TUNNELS & TUNNELLING

The International Journal of Underground Works

October 1988

TBM back-up Lubuge hydro in China Conveyors Microtunnelling

Backing up a TBM

***Peter J Tarkoy**, GeoConSol, and **John Wagner**, Project Manager, Grow Tunneling Corporation*

Geological conditions are often unjustly blamed for tunnelling difficulties. Similarly, credit for successful tunnel excavation is given without the specific details or reasons for success. General claims about project performance often do less than justice to the creative forces behind a successful TBM case history. Broad claims also hide difficulties encountered, methods used to overcome them and lessons learned. A practical analysis of the relationship between geological conditions, project management and TBM performance on the Sultan River hydroelectric project in Washington, USA acts as an example.

An almost universal source of difficulties in tunnel excavation is a disregard for the principles that: a) geology is the independent variable; b) TBM performance is the dependent variable; and c) design and managerial intervention is the only effective mechanism which can influence the cause-and-effect relationship between geology and performance.

A well-planned back-up system, responsive project management and an assessment of anticipated conditions is fundamental to the intervention between geology and the manner in which it affects construction. An understanding of the impact of geotechnical conditions on construction experience can alter the relationship between geology and TBM performance.

Documented and reported TBM case histories are useful pointers to performance but too much reliance on past performance holds the danger that possibilities for improving performance are limited and may also blind us to other principles of success. The relationship between cause and effect must be well understood to permit improvement in the state-of-the-art of TBM performance. To accomplish such a feat, the accurate interpretation of quantitative data is essential. Matching geological data and quantitatve performance records with off-the-cuff opinions usually does not take account of the more subtle and important considerations for success or failure of a project. It is also misleading and dangerous.

Anticipated and actual conditions and performance

Relevant anticipated and actual conditions for TBM excavation can be defined by the average and most adverse rock and rock mass properties as they affect boreability, stability, and dictate construction and support requirements. TBM performance (penetration rates and cutter costs) may be estimated from rock Total Hardness[1-4]. Unavailability of Total Hardness in the contract documents may cause over-optimistic estimates of penetration rates and cutter wear. Compressive strengths, if available, have been grossly misleading as indicators of TBM performance.

The anticipated and actual conditions and TBM performance are summarised in Table 1 and Figs 1 and 2.

TBM configuration

Machine variables and the machine's configuration govern the maximum penetration rates that a TBM can sustain. Important machine variables are summarised in Table 2. The Robbins TBM used for this project is illustrated in Fig 3.

Investigation of cause and effect

The relationship between relevant geological conditions, simple measures of TBM performance and managerial intervention where appropriate will be analysed and illustrated. The effect of good project management may not always be

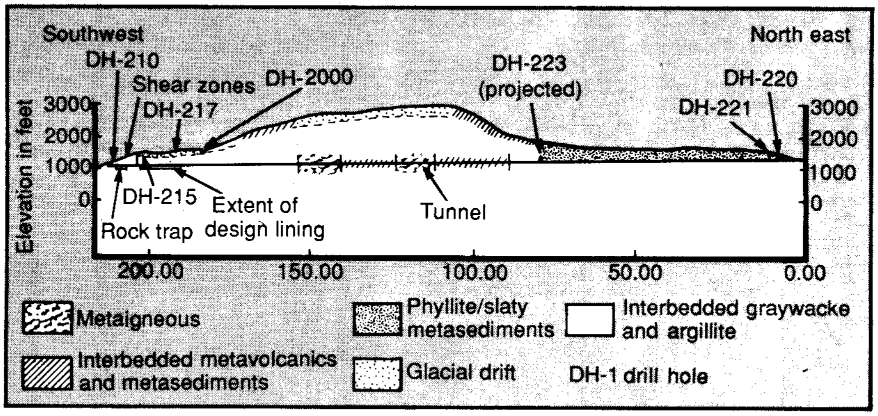

Fig 1. The Sultan River Blue Mountain Tunnel profile (after Arnold, 1987).

