* En esta versión aparecen corregidas las erratas en la edición de T&T.
* In this reprint, corrections were made following errata to the original version.
* Nesta versão aparecem corrigidas as erratas da edição T&T.

Specific energy of excavation in detecting tunnelling conditions ahead of TBMs

The concept of the 'specific energy of excavation' is not new, dating back to the 1960s, but an innovative application of its main component during trials in TBM tunnels in Spain showed that it can be used effectively to detect changes in tunnelling ground conditions based on real-time recording of the machine performance as construction proceeds, as the authors explain

Authors

This article is an edited version of the paper 'The Specific Energy of Excavation as an Aid for Detecting real-time Changes in Tunnelling Conditions ahead of TBMs' by Prof Richard Z T Bieniawski of Bieniawski Design Enerprises, Arizona, US and by Benjamin Celada, Isidoro Tardaguila and Alejandro Rodrigues of Geocontrol, Madrid, Spain.

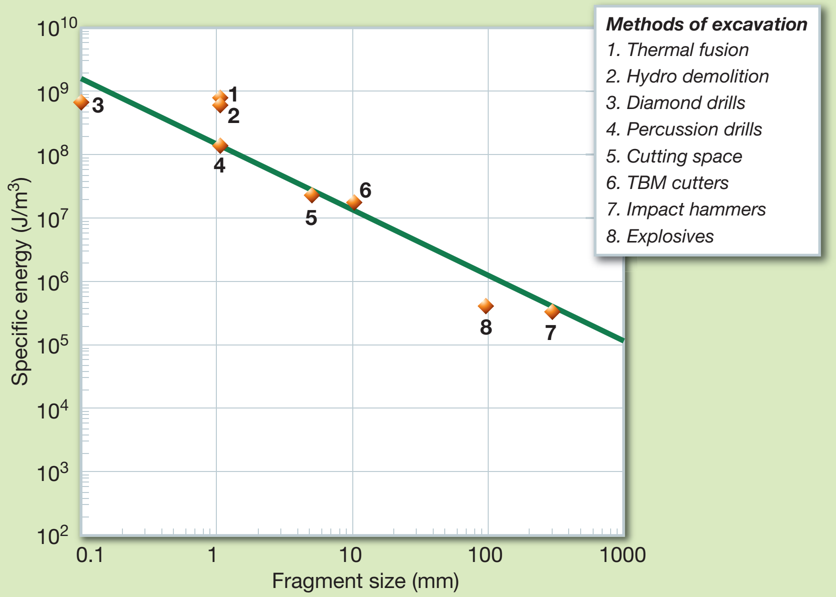
The specific energy of excavation (SEE) is defined as the relation between the energy involved during the process of excavation, expressed in megaJoules (MJ), and the volume of ground excavated in m^3.

The concept of the SEE has been utilised for many decades to assist in assessing the efficiency of the drilling processes and excavating in rock masses. First reported in the petroleum industry (Teale, 1965), it is a parameter that can be determined in real time from the data recording the performance of a drilling machine or a TBM. In addition, what makes this parameter particularly attractive is its correlation to the mechanical properties of the rock mass (Acaroglu et al, 2008).

During the past three years, Geocontrol of Madrid, Spain, conducted investigations with a partial grant from the Center for Industrial Development (CDTI) of Spain utilising the SEE to characterise rock masses for use in TBMs. As a result of this effort (Geocontrol, 2011) this article presents new findings to assess the excavation process and estimate the quality and other key characteristics of the rock mass as the TBM progresses.

Dependency

The specific energy of excavation depends on rock mass condition and on the excavation process. Cook and Joughim (Cook and Joughim, 1970) performed tests examining the various methods of excavation in quartzitic rock masses found in South African gold mines, the uniaxial compressive strength of which could exceed 200 MPa. They measured the SEE by each method studied as a function of the size of rock fragments produced during the various processes of rock breaking. The results are shown in Figure 1, below.



Right: Figure 1, correlation between the energy consumed by various methods of excavation and the size of rock fragments in mm

This figure leads to the important conclusion that the SEE is related exponentially to the size of rock fragments produced during the rock breaking process, and that excavation by explosives consumes the least amount of energy among the methods studied. TBM boring falls in the middle of the range.

