Predicting TBM excavability - Part II

In Part I of this paper, published in September[1], a new Rock Mass Excavability (RME) index was described. Here in Part II, Z T Bieniawski, of Bieniawski Design Enterprises, and Remo Grandori, of SELI SpA, present applications of the RME index on three tunnels currently under construction in Ethiopia. In the process, a number of revisions to the index were introduced, but the overall applicability of the RME is believed to be confirmed

In 1995, SELI was awarded a subcontract from Salini Costruttori for the execution of three long TBM tunnels in Ethiopia for two major Hydropower plants, the Gilgel Gibe II Hydroelectric project and the Beles multipurpose project (figure 1). In particular these tunnels were:

Gilgel Gibe II Headrace tunnel: a 26km long, 7m diameter tunnel driven by two Double Shield TBMs starting from the opposite Intake and Outlet portals. The foreseen rock formations were hard volcanic rocks (basalts, rhyolites, dolerite and trachyte) with high to very high uniaxial compressive strength (UCS) and good to fair RMR classes (figure 2).

Beles Headrace tunnel: a 12km long, 8.1m diameter tunnel driven by one EPB-Double Shield Universal TBM starting from the outlet portal. The project is located near the East African Rift System. The foreseen formations are volcanic rocks (basalts, tuff) for the first 10km and then 2km in weak lacustrine deposits where EPB operational mode is to be applied. In the volcanic formations, RMR reaches ratings of over 80 (figure 3).

Beles Tailrace tunnel: a 7.2km long, 8.07m diameter tunnel driven by one Double Shield Universal TBM starting from the outlet portal. The foreseen formations are mainly the volcanic rocks.

The design of these tunnels was based on the RMR classification, which proved successful for assessing rock mass conditions, but as the system is not directly related to TBM performance it was a challenge to predict the TBM advance rates on these projects; instead, estimating from experience and relevant case histories had to be made.

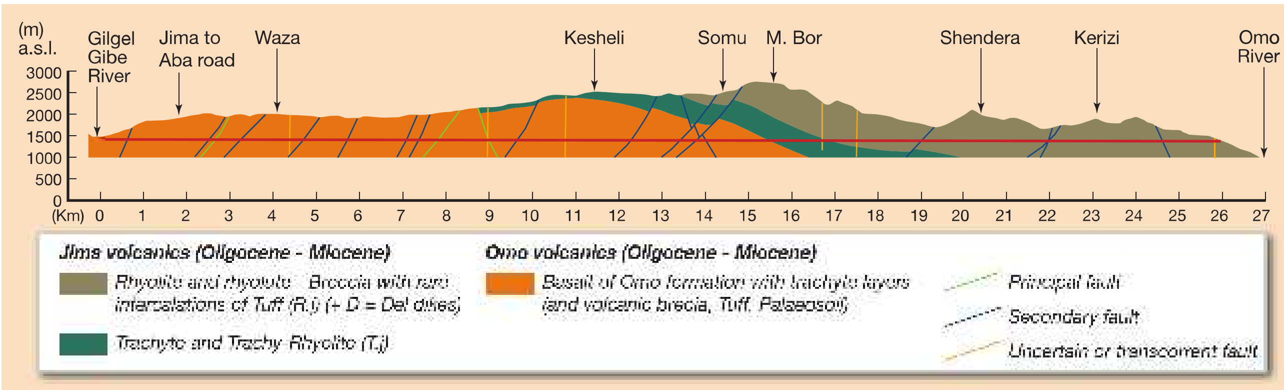
Accordingly, the authors and SELI decided to record the tunnelling data by the RME index as the TBM construction proceeded, in parallel with the RMR classification system, and - in addition - to back-analyse the data from the start of excavation. This procedure has been in use since 01 January 2007, and is continuing to date.

In essence, the 45km of tunnels driven by four shielded TBMs in volcanic rock formations provided a great opportunity to apply and test the RME index, leading to 'fine tuning', as necessary.

