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New applications of the excavability index for selection of TBM types and predicting their performance

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SYNOPSIS : Following the introduction of the Rock Mass Excavability (RME) Index at the ITA Congress 2006 in Korea, specific correlations between the RME and the average rate of advance (ARA) were developed for Double Shield TBMs, based on data from tunnels constructed in Spain and in Ethiopia. The remaining major task was to complete the RME-ARA correlations for Open TBMs and Single Shield TBMs, which was done during the later part of 2007, involving statistical analysis of data from the tunnels being constructed in Germany, Switzerland and Spain. In the process, very promising results were obtained. The paper describes the selected significant developments, with the emphasis on the following findings:

1. Charts are presented for more accurate determination, of the five input parameters of the RME, using graphical representation;
2. New expressions to evaluate the influence of the efficiency of the TBM crew and the tunnel diameter are formulated;
3. Specific correlations between RMR and the ARA are proposed for Open TBMs and Single Shield BMs;
4. Specific criteria are established to select the most suitable type of a TBM when planning tunnel construction.

1. INTRODUCTION

The Rock Mass Excavability (RME) index was first presented in 2006 at the ITA World Tunnel Congress in Korea[1]. Its purpose is to evaluate rock mass excavability in terms of TBM performance and to serve as a tool for choosing the type of TBM most appropriate for tunnel construction in given rock mass conditions.

The RME is calculated using five input parameters having these initial ratings:

- uniaxial compressive strength of intact rock material, σ_{ci}: 0 - 15 rating points;
- drilling rate index, DRI: 0 - 15 points;
- number of discontinuities present at tunnel face, their orientation with respect to tunnel axis and homogeneity at tunnel face: 0 - 40 points;
- stand up time of the tunnel front: 0 - 25 points; and
- water inflow at tunnel front: 0 - 5 points.

The sum of the ratings of the above parameters varies between 0 - 100 rating points and it is expected that the higher the RME value, the easier and more productive the excavation of the tunnel.

However, since its introduction, continued improvements were made to the RME index [2][3] as more case histories were collected for Double Shield TBMs and, in addition, a major contribution was made by Dr Remo Grandori of SELI SpA in applying this index to Gibe Project tunnels in Ethiopia [4][5]. Furthermore, new data were obtained recently by the authors for Open TBMs and Single Shield TBMs from tunnels constructed in Germany, Switzerland and Spain. As a result, the score for σ_{ci} changed from 0-15 points to 0-25 and for the discontinuities decreased from 0-40 to 0-30 points.This is depicted in Table 1 and Figure 1. Note that the graphs enable more accurate determination of the RME values than Table 1.

2. CRITERIA FOR PREDICTING TBM ADVANCE

To utilize the RME as a tool for predicting TBM advance, it was decided to employ the concept of the AVERAGE ADVANCE IN A TUNNEL SECTION, otherwise understood as the "Average Rate of Advance (ARA)". The ARA is calculated by dividing the length of a characteristic tunnel section over the time of completion of the excavation, expressed in meters per day, m/d.

It is important to note that a characteristic section utilized for obtaining the ARA must meet certain conditions:

- the section length should be > 30 meters;
- the section should not have significant variations in the value of RME and have a representative rock mass quality RMR, that is, not varying by more than 10 points;
- the section should not feature extraordinary repairs to the TBM; and
- during the period of section excavation the TBM utilization should be within 30% to 60% of the cycle.

2.1 *Avoiding errors of prediction*

To prevent errors in prediction, this approach avoids calculating the ARA from the Rate of Penetration (PR) which normally varies between 6 and 60 mm/min; this is so because while PR can be accurately measured in the TBM controls, but the actual daily ARA depends on a number of factors which constitute uncertainties. They are, for example, the mechanical condition of the machine, the excavation strategy adopted by the TBM crew and the percentage of TBM utilization exclusively dedicated to excavation. ARA is closer than average speed concept of the TBM rather than the peak output in a day.

