*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

Forecasting tunnelling behaviour

Most rock characterisation and ground behaviour prediction has concentrated on TBM drives, but the authors of this paper go into forecasting tunnel behaviour for feasibility and planning purposes when using conventional tunnelling methods, using new methodology from Spain. Prof Richard Z T Bieniawski of US-based Bieniawski Design Enterprises, David Aguado and Benjamin Celada of Geocontrol and Alejandro Rodriquez CDIAM (both companies in Spain) present the argument

In the process of designing a tunnel, knowledge of a foreseen length of advance as a function of rock mass conditions, tunnel size and shape and a method of excavation has received much attention in recent years, particularly for tunnels excavated by mechanical means, such as TBMs. For tunnels excavated by conventional methods an early prediction, for feasibility and planning purposes, is also important with respect to achieving the desired progress.

In this respect, the selection of tunnel support depends not only on rock mass quality but also on other factors, such as the depth below surface and method of excavation.

In this article, a new methodology from Spain is presented for forecasting the behaviour of tunnels constructed by conventional methods based on an evaluation, combining theoretical and empirical approaches, of the degree of tunnel stability.

Elastic behaviour

To evaluate the elastic behaviour of an underground excavation, one may recall the classic equations of Kirsch, dating back to 1898.

For the purposes of this discussion, the Kirsch solution for stresses at the perimeter of a circular excavation subjected to uniaxial compression provides two expressions for the maximum tangential stress σ_θ:

for $K_0 \leq 1$: $\sigma_{\theta MAX} = (3-K_0)\ \sigma_o$

for $K_0 \geq 1$: $\sigma_{\theta MAX} = (3K_0-1)\ \sigma_o$

where K_0 is the ratio of the horizontal to the vertical applied stresses, and the vertical principal stress $\sigma_o = \gamma H$.

Hence, assuming an elastic behaviour, and in terms of effective stresses, one obtains:

if $K_0 \leq 1$: $\sigma_{CM} \geq (3-K_0) \cdot \gamma \cdot H$

or $$\frac{\sigma_{CM}}{(3-K_0) \cdot \gamma \cdot H} > 1$$

if $K_0 \geq 1$: $\sigma_{CM} \geq (3K_0-1) \cdot \gamma \cdot H$

or $$\frac{\sigma_{CM}}{(3K_0-1) \cdot \gamma \cdot H} > 1$$

where σ_{CM} is the uniaxial compressive strength of rock mass.

Now we introduce an index of elastic behaviour (ICE - Índice de Comportamiento Elástico) (ref 1) by the following expressions:

for $K_0 \leq 1$ $$ICE = \frac{100\sigma_{CM}}{(3-K_0) \cdot \gamma \cdot H}$$

for $K0 \geq 1$ $$ICE = \frac{100\sigma_{CM}}{(3K_0-1) \cdot \gamma \cdot H}$$

considering a specific average value of:
$\gamma = 0.027\ MN/m^3$
and adopting the Kalamaras-Bieniawski relationship (ref 2) of:

$$\sigma_{CM} = \sigma_{ci} \cdot e^{\frac{RMR-100}{24}}$$

where σ_{ci} is the uniaxial compressive strength of intact rock, the following expressions for ICE are obtained:

Table 1: Designation of stress-deformation behaviour of a tunnel section as a function of the Index of Elastic Behaviour ICE

ICE	Stress-deformation behaviour
>130	Completely elastic
70-130	Elastic with incipient yielding
40-69	Moderate yielding
15-39	Intensive yielding
<15	Mostly yielding

$$\text{for } K_0 \leq 1: \quad ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3-K_0) \cdot H}$$

$$\text{for } K_0 \geq 1: \quad ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3K_0-1) \cdot H}$$

Since the equations of Kirsch are only applicable to circular tunnels, for non-circular excavations a factor of correlation, F, is introduced.

To quantify the values of F, calculations were performed using the program FLAC 3D, including a plastic behaviour and four types of underground excavations:

1. Circular tunnel 6m in diameter;
2. Circular tunnel 10m in diameter;
3. Conventional oval tunnel 14m wide; and
4. Chambers 25m wide and 60m high.

For each case of these 288 calculations were performed combining the following values of the variables in the index ICE:
H = 100 m; 200 m; and 400 m.
σ_{ci} = 30; 50; 70 and 100 MPa.
RMR = 20; 30; 50 and 70.
K_0 = 0.6; 0.8; 1.0; 1.5; 2.0; 2.5.

For each of the 1152 problems solved with the program FLAC 3D, the values of ICE were calculated and compared with the thickness of the plastic zone around each excavation.

