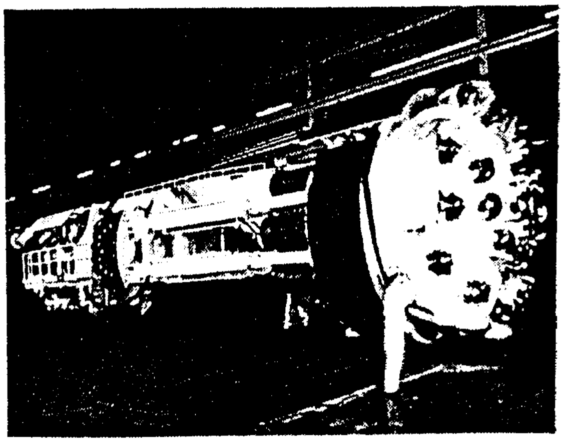


Figure 2. TBM used on project B.



2 TBM PERFORMANCE

Comparison of TBM performance is generally made by industry standard methods used to define boring performance as described in the following section.

2.1 TBM Performance Terms

TBM performance can be defined entirely by three variables (penetration, utilization, and cutter costs). In addition, a fourth (advance rate) is used to summarize the first two for purposes of estimating. They are as follows:

1. **AVERAGE PENETRATION RATE**, m/hr =

$$\frac{\text{length of tunnel bored, m}}{\text{elapsed boring time, hrs}}$$

(on a per shift basis)

INSTANTANEOUS RATE, mm/rev =

depth of cutter penetration/revolution

MINING RATE, m^3/hr =

$$\frac{\text{volume of intact rock excavated}}{\text{elapsed mining time, hrs (per shift)}}$$

2. **UTILIZATION**, % =

$$\frac{\text{elapsed machine time, hrs (per shift)}}{\text{excavation shift time, hrs (per shift)}}$$

3. **CUTTER COSTS**, \$/m^3 **OR** \$/m of tunnel

CUTTER LIFE, m^3 of rock cut/cutter

ROLLING PATH LIFE, km

4. **ADVANCE RATE**, m/day =

PENETRATION RATE x 24hrs x UTILIZATION
(for three 8-hr shifts)

The **penetration rate** is used to measure the progress when a full tunnel face or heading is advanced simultaneously. The **instantaneous penetration rate** is used to define the depth of cutter penetration per pass of the cutter.

The **mining rate** is generally used to measure progress when a part-face machine (roadheader or MOBILE MINER) is used to advance the heading by part-face mining.

The remaining portion of the shift time in addition to the utilization is the **downtime**. Downtime is predicted, encountered, and can be classified into some very common categories as will be seen in the analyses of the two tunnels.

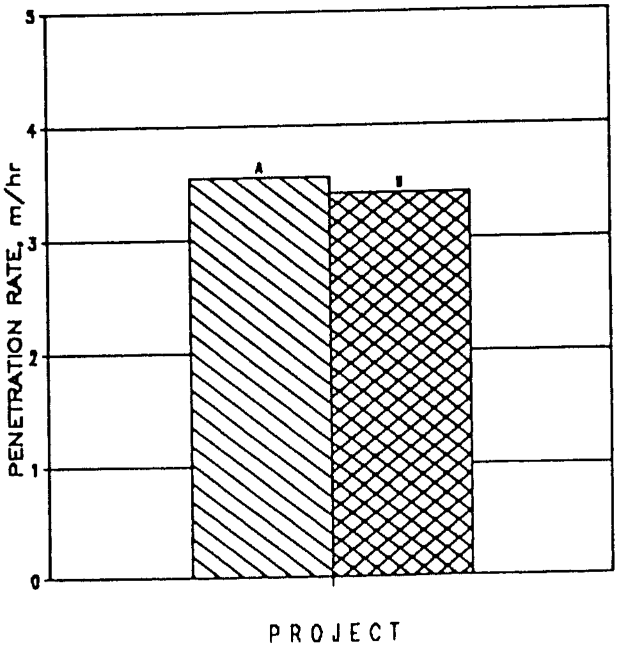
2.2 TBM Penetration

The TBM penetration rate is a function of cutter load, cutterhead rotational rate, and rock hardness. Both the rotational rate and cutter load can be varied, however, they are kept at a maximum under normal conditions to maintain the highest penetration rate. Load and rotation are only reduced when blocky, soft rock, or other adverse conditions are encountered. Consequently, the TBM is generally performing at its fullest capability throughout the excavation.