3. THEORETICAL AND REAL ARA

The RME was aimed originally at evaluating rock mass excavability by considering the aspects

Table 1. The ratings for RME input parameters

<table>
<tr><th colspan="11">Uniaxial compressive strength of intact rock [0 - 25 points]</th></tr>
<tr><td colspan="2">σ_c (MPa)</td><td colspan="2"><5</td><td colspan="2">5-30</td><td colspan="2">30-90</td><td colspan="2">90-180</td><td>>180</td></tr>
<tr><td colspan="2">rating</td><td colspan="2">4</td><td colspan="2">14</td><td colspan="2">25</td><td colspan="2">14</td><td>0</td></tr>
<tr><th colspan="11">Drillability [0 – 15 points]</th></tr>
<tr><td colspan="2">DRI</td><td colspan="2">>80</td><td colspan="2">80-65</td><td colspan="2">65-50</td><td colspan="2">50-40</td><td><40</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">15</td><td colspan="2">10</td><td colspan="2">7</td><td colspan="2">3</td><td>0</td></tr>
<tr><th colspan="11">Discontinuities in front of the tunnel face [0 – 30 points]</th></tr>
<tr><td colspan="3">Homogeneity</td><td colspan="5">Number of joints per meter</td><td colspan="3">Orientation with respect to tunnel axis</td></tr>
<tr><td colspan="2">Homogeneous</td><td>Mixed</td><td>0-4</td><td>4-8</td><td>8-15</td><td>15-30</td><td>>30</td><td>Perpendicular</td><td>Oblique</td><td>Parallel</td></tr>
<tr><td>Rating</td><td>10</td><td>0</td><td>2</td><td>7</td><td>15</td><td>10</td><td>0</td><td>5</td><td>3</td><td>0</td></tr>
<tr><th colspan="11">Stand up time [0 – 25 points]</th></tr>
<tr><td colspan="2">Hours</td><td colspan="2"><5</td><td colspan="2">5-24</td><td colspan="2">24-96</td><td colspan="2">96-192</td><td>>192</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">0</td><td colspan="2">2</td><td colspan="2">10</td><td colspan="2">15</td><td>25</td></tr>
<tr><th colspan="11">Groundwater inflow [0 – 5 points]</th></tr>
<tr><td colspan="2">Liters/sec</td><td colspan="2">>100</td><td colspan="2">70-100</td><td colspan="2">30-70</td><td colspan="2">10-30</td><td><10</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">4</td><td>5</td></tr>
</table>

relevant to rock mass characteristics and TBM performance, such as the orientation of the tunnel axis with respect to the most important set of discontinuities and the standard drilling rate index DRI. Accordingly, to include other important factors such as the diameter of the tunnel or the experience and efficiency of the TBM crew calls for introduction of the term ARA real (ARA_R). At the same time the ARA derived directly from the RME was designated [2][3] as ARA theoretical (ARA_T).

The applicable relationship is as follows:

$$ARA_R = ARA_T \times F_E \times F_A \times F_D \qquad \ldots(1)$$

where F_E = factor of crew efficiency;

F_A = factor of team adaptation to the terrain; and

F_D = factor of tunnel diameter.

3.1 *Factor of Crew Efficiency (F_E)*

Based on the experience gained during the construction of the Guadarrama twin tunnels in Spain [4], 28 km long and excavated by four TBMs, each of them manufactured by Wirth and Herrenknecht, and based on the proposal by Dr Remo Grandori [5], the following relationship is applied:

$$F_E = 0.7 + F_{E1} = F_{E2} + F_{E3} \qquad \ldots(2)$$

Table 2 provides the appropriate values for the above coefficients. Note that the minimum value of F_E is 0.7 and its maximum is 1.20 which is consistent with the observations made at Guadarrama [3].

Table 2. Criteria for evaluation of coefficients F_{E1}, F_{E2} and F_{E3} (after Grandori [5])

Contractor's TBM experience	No experience	1 to 5 tunnels built	6 to 10 TBM tunnels built	11 to 20 TBM tunnels built	>21 TBM tunnels built
Value of F_{E1}	0	0,05	0,10	0,15	0,2

Qualifications of the tunnelling crew	Little trained and none with TBMs	Trained but none with TBMs	Trained overall and with TBMs
Value of F_{E2}	0	0,1	0,15

Resolutions of disputes	TBM manufacturer rep on site	No TBM manufacturer rep on site	Time to resolve problems: < 1 month	Time to resolve problems: > 1 month
Value of F_{E3}	0.075	0	0.075	0

3.2 *Factor of Adaptation to the Terrain (F_A)*

Also during the construction at Guadarrama, it was discovered that after excavation of a number of kilometers of the tunnel, even when having a similar RMR, the rate of advance increased beyond what was expected from a typical "learning curve" phenomenon; the increase depended clearly on the completed length of the tunnel thus signifying a higher degree of adaptation - by the crew - to the encountered terrain. This is depicted in Figure 2 which thus defines Factor F_A.

