DESIGN AND CONSTRUCTION OF TUNNELS
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Analysis of controlled deformation in rocks and soils (ADECOR-S)
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About the Author

Pietro Lunardi

A civil engineer in the field of transport, he is one of the greatest experts in the world on the design and construction of underground works, the creator of highly innovative solutions: the cellular arch, developed for the construction of the Porta Venezia station on the Milan Railway Link Line for which he was nominated “Man of the Year in the construction field” by the United States journal “Engineering News-Record”; shells of improved ground using jet-grouting techniques; full face mechanical precutting, face reinforcement using fibre glass structural elements; he devised and developed the revolutionary new approach to design and construction, known by the acronym ADECO-RS, described in detail in this book, which for the first time has made it possible to construct tunnels even in the most difficult geological-geotechnical and stress-strain conditions with reliable forecasting of construction times and costs.

A former university lecturer in “Soil and rock improvement” in the Faculty of Engineering of the University of Florence and in the “Defence and conservation of the soil” in the Faculty of Engineering of the University of Parma, he has filled many institutional roles including that of Minister of Infrastructures and Transport for five years in the second Berlusconi government (2001-2006).

The author of more than 130 publications he has held more than 40 national and international conferences on the subjects of tunnelling and geo-engineering.
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Geological hazard and the lack of appropriate survey, design and construction instruments for tackling those terrains we call “difficult”, with good prospects of success, have always made the design and construction of underground works a risky affair, which could not therefore be faced with the same degree of accuracy as other civil engineering works. As a consequence they have always occupied a subordinate position with respect to similar surface constructions and in the past they were only resorted to when the latter seemed impractical or of little use.

However, decisive progress made in the field of geological surveys, the availability of powerful computers for making calculations and above all the introduction of excavation technologies that are effective in all types of ground have created the conditions for a qualitative quantum leap forward. The last formidable negative factor to be overcome to achieve that transparency in this field, which has until now been the prerogative of traditional surface works, remains the absence of a modern and universally valid design approach, capable, that is, of integrating and exploiting the new capabilities and of guiding the design engineer through the stages of design and construction. In fact even today the answer to the apparently obvious and banal question, “What does the design and construction of an underground work consist of?”, would find many design engineers in disagreement not only on the form but also on contents of design. And this is not surprising because this type of problem has always been addressed in a very indeterminate fashion. Until not very long ago the inadequacy of the available knowledge and means meant that the design of an underground construction had to be improvised during tunnel advance. As a consequence, the design of such a construction was merely a question of identifying the geometry of the route and some of the tunnel section types, while the means of excavation, intervention to stabilise the tunnel and which linings to use were largely decided during construction as the tunnel advanced.

The practice of “observing” the response of the ground to excavation in order to devise appropriate countermeasures to stabilise a tunnel in the short and the medium term has therefore always lain at the basis of underground construction. In the last century some engineers sought to develop design and construction “methods” around this practice and although they were based on incorrect scientific theory, they nevertheless constituted significant progress at the time. This brought them great success at first, and despite many clamorous failures, they have managed to survive and flourish, assisted by a lack of alternative ideas caused by an unexplainable, lazy, and far too common tendency to conform. These methods, led by the NATM, were not only found to be inadequate in really difficult geotechnical and geomechanical conditions, but they also appear very much behind the times, because they cannot, by their very nature, furnish solutions which will enable construction to be planned in any way, in terms of finance and schedules, an undoubtedly essential requirement for transparent and prudent management of resources in modern societies.
This is the context in which, a little more than ten years ago, the presentation of the approach based on the Analysis of Controlled Deformation in Rocks and Soils (ADECO-RS) was met with great general interest, mixed with a degree of scepticism. I and my research team had developed it over a long period of theoretical and experimental research conducted outside traditional lines. It finally recognised how important the three dimensional nature of statics and the dynamics of tunnel excavation was and by taking this to its ultimate consequences and by appropriately exploiting the new technologies, it seemed to hold the promise of that long awaited quantum leap forward. It would for the first time enable an underground work to be designed before construction commenced with all the consequent advantages in terms of planning, construction costs and schedules.

Since then the validity of the approach has been tested on the construction of more than 300 km of tunnel and at least 150 km of this was under very difficult stress-strain conditions. These have been fully discussed as the occasion arose in conferences and publications in which it has been demonstrated beyond any doubt that we know how to transform our promises into reality. The approach had in fact made it possible to predict times and costs for the construction of underground works with a fair degree of precision (proportional to the knowledge of the geology acquired beforehand), minimising unforeseen events and eliminating tunnel advance problems, which were previously encountered under the same ground and overburden conditions. It seemed to have become finally possible to make a reliable estimate of the cost benefit ratio for an underground project, a fundamental parameter in the decision making progress of selecting design alternatives.