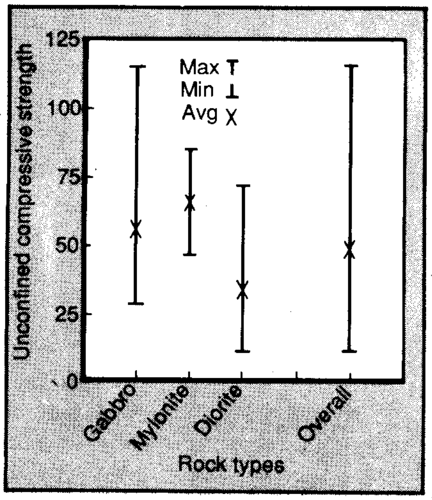

Fig 2. Range of uniaxial strengths.

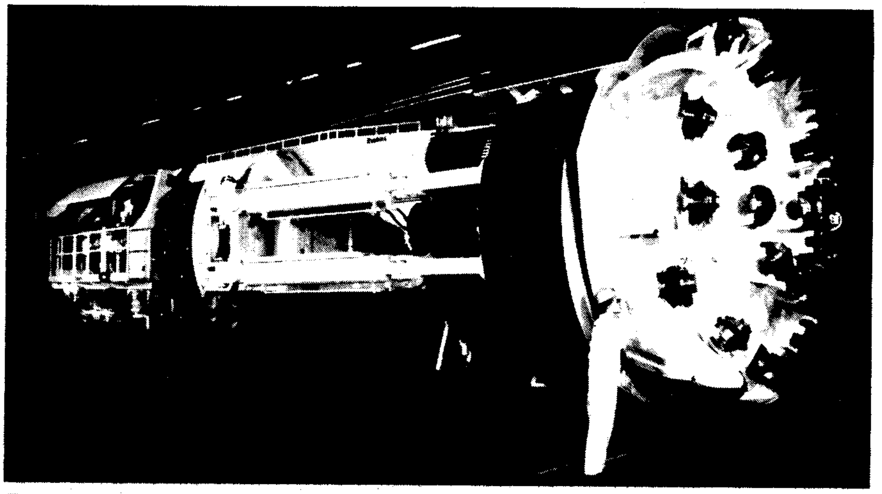

Fig 3. The Robbins 147-210 TBM used on the Sultan River Project.

Table 1. Anticipated and actual conditions and performance

	Anticipated Bechtel	Anticipated SA Healy	Actual SA Healy
Uniaxial strength, psi	— See Fig 2 —		
Support: Unsupported	75%		
Rock bolts or shotcrete	10%	90%	71%
Steel ribs and lagging	15%	10%	29%
Tunnel length, ft	20 632		
m	6289		
Penetration, ft/h		8.08	11.21
m/h		2.46	3.41
Utilisation		60.0%	49.5%
Advance, ft/day		92.00	127.35
m/day		28.04	38.82
Cutter costs, $/linear ft		2.25	0.85
$/m		7.38	2.79
Total number of cutter changes:			499

easy to illustrate specifically, other than by the ultimate results.

TBM performance variables

TBM performance can be defined by three variables and a fourth is used to summarise the first two for the purposes of estimating, as follows:

1. Penetration rate, m/h = $\dfrac{\text{length of tunned bored, m/shift}}{\text{elapsed boring time, h/shift}}$

2. Utilisation, % = $\dfrac{\text{elapsed machine time, h/shift}}{\text{excavation shift time, h/shift}}$

3. Cutter costs, $/m^3 or $/m of tunnel

4. Advance rate, m/day = Penetration rate × 24h × utilisation (for three 8h shifts)

TBM performance analyses

A standard series of analyses has been developed for analysing TBM performance. They consist of:

1. time and progress analysis (velocity curve);
2. graphic representation of (on a shift basis):
   penetration,
   utilisation,
   advance, and
   tool wear and replacement
3. graphic summary of downtimes (on a shift basis).

These analyses have always proved useful. In other instances, averages of the aforementioned performance parameters have been particularly revealing when summarised for each particular geological unit.