Figure 1 shows the yielding zone around a conventional tunnel, 14m wide with six ICE values for K_0=0.8 and 1.5. From the results of these calculations, factor F was determined as follows:

1. Circular tunnel, diameter Ø = 6 m
   F = 1.3
2. Circular tunnel, diameter Ø = 10 m
   F = 1.0
3. Conventional tunnel diameter Ø = 14 m
   F = 0.75
4. Chambers 25m wide x 60m high
   F = 0.55

Incorporating factor F, the final expressions of the index ICE are:

$$\text{for } K_0 \leq 1: \quad ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3-K_0) \cdot H} \cdot F$$

$$\text{for } K_0 \geq 1: \quad ICE = \frac{3704\sigma_{ci} \cdot e^{\frac{RMR-100}{24}}}{(3K_0-1) \cdot H} \cdot F$$

On the basis of the completed calculations, it was found (ref 3) that the ICE index provides sufficiently realistic estimates of the stress-deformation behaviour of a section of a tunnel using the criteria presented in Table 1.

Determining rate of advance

A development reported in *T&TI* in 2007 (ref 4) proposed an index of Rock Mass Excavability (RME) on the basis of the experience gained during the construction of the tunnels of Guadarrama, Abdalajis and San Pedro; all in Spain. This index is determined using five parameters as follows:

1. Uniaxial compressive strength of the intact rock material: 0 - 25 points;
2. Drilling Rate Index (DRI): 0 - 15 points;
3. Effect of discontinuities at the front of the excavation: 0 - 30 points;
4. Stand up time of unsupported rock mass: 0 - 25 points;
5. Influence of water at the front of the excavation: 0 - 5 points.

A recent publication (ref 3) provides a convenient way of determining the above parameters.

While the RME was first directed at tunnelling with TBMs, the process of tunnel construction using conventional methods, such as drilling and blasting, is based on repetition of a cycle of operations. This involves the activities of excavation, loading the volume of rock to be removed and introducing support for reinforcement around the perimeter of the excavated tunnel. The length of a tunnel section excavated during each cycle of operation defines the round of advance; it is usually between 0.5m and 6.0m, and affects the overall performance of a tunnel project.

In the case of tunnels excavated in ground characterised by elastic behaviour, various operational factors play a decisive role in the resulting round of advance; bearing in mind the construction of tunnels is organised into two to three shifts every

