The well known methodology the "New Austrian Tunneling Method" (NATM) has been used in Europe since Rabcewicz 1964 but was redefined recently as the “Observational Method for Conventional Tunnelling” published in 2008 by the Austrian Geotechnical Society.

In Spain, Celada 2011 presented a rationale for a new approach for rock engineering methodology called the “Interactive Structural Design” (DEA). The principles of DEA have been applied with success during construction of over 100 tunnels for highways, railroads and hydro schemes.

It should be noted that the NATM of the 1960’s was essentially a method both empirical and observational which was based on selection of tunnel support using rock mass classifications and confirmation during construction by extensive instrumentation.

The empirical selection of tunnel support had certain problems resulting in collapses when sections of tunnels involved solutions solely based on experience. On the other hand, purely observational monitoring, without the help of reliable calculations was also the source of frequent incidents.

During the decade of the 1970’s, the appearance of the Method of Characteristic Curves gave a scientific basis to the NATM but while it could explain the concept of rock-support interaction, it could not provide actual dimensioning of support in terms of the amount and placing of its different components.

Nevertheless, in those years it became evident that the extensive instrumentation required by the NATM was expensive, and above all, in some cases the results obtained from measurement primarily served to predict an inevitable collapse.
The methodology of the Interactive Structural Design (Diseño Estructural Activo, DEA) was developed by Geocontrol in the decade of the 1990’s after being confronted with the problem, in many tunnels, of the difficulty of calculating with accuracy the movements of excavations, given the variability of the strength-deformation properties of rock masses and the difficulty of determining reliably the ratio of the in situ principal stresses $K_0$.

To resolve this difficulty it became apparent that *dimensioning of tunnel support should be undertaken during the construction of the tunnel.*

Another significant fact, discovered during the construction of the Vallvidrera Tunnel (Barcelona, 1990), was that the convergence measurements made with mechanical extensometers are sufficiently accurate to detect the effects of tunnel advance, with enough time available to initiate the process of stabilization.

It should be noted that an extensometer, costing only $3,000 can measure the convergence in 10 minutes in an excavation of 15m in width, with an error of +/- 0.1mm.

In accordance with the above facts, the DEA was developed as a methodology consisting of three phases: characterization of the terrain, structural design and confirmation during construction. It is based on the following principles:

(i) Characterization of the rock mass in a realistic form;

(ii) Dimensioning tunnel support using reliable calculations, specifically of the expected convergence to be measured during construction;

(iii) Measuring the convergence during tunnel construction and comparing it to what was predicted by the calculations. In the case of movements being excessive, the support is reinforced compatible with the new calculations.

**Figure 1** shows a diagram of the activities involved in the application of the methodology of Integrated Structural Design (DEA).
THE PHASE OF SITE CHARACTERIZATION

The objective of this phase is to develop a geotechnical profile, that is, a geotechnical model which features homogeneous sections of the same rock mass quality and stress-strain characteristics (sections will vary across the tunnel length).

The geotechnical profile is obtained in two stages: in the first, after the usual investigations, geophysical, borehole, tests in situ and in the laboratory, one obtains a preliminary profile characterization in which the strength and deformability properties of each of the lithological units are presented and specific risks of a geotechnical nature are identified.

With the above data and the results of the evaluation of the in situ state of stresses, one estimates the stress-strain characteristics of each tunnel section. This is done using the Index of Elastic Behavior ICE (Índice de Comportamiento Elástico) after Celada et al (2010) and Bieniawski et al (2011).
The ICE concept is based on calculations, following the classic model of Kirsch(1898), of the stress distribution induced in the rock mass during the excavation of a circular tunnel. This is defined by the following equations:

For $K_0 \leq 1$

$$ICE = \frac{3704 \cdot \sigma_{ci} \cdot e^{24} \cdot RMR-100}{(3 - K_0) \cdot H} \cdot F$$

For $K_0 \geq 1$

$$ICE = \frac{3704 \cdot \sigma_{ci} \cdot e^{24} \cdot RMR-100}{(1 + K_0) \cdot H} \cdot F$$

where $K_0$ is the coefficient of the ratio of the in situ principal stresses;

$\sigma_{ci}$ is the uniaxial compressive strength of intact rock material (MPa). $RMR$ is the Rock Mass Rating corrected for the orientation of the discontinuities.

H is the depth below surface (m).

F is the factor of the tunnel shape having the following values:

- F = 1.3 for circular tunnels 6m diameter
- F = 1.0 for circular tunnels 10m diameter
- F = 0.75 for conventional tunnels 14m diameter
- F = 0.55 for caverns 25m in width and 60m high.