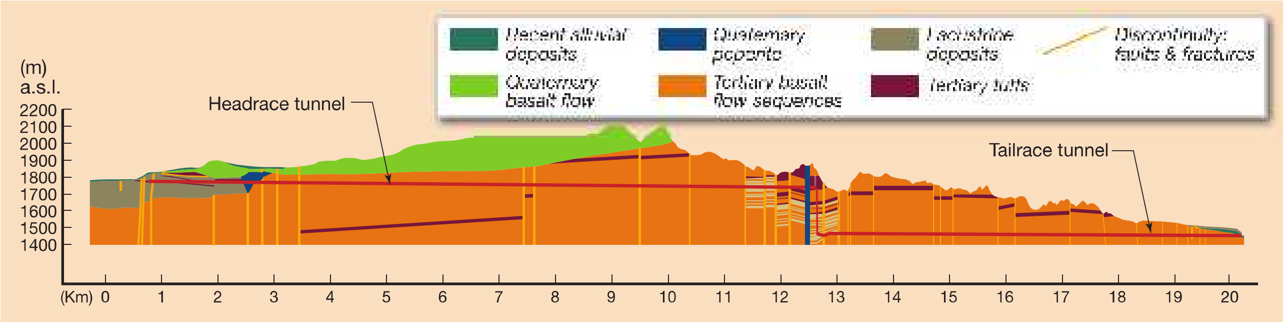
Right: **Fig 1 - Location of projects in Ethiopia**

Data recording

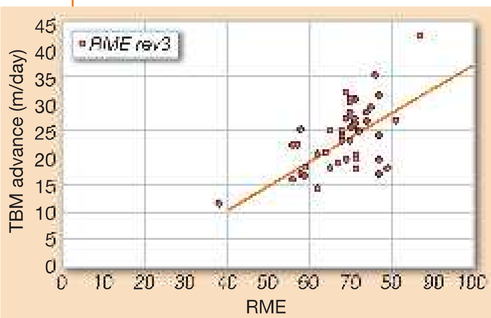
In conformance with the input data collection procedures, described in Part I, we used the data recording sheet, shown in Table 1. Since all data recordings are computerised, the recording sheets were customised for this purpose after a number of trials. As can be seen, this includes extensive rock mass parameters as well as TBM characteristics and performance data.



Above: **Fig 2 - Gibe II tunnel geological cross-section**

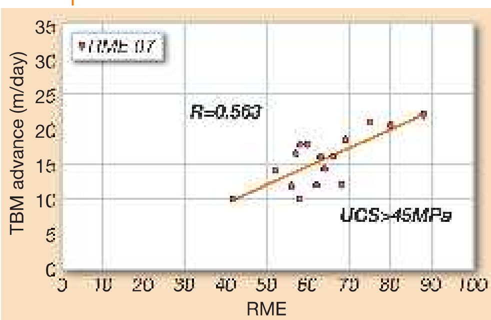


Above: **Fig 3 - Beles tunnels geological cross-section**



Above: **Fig 4 - Gibe II Tunnel Outlet, RME index correlation with the actual TBM advance rates**

Below: **Fig 5 - Gibe II Tunnel Inlet, RME index correlation with the actual TBM advance rates**



The purpose of this undertaking is three-fold: (i) to compile the RME index quickly and reliably from day-to-day tunnel operations and relate it to the average rate of TBM advance; (ii) to 'fine-tune' the correlation for the highest coefficient by adjusting the ratings of the RME input parameters, as appropriate for the prevailing tunnelling conditions; and (iii) to predict the TBM advance and penetration rates for the tunnel sections ahead, together with - if possible - such TBM parameters as thrust, torque and machine utilisation.

RME at Gibe II and Beles

Once the RME input parameters were collected, the actual index was determined by summation of the ratings allocated to each parameter, and entered into the computer data. For this purpose, Table 2 presents the tabulation of the RME_{rev3}, which is currently used on the Ethiopian projects. It should be noted that while this is similar to the RME07 described in Part I, 'fine-tuning' was applied for the parameters Stand-Up-Time and Groundwater Inflow, which have the minimum values of zero (important for swelling and squeezing rock masses) instead of "< 5" hours and "< 10 liters/min", respectively, as used on the Spanish projects.