Elapsed time and progress

The fundamental time vs. progress analysis shown in Fig 4 illustrates the tunnel heading advance. The slope of the curve can be used to evaluate learning curves, monitor project performance and identify major delays. Early during project excavation, a delay associated with support placement is noted. A subsequent delay is associated with generally slow excavation through a shear zone. Succeeding delays for support are imperceptible because the crew size was adjusted to maintain consistent progress throughout excavation.

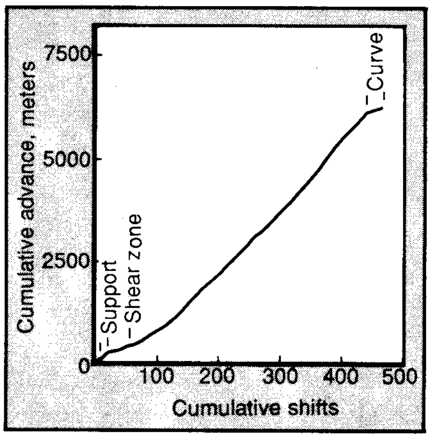

Fig 4. Time and progress analysis.

A smooth curve (ie one devoid of major delays), such as shown in Fig 4, is uncommon for tunnel excavation. It was only achieved through unfailing intervention by management, which was constantly aware of support requirements and necessary crew sizes for efficiency. A tunnel in similar geology with only 5% support sustained only 34% utilisation compared to the 50% utilisation here.

It is notable that the early delays for support installation and passing through the shear zone were sustained after the learning curve (without support) was passed, as illustrated by the initial segment's steep slope. A learning curve for support installation and the shear zone was sustained separately after the initial learning curve.

TBM excavation through the curve at the inlet end of the tunnel was slowed because part of the trailing gear had to be removed in order to negotiate a small radius curve.

Penetration rate

The penetration rate is influenced by rock properties and it is not uncommon for penetration rates to reflect geological units of varying hardnesses. A summary of penetration rates (by shift) for the Blue Mountain Tunnel is illustrated in Fig 5. Penetration has been summarised for a number of lithological, geotechnical, and physical distinctions, consistent with variations in penetration, in Fig 6.

Slower penetration rates in the altered diorite and the shear zone are normal because TBM thrust must be decreased in very soft rock to prevent over-torqueing,

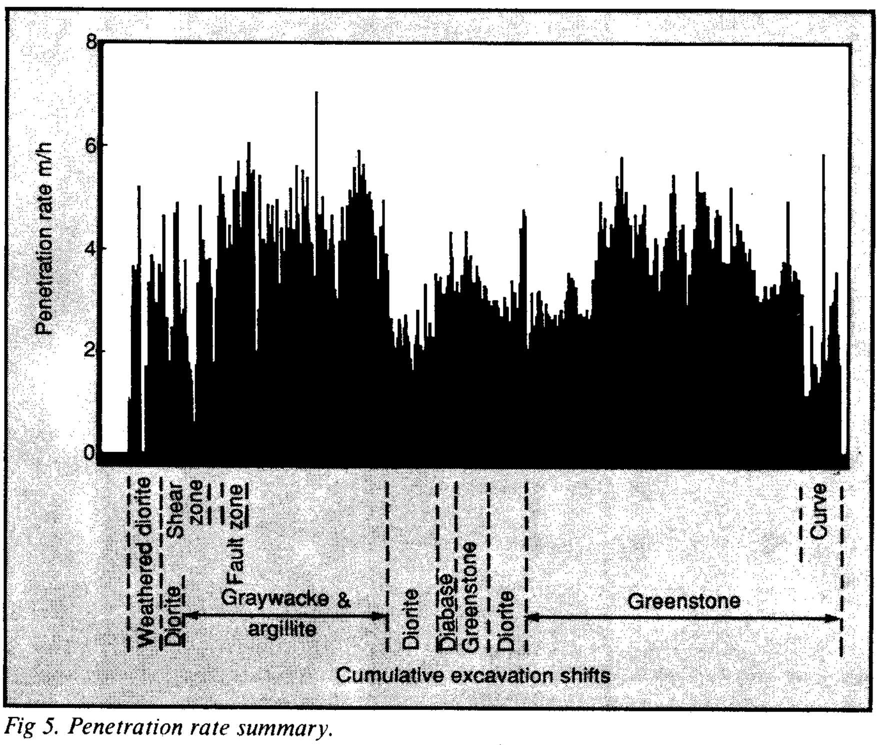

Fig 5. Penetration rate summary.

