DIMENSIONING TUNNEL SUPPORT BY DESIGN METHODOLOGY

"INTERACTIVE STRUCTURAL DESIGN"
Diseno Estructural Activo, DEA)

Benjamín Celada Tamames, Director General, Geocontrol, Madrid

Translated from: *Taller sobre Diseño de Túneles de Carretera*
Manual de Túneles y Obras Subterráneas,
Tomo 1, Capítulo 23, p.815--854.

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.

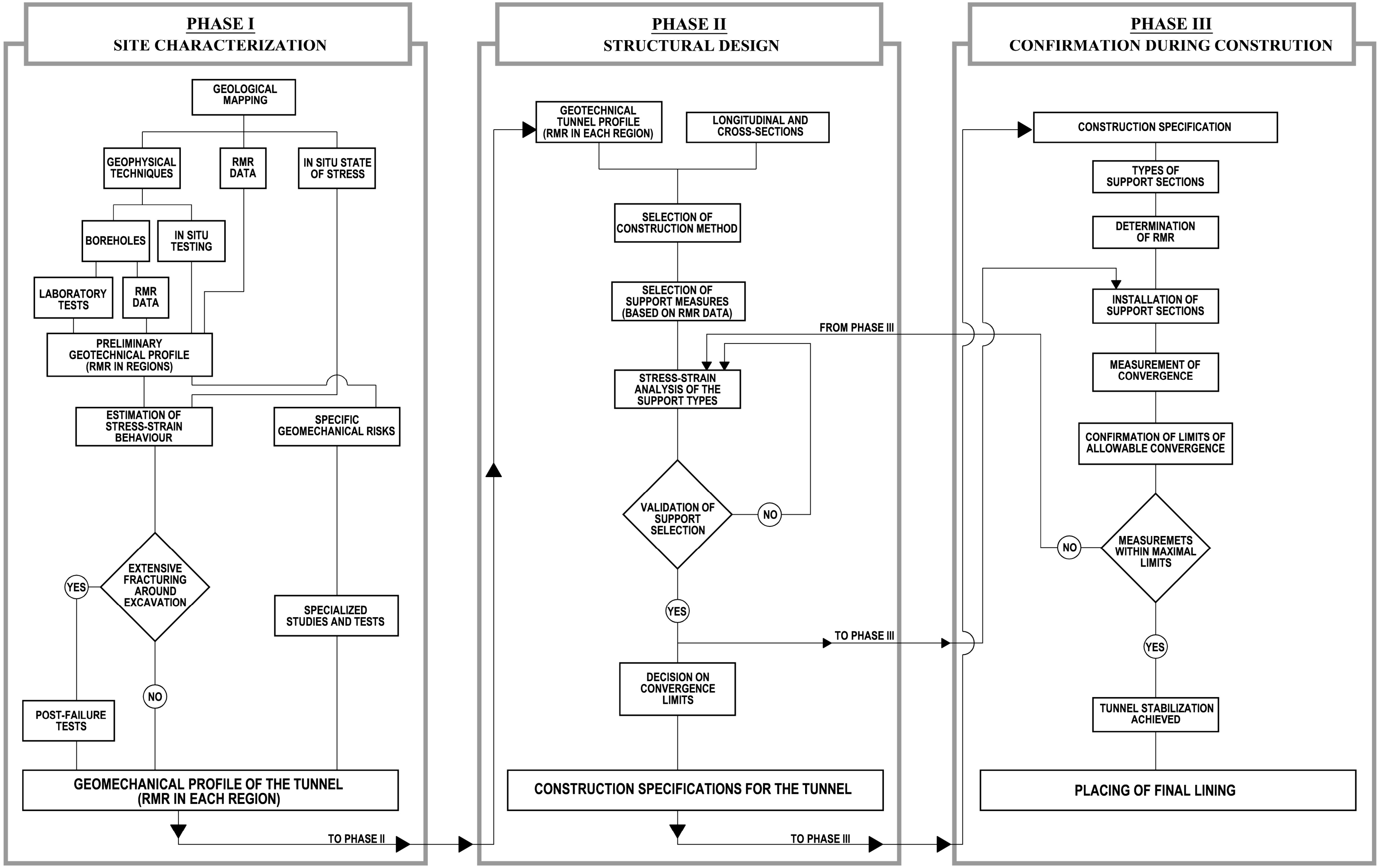
Figure 1 shows a diagram of the activities involved in the application of the methodology of Integrated Structural Design (DEA).

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 Elastico) after Celada et al (2010) and Bieniawski et al (2011).


PHASE I
SITE CHARACTERIZATION
GEOLOGICAL MAPPING
GEOPHYSICAL TECHNIQUES
RMR DATA
IN SITU STATE OF STRESS
BOREHOLES
IN SITU TESTING
LABORATORY TESTS
RMR DATA
PRELIMINARY GEOTECHNICAL PROFILE (RMR IN REGIONS)
ESTIMATION OF STRESS-STRAIN BEHAVIOUR
SPECIFIC GEOMECHANICAL RISKS
EXTENSIVE FRACTURING AROUND EXCAVATION
YES
NO
SPECIALIZED STUDIES AND TESTS
POST-FAILURE TESTS
GEOMECHANICAL PROFILE OF THE TUNNEL (RMR IN EACH REGION)
TO PHASE II
PHASE II
STRUCTURAL DESIGN
GEOTECHNICAL TUNNEL PROFILE (RMR IN EACH REGION)
LONGITUDINAL AND CROSS-SECTIONS
SELECTION OF CONSTRUCTION METHOD
SELECTION OF SUPPORT MEASURES (BASED ON RMR DATA)
FROM PHASE III
STRESS-STRAIN ANALYSIS OF THE SUPPORT TYPES
VALIDATION OF SUPPORT SELECTION
NO
YES
TO PHASE III
DECISION ON CONVERGENCE LIMITS
CONSTRUCTION SPECIFICATIONS FOR THE TUNNEL
TO PHASE III
PHASE III
CONFIRMATION DURING CONSTRUTION
CONSTRUCTION SPECIFICATION
TYPES OF SUPPORT SECTIONS
DETERMINATION OF RMR
INSTALLATION OF SUPPORT SECTIONS
MEASUREMENT OF CONVERGENCE
CONFIRMATION OF LIMITS OF ALLOWABLE CONVERGENCE
MEASUREMETS WITHIN MAXIMAL LIMITS
NO
YES
TUNNEL STABILIZATION ACHIEVED
PLACING OF FINAL LINING

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

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

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

σ_{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

σ_{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*.