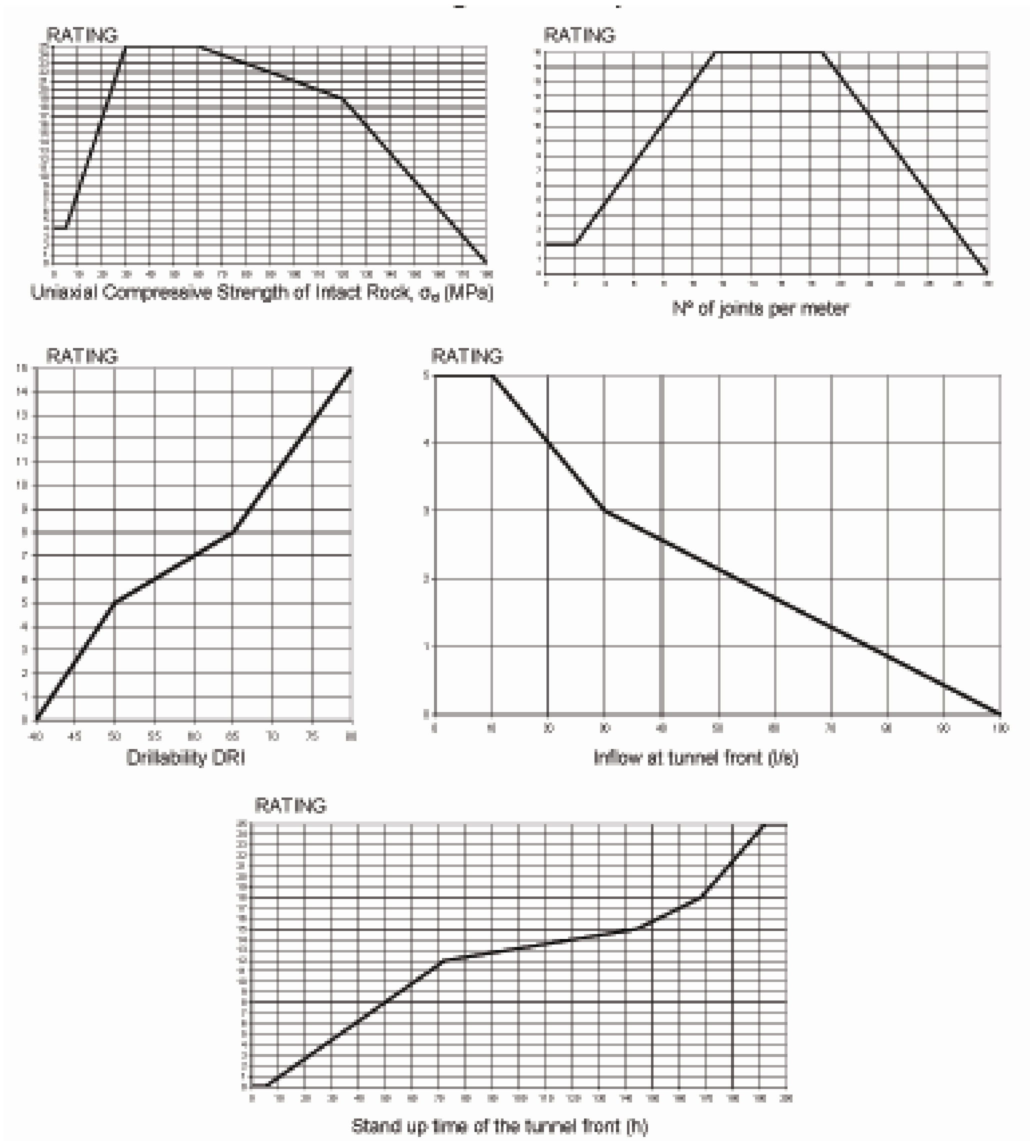


Figure 1. Graphs for determination of the ratings for RME input parameters.

