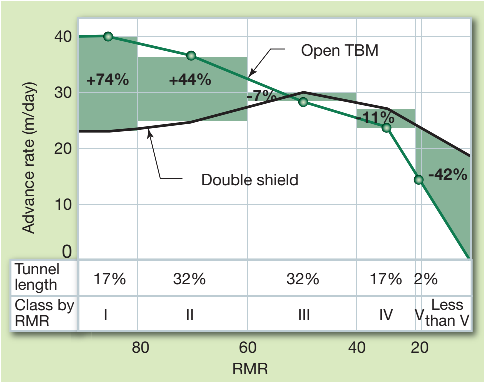
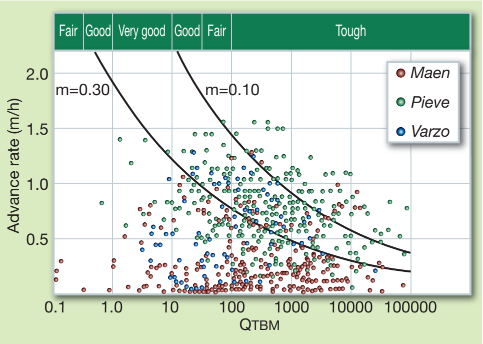
Predicting TBM excavability

Z T Bieniawski, of Bieniawski Design Enterprises, and Benjamín Celada and José Miguel Galera, both of Geocontrol SA, Spain, discuss the latest data for the newly introduced Rock Mass Excavability (RME) index for the prediction of TBM advance rates



Top: Fig 1 - Evinos Tunnel advance rate versus rock mass quality rating RMR for two TBM types (Grandori et al, 1995)



Right: Fig 2 - Advance rates for three TBM tunnels versus Q_{TBM} (Sapigni et al, 2002)

Over 500 case histories were analysed in two years to bring the Rock Mass Excavability (RME) index to fruition and demonstrate its effectiveness on five current projects. It should be emphasised that the RME index does not replace the RMR or Q systems as used in tunnel design and construction; indeed one of the RME input parameters, the stand up time, is determined from the RMR. However, the approach reported here introduces a specialised tool relevant to TBM tunnel construction, featuring double-shield and open-type TBMs.

This is Part I of two articles on this topic. Part II will be published in a later issue of *T&TI* and will include applications to single-shield TBMs as well as additional case histories leading to further improvements as more experience is gathered with predicting TBM excavability.

Previous investigations

In the history of tunnelling technology, the emergence of modern TBMs stands out as the major milestone which provided spectacular advantages and achievements, as well as complex challenges to designers and constructors who faced significant shortcomings in understanding the interaction of rock mass conditions and TBM design and performance.

In fact, when Terzaghi introduced his rock-load idea in 1946, followed by Lauffer's stand up time concept in 1958 and Deere's RQD index in 1964, these design approaches were directed to selection of rock reinforcement for tunnel construction by drill and blast. The equipment for tunnel excavation was left to the discretion of the contractor, with little input by the designer. Even the subsequent 'modern' rock mass classification methods, proposed in the 1970s, by Wickham at al[1], Bieniawski[2] and Barton[3] were predominantly directed to drill and blast tunnels, independent of TBM characteristics.

Today, this is no longer the case. TBMs have increased in power, size and type to such an extent that they directly influence tunnel design. Moreover, they can be the source of tremendous satisfaction due to the machine's increased safety provisions and higher performance rates, as well as deep despair when unexpected ground conditions are encountered and the TBM may be immobilised for months and sometimes has to be rescued by old fashioned hand mining or drill and blast. In less drastic cases, TBM progress in unfavourable conditions can be disrupted and the output decreased severely.

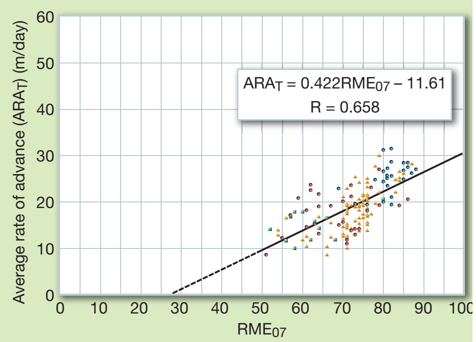
In this situation, a significant problem has emerged: how to assess effectively the interaction between rock mass conditions, as described by the RMR or Q classification systems, and the design and performance characteristics of the TBM. Certainly, some attempts to solve this problem have been made, but the responsibility still rests on the TBM manufacturers and tunnel contractors who must rely on their experience, ingenuity and even their will to battle adverse conditions.