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

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.

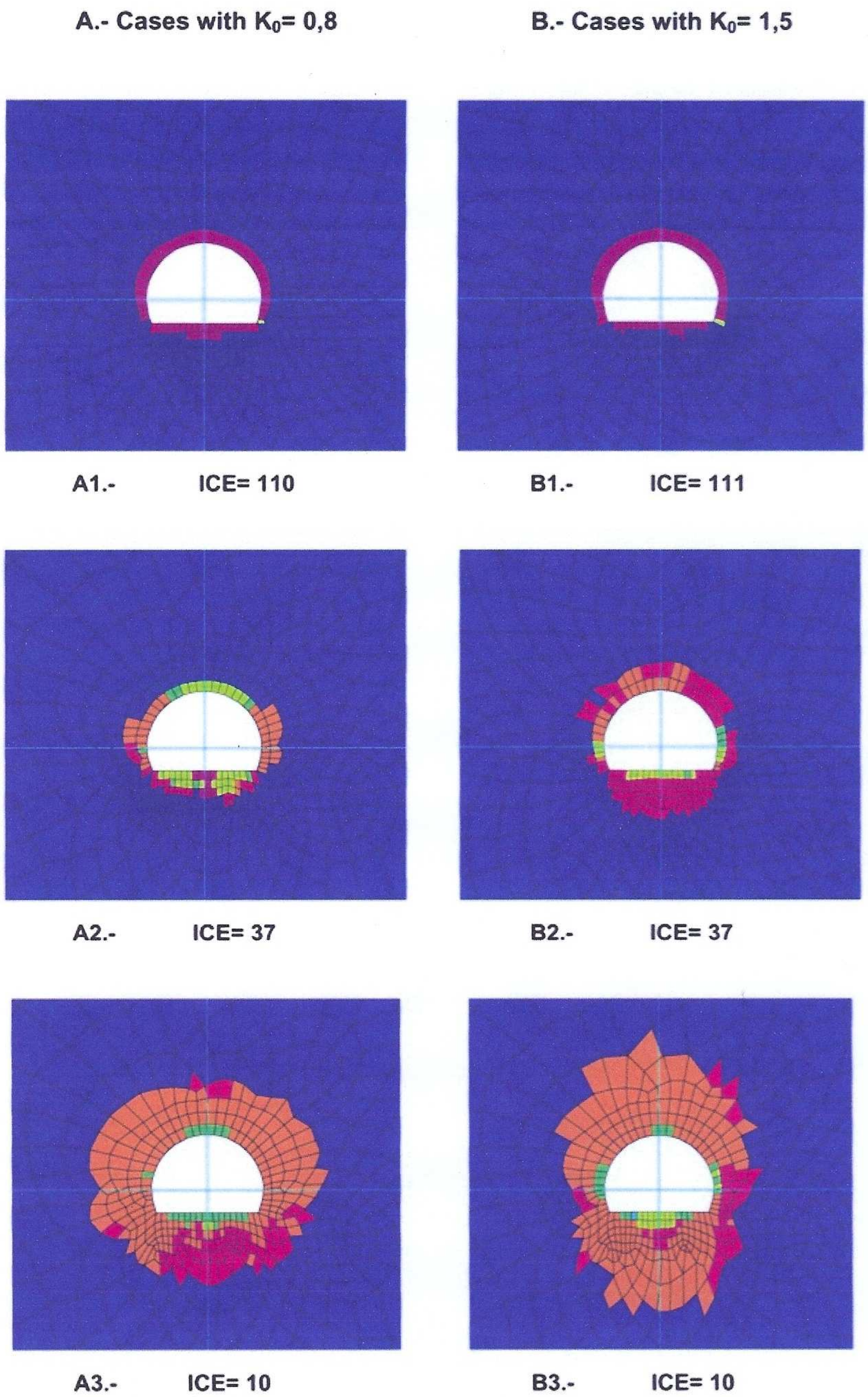


Figure 2. Typical zones of strata for various values of the Index of Elastic Behaviour *ICE*.

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.

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	Top heading and bench	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	By RMR and Q	Cast concrete and invert (0.1 x excavation width)
15–39	Intensive yielding			TH-29 Steel arches 1m spacing	Elephant foot, heavy forepoling umbrellas and grouting under elephant foot		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

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

Celada Benjamín (2011). Diseño Estructural Activo. *Manual de Túneles y Obras Subterráneas*, Madrid, Tomo 1, Capítulo 23, p.815-854.

Celada B, Fernández M, Rodríguez A and Tardáguila I (2010). Definición preliminar de las secciones tipo de sostenimiento en los túneles proyectado por métodos convencionales. *Ingeopres,*_no.192, May, 16-22.

Bieniawski Richard ZT, Aguado D, Celada B and Rodríguez A (2011). Forecasting Tunnel Behaviour by conventional methods. *Tunnels & Tunnelling Int.,* August 2011, pp. 39-42.