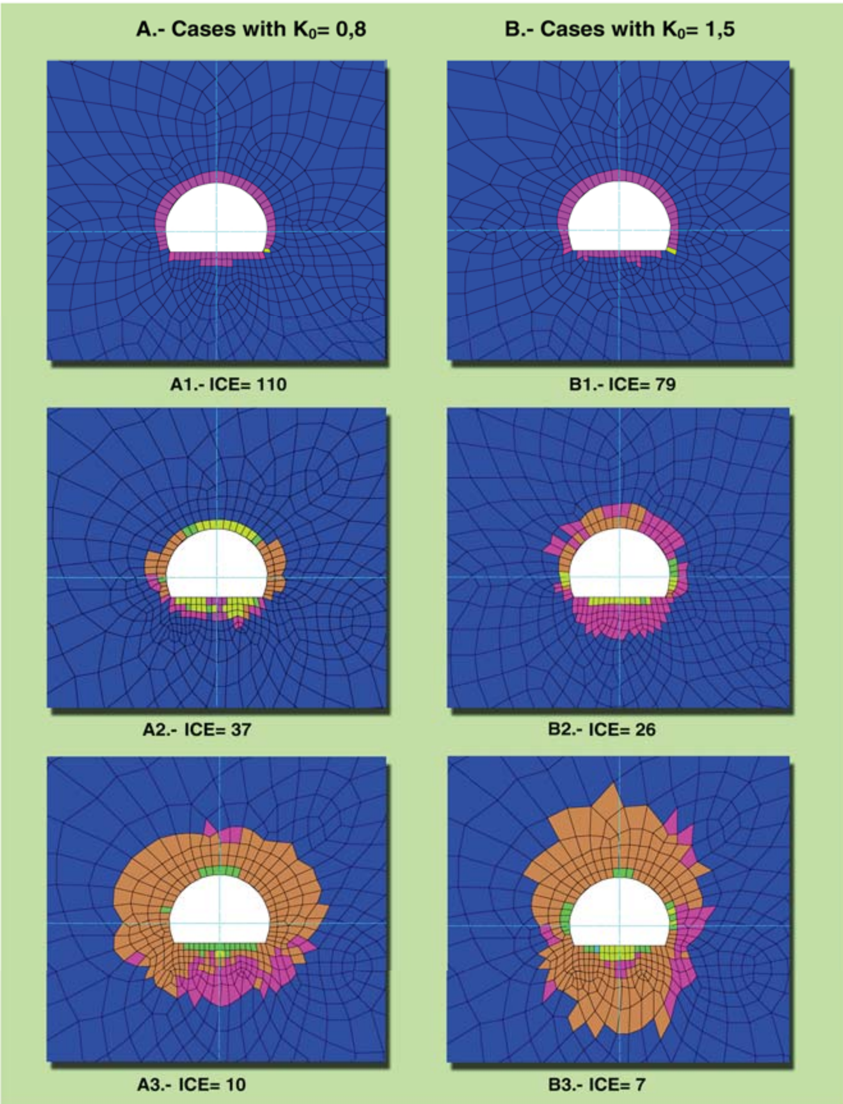

Fig 1: Typical yielding zones for various values of the Index of Elastic Behaviour ICE and K_0.

Table 2: Data on tunnels studied in this investigation

No.	Tunnel	Locality	Purpose	Length (m)	Excavated cross section (m^2)	Number of rounds of advance studied
1	Castro	Pontevedra	High speed railways	380	110	6
2	Reboredo			650	110	8
3	Ardilleiro			570	110	11
4	Curro			750	110	8
5	Prado			260	98	9
6	Bascuas			320	98	2
7	Portiño			478	110	6
8	Caldelás			510	110	5
9	A Pena			815	110	48
10	Vilar Do Xestal			1215	110	9
11	Bendoiro			400	110	8
12	Anzo			545	110	19
13	Archidona	Málaga	Road	1110	140	33
14	Candelaria	Canaria Island		500	94	5
15	Mogán			600	94	36
Total number of rounds of advance studied						213

day. In essence, the question arises whether a full cycle can be completed in one shift or is it preferable to adopt a longer round of advance, which would make it necessary to complete the cycle over a few shifts.

In such cases the round of advance is dependent on downtimes at the face, on the capacity to transport the excavated rock, and on the difficulties that the ground might offer for drilling and blasting. In tunnels with a total length of less than 2.5 km, which represent most of those constructed by conventional methods, the downtimes at the face are similar due to the operations of transport vehicles. In essence, in the case of modern large highway tunnels or long railroad tunnels constructed by conventional methods, the round advance is dictated by rock mass excavability if an excavation behaves elastically, so that the tunnel sections have sufficient stand-up time without support throughout their length. In such cases, the RME index can be used to decide the advance round.

When an excavation does not behave elastically and loosening takes place, the round of advance will be governed by the degree of stability of the rock mass and, in this case, one should utilise the RMR classification (ref 4) or the Q-system.

Data collection

To carry out the present investigation, a comprehensive program of data collection from tunnels during construction was undertaken. In each case, data were obtained including the RME and RMR of the rock mass, as well as other data related to the process of construction.

Recent research showed (ref 3) that the RME was equally applicable to tunnels constructed with TBMs as well as with conventional methods.

To prove this finding in the course of this investigation, beginning in the second half of 2009, extensive data collection was carried out from 15 tunnels which were part of the high speed train network in Spain, as well as others from highway tunnels, as depicted in Table 2.

In total, 213 rounds of advance were analysed; 129 of them – representing 60 per cent of the total – were excavated with explosives and the remaining 40 per cent by mechanical means. It is believed that the tunnels studied contain a sufficient number of cases, including a wide variation in rock mass conditions.

Analysis

The data obtained from the collection of 213 tunnel sections were analysed statistically to develop representative correlations between the round advance (RA) and indices RME, RMR and ICE.

The best correlation relating the three indices with the round advance (RA) was found to be in the form of a hypersurface having this equation:

$$\left(\frac{RME}{86}\right)^2 + \left(\frac{RMR-50}{44}\right)^2 + \left(\frac{RA-3,3}{4}\right)^2 + \left(\frac{LogICE-2}{4}\right)^2 = 1$$

The coefficient of correlation $r^2 = 0.896$ is considered very high.

Once this correlation was established, the next step was to identify the ranges of physical meaning of the round of advance RA. The first two ranges were characterised by ICE < 130 and ICE > 130, corresponding to plastic ground and that of elastic behaviour respectively. Following these delineations, these were the correlations obtained:

For plastic behaviour (ICE<130):

$$RA\ (m) = 3 - 3 \cdot \sqrt{1 - \frac{RMR}{50}}$$

The coefficient of correlation $R^2 = 0.87$ is very high. In this case the length of tunnel advance would be between 0 and 3 m; such that the yielding condition of the terrain would not allow any stand-up time without support for a tunnel length greater than 3m.