We are therefore on the right track; however, I do feel that much investigation and study is still necessary. The purpose of this book is not just to illustrate the basic concepts of the approach as fully and exhaustively as possible and to show how, by following its principles, underground works can be designed and constructed with a reliability and accuracy never attained before. Its purpose is above all to furnish the scientific community with a useful reference text around which all may work together to improve the ADECO-RS approach or even to go beyond it.

Pietro Lunardi
A note to the reader

I was concerned in writing this book to make it as easy and pleasurable to read as possible, despite the very technical and highly specialised nature of the contents. I therefore drew on the experience I had acquired in past years as a university lecturer, trying throughout the book to imagine the curiosity and desire for greater explanation that might arise in my readers. It was by trying to respond to this curiosity, which sometimes even led me to touch on to subjects apparently quite distant from those being dealt with, that I felt I was often able to make the explanation more straightforward and to stimulate the attention of my readers, even on the more complex concepts.

The outcome is a book with two sets of contents, one for odd numbered pages on which the central theme of the book unfolds and one for even pages, which can be read independently of the text. It is on these pages that I have sought to satisfy the reader’s desire for greater explanation with observations and extra detail.
To complete this book, which collects together experiences from forty years of working on numerous construction sites, in universities and other professional environments, I wish to sincerely thank those who have believed in me over these long years, teaching me and advising me. They include Angelo Palleschi from Capistrello, one of the many tunnel miners who have helped me during those long hours spent on tunnel construction sites, Angelo Farsura, an enlightened entrepreneur who gave me the chance in the 1960's and 1970's to follow the works on site for the Gran Sasso tunnel, one of the most complex and fascinating projects of the last fifty years and so many other people who I obviously cannot mention here, but to whom I am bound, through my memories, by gratitude and friendship.

Finally, I wish to say a special thank you to those who have worked most closely with me, Renzo Bindi, Giovanna Cassani and Alessandro Focaracci, who, with their shrewd engineering sense, have helped me to develop this new approach to the design and construction of underground works. It is an approach, which I hope will serve as a useful guide for young engineers who wish to study and implement these works, which differ from other civil engineering works because of the extreme and continuous variation in the geological, geotechnical and stress-strain conditions in which the design engineer is obliged to operate.

Pietro Lunardi
There are no tunnels which are easy or difficult because of the overburden or the ground to be tunnelled, but only stress-strain situations in the ground in which it is, or is not possible to control the stability of the excavation, which will depend on our knowledge of the pre-existing natural equilibriums, on a correct approach to the design and on the availability of adequate means for excavation and stabilisation.
1.1 The basic concepts

Anyone who sets out to construct underground works, finds themselves having to tackle and solve a particularly complex civil engineering problem, because it is far more difficult to determine the basic design specifications for underground works in advance than it is for surface constructions (Fig. 1.1).

It is not, as with surface constructions, a question of gradually assembling materials (steel, reinforced concrete, etc.) with well known strength and deformation properties to build a structure which, when subject to predictable loads, finds its future equilibrium in the desired final configuration. On the contrary, one has to intervene in a pre-existing equilibrium and proceed in some way to a “planned disturbance” of it in conditions that are only known approximately.

Another peculiarity of underground works, well known to design and construction engineers, but not always given sufficient weight, is that very often, the stage at which the structure is subject to most stress is not the final stage, when the tunnel is finished and subject to external loads predicted at the design stage, but the intermediate construction stage. This is a very much more delicate moment because
The arch effect

In a similar fashion to the lines of flow in the current of a river, which are deviated by the pier of a bridge and increase in speed as they run around it, the flow lines of the stress field in a rock mass are deviated by the opening of a cavity and are channelled around it to create a zone of increased stress around the walls of the excavation. The channelling of the flow of stresses around the cavity is termed an arch effect. The arch effect ensures that the cavity is stable and will last over time.

THE FORMATION OF AN ARCH EFFECT IS SIGNALLED BY THE DEFORMATION RESPONSE OF THE ROCK MASS TO EXCAVATION
the effects of the disturbance caused by excavation have not yet been completely confined by the final lining at this stage, when the pre-existing stresses in the rock mass are being deviated by the opening of the cavity and channelled around it (arch effect) to create zones of increased stress on the walls of the excavation.