It thus becomes evident that TBM penetration is relatively fixed and depends on maximum TBM capabilities, rock hardness, and occasional adverse geological conditions. Once the TBM is designed, built, and installed in the tunnel, very little can be done to improve the rate of penetration.

It can be seen from Figure 3 that there was little difference in the penetration rates between the two tunnels. The smaller machine's higher rate, in spite of the higher rock strength (Table 1), is consistent with its higher cutterhead rotational rate (Table 2). In effect, both machines appear to offer the same potential for performance, at least in terms of the penetration rate.

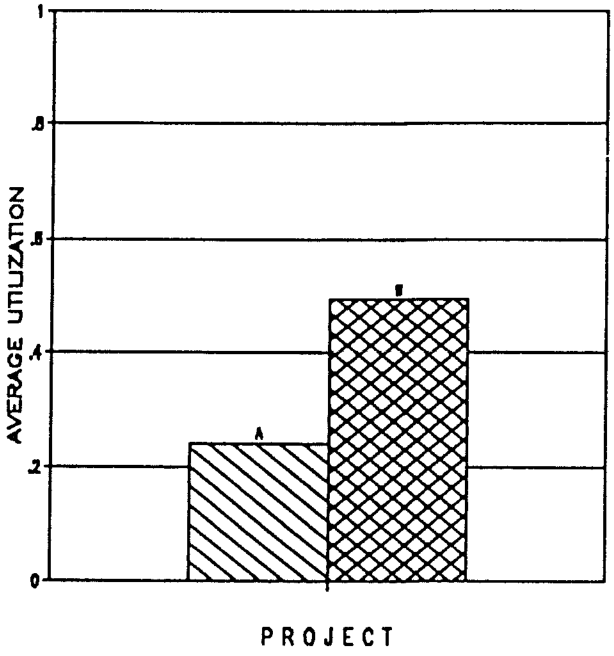
Figure 3. Average penetration rates.



2.3 TBM Utilization

So far, we have found that the penetration rate of both machines are relatively close. **In examining the encountered utilization sustained by these two contractors, we find sizable differences** as shown in Figure 4. The TBM on Project B was running for twice as much of the shift time compared with TBM A.

Figure 4. Average TBM utilization.



2.4 TBM Downtime

Although significant for comparison and for job performance summaries, TBM utilization provides no clue to the actual cause of actual performance differences. To find the underlying causes, **it is necessary to examine various downtimes sustained**, which diminish utilization. Categories of downtime sustained in each of the two tunnels have been classified according to convention in Table 3 and illustrated in Figures 5 A and B.

Project B sustained a great deal of downtime for placing support and waiting for or switching trains. It is understandable that with a high penetration rate, larger bore diameter, and high utilization, the limiting factors are length and volume dependent downtime. In spite of substantial downtimes in these two categories, a lower level of downtime was sustained in other categories as compared to project A. Furthermore, over all, the total downtime in B was only half of the downtime in project A.