Table 3: Tentative recommendations for tunnels 14m wide, based on ICE values

ICE	Excavation behaviour	Excavation size	Support	Special elements of support	Advance length	Tunnel lining
>130	Completely elastic	Full face	Rock bolts L=4.5m Sp=2–2.5 m Shotcrete: 5cm	None	By RME	Cast concrete. No invert.
70–130	Elastic with incipient yielding		Rock bolts L=4.5m Sp=2m Shotcrete: 10cm	None		
40–69	Moderate yielding		Rock bolts L=4.5m Sp=1.5m Shotcrete: 15cm	None		Cast concrete and invert (0.1 x excavation width)
15–39	Intensive yielding	Top heading and bench	TH-29 Steel arches 1m spacing	Elephant foot, heavy forepoling umbrellas and grouting under elephant foot	By RMR and Q	Cast concrete and invert (0.2 x excavation width)
<15	Mostly yielding		HEB-180 Steel arches 1m spacing	As above plus face bolted		Steel reinforced concrete in circular cross section

In the case of a tunnel section excavated in ground characterised by elastic behaviour, better correlations were obtained when this region was subdivided into two conditions: RMR > 50 and RMR < 50. The correlations in both cases are as follows:

For ground with elastic behaviour (ICE > 130) with RMR > 50:

$$RA_{(m)} = 3 + 4.4 \cdot \sqrt{1 - \frac{RME}{90} - \frac{(RMR-50)^2}{55}}$$

The coefficient of correlation was obtained as $r^2 = 0.77$ which is reasonably good.

In this case, the expected round of advance would range between 3.5 and 5.5m.

For ground with elastic behaviour (ICE > 130) with RMR < 50:

$$RA_{(m)} = 3 - 5 \cdot \sqrt{1 - \frac{RME}{90} - \frac{(RMR-50)^2}{42}}$$

The coefficient of correlation is r^2=079, which is again, reasonably good.

Selecting temporary support

One of the applications of the ICE concept is to provide recommendations for primary tunnel support for the tunnel sections when the value of ICE remains practically constant, as this index includes the RMR of the rock mass, the depth below surface and the length of advance.

On the basis of the experience of the authors, acquired over many years from 337 tunnels of various types, tentative recommendations on tunnel support are proposed in Table 3 for an example of excavations 14 m in width.

These recommendations include guidelines for conventional excavation involving primary support as well as final lining, subject to measurements of the magnitude of tunnel convergence and monitoring the stability of the tunnel during construction.

Conclusions

Based on the equations developed by Kirsch and supported by 288 calculations of stress-strain analyses using the software FLAC 3D, an index ICE (Índice de Comportamiento Elastico – Index of Elastic Behaviour) was developed. This approach proved useful for assessing stress-strain behaviour of tunnels constructed by conventional methods.

In addition, several tunnels under construction were analysed, providing correlations between the length of advance and the values of the RME (Rock Mass Excavability) and the RMR (Rock Mass Rating), distinguishing between tunnels behaving elastically and those involving a degree of yielding behaviour.

The authors

The research presented in this article was performed in Spain under the initiative of Geocontrol, a civil engineering company established in Spain in 1982 and with branches in Chile, Colombia and Brazil.

Initially specialising in applied rock mechanics, since 1987 the company has been oriented towards design and construction of tunnels.

Prof Bieniawski, the principal of Bieniawski Design Enterprises, has been associated with research and consulting with Geocontrol since 1987.

Dr Benjamin Celada, former professor and chair of underground rock engineering at the Technical University of Madrid, leads the company as its president and technical director.

References

1. Celada B, Fernandez M, Rodriguez A & Tardaguila I (2010). 'Definicion preliminar de las secciones tipo de sostenimiento en los tuneles proyectado por metodos convencionales' *Ingeopres*, no.192, May, 16-22, 2010.

2. Kalamaras G & Bieniawski ZT (1995). 'A rock mass strength concept incorporating the effect of time', Proc ISRM International Congress 1995, Tokyo, Japan, Sep pp295-302.

3. Bieniawski ZT, Celada B, Galera JM & Tardauila I (2008). 'New applications of the Excavability Index for selection of TBM types and predicting their performance', Proc World Tunnel Cong, Agra, India, 2008, pp1618-1629.

4. Bieniawski ZT, Celada B & Galera JM (2007). 'Predicting TBM excavability', *Tunnels & Tunnelling International*, Sep. 2007, pp25-29.

5. Barton N & Bieniawski ZT (2008). 'Setting the record straight', *Tunnels & Tunnelling International*, Feb 2008, pp26-30.