The particular delicacy of this intermediate stage becomes clear if one considers that it is precisely on the correct channelling of stresses around the cavity that the integrity and life of a tunnel depends. Channeling can be produced, depending on the size of the stresses in play and the strength and deformation properties of the ground, as follows (Fig. 1.2):

1. close to the profile of the excavation;
2. far from the profile of the excavation;
3. not at all.

The first case occurs when the ground around the cavity withstands the deviated stress flow around the cavity well, responding elastically in terms of strength and deformation.

The second case occurs when the ground around the cavity is unable to withstand the deviated stress flow and responds anelastically, plasticising and deforming in proportion to the volume of ground involved in the plasticisation phenomenon. The latter, which often causes an increase in the volume of the ground affected, propagates radially and deviates the channelling of the stresses outwards into the rock mass until the triaxial stress state is compatible with the strength properties of the ground. In this situation, the arch effect is formed far from walls of the excavation and the ground around it, which has been disturbed, is only able to contribute to the final statics with its own residual strength and will give rise to deformation, which is often sufficient to compromise the safety of the excavation.

The third case occurs when the ground around the cavity is completely unable to withstand the deviated stress flow and responds in the failure range producing the collapse of the cavity.

It follows from this analysis of these three situations that:

- an arch effect only occurs by natural means in the first case;
- an arch effect by natural means is only produced effectively in the second case if the ground is “helped” with appropriate intervention to stabilise it;
- in the third case, since an arch effect cannot be produced naturally, it must be produced by artificial means, by acting appropriately on the ground before it is excavated.

The first and most important task of a tunnel design engineer is to determine if and how an arch effect can be triggered when a tunnel is excavated and then to ensure that it is formed by calibrating
If we simplify to the maximum, we can say that there are three main mediums in nature: sand, clay and rock, which have three different natural consistencies:

- the consistency of sand, which has its effect above all in terms of friction, giving rise to loose type behaviour;
- the consistency of clay, which has its effect above all in terms of cohesion, giving rise to cohesive type behaviour;
- the consistency of rock, which has its effect in terms of cohesion and friction, with markedly higher values than in the case of sand and clay giving rise to rock type behaviour.

It is the natural consistency of the medium which determines local differences in the earth’s crust.

In its natural state, the medium appears with the characteristics of its own type of consistency, however, when tackled underground, where it is subject to stresses which increase with depth, it has a consistency which varies as a function of the entity and anisotropy of the stress tensor (acquired consistency).

The manner in which the consistency of the medium varies as a function of its stress state is studied by means of triaxial tests on samples and is described by the intrinsic curve and stress-strain diagrams.
excavation and stabilisation operations appropriately as a function of different stress-strain conditions.

To achieve this, a design engineer must have a knowledge of the following (Fig. 1.3):

- the medium in which operations take place;
- the action taken to excavate;
- the expected reaction to excavation.

### 1.2 The medium

The medium, and that is the ground, which is in practice the actual “construction material” of a tunnel, is extremely anomalous when compared to traditional materials used in civil engineering: it is discontinuous, unhomogeneous and anisotropic. On the surface, its characteris-
Three characteristic zones can be identified during tunnel advance in an unlined tunnel.

1. an undisturbed zone, where the rock mass is not yet affected by the passage of the face;
2. a tunnel face or transition zone, corresponding to the radius of influence of the face, in which its presence has a considerable effect;
3. a stabilisation zone, where the face no longer has any influence and the situation tends to stabilise (if possible).

It is important to observe that in passing from the undisturbed zone to the stabilisation zone, the medium passes from a triaxial to a plane stress state and that the face zone is where this transition takes place. Consequently, this is the most important zone for the design engineer. It is here that the action of excavation disturbs the medium and it is on this zone that all the attention of the design engineer must be focused for proper study of a tunnel. It is not possible to achieve this without employing three dimensional analysis approaches.
tics vary but this depends solely on its own intrinsic nature (natural consistency), which conditions the morphology of the earth’s crust, while at depth its characteristics also change as a function of the stress states it is subject to (acquired consistency) and this conditions its response to excavation [1] (Fig. 1.4).

### 1.3 The action

The **action** is that whole set of operations performed to excavate the ground. It is seen in the advance of the face through the medium. It is therefore a *distinctly dynamic phenomenon*: the advance of a tunnel may be imagined as a disk (the face) that proceeds through the rock mass with a *velocity* $V$, leaving an empty space behind it. It produces a *disturbance in the medium*, both in a longitudinal and transverse direction, which upsets the original stress states (Fig. 1.5).