The meaning of TBM excavability

Excavability is defined as the rate of excavation expressed in machine performance in meters per day. It was investigated as early as 1982 by Kirsten[4]. Pioneering work by Tarkoy[5], Nelson[6] and Ozdemir[7] was performed on rock borebility and disk cutting in the 1990s. TBM excavability or performance prediction models were studied by a number of researchers since 2000: Barton[8], Alber[9], Blindheim[10], Sapigni at al[11] and Palmström and Broch[12]. Last year, at the ITA Congress in Korea, based on case histories from over 400 tunnel sections in Spain, the authors introduced the Rock Mass Excavability (RME) index[13]. This year, new case histories enabled further and more specific applications for double-shield TBMs which was presented at the RETC in Toronto[14]. Since submission of the RETC paper, over 100 tunnel sections were analysed from one tunnel in Spain and two tunnels in Ethiopia, forming the Gibe II hydroelectric project (*T&TI* April).

Most of all, the timeliness of introducing the RME was confirmed to date by an increasing demand to be able to predict TBM advance rates based on both rock mass quality and machine performance interaction, because the current indices based solely on rock mass conditions have proved insufficient[13].

In this respect, figure 1 shows early promising research by Grandori[15] in 1995 involving the RMR for correlation with TBM rate of advance. This provided some interesting trends for the Evinos Tunnel in Greece, comparing the performance of open TBMs and double-shield TBMs. It showed



Above: **Fig 3 - Correlation between RME index and the average rate of advance for double-shield TBMs (Bieniawski et al., 2006). The colour symbols represent individual tunnels**

RECORD of DATA Form for Rock Mass Excavability RME

Name of Tunnel...
Initial chainage of section.............................. Final chainage of section..................................
Length of section.............................m (should be > 40 m)
Duration of excavation (days)... (number + 1 decimal)

Average Rate of Advance ***ARA*** = ...m/day

Lithology... Average depth....................m
Rock Mass Rating ***RMR:*** range.................................. average...................

ROCK MASS EXCAVABILITY PARAMETERS

1) Uniaxial compressive strength of intact rock (σ_c): range..........................average............MPa

2) Drilling Rate Index ***DRI:*** range.................................. average...............................

3) Type of homogeneity at excavtionn face............................Nº of joints per meter......................

Orientation of discontinuities with respect to tunnel axis

(perpendicular, parallel or oblique)..

4) Stand up time.....................hours 5) Groundwater inflow at tunnel face.............liters/sec

Rock Mass Excavability ***RME*** range...................................average....................

TBM PERFORMANCE PARAMETERS

Average speed of cutterhead rotation...........................rpm Applied Thrust.......................kN

Specific Penetration..................................mm/rev Torque........................m. kN

Rate of Penetration......................................mm/min

Nº cutters changed:.................................... Rate of TBM utilization............................%

OTHER observations

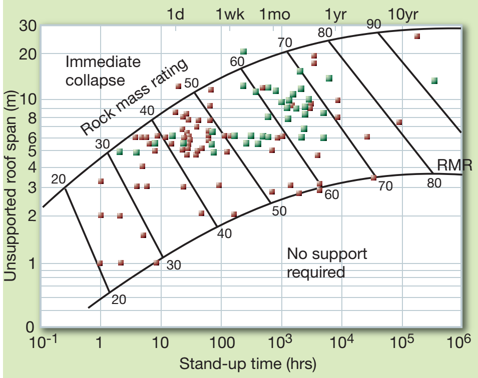
Ex. in situ stress conditions, squeezing rock, rockbursts, etc..

....

that RMR Class III provided a peak in production for double-shield TBMs, while they would not be recommended for neither Class V (very poor) nor Class I (very good) rock masses. However, recent data reported by Della Valle from Spain[16], showed that an attempted correlation between the TBM rate of advance and the RMR resulted in a considerable scatter, although there was a trend similar to that discovered by Grandori.