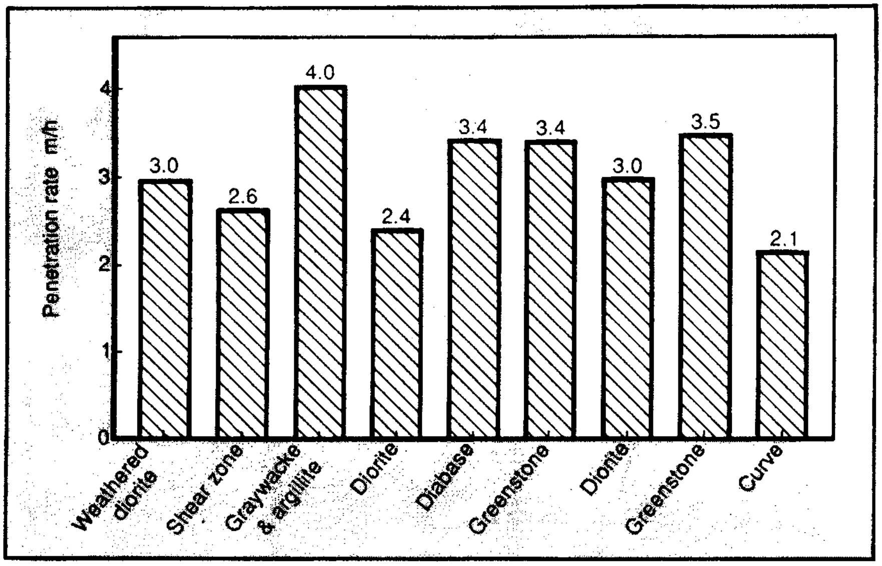

Fig 6. Penetration rate by tunnel zone.

stalling or damaging the cutterhead or gearboxes. Similarly, the thrust is lowered in a curve to prevent damage to cutters and components by eccentric loading. Lower penetration rates were sustained in the harder materials such as diorite, debase and greenstone and higher rates in the softer graywacke and argillite.

Utilisation

Utilisation is summarised on a per shift basis in Fig 7. Following a high initial utilisation, downtime increased. The high downtime (average of about 80%) diminished after the early difficulty with shear zone and associated support installation delays. Utilisation is summarised in Fig 8 for each of the lithological, geotechnical and physical distinctions made previously.

The following observations may be noted:

1. Substantial production losses were sustained as a result of support installation.
2. The initial high utilisation of 70-75% (average 49%) dropped to 21% in the shear zone (Fig 7).
3. In spite of the required steel support, a flexible crew size was able to minimise downtime for support installation and utilisation increased and stabilised at nearly 50% for the remainder of the project.
4. Unusually high utilisation was sustained in ground requiring 100% support with nearly 30% being steel ribs and lagging.
5. A high penetration in the graywacke and argillite produced a comparatively low utilisation.

An increase in TBM penetration generally produces a decrease in utilisation as illustrated in Fig 9. As the penetration rates increase, length dependent downtimes increase proportionally, decreasing TBM utilisation. The experience in the curve and the shear zone have been omitted for obvious reasons.

Downtime

A detailed daily graphic summary of all downtime categories can be related to the tunnel stationing, geology and location of other phenomena. The downtime summary in Table 3 lists total downtime in each category for the entire job. Conclusions can then be drawn from those results.