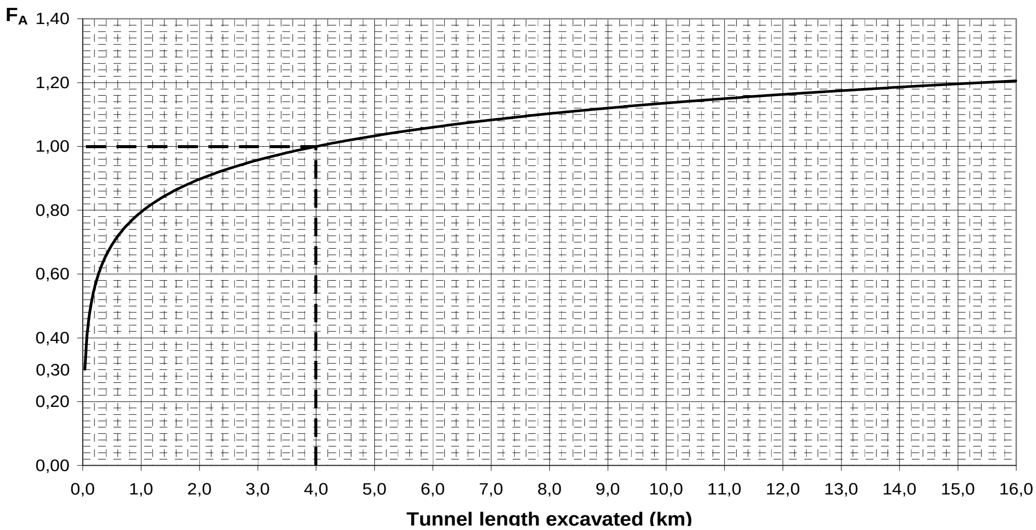


Figure 2. Variation of factor F_A with the excavated tunnel length

3.3 *Factor of Tunnel Diameter (F_D)*

To include the effect of tunnel diameter - important because in the case histories collected different tunnel sizes are involved - a Factor F_D was introduced as follows [3]:

$$F_D = 10/D \qquad \ldots(3)$$

where D is the tunnel diameter in meters. Figure 3 shows the variation of this factor with tunnel size.

4. CORRELATIONS BETWEEN RME AND ARA_T FOR THE MOST COMMON TYPES OF TBMs

To correlate the RME with the ARA for different types of TBMs, one should first note that the ratings for the uniaxial compressive strength of the rock material, as depicted in Figure 1, offer two completely different scenarios for TBM performance. It is observed form this figure, for example, that the rating of 16 points is allocated to terrains with the intact rock strength of 20 MPa as well to those with 130 MPa. Thus, assuming that all other input parameters are the same, these two terrains will feature the same RME index.

Yet it is evident that a TBM working in a rock mass having σ_{ci}= 20 MPa will obtain much higher advance than one working in a terrain with σ_{ci}=130 MPa.

For this reason, and based on research and tunnelling data [3], it was decided that the most meaningful correlations between RME and ARA_T for the common TBM types are when two ranges of the uniaxial compressive strength of intact rock are selected: the strength σ_{ci} greater or lesser than 45 MPa.

4.1 *Open TBMs*

For this oldest type of TBMs, using grippers to advance and conventional rock support, 49 case histories were accumulated of tunnels totalling 1,724 m and leading to the following relationships and their correlation coefficients, as depicted in Figure 4:

For $\sigma_{ci} > 45$ MPa $\quad ARA_T = 0.839x$

RME - 40.8 R=0.763 …(4)

For $\sigma_{ci} < 45$ MPa $\quad ARA_T = 0.324x$

RME - 6.8 R=0.729 …(5)