Figure 2 shows the results from Norway of an attempted correlation using the Q_{TBM} index. It was found that the scatter of the results was so large and Q_{TBM} so complex, by involving 21 parameters, that its use was not recommended in the technical literature[10,12]. We have also examined Q_{TBM} as an option but could not make it work for our case histories, for a number of reasons, including the problem of determining the rock mass strength.

It became clear from these and other analyses[13] that modifying the RMR or Q rock mass quality classifications for prediction of rock mass excavability - for which these indices were not intended - is not the correct approach. Much better correlations can be obtained with the new RME index. This is demonstrated in figure 3 depicting the work on RME[14] presented in the RETC proceedings.



Above: **Fig 4 - Stand up time as a function of RMR and unsupported tunnel span (Bieniawski, 1989). Red squares represent tunnelling cases, green squares are mining data**

RME input parameters

The database analysed includes the following information collected for each tunnel section (geo-structural region):

Geometrical data: tunnel location, length and diameter.

Rock mass data: RMR and its input parameters, DRI, discontinuities data, and water inflow.

TBM data: advance rate, utilisation coefficient, penetration rate, rotation speed, torque, thrust, no. of cutters changed and the specific energy of excavation[14].

It is important to note that a tunnel section studied for RME is defined as a geological structural region of the tunnel, that is, the same section for which the RMR is determined, and within which uniform characteristics exist, such as discontinuity spacing and conditions, the same rock type lithology and the RMR not varying by more than half-class (10 points). A section is not arbitrarily delineated by the number of full days tunnelled or by having only the same rock material. In fact, the section selected should be preferably longer than 40m, the time of excavation should be given in days to one decimal fraction and the TBM utilisation should not be less than 30%. All these aspects are important for comparing different tunnelling case histories.

Table 1 (above) shows the 'record of data form' developed for two purposes; on existing projects, for correlation between the RME index and the TBM parameters; and for planned projects, to estimate the TBM rate of advance, and some machine parameters. Table 1 includes therefore both the rock mass quality parameters, as well as the TBM performance parameters. While all the input parameters are customary and straightforward, it should be noted that the RMR is required to estimate the Stand-Up-Time parameter, while the Drilling Rate Index (DRI) is needed because it is significant in tunnel boring construction. Here the DRI is defined[17] in terms of the brittleness value and the Sievers' J-value. Both these tests have been standardised in the tunnelling industry and are performed by commercial or university laboratories.

Figure 4 shows the RMR chart for estimation of the Stand-Up Time parameter. Since this chart was originally developed for drill-and-blast tunnels, a correlation is available between the $RMR_{D\&B}$ and RMR_{TBM} based on work by Alber[9] for TBM tunnels. The following equation is applicable:

$$RMR_{TBM} = 0.8 \times RMR_{D\&B} + 20$$

Construction by TBM generally results in higher RMR values than for the same tunnel

Uniaxial compressive strength of intact rock [0-25 points]					
σ_C (MPa)	<5	5-30	30-90	90-180	>180
Rating	4	14	25	14	0

Drillability [0-15 points]					
DRI	<80	80-65	65-50	50-40	<40
Rating	15	10	7	3	0

Discontinuities in front of the tunnnel face [0-30 points]									
Homogeneity		**Number of joints per meter**					**Orientation with repect to tunnel axis**		
Homogeneous	Mixed	0-4	4-8	8-15	15-30	>30	Perpendicular	Oblique	Parallel
Rating 10	0	2	7	15	10	0	5	3	0

Stand up time [0-25 points]					
Hours	<5	5-24	24-96	96-192	>192
Rating	0	2	10	15	25

Groundwater inflow [0-5points]					
Liter/sec	>100	70-100	30-70	10-30	<10
Rating	0	1	2	4	5

section excavated by drilling and blasting because of the favourable circular tunnel shape and lesser damage to the surrounding rock mass by the process of machine boring.

Determination of the RME Index

The RME index is obtained from summation of the five input parameters in Table 2 (above) which tabulates the ratings appropriate for the ranges listed. Note that the values given are the average ratings, for a more precise determination of these input ratings, convenient graphs can be found elsewhere[12]. Once the RME is determined, a TBM average rate of advance (ARA) may be estimated from figure 3 or the latest ones that follow. In addition, other correlations have also been obtained by the authors[13] such as those between the RME and the penetration rate (PR) for double-shield TBMs, as well as correlations with the specific energy of excavation (MJ/m^3), thrust and torque[14]. They will be discussed in Part II of this series.