Calculation

The Specific Energy of Excavation can be calculated using the expression by Teale (Teale, 1965) who was the first to publish research about the use of the Specific Energy in the process of drilling large diameter samples of rock. He proposed that the Specific Energy of Drilling (EEP) is calculated using the following expression:

$$EEP = \frac{F}{A} + \frac{2\pi \omega T}{A u}$$

where:

- EEP is the specific energy of drilling (in MJ/m^3),
- F is the total thrust (in kN),
- A is the area of drilled (in m^2),
- ω is the speed of rotation (in rev/s),
- T is the applied torque (in kNm),
- u is the drilling advance rate (in m/s).

The first part of the above equation corresponds to the energy proportional to the thrust imposed while the second part is the energy consumed for drill bit rotation.

If one uses the concept of specific penetration for each revolution, $P = \frac{u}{\omega}$, then the above expression is:

$$EEP = \frac{F}{A} + \frac{2\pi T}{A \times p}$$

Teale (1965) has shown that $\frac{F}{A}$ represents only one per cent of the total energy and thus this can be neglected for practical purposes.

During field trials by Geocontrol in the Pontones Tunnel in Spain (2009-2010), excavated by a Herrenknecht single-shield TBM, the above expression was tested and the Specific Energy of Excavation (SEE) during tunnelling was calculated. Again, it was found, as in the case of large diameter drilling, that the thrust component corresponded to only one per cent of the total energy in normal conditions. However, in the case of TBM being trapped, this component can amount to 30 per cent of the energy; a figure that can no longer be reasonably neglected.

Accordingly, for tunnel excavation by TBMs, it can be stated:

$$SEE = EE_{THRUST} + EE_{ROTATION}$$

In this equation, the first component (EE_{THRUST}) represents the specific energy consumed to advance the TBM (which as indicated is about one per cent of the total in most instances) while the second term ($EE_{ROTATION}$) is the specific energy to rotate the cutterhead, which actually produces the excavation in the rock mass.

Lab tests

The specific energy in the process of rock fracture in compression can also be determined in laboratory tests The specific energy during the process of rock fracture in compression may be determined in laboratory tests from complete stress-strain curves obtained on rock samples tested in high stiffness, servo-controlled presses; the value of the specific energy in compression tests (EEC) coincides with the area under the curve along the axis of strain, as illustrated in figure 2, below.

Lab/site comparison

The specific energy of excavation in situ is much greater than the specific energy of fracture in a laboratory test. From the data obtained during the TBM excavation in the Pontones Tunnel in Spain, the specific energy of excavation (SEE) was calculated for various values of the rock mass quality (RMR) which led to the findings that when RMR < 35, the SEE is less than $10MJ/m^3$ and when RMR > 45, the SEE is greater than $32MJ/m^3$. At the same time, in the tests on intact rock samples from the tunnel rock formations in uniaxial compression, using a servo-controlled machine, the values of EEC (lab) were 10 to 20 times less than those of the SEE in the field. Such results seemed contradictory. After all, due to the fact that a rock mass includes discontinuities and rock material does not, this suggests that the specific energy of excavation to break up a rock mass should be less than that necessary to fracture rock material. A probable explanation of the results obtained might be that the process of rock fracture in compression is more efficient than that of excavation by TBM.

SEE analysis

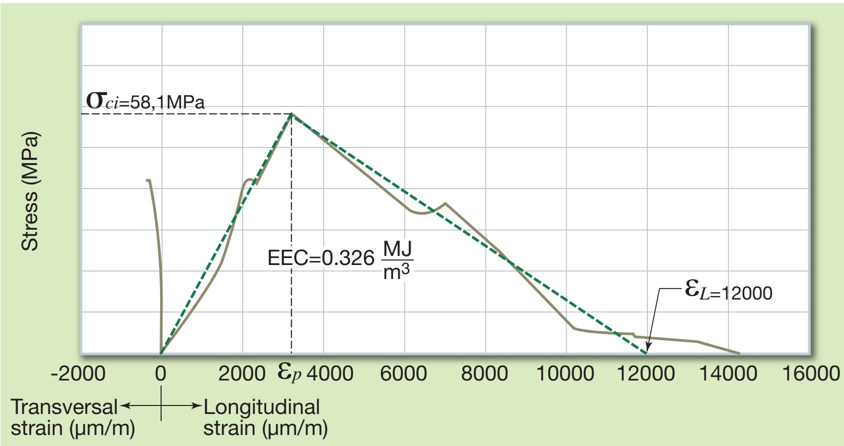
To control the work of a TBM it is necessary to analyse the specific energy of excavation by its principal components. The specific energy component due to the rotation of the cutterhead (EEG), under normal conditions, is responsible for 99 per cent of the energy used during TBM excavation. In fact, it is made up of three terms:

$$EEG = EEG_r + EEG_f + EE\varepsilon$$

EEG_r is the specific energy required to press the TBM cutterhead to the tunnel face. In normal conditions, EEGr consists of 57-77 per cent of the total SEE; the higher values corresponding to the higher RMR ratings of the rock mass excavated.

EEG_f is the specific energy used to rotate the cutterhead against the terrain previously indented by the TBM cutter. In normal conditions, EEG_f accounts for 31-41 per cent of the total specific energy of excavation SEE. Contrary to the EEG_r, the higher values of EEG_f correspond to much lower ratings of RMR.

The term $EE\varepsilon$ entails the rest of the specific energy of excavation, which is spent on activities relating to the action of the cutterhead. These constitute about two



Right: **Figure 2, determination of the specific energy of rock fracture in laboratory EEC using a complete stress-strain curve in uniaxial compression** per cent of the total; and thus negligible.

In normal conditions of the functioning of the TBM, both EEG_r and EEG_f maintain the proportion of the total energy as indicated, however when the rock mass conditions change significantly and become more difficult, the proportion of EEG_r approaches 77 per cent of the total energy expended, and at the limit when the terrain just cannot be excavated, it reaches 100 per cent.

In the opposite case, when the rock mass loses its strength and becomes unstable at the tunnel face, the cutters have great difficulty in being effective, then the other component EEG_f amounts to 100 per cent of the total energy.

For the purpose of assessing and maintaining efficient functioning of the TBM, an index of efficiency of excavation (IEE) becomes very useful, and can be calculated in real-time of TBM operation, based on the parameters recorded during the advance of the machine, which are typically obtained automatically every ten seconds. These, lmited by contract on the trails, are thrust (kN), torque (kNm), rotational speed (rev/min) and advance rate (m/s).

Based on the experience gained and observations during the field trials, the index of efficiency of excavation defines the following ranges of TBM functioning:

- If IEE < 0.25, the TBM runs the risk of being immobilised at the cutterhead due to instabilities at the tunnel face;
- If 0.25 < IEE < 1.75, the TBM works normally;
- If IEE > 1.75 the TBM has great difficulties in excavating the terrain due to the high strength and abrasivity of the rock mass.

Depending whether the IEE is lower or higher than one, EEG_r and EEG_f are calculated according to the following:

if IEE < = 1:

$$EEG_r = \frac{4}{5}\, K_t \frac{f_c}{1000\,\mu}$$

$$EEG_f = EEG_{Teale} - EEG_r$$

if IEE > 1

$$EEG_r = \frac{1}{5}\, K_i \cdot cec \frac{f_c}{1000\,\mu}$$

$$EEG_r = EEG_{Teale} - EEG_f$$

where:

- EEG = total specific energy of rotation after Teale (1965)
- EEG_r = specific energy of rotation when advancing the cutterhead (in MJ/m^3)
- EEG_f = specific energy of rotation due to friction when turning the cutterhead (in MJ/m^3)
- f_c = thrust of the cutter (in kN)
- Coefficient $\mu = \frac{\sqrt{p}}{\sqrt{d}}$ according to Sanio *(Sanio, 1985),*

  where p is penetration per revolution and d is the diameter of the cutter (in mm).

- Kt = Constant characteristic for a TBM type: $\frac{N}{R\sqrt{d}}$ $[1/m^2]$

  where N is the number of cutters and R is the radius of the cutterhead, m.