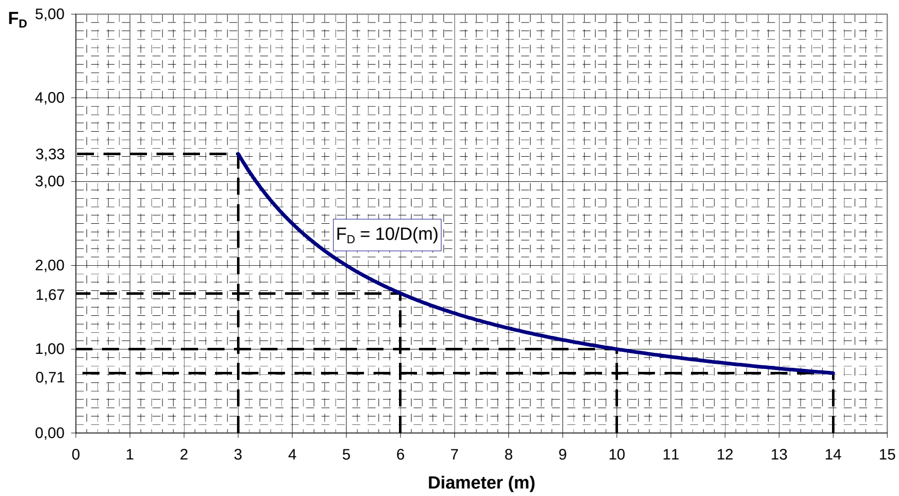
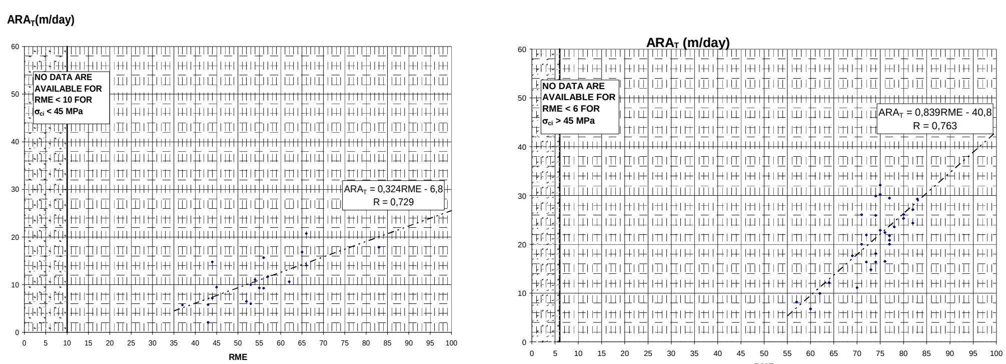


Figure 3. Variation of factor F_D with tunnel diameter



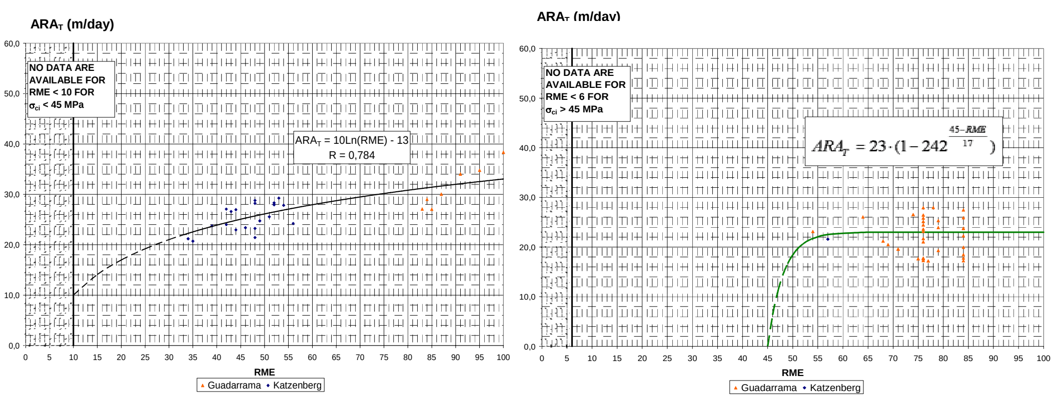
I.- For terrains with $\sigma_{ci} < 45$ MPa

II.- For terrains with $\sigma_{ci} > 45$ MPa

Figure 4. Correlations between RME and ARA_T for Open TBMs.

Based on these correlations, we reach the following conclusions:

- For terrains with $\sigma_{ci} > 45$ MPa, the highest average rate of advance for Open TBM is about 43 m/day, while in the case of $\sigma_{ci} < 45$ MPa, the average advance reduces to about 25 m/day.
- In the case of terrains with $\sigma_{ci} > 45$ MPa, the Open TBM average advance for RME < 55 is at least 6 m/day. No data are available for RME < 35 in this case, although for $\sigma_{ci} < 45$ MPa the average advance for Open TBMs in such terrains would be less than 5 m/day.



I.- For terrains with σ_{ci} < 45 MPa   II.- For terrains with σ_{ci} > 45 MPa

Figure 5. Correlations between RME and ARA$_T$ for Single Shield TBMs.

4.2 *Single shield TBMs*

This type of TBMs does not feature conventional rock reinforcement and lining but instead uses rings of concrete segments pre-fabricated, with the machine advance achieved by reacting against its list ring.