1. Most time, nearly 13 per cent of available time, was lost waiting for trains on a consistent basis throughout the reports; this category is probably the one that could be reduced most on future projects by providing two locomotives for the two trains under a double track gantry,
2. Support placement at $12^1/_2$ per cent was the second largest cause for lost time even though crews were increased to mitigate the impact on progress,
3. Cutter checks and cutter replacement accounted, at something over 8 per cent, for the third largest loss of boring time, even thought the average time per cutter was 39 minutes.
4. The time lost for safety meetings and shift changes could be eliminated if the men were paid to meet and to travel before the regular shift began.
5. The time lost due to derailments (probably because of the worn muck car wheels) was very low, at 1.81% compared to a figure double for contractors that pay less attention to

Table 2. TBM specifications

Robbins designation								147-210
TBM diameter,	ft	14.17		m				4.32
Maximum thrust,	lbs	1 575 000		kg				551 579
Maximum torque,	ft-lbs	631 000		kgm				87 2673
Horsepower,	hp	900		kW				671
Cutterhead	rev/min	7.5						
Stroke,	ft	5.0		m				1.5
Number of cutters		4	Dia.	in:	12	cm:		30.5
		31		in:	15	cm:		38.1

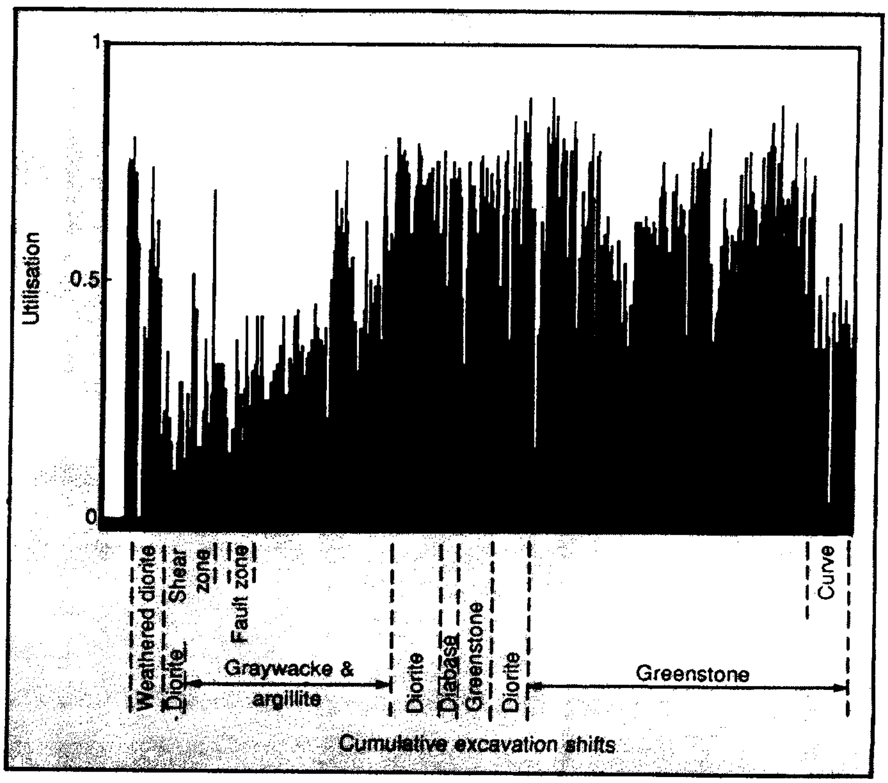

Fig 7. Utilisation summary.

Table 3. TBM downtime analysis summary

Sultan River Project — SA Healy Co
Peter J Tarkoy — Geotechnical and TBM Consultant

Legend	Downtime activity	Shift %	Time lost hours
A	Scaling rock	.00	.000
B	Gripper bearing, cribbing	.78	29.300
C	Cutter check/change/tighten bolts	8.38	313.067
D	Derailment	1.86	69.483
E	Electric problems/no power/motors	1.45	54.150
F	Shift change and safety meetings	3.16	118.150
G	Gas	.19	7.133
H	Hydraulics and related problems	.41	15.400
I	Lunch/sandwiches	.16	5.800
J	Rock jam/clean muck from cutterhead	1.07	39.833
K	Clear rock fallout	.00	.000
L	Lubrication	.07	2.550
M	Maintenance & repair, general inspection	1.42	53.017
N			
O	Other/unknown	.80	29.967
P	Probe drilling or other drilling	.18	6.683
Q	Survey, engineering or alignment	.15	5.617
R	Re-stroke/regrip TBM	.44	16.267
S	Support placement	12.50	466.983
T	Train wait/unloading	12.91	482.183
U	Utility installation (water, air, drain)	1.69	63.133
V	Ventilation installation/problems with	.08	2.967
W	Water inflow, etc.	.05	2.033
X	Tracks problem/track placement	.06	2.267
Y	Conveyor problem	.79	29.333
Z	Clearance around curves or steel sets	.16	6.050
	Total reported downtime	48.75	1821.367
	Unreported downtime	1.91	