- Ki = Constant characteristic of the excavation process by TBM: $\frac{100EEG}{f_c/\mu}$ $[1/m^2]$

  where f_c is thrust per cutter (in kN).

- cec = Coefficient of cutter efficiency

$$cec = \frac{1}{IEE}$$

RMR related to SEE

The RMR of the rock mass at the TBM face may be estimated as a function of the specific energy of excavation.

Based on the data from two tunnels in Spain (Pontones Tunnel II and Sorbas Tunnel I), as well as one (Los Bronces Tunnel) in Chile, the following correlation was obtained, as depicted in figure 3, below.

This figure allows one to estimate the values of RMR of the terrain excavated at the front of the TBM with an error of only +/-5 points using the following correlation:

$$RMR = \frac{5.Ln\,(EEG_r/80) - 100}{Ln\,(EEG_r/80) - 1}$$

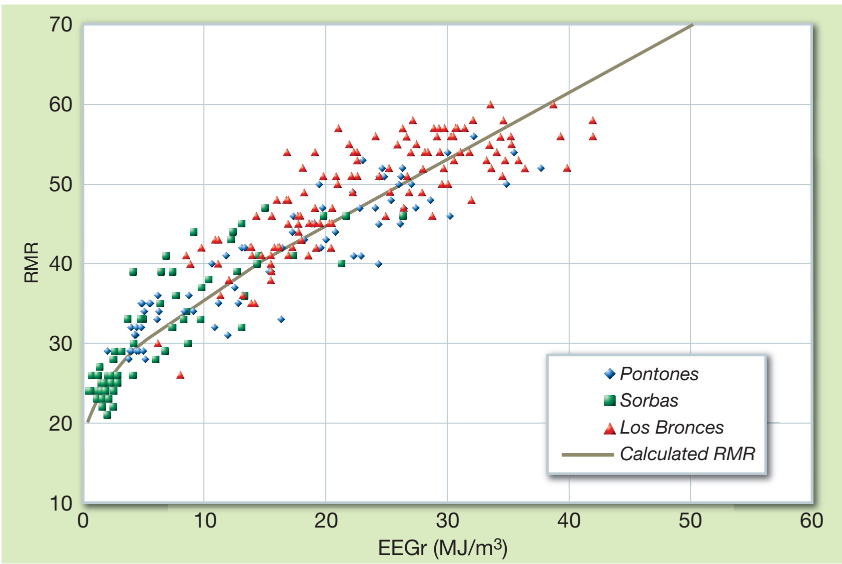
r^2 : 0,86 1< EEG_r (MJ / m^3) < 40

An estimation of the rock mass quality RMR of the terrain excavated in front of the TBM is most useful as a warning of approaching adverse conditions and, if necessary, to allow selection of the appropriate rock mass reinforcement which can be installed from the TBM as is done with open-type TBMs.