The correlations between RME and ARA$_T$ in this case were derived from 62 tunnels sections studied at the Tunnels of Guadarrama (Spain) and at the Katzenberg Tunnel in Germany, all totalling 3,620 m in length. The following relationships were obtained, as depicted in Figure 5:

For σ_{ci} > 45 MPa $ARA_T = 23\,[1 - 242^X]$

where x = (45 - RMR)/17   …(6)

For σ_{ci} < 45 MPa $ARA_T = 10 \ln RME - 13$

R=0.784   …(7)

Based on these correlations, we reach the following conclusions:

- For terrains with σ_{ci} < 45 MPa, the highest average rate of advance for Single Shield TBM is about 33 m/day, while in the case of σ_{ci} > 45 MPa, the average advance reduces to about 23 m/day.
- For terrains with σ_{ci} > 45 MPa, the TBM advance is independent of the value of RME, above RME = 55.
- In the case of terrains with σ_{ci} < 45 MPa, the experience indicates that Single Shield TBMs can obtain a reasonable rate of advance in the whole range of RME, although data are lacking for RME < 34.

4.3 *Double shield TBMs*

TBMs of this type represent a combination of an Open TBM and a Single Shield TBMs, featuring grippers when necessary in good conditions, and also an erector of pre-cast lining segments, against which the machine can advance if poorer terrain is encountered.

The correlations between RME and ARA$_T$ for Double Shield TBMs are based on the largest number of cases: 225 sections from the tunnels of Guadarrama and Abdalajís West in Spain and Gibe II Inlet and Gibe II Outlet in Ethiopia, all totalling 20.7 km in length (the average section length being

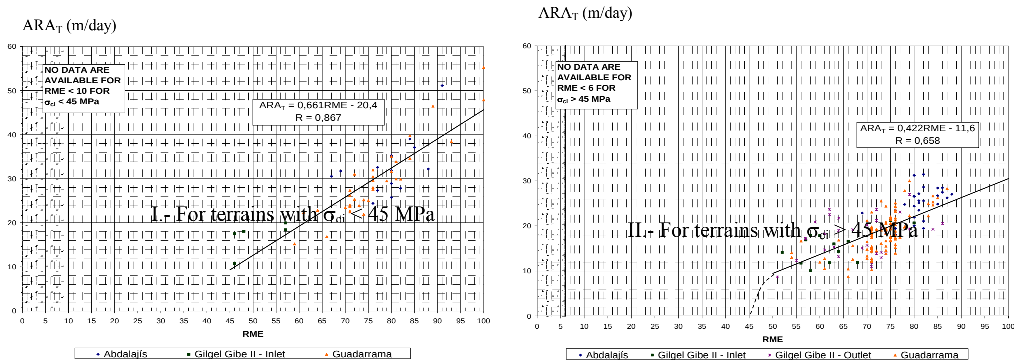


Figure 6. Correlations between RMR and ARA$_T$ for double shield TBMs.

92 m). The following relationships were obtained, as depicted in Figure 6:

For $\sigma_{ci} > 45$ MPa $ARA_T = 0.422 \times RME - 11.6$ $R=0.658$ …(8)

For $\sigma_{ci} < 45$ MPa $ARA_T = 0.661 \times RME - 20.4$ $R=0.867$ …(9)

Based on these correlations, we reach the following conclusions:

- For terrains with $\sigma_{ci} < 45$ MPa, the highest average rate of advance for Double Shield TBM is about 45 m/day, while in the case of $\sigma_{ci} > 45$ MPa, the average advance reduces to about 30 m/day.
- For terrains with $\sigma_{ci} < 45$ MPa and RME < 45, there are not sufficient data to establish a trend.
- In the case of terrains with $\sigma_{ci} > 45$ MPa and RME < 50 points the data are also lacking but it is expected that at RME = 35, for either σ_{ci}, the advance will be practically zero.

5. SELECTION OF TBM TYPE

Each of the three common TBM types can be selected on the basis of the RME index and the range of the rock material strength σ_{ci} as was shown above. The specific criteria may be identified as follows :

5.1 *Terrains with $\sigma_{ci} > 45$ MPa*

As depicted in Figure 7a, the combined data for the three common TBM types and “Double Shield Optimized”, that represents a combination of the most favourable correlations between Single Shields and Double Shields using the grippers, show clear differentiations of performance based on the RME and for the case of $\sigma_{ci} > 45$ MPa. These are rock masses characterized by RME = 45 which are conventionally designated as "hard rock tunnelling".

Based on this figure, the following criteria are evident:

- Around the values of RME = 75, the average advances of all the three TBM types are about 22 m/day.