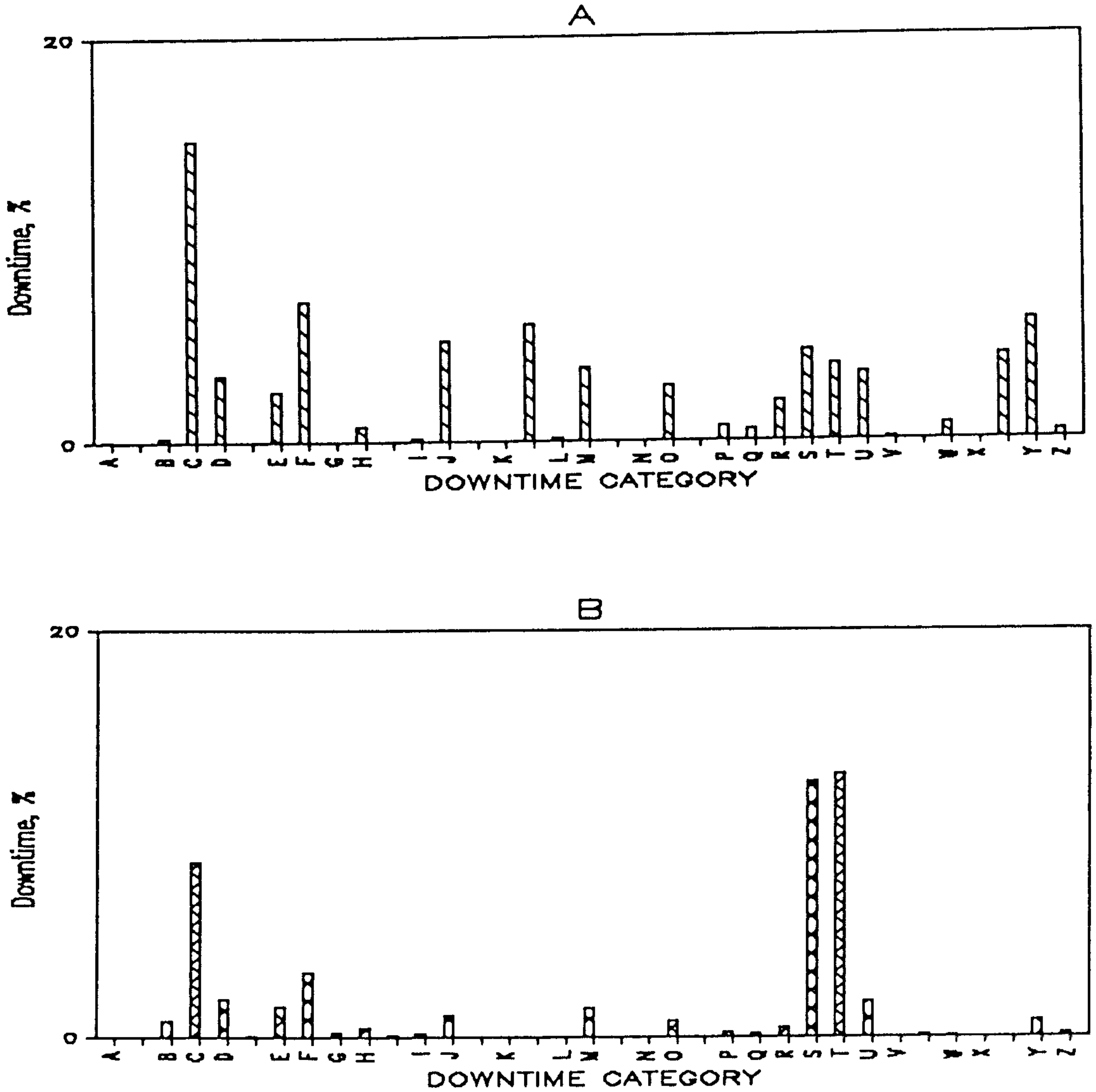
The project B tunnel required 100% primary support with 29% of it being ribs and lagging and the remainder rock bolts. Tunnel A had less than 10% support yet the downtime for support is only one-third that of project B.

Downtimes sustained in tunnel A (particularly: derailments (D), shift changes (F), muck clean-up in work area (J), TBM repair (K) and maintenance (M), utility installation (U), and other excavation delays, and problems with the conveyor (Y)) were generally higher than in tunnel B.