Within this disturbed zone, the *original field of stresses*, which can be described by a network of flow lines, *is deviated* by the presence of the excavation (Fig. 1.2) and concentrates in proximity to it, producing increased stress, or, to be more precise, an increase in the stress deviator. The size of this increase determines the amplitude of the disturbed zone for each medium (within which the ground suffers a loss of geomechanical properties with a possible consequent increase in volume) and, as a result, the behaviour of the cavity in relation to the strength of the rock mass $\sigma_{gd}$.

The size of the disturbed zone in proximity to the face is defined by the *radius of influence of the face* $R_f$, which identifies the area on which
The type and the development of the deformation response (reaction)

The deformation response of the medium to excavation manifests in different forms depending on the range in which it occurs and these can be described with simple diagrams. For example:

a **solid load** response, primarily when the failure occurs in a medium generally subject to stress in the elastic range, which is localised and produced mainly as a result of gravity, when the strength of the medium is exceeded along pre-existing discontinuity surfaces;

a **plasticised ring or band response**, primarily when the failure is generated in the elasto-plastic range, which spreads around the excavation and is produced along helicoid surfaces that are generated inside the medium after it has plasticised.

Let us now consider the three characteristic zones illustrated on page 8 and examine how the stress and deformation situation evolves in each of them.

1. **Undisturbed zone** characterised by:
   - natural stress field;
   - triaxial stress state at all points;
   - nil deformation.

2. **Face or transition zone** (corresponding to the radius of influence of the face $r_f$), characterised by:
   - disturbed stress field (variation in the stress state);
   - the stress state evolves from triaxial to biaxial (increase in the stress deviator);
   - increasing, immediate and negligible deformation if in the elastic range, deferred and large deformation if in the elasto-plastic range.

3. **Stabilisation zone** for deformation phenomena (if the design specifications implemented in the face zone were correct) characterised by:
   - equilibrium of the stress field restored;
   - biaxial stress state;
   - plane deformation state;
   - deformation phenomena at an end or ending.

Experimental measurements indicate that no less than 30% of the total convergence deformation produced in a given section of tunnel develops before the face arrives. It follows that the ground ahead of the face is the first to deform and that it is only after it has deformed that convergence of the cavity is produced. It also follows that the convergence measurements taken inside the tunnel only represent a part of the total deformation phenomenon that affects the medium.
The design engineer must focus his attention and within which the passage from a triaxial to a plane stress state occurs (the face or transition zone); proper study of a tunnel therefore requires three dimensional methods of calculation and not just plane methods.

1.4 The reaction

The reaction is the deformation response of the medium to the action of excavation. It is generated ahead of the face within the area that is disturbed, following the generation of greater stress in the medium around the cavity. It depends on the medium and its stress state (consistency) and on the way in which face advance is effected (action). It may determine the intrusion of material into the tunnel across the theoretical profile of the excavation. Intrusion is frequently synonymous with instability of the tunnel walls.

Three basic situations may arise (Fig. 1.6).

If on passing from a triaxial to a plane stress state during tunnel advance, the progressive decrease in the confinement pressure at the face ($\sigma_3 = 0$) produces stress in the elastic range ahead of the face, then the wall that is freed by excavation (the face) remains stable with limited and absolutely negligible deformation. In this case the channelling of stresses around the cavity (an “arch effect”) is produced by natural means close to the profile of the excavation.

If, on the other hand, the progressive decrease in the stress state at the face ($\sigma_3 = 0$) produces stress in the elasto-plastic range in the ground ahead of the face, then the reaction is also important and the wall that is freed by excavation, the face, will deform in an elasto-plastic manner towards the interior of the cavity and give rise to a condition of short term stability. This means that in the absence of intervention, plasticisation is triggered, which by propagating radially and
The three fundamental situations of stability

The behaviour of the medium at the face as a result of being ‘deconfined’ depends above all on its acquired consistency.

If the **consistency** is that of rock then rock type behaviour and therefore a stable face situation results.

If the **consistency** is that of clay (cohesive type behaviour), the face and the perimeter of the cavity deforms plastically intruding into the tunnel giving rise to a stable face in the short term situation.

If the **consistency** is that of sand (loose type behaviour) an unstable face situation results.

As we will see, the stability of the face plays a very decisive role in regulating and controlling deformation phenomena and therefore also for the short and long term stability of an underground construction. It is in the face (or transition) zone that the design engineer must intervene to regulate and control the deformation response.
longitudinally from the walls of the excavation, produces a shift of the “arch effect” away from the tunnel further into the rock mass. This movement away from the theoretical profile of the tunnel can only be controlled by intervention to stabilise the ground.