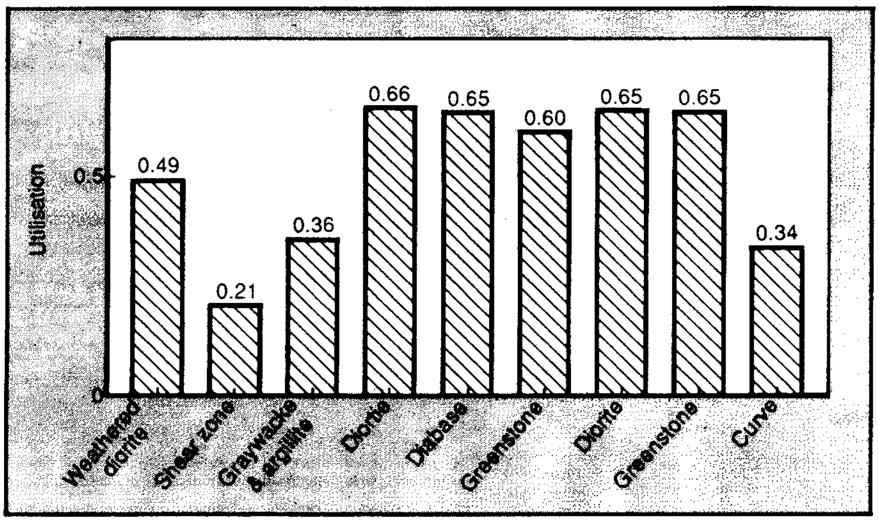

Fig 8. TBM utilisation by tunnel zone.

laying good rail.

6. Since only 1.71% of the downtime was not accounted for in the shift records, the records may be considered good.

The downtime for support installation is shown on a per shift basis in Fig 10. It illustrates extensive downtime early in the project, when encountering the weathered diorite, the shear zone, the fault zone, and the graywacke and argillite. Downtime for support decreased as crew sizes were adjusted to deal with support delays.

Advance rate

Daily advance is a function of TBM penetration rate and TBM utilisation. The penetration is most directly related to rock hardness whereas utilisation is related to support placement, downtime and the penetration rate. The advance rate is thus an indicator of overall progress and is sensitive to both penetration and utilisation.

The results shown in Fig 11 illustrate that an average advance of 54m/day (3 × 8h shifts) was well established before encountering the problems with the shear zone and associated support. The effect of the curve is also demonstrable. Although a higher than anticipated

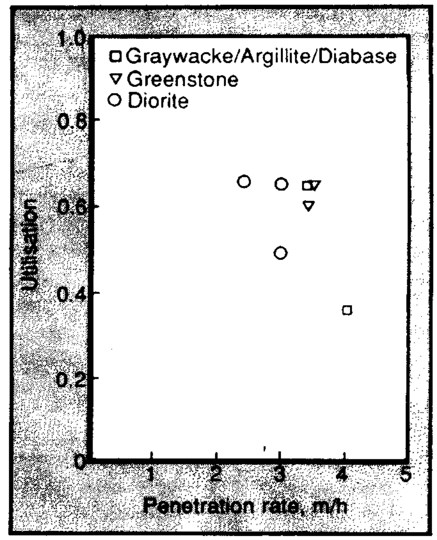

Fig 9. Effect of penetration on utilisation.

advance rate was sustained on this project it was in fact limited by the unanticipated amount of steel support required.

This project is a typical example of adverse conditions being mitigated by the action of the contractor through increasing crew sizes to deal with the unanticipated steel support which caused delays.