To cross-check the results, the ICE data were compared with those obtained using the program FLAC3D modeling 1,152 problems resulting from the combination of the following parameters:

- H = 100m, 200m and 400m depth
- $\sigma_{ci}$ = 30, 50, 70 and 100MPa
- $RMR$ = 20, 30, 50 and 70
- $K_0$ = 0.6, 0.8, 1.0 and 1.5.

Figure 2 shows the values of ICE for six of the cases studied, three with $K_0 = 0.8$ and another three with $K_0 = 1.5$.

The ICE concept has been studied on the basis that the value 100 corresponds to the elasto-plastic limit of the excavation; however, given that this index involves parameters which contain some uncertainty, one may postulate that the behavior of an excavation falls in a transition range between elasticity and plasticity in which the ICE is within an interval of 90 to 130.
In Table 1 one can observe the criteria of a behavior characterizing the stress-strain relationship of a tunnel, without support, as a function of the ICE.

**Table 1.** Estimation of stress-deformation behaviour of a section of tunnel as a function of the Index of Elastic Behaviour *ICE*.

<table>
<thead>
<tr>
<th>ICE</th>
<th>Behaviour stress-deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;130</td>
<td>Completely elastic</td>
</tr>
<tr>
<td>70-130</td>
<td>Elastic with incipient yielding</td>
</tr>
<tr>
<td>40-69</td>
<td>Moderate yielding</td>
</tr>
<tr>
<td>15-39</td>
<td>Intensive yielding</td>
</tr>
<tr>
<td>&lt;15</td>
<td>Mostly yielding</td>
</tr>
</tbody>
</table>

In the case involving an intensive plastification, ICE < 39, it is necessary to perform laboratory tests with deformation measurements of the *post-failure* stress-strain region using a servo-control press. This enables subsequent modeling of the process of plastification.

Equally, to identify the specific risks involved, it is necessary to perform laboratory tests which permit quantifying the response of the terrain to any specific phenomena identified.

With the results of the tests of the post-failure region and the special tests above, one can identify the complete stress-strain behavior of all the tunnel sections and compile a geotechnical profile of a given tunnel.
Figure 2. Typical zones of strata for various values of the Index of Elastic Behaviour $ICE$. 
THE PHASE OF STRUCTURAL DESIGN

The phase of Structural Design is initiated once the Geotechnical Profile of the tunnel is compiled (includes the geological profile, its extent and the geotechnical properties of the rock mass sections). This allows one to decide upon the appropriate construction method.

The next step consists of selecting the support types; an undertaking carried out with the help of the index ICE and utilizing the criteria contained in Table 2.

Each support type should be validated by stress-strain modeling (analyzing acceptable deformations and factors of safety), employing an iterative process and applying the methodology presented in the next section.

The outcome of this validation is establishing the limits for acceptable convergences that are to be measured during the construction of the tunnel.

Table 3. Recommendations for tunnels 14 m wide based on various ICE values.
THE PHASE OF CONFIRMATION DURING CONSTRUCTION

This phase is initiated when tunnel construction begins and has the object of confirming the predicted deformation and safety factors in each structural region (rock mass quality and support type section) in order to maintain the limits of tunnel behavior (convergence) established in the Construction Profile of the tunnel.

For this purpose, for each tunnel section constructed with its distinct support type one should choose convergence measuring stations placed at the distance from the face of the tunnel as determined during the design stage. A typical distance between the convergence stations is 25m.

Given the difficulties in accurately characterizing the rock masses of poor quality (RMR < 40) and in determining the value of the ratio of the in situ principal stresses, one of the first activities to undertake when tunnel construction starts is to confirm the levels of the convergences foreseen by calculations, that is, comparing them with the actual movement in the works.

When the measurements of the convergence are found to be within the limits established during design, it means that the process of stabilization does not require any reinforcement of the tunnel support.

Conversely, if the convergences measured exceed the values envisaged in the Construction Profile, it is necessary to reinforce tunnel support and perform new stress-strain analyses to quantify the allocated reinforcement.

Once the stabilization of the tunnel displacements is attained, the final tunnel lining is installed; this operation is typically performed once the tunnel has been driven through with its primary support.
ADVANTAGES OF THE DEA

The advantages offered by the Interactive Structural Design (DEA) concept as the design methodology of tunnels may be summarized by the following aspects:

[I] *Increased safety during construction* due to tunnel deformations being confirmed by stress-strain analyses which ensure effectiveness of each support type.

[II] *Opportunity to compare analytical calculations with the actual measured deformations* thus providing reliable values of the convergence which reflects the behavior of rock masses.

[II] *Minimization of the instrumentation in the tunnel* because the control of rock mass behavior is based on only measurements of the convergence which costs less and yet is sufficiently accurate.

References