Recent analyses and results

After the introduction of the RME index last year, comments were requested from the leaders in the field and their contributions, together with the new case histories that became available, led to 'fine tuning' of the index (adjusting the ratings of some input parameters) and to re-runs of the correlation analyses. Particularly valuable suggestions were gratefully received from Dr Remo Grandori, President of SELI, Italy, Dr Evert Hoek, of Canada, Dr Sigismund Babenderede, of Germany, Dr Felipe Mendaña, of Spain, Dr Harvey Parker, of USA, and Ing. F Antonini of SELI.

Most of all, the extensive use of the RME index on its new tunnels by SELI, in Ethiopia, provided not only new valuable case histories but also further considerations of possible adjustment factors that might influence rock mass excavability and better prediction of the TBM rates of advance. In the meantime, some considerations based on TBM experience in Spain, are elaborated below.

1) Influence of the TBM crew:

In tunnel construction, it seems evident that the qualifications and experience of the TBM crew, who handle the tunnelling machine every day, have an important influence on the performances achieved.

In order to include this effect, the experience gained during the construction of the Guadarrama tunnels was used and is defined as shown in Table 3.

2) Influence of the excavated length:

Again based on the data from the Guadarrama tunnels, it is known that increased performance is obtained as the tunnel excavation increases. This factor may be defined as shown in Table 4.

3) Influence of the tunnel diameter:

It should be noted that the correlation in figure 3 was derived for tunnels with diameters close to 10m. In order to take into account the influence of different tunnel diameters, D, a coefficient F_D was proposed such that:

$$F_D = -0.007D^3 + 0.1637D^2 - 1.2859D + 4.5158$$

Therefore, for D = 10m, $F_D = 1$, while for D = 8m, $F_D = 1.12$ but for D = 12m, $F_D = 0.5$, that is, one-half of the coefficient for D = 10m.

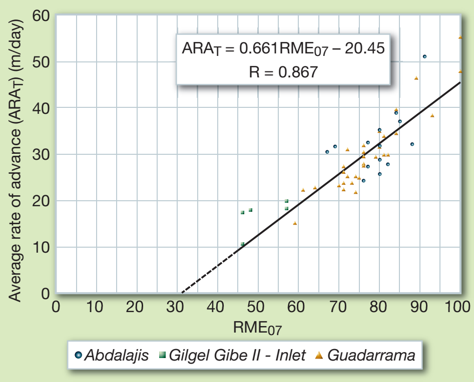
Combining the effects as seen above, the 'real' average rate of advance (ARA_R) that is determined from tunnels whose excavation diameter is different from 10m, can be used to obtain the 'theoretical' average rate of advance (ARA_T), which is the one correlated with the RME:

Table 3:

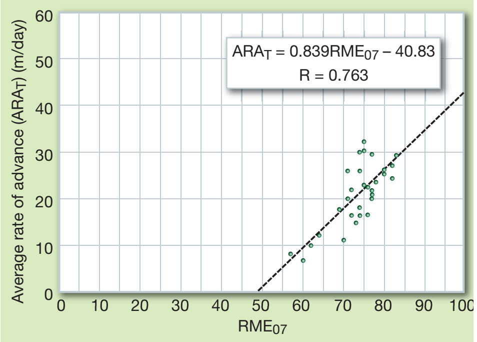
Effectiveness of the crew handling TBM and terrain	**Crew factor (F_E)**
Less than efficient	0.88
Efficient	1.00
Very efficient	1.15

Table 4:

Tunnel length excavated (km)	**Adaptation factor (F_A)**
0.5	0.68
1.0	0.80
2.0	0.90
4.0	1.00
6.0	1.08
8.0	1.12
10.0	1.16
12.0	1.20



Above: Fig 5 - RME data for three tunnels excavated with double-shield TBMs in rock with strength $\sigma_C < 45MPa$