Cutter life

Cutter life is measured by cutter rolling path life, the total distance that a cutter rolls. The cumulative average cutter life for the project is illustrated in Fig 12. Cutter life increases continuously from the very beginning because of the increased use of the original dressing. With each cutter replacement, the fluctuation is attenuated with ongoing time.

Only a few cutters needed to be replaced in the shear zone. The harder diorite and greenstone can easily be associated with decreases in the cutter rolling path life, perhaps with some lag typical of cutter wear.

The cutter rolling path life was excellent, particularly in view of the rock hardness encountered. The exceptional cutter life is attributable to the excellent maintenance provided.

Implications for TBM feasibility

The feasibility of using a TBM for tunnel excavation is based on the ability of a TBM and associated back-up equipment to perform efficiently under the average, the most adverse and the most favourable geological and tunnelling conditions. Consequently, it is necessary to define geological averages and ranges, and the most adverse and favourable anticipated conditions along the tunnel alignment.

In turn, this range of conditions must be taken into account in the planning of geotechnical exploration, assessment of anticipated conditions, tunnel design, presentation of geotechnical information, contract documents, estimating and bidding, TBM design, back-up system design and execution of construction.

Often overlooked are the most favourable conditions and associated high performance, particularly in designing a back-up system to keep up with this high rate of excavation. If the performance associated with adverse conditions cannot be offset by the best performance associated with the most favourable conditions, then the average overall performance will be less than possible.

Typical average, adverse and favourable conditions should be considered in terms of rock hardness, rock mass properties, water inflow, support requirements, etc. Adverse conditions generally consist of extreme rock hardness, poor rock mass properties in shear zones, fault zones, or in areas of weathering and alteration, high water inflow, and other unanticipated conditions.

Generally, engineers have been reluctant specifically to define the most adverse geological conditions in most tunnel contracts and specifications since such an exercise might promote contingencies.

Selection of back-up equipment

The primary consideration for the selection and design of TBM back-up equipment is that it can cope with all anticipated conditions and excavation rates. These considerations include muck handling from the face to the dump, effective support at the face and over the working area (shield, finger shield, etc) efficient placement of all types of support, particularly the most common type, as well as the capacity to deal with water inflow and other unusual conditions such as soft sidewalls affecting gripper reactions, etc. Time saved in these activities will increase daily production rates.

Optional equipment

Optional equipment that can contribute to maintaining and enhancing performance under all anticipated and some unanticipated conditions might include an automated guidance system, dust suppression system, hydraulic drills, probe hole drilling capability and ancillary support erection equipment.

Conclusions to be drawn

General conclusions that can be drawn from the experience encountered at Sultan are:

- penetration rate is relatively fixed by the TBM design, variables and the rock encountered;
- as penetration rate increases, utilisation tends to decrease;
- decreasing downtime (increase in utilisation) is the most, and generally the only, effective means of increasing overall TBM performance;
- it is possible to reduce downtime merely by using larger crews in general (compared with other projects) and specifically when installing heavy supports;
- downtime can be effectively reduced by appropriate back-up and optional equipment design, adpatable crew sizes and deliberate intervention by management;

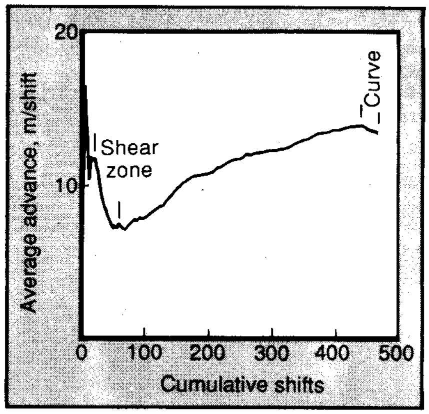

Fig 11. Cumulative average advance rate.