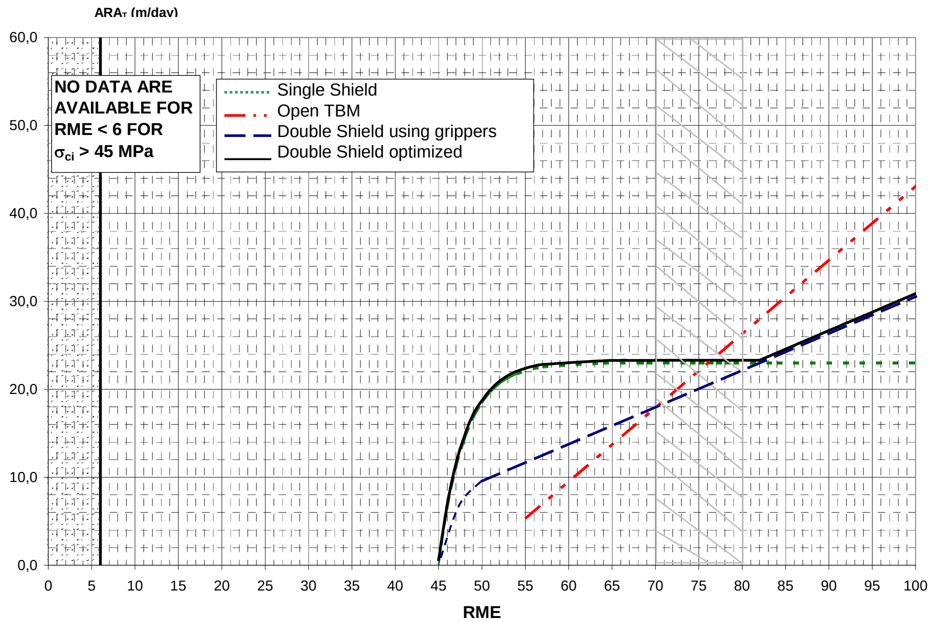


Figure 7a. Correlations between RME and ARA$_T$ for four types of TBMs in rock masses featuring rock material with σ_{ci} > 45 MPa.

- For terrains with RME > 75, the best results are obtained with Open TBMs.

- For terrains with RME < 75, the best results are obtained with Double Shield TBMs.

- The Single Shield TBMs give the poorest performance in these terrains with σ_{ci} > MPa.

- Rock masses with RME < 45 present the greatest difficulties for TBM excavation and the three types of machines obtain mediocre results in them.

5.2 *Terrains with σ_{ci} < 45 MPa*

Figure 7b presents the combined data for the same TBM types also showing clear differentiations of performance based on the RME, but for rock mass conditions featuring rock material strength σ_{ci} < MPa. The following TBM selection criteria are evident for this case:

- In the terrains with σ_{ci} < 45 MPa the best results are obtained with Double Shield TBMs of 'Optimized', for all values of RME.

- Only when the terrains have values of RME < 77, the best results belong to Single Shield TBMs, even as Double Shield provide similar results but the former are easier to use and it requires a smaller investment.

- With Open TBMs one obtains the worst performance in these terrains, whatever the value of RME may be.

6. CONCLUSIONS

The work conducted on the concept of the RME during the second half of 2006 and in the year 2007 has established significant correlations between the RME index and the Average Rate of Advance theoretical (ARA$_T$) for predicting the performance of three types of TBMs used most frequently: Open TBMs, Single Shield TBMs and Double Shield TBMs.