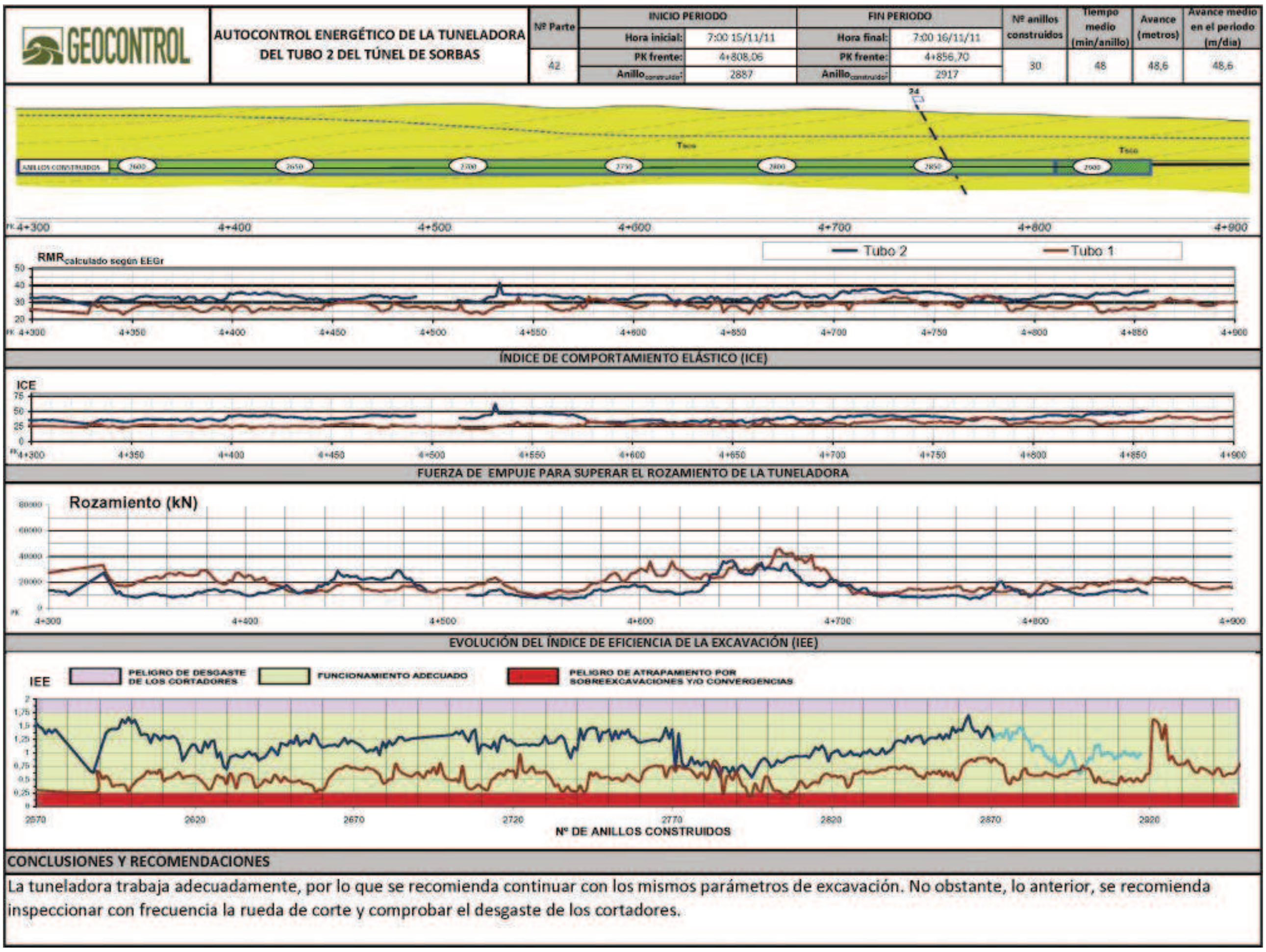
Real-time conditions

The parameters controlling the progress of a TBM, provide information on how the machine progresses in real-time; thus developing vital data which can be used as a guide to optimie TBM advance. A similar methodology, although less precise at the time, was used during the construction of the well-known Guadarrama Tunnels in Spain (Tardaguila & Suarez, 2005).

As result of this project, a monitoring system called 'Auto-Control of TBMs by energy parameters' (ACT) has been developed. This system allows, in real time, recording of the following parameters:



Right: Figure 3, correlation between the Specific Energy of Excavation and RMR at the front of the TBM. Data of 270 values from three tunnels.



Above: Record of information in real time obtained during TBM excavation of the Sorbas Tunnel in Spain

- RMR, calculated from EEG_r;
- Index of elastic behaviour (ICE), after (Bieniawski et al, 2011);
- Thrust to advance the TBM (in kN).

As an example, Figure 4, above, presents the data automatically recorded in real-time at the Sorbas Tunnel, based on the ACT installed in the TBM.

The chart (Figure 3) shows EEG_r correlates closely with RMR. As both can be automatically recorded during TBM operation and expressed as the efficiency index IEE, any significant change in the index can alert the operator to a possible change in the rock mass quality RMR – thus warning of adverse conditions.

Conclusion

The concept of the specific energy of excavation has been revised and further developed for use with TBMs demonstrating a correlation between its main component of EEG_r (the specific energy of rotation) and also rock mass quality (RMR).

An index of excavation efficiency has been introduced based on field trials of three tunnels in Spain over the past three years. Serving as a warning of adverse conditions, any significant change in the index in real-time can alert the TBM operator to a possible change in the rock mass quality.

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