In addition, the rating weights of some of the RME input parameters were slightly adjusted. In particular, more weight was given to the unconfined compressive strength of the rock because this parameter has a strong influence on TBM performance; in contrast, less weight was given to the frequency and orientation of the joints, to balance the representation; stand up time ranges were modified due to the fact that TBMs advance rapidly and thus any instability that occurs after 12 hours does not affect the TBM operation.

These revisions proved very beneficial, leading to a practically linear correlation between the measured RME and the TBM rate of advance, and thus improving dramatically the prediction of the TBM performance from that originally based on the RMR.

RECORD of DATA Form for Rock Mass Excavability RME

Name of Tunnel... ***GILGEL GIBE II HYDROELECTRIC POWER PROJECT - OUTLET POTAL-***

Initial chainage of section....... ***7285.84*** .... Final chainage of section......... ***7331.43*** ....

Length of section......... ***45.59*** ....m

Duration of excavation (days)............................. ***2*** .... (number + 1 decimal)

Average Rate of Advance ***ARA*** = ... ***22.80*** ....m/day

Lithology................................ ***Rhyolite*** .... Average depth......... ***450*** ....m

ROCK MASS EXCAVABILITY PARAMETERS

Uniaxial compressive strength of intact rock (σ_c): .... ***120*** ....MPa

Drilling Rate Index ***DRI:*** ... ***55*** ....Type of homogeneity at excavation front......... ***Homogeneous*** ......

N° of joints per meter........ ***6*** ....Rock Mass Rating RMR: range...... ***65-68*** .....Average....... ***67*** ....

Orientation of discontinuities with respect to tunnel axis

(perpendicular, parallel or oblique)......................... ***Oblique*** ....

Stand up time...... ***>48*** ....hours Groundwater inflow at tunnel face........ ***0*** .....liters/sec

Rock Mass Excavability **Bieniawski RME................. *71* ....**

TBM PERFORMANCE PARAMETERS

Make.................. ***SELI*** ....Type......... ***DSU 0698 - 109*** ....Diameter........ ***6.98*** ....m

Average speed of cutterhead rotation........... ***5.50*** ....rpm Applied Thrust....... ***4634*** ....kN

Specific Penetration................ ***8.84*** ....mm/rev

Rate of Penetration.................... ***48.6*** ....mm/min

N° cutters changed:................... ***4*** .... Rate of TBM utilization.......... ***32.56*** ....%

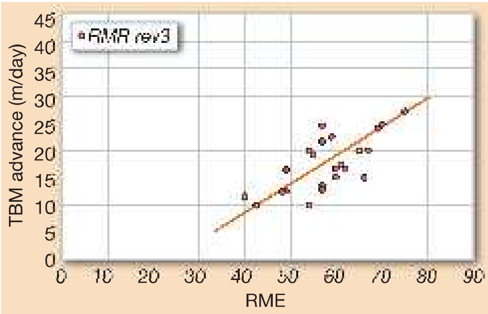
Above: **Table 1 - Record summary for a tunnel section**

Uniaxial compressive strength of intact rock [0-25 points]					
σ_c (MPa)	<5	5-30	30-90	90-180	>180
Ave. rating	4	14	25	14	0
Drillability [0-15 points]					
DRI	>80	80-65	65-50	50-40	<40
Ave. rating	15	10	7	3	0