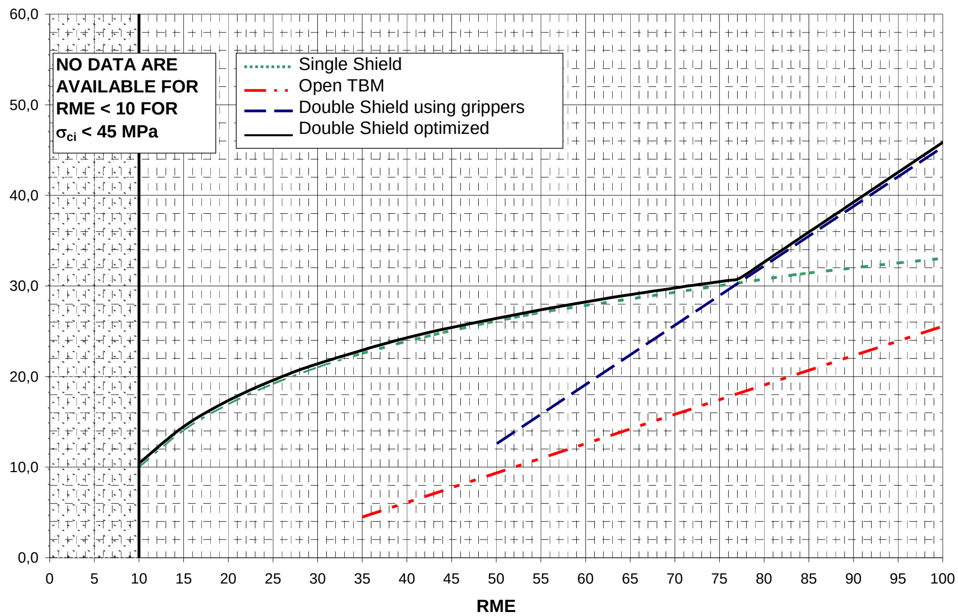


Figure 7b. Correlations between RME and ARA_T for different types of TBMs in rock masses featuring rock material with σ_{ci} < 45 MPa.

The analysis of these correlations has led to the following general recommendations:

I. For terrains of very good excavability, with RME > 80 and σ_{ci} > 45 MPa, the Open TBMs are the machines of choice offering the best performance; while in the case of σ_{ci} < 45 MPa but RME > 80, the Double Shield TBMs are preferable.

II. For terrains of good excavability, with RME falling between 70 and 80 points, all types of TBMs feature similar performance if σ_{ci} > 45 MPa. In the case of the uniaxial compressive strength of the rock material being less than 45 MPa, the Open TBMs provide much lesser advances than the single shield TBMs.

III. For terrains of medium or poor excavability, with RME < 70 points, the Single Shield TBMs are the most appropriate.

Unfortunately, space limitations do not allow discussion of other correlations obtained between the RME and the ARA_T specifically for tunnelling in fault zones which enable calculation of the net time of excavation with each type of TBMs and hence the selection of the most appropriate TBM type for fault conditions encountered.

At present, work is in progress along two lines to improve further applications of the RME index. The first is devoted to calculations of the actual time for completion of tunnel excavation, and the second line of investigation is directed to obtaining criteria for improving the performance of the TBMs featuring the RME together with the Rock Mass Rating (RMR) and the Specific Energy of Excavation defined elsewhere [2].

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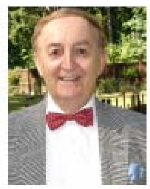
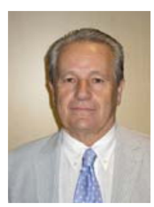
BIOGRAPHICAL DETAILS OF THE AUTHORS



Professor Z.T. Richard Bieniawski was born in Poland, educated in South Africa and practiced tunnelling and mining engineering in the USA. A professional mechanical engineer by training he obtained D.Sc. (Eng) cum laude in Pretoria, South Africa, and served as Vice Chairman of the So. African Com. on Tunnelling. After becoming Professor of Mineral Engineering at the Pennsylvania State University in 1977, he conducted extensive tunnelling research publishing 12 books and 180 papers. He is past Chairman of the U.S. National Committee on Tunnelling Technology and Doctor Honoris Causa 2001 from University of Madrid, Spain. He lives in Prescott, Arizona, USA, writing science fiction stories for his 8 grandchildren.



Professor B. Celada, was born in 1945 in Zaragoza, Spain, and in 1970 completed his studies as Mining Engineer at the University of Oviedo. In 1979 he obtained the title of Dr. Ingeniero for a thesis on “Control del sostenimiento mediante bulonaje”. In the first 10 years of his career, he worked in the coal/potash mining and tunnel construction. In 1982 he funded GEOCONTROL, a company specializing in design and supervision of tunnel construction. In 1970 he started teaching Rock Mechanics at the School of Mines in Oviedo and in 1979 continued with the same at the School of Mines in Madrid; there in 1992 he obtained the position of Catedrático de Obras Subterráneas (Chair of Underground Works).

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I. Tardáguila was born in 1960 in Salamanca, and in 1983 completed his studies as Geologist in Salamanca. He first worked in the area of hydrogeology for five years and subsequently in the supervision of construction of all types of tunnels. In 1990 he joined Geocontrol, the company where he continues to work as a Senior Geotechnician in the construction of underground works. Recently he has participated in the construction of the Tunnels of Guadarrama (2 x 28,3 km) and the Tunnel of San Pedro (2 x 9 km), both featured in this publication.