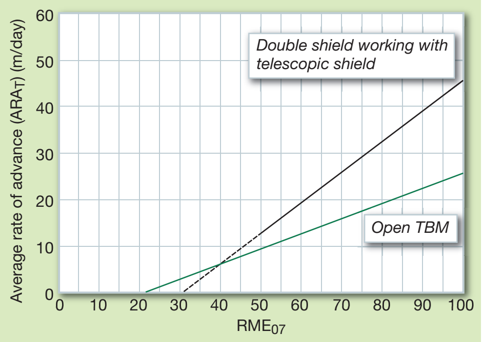


Above: Fig 6 - RME data for San Pedro Tunnel excavated with open-type TBM in rock with strength $\sigma_C > 45MPa$

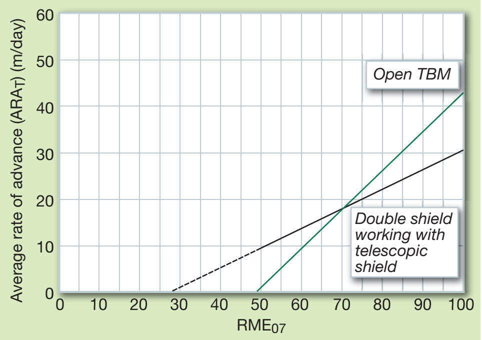
$$ARA_T = \frac{ARA_R}{F_E \bullet F_A \bullet F_D}$$

Influence of the type of TBM

To ensure full application of the RME, studies have been carried out to establish specific correlations between the ARA and the RME



Left: **Fig 7 - Comparison of TBM performance versus excavability index RME for open and double-shield TBMs boring in rock with strength $\sigma_C < 45$MPa**



Above: **Fig 8 - Comparison of TBM performance versus excavability index RME for open TBMs and double-shield TBMs in rock with strength $\sigma_C > 45$MPa**

for the typical hard rock TBMs, namely; open TBMs; single shield TBMs; and double shield TBMs.

We started with the analyses of the tunnel sections excavated by double shield TBMs because most of the case histories in the database involved this type of machine.

Thus, for double-shield TBM construction, figure 5 depicts the ARA_T values, in m/day, for three tunnels. The correlation co-efficient of R=0.867 is significantly high. The data from one tunnel in Ethiopia has been kindly provided by Dr Remo Grandori of SELI.

For open-type TBM excavation of 49 tunnel sections, figure 6 shows the ARA_T values for the San Pedro Tunnel in Spain, excavated in rock having a $\sigma_C > 45$MPa. The correlation co-efficient of R=0.763 is also high.

Analyses are not yet completed for tunnels excavated with single-shield TBMs. This will be featured in Part II of this series.

Double-shield and open TBMs

It was found that improved correlations are obtained when one differentiates between case histories featuring rocks with the uniaxial compressive strength of the intact rock $\sigma_C > 45$MPa and those $\sigma_C < 45$MPa. This is due to an increasing and decreasing trend in the ratings of the σ_C parameter, reaching the favourable average value for TBM excavability at 45MPa.

Figure 7 shows the regression lines which were obtained for the machines excavating in ground with $\sigma_C < 45$MPa.

It is clear that in this case double shield TBMs always give better results than open TBMs, if the intact rock strength is less than 45MPa.

Figure 8 shows the regression lines for the machines operating in the ground with $\sigma_C >$ 45MPa.

In this case, in better exacavability conditions, RME > 75, the use of open TBMs clearly gives better performance than by double shield TBMs.

However, in terrains whose excavability is between 65 < RME < 75 both types of tunnelling machines provide similar results.

Finally, in terrains whose excavability is between 50 < RME < 65, double-shields allow better performance than open TBMs.

Future lines of research

To complete this research it is proposed to analyse correlation between RME and ARA_T for single-shield TBMs, mainly in the tunnel sections excavated in low strength rocks, $\sigma_C < 45$MPa; where this kind of tunnelling machines can provide better results.

For this task, data will be used from sections excavated by single-shield TBMs as well as those excavated working with double-shield TBM working in single-shield mode.

These aspects and further case histories will be included in Part II of this series.

Conclusion

In closing, the case histories database for the Rock Mass Excavability (RME) index has been increased significantly since its introduction a year ago. The results obtained to date are promising and we welcome comments and suggestions to: prof-ztb@mindspring.com

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