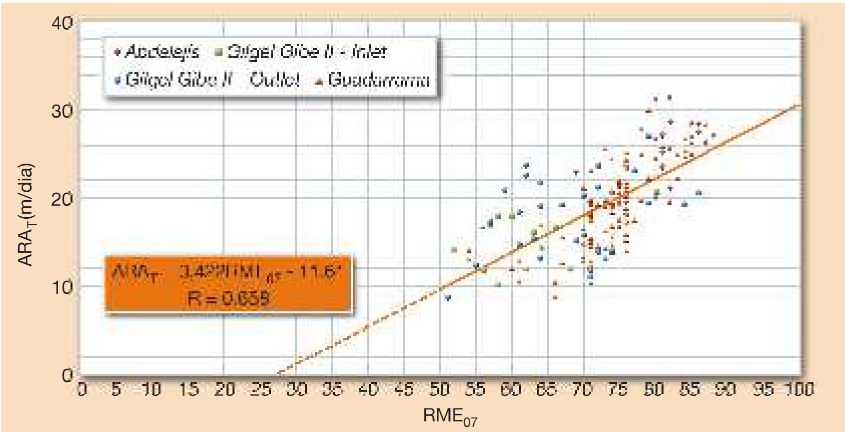
Discontinuities at the tunnel face [0-30 points]										
Homogeneity			**Number of joints per meter**					**Orientation with repect to tunnel axis**		
Homogeneous		Mixed	0-4	4-8	8-15	15-20	>20	Perpendicular	Oblique	Parallel
Ave. rating	10	0	2	7	15	10	0	5	3	0

Stand up time [0-25 points]					
Hours	0	<5	5-12	12-48	>48
Ave. rating	0	2	10	15	25
Groundwater inflow [0-5points]					
Liters/sec	>100	50-100	20-50	<20	0
Rating	0	1	2	3	5

Above: Table 2 - Input parameters ratings for the RME_{rev3} index in Ethiopia (from 03/03/07)



Above: Fig 7 - Beles Headrace Tunnel, RME index correlation with TBM advance rates



Above: Fig 6 - Consolidation of the Gibe II data with the Spanish cases histories

This is illustrated in figures 4 and 5, which show the new RME_{rev3} data with convincing correlations.

The most significant finding was, moreover, that the new Gibe results from Ethiopia fitted well into the overall correlation found from the Spanish case histories. This is shown in figure 6. These consolidated analyses were performed in Spain and the authors wish to acknowledge the contributions of Prof. Benjamín Celada and his staff from Geocontrol, Madrid.

Some comments are appropriate in connection with figure 4: note that the measured RME values are concentrated in a range between 55 and 85, which is the typical range of RME data for the encountered rock conditions and TBM performance in the featured tunnel Outlet.

This is balanced by the data from Gibe II Inlet (figure 5), driven in very weak rock, but more data is needed for such rock conditions.

The Beles Headrace tunnel is driven in very hard rock, RMR Class I, and the RME results, just compiled, are discussed in a later section, and are still in progress.

With reference to the above figures, an interesting aspect should be pointed out: it is a characteristic of the RME index that even in the worst geological conditions or TBM performance, the RME has values above zero.

For example, a very weak rock with no stand up time and in presence of water will still be rated RME between 30 to 40 depending on the jointing, or an extremely hard rock with very low DRI may be rated from 40 to 50 depending on the jointing.

The explanation for this phenomenon is that correlations between the RME and TBM advance rate do not start at zero; instead there is a minimum RME value below which a given TBM type is not appropriate. In fact, it is the aim of this investigation to determine the applicable limits of suitability for various TBM types, as discussed in Part I.

Other factors influencing TBM advance

It is recognised that geological conditions are not the only factors influencing the performances of a TBM.

One of the SELI Double-Shield TBMs that drove the Gilgel Gibe II Headrace


The Gilgel Gibe II Headrace tunnel, in Ethiopia

In particular, for tunnelling in Ethiopia the following factors were identified as affecting TBM advance rates:

1) Tunnel diameter: The diameter affects the TBM performance in different ways:

- The cutterhead revolution speed (and thus the TBM rate of penetration) decreases almost linearly with an increase in the diameter
- The time to erect the precast lining also increases with the tunnel diameter
- The influence of these two items is such that by increasing the diameter from 3.5m to 12m the average TBM advance rate is reduced by approximately 50%

2) Site Efficiency: The site efficiency is dependent on:

- The experience and know-how of the company and of the staff at the site
- The quality and skill of the manpower
- The location of the site (transport time to the site of spares and consumables, import/custom clearance time, availability of local suppliers of components and equipped workshop for urgent repairs)

These factors can reduce the average TBM performance by another 50%.