Table 3. Downtime categories.

Code	DOWNTIME CATEGORY
A	fallout/scaling rock scaling and rock jam
B	gripper bearing/cribbing
C	cutter check/change/tighten bolts
D	derailment/track problems track problem / track placement
E	electric/no power/extend cables
F	shift change/safety meetings
G	gas/test gas detectors
H	hydraulics/lube lube
I	lunch/sandwiches
J	clear rock/muck clear rock fallout
K	segment hoist related downtime tbm repair
L	unclassified failures/breakdowns
M	prev. maintenance/inspection/lube repair/maintenance/inspection
N	re-mine/ream
O	other/unknown shaft/portal operations
P	probe drilling/other drilling
Q	surveying/engineering/set laser
R	re-stroke/re-grip tbm
S	support placement
T	train wait/unload/breakdown/hangup
U	utilities (water/air/drain)
V	ventilation/problems with dust ventilation installation/problems
W	water inflow/etc.
X	personal injury D & B / other excavation
Y	conveyor/gantry/trailing gear
Z	clearances/hangups/etc

Figure 5. Summary of TBM downtimes.



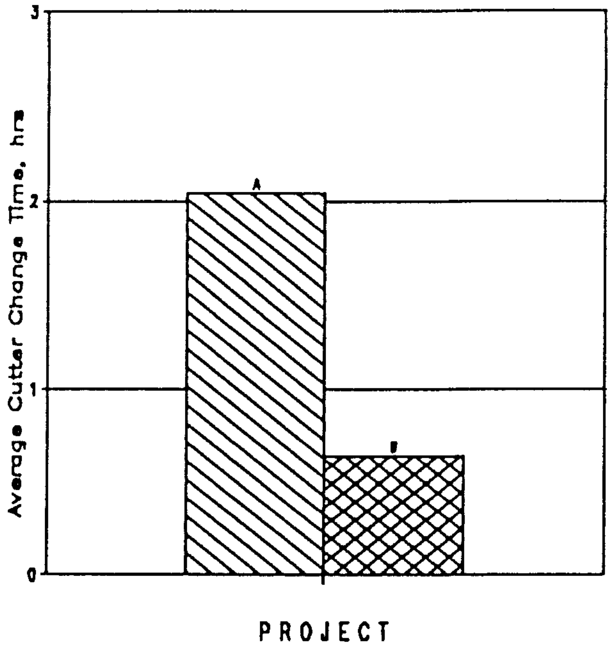
Consistent with the hard rock bored on both projects, a large percentage of lost shift time was caused by **cutter related downtime**. However, a comparison of average cutter change times in Figure 6, indicates that nearly three times as much time was spent on cutters on project A. Project A was one of the earliest uses of the 17 cutters and the crew was not keeping the bolts tight, therefore, the cutters fell off, became damaged, and damaged the cutterhead itself. Some of the project atmosphere may also have had an impact on the overall care of operations.

Miscellaneous / unknown delays (O) and derailments (D) were also greater on project A than B.

Some of the extensive downtimes are easily explainable, others are related to a high labor turnover associated with high water inflows, a cold climate, and other project and management conditions.

In project A, the smaller than normal crews can be related to TBM delays due to installation of utilities (U). The more extensive time to re-stroke (R) and to change shifts (F) is a mystery. It may be related to the attitude of the work force reflecting environmental and management conditions.

Figure 6. Average cutter change time.



A major difference was notable in project management. Site A was managed from 4000 miles away, while the project manager of site B had extensive on site TBM experience. The difference in management style showed up in the amount of time and number of breakdowns of equipment, such as the TBM (K), conveyor (Y), and more time for required maintenance (M), and certainly in the pervasive project attitude.