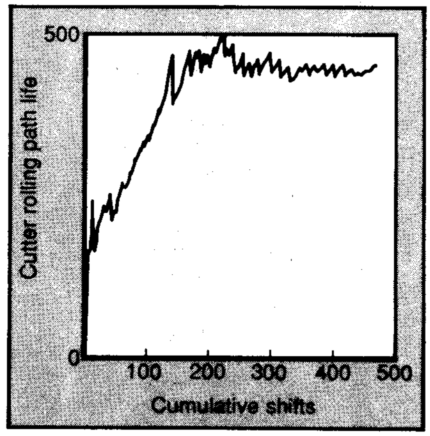

Fig 12. Cutter rolling path life summary.

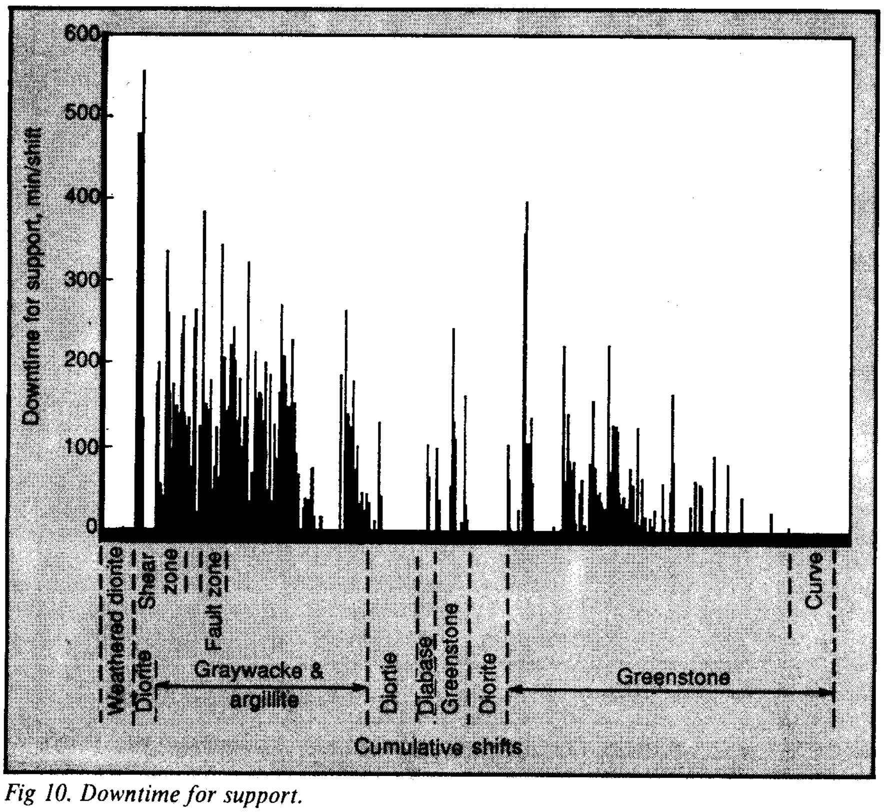

Fig 10. Downtime for support.

- it is essential to know the underlying cause-and-effect relationships that are unique to every project before optimum TBM performance can be achieved.

Specifically, the Sultan River Project illustrates the effect of management intervention between the (cause) geology and (effect) TBM performance.

On many critical and difficult projects, the engineer does not allow adequate opportunities for the contractor to be innovative. On other occasions, successful innovations by contractors are all too often claimed by engineers. □

References

1. Tarkoy, P.J. (1973). Predicting TBM Penetration Rates in Selected Rock Types, *Proceedings, 9th Canadian Symposium on Rock Mechanics*, Montreal, Dec. 13-15.
2. Tarkoy, PJ, (1984). Report to SA Healy Company.
3. Shani Wallis, (1984). Overcoming Those TBM Downtime Blues, *Tunnels & Tunnelling*, April, 1983.
4. Tarkoy, P.J. (1986). Practical Geotechnical and Engineering Properties for Tunnel-Boring Machine Performance Analysis and Prediction, *Transportation Research Record 1087*.
5. Arnold, Arthur, (1987). Geology and TBM Performance in the Blue Mountain Tunnel, Sultan River Hydroelectric Project, *Proceedings RETC, P50-60*, New Orleans, June, 1987.

John Wagner was formerly project manager, Sultan River Project for SA Healy Co, Inc.