3) Learning Curve: During the initial months of TBM operation, the production is reduced due to the learning period. This period is needed to train the crews, set up the TBM and learn about the behaviour of the specific rock formation.

Prediction of TBM performances

In parallel with the RME index, the authors advocate an approach to forecasting TBM performance based on the RME but including also the above-mentioned factors. A preliminary method/formula tested in the field is as follows:

The baseline (ideal) conditions to achieve the best average TBM performance are defined as:

- RME index equal to 100
- TBM diameter 3.5m
- Full site efficiency

In these conditions, a TBM can achieve 120m/day of peak production and 60m/day of average production. In a given project, the 60m/day of the average advance rate is adjusted by the following formula:

ARA (ave. TBM rate of advance, m/day) = 60 x (RME/100) x C_D x C_E x C_L + 0.23 RME - 14.5

where:

RME is the measured/foreseen RME index in a given tunnel section;

C_D is a coefficient of the actual TBM excavation diameter (D_e) calculated as: $C_D = 1.2058 - 0.0588\ D_e$

C_E is a coefficient of the site efficiency estimated by the formula: $C_E = (0.5 + C_c + C_m + C_a)$

where C_c takes into account the experience of the Contractor in TBM projects and varies from 0 to 0.2.

C_m takes into account quality of the manpower in the project and varies from 0 to 0.15.

C_a takes into account the logistic conditions of the area/country where the site is located and varies from 0 to 0.15 depending upon two main factors:

Transport time to the site including customs/import clearance: less than 1 month = 0.075, more than 1 month = zero.

Availability of local suppliers/workshops: no availability - zero, availability = 0.075.

C_L is a coefficient of the learning period and varies from 0.85 to 1.00 depending on the total tunnel length to be excavated.

EXAMPLE: Adjustments coefficients for the Gibe II and Beles tunnels:

$C_D = 1.2058 - 0.0588*7 = 0.7942$

$C_E = 0.5 + 0.2 + 0 + 0 = 0.7$

$C_L = 1$

For Beles, $C_D = 0.729$

The corresponding average rates of TBM advance (ARA), incorporating the above coefficients, are calculated as follows for the different RME values encountered for the Ethiopian projects:

RME_{rev3}:	40	50	60	70	80	90
ARA, m/day:	8.04	13.68	19.31	24.95	30.58	36.22

The above ARA values correspond well enough for practical purposes to the actual production rates for the different RME values, as shown in figure 7 for the Beles Headrace tunnel.

Future activities

SELI plans to introduce the RME index system in all its major rock TBM projects to be bored in the future. Among these are:

- The 6km long, 3.7m diameter tunnel of the Val Passirio (Bozen - north Italy), in gneiss formations
- The 10km long, 6.3m diameter tunnel for Brenner, in granitic formations

Conclusion

The Gibe II and Beles tunnels under construction in Ethiopia represent a very comprehensive test for verification and 'fine tuning' of the RME system and for improving the correlations with TBM advance rates in a wide-range of rock conditions.

Together with the other factors influencing TBM performance, RME was found well suited for practical forecasts of TBM advance in foreseen rock mass conditions. This would be particularly helpful in the design phase of tunnelling projects.

SELI plans to implement the RME system as a standard in all its future rock TBM projects, particularly in the Brenner service/exploratory tunnel. This tunnel, to be driven by a SELI machine, will explore the rock mass for the later larger tunnels to be constructed by TBMs. T&T

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REFERENCES

1. ZT Bieniawski, B Celada & JM Galera, 2007. Predicting TBM Excavability - Pt I, *T&TI*, September ‘07, p25.