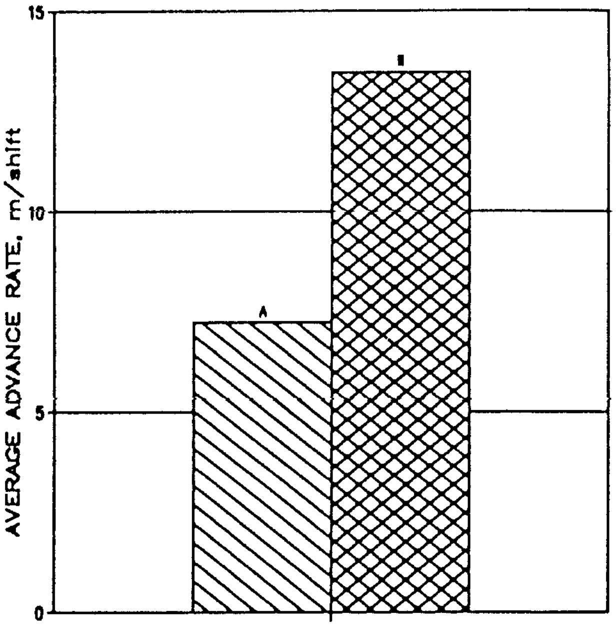
2.5 TBM Advance

The combination of nearly equal penetration rates and a difference of a factor of two in the utilization has resulted in different rates of advance as illustrated in Figure 7. Tunnel advance on project B was double that of A. If that is not significant enough, consider that it took only 7 months to excavate tunnel B.

One cannot help but wonder how many bored tunnels could have been excavated in half of the time ?

Similarly, can a low bidder, having based production estimates on his experience in tunnel A, contemplate and find the means to excavate the newly acquired project at production rates such as in tunnel B ?

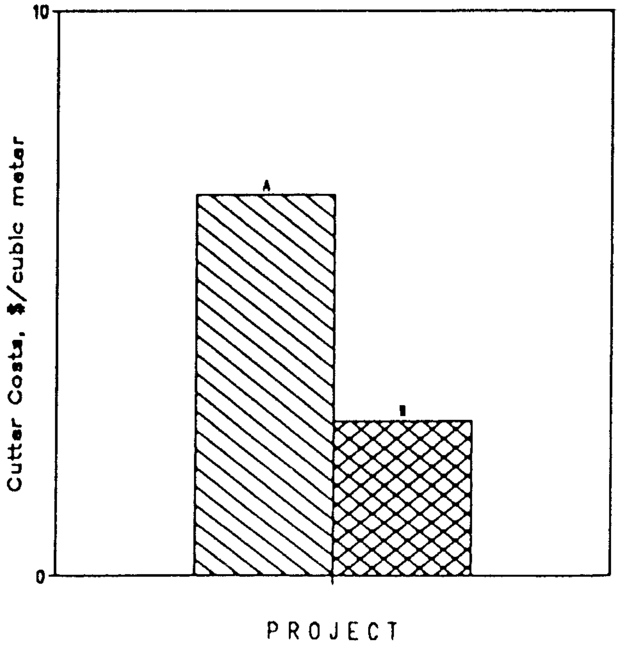
Figure 7. Average advance.



2.6 Cutter Costs

Since rock of higher strength was anticipated on project A, it is not surprising that cutter costs were also higher as illustrated in Figure 8.

Figure 8. Cutter Costs.



However, the shift reports in project A describe a number of problems with the cutters. The bolts would come loose, they were not be checked systematically, and it was not uncommon to have them fall off the cutterhead.

3 CONCLUSIONS

It is possible to enhance TBM performance beyond what is typical in the industry today.

The prospect of higher profit by design and planning, is not commonly pursued aggressively, even by the average contractor. Nevertheless, it is possible, to augment the possibility of high TBM excavation rates at the design stage through the contract specifications (Tarkoy, 1982 & 1989).

The opportunity to effectively reduce costs and risk are often missed during project planning and design, by both owner/engineers as well as contractors.

4 REFERENCES

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