If, finally, the progressive decrease in the confinement pressure at the face ($\sigma_3 = 0$) produces stress in the failure range in the ground ahead of the face, then the deformation response is unacceptable and a condition of instability exists in the ground ahead of the face, which makes the formation of an “arch effect” impossible: this occurs in non-cohesive or loose ground and an “arch effect” must be produced in it artificially since it cannot occur by natural means.

It therefore follows that it is important from a statics viewpoint to avoid over-break and to keep to the theoretical profile of the tunnel, especially in fractured and stratified rock masses. Accidental over-break, caused mostly by the geological structure of the ground, helps to shift the arch effect away from the walls of the cavity and this decreases the stability of a tunnel (Fig. 1.7).

However, the most important conclusion to be drawn is that the formation of an arch effect and its position with respect to the cavity (on which we know that the long and short term stability of a tunnel depend) are signalled by the quality and the size of the “deformation response” of the medium to the action of excavation.

The next chapter illustrates the evidence accumulated over the last twenty five years from research study on the relationships between changes in the stress state in the medium induced by tunnel advance and the consequent deformation response of the tunnel.
2.1 The experimental and theoretical research

In the previous chapter, we carefully examined the statics and dynamics of tunnel advance to arrive at two important considerations:

1. the short and long term stability of an underground cavity is closely connected with the formation of an arch effect, which must therefore be the primary object of study for a tunnel designer;
2. the formation of an arch effect and its position with respect to the cavity are signalled by the “deformation response” of the medium to the action of excavation, in terms of both size and type.

When reasoning over these two important considerations around thirty years ago (it was 1975), we felt the need to conduct in-depth studies on the relations between the stress state in the medium, induced by tunnel advance (action), and the consequent deformation response (reaction). These studies were conducted as part of theoretical and experimental research, which, although still in progress, has already furnished important and very useful indications.

It was developed in three stages.

The first research stage was dedicated above all to systematic observation of the stress-strain behaviour of a wide range of tunnels during construction. Particular attention was paid to the behaviour of the face and not just that of the cavity as is normally done. Very soon, the complexity of the deformation response, what we were studying, became clear as did the consequent need to identify new terms of reference in order to be able to define it fully (Fig. 2.1):

- the **advance core**: the volume of ground that lies ahead of the face, virtually cylindrical in shape, with the height and diameter of the cylinder the same size as the diameter of the tunnel;
- **extrusion**: the primary component of the deformation response of the medium to the action of excavation that develops largely inside the advance core. It depends on the strength and deformation properties of the core and on the original stress field to which it is subject. It manifests on the surface of the face along the longitudinal axis of the tunnel and its geometry is either more or less axial symmetric (bellying of the face) or that of gravitational churning (rotation of the face);
- **preconvergence of the cavity**: convergence of the theoretical profile of the tunnel ahead of the face, strictly dependent on the relationship between the strength and deformation properties of the advance core and its original stress state.
Two main types of approach have been followed to date in the design and construction of underground works: one is mainly empirical, the other theoretical. Some authors working on the first type have proposed systems to assist design engineers in the design of tunnel stabilisation and lining works, which are based on geomechanical classifications.

Some of the most well known of these are those produced by Bieniawski (R.M.R. System) [2] and by Barton (Q System) [3]. Both identify geomechanical classes on the basis of a series of geomechanical and geostuctural parameters. Stabilisation works which determine tunnel section designs are associated with each class. In theory it is possible to immediately select the most appropriate tunnel section type to ensure the long and short term stability of a tunnel by extrapolating the necessary parameters from core samples and direct measurements at the face.

Unfortunately, as the authors themselves have sometimes complained, an extremely distorted use of this type of classification has been made, as people have tried to use them as the basis for complete design and construction methods and not as a simple support tool for tunnel designers which the creators of the systems intended. It is interesting in this respect to quote some thoughts taken from an article written by Bieniawski and published in the July 1988 edition of the journal Tunnels & Tunnelling [4]: “When used correctly and for the purpose for which they were intended, rock mass classifications can be a powerful aid design. When abused, they can do more harm than good. … Rock mass classifications are not to be taken as a substitute for engineering design. … There are instances when rock mass classifications simply do not work.”

When used for purposes other than those for which they were designed, geomechanical classifications, and as a consequence those design and construction methods that are based on them, such as the NATM, suffer from considerable shortcomings.

They are difficult to apply in the domains of soft rocks, flysch and soils, give insufficient consideration to the effects of natural stress states and the dimensions and geometry of an excavation on the deformation behaviour of a tunnel and fail to take account of new constructions systems. These constitute objective limitations, which make design and construction methods that are based on them inevitably incomplete and not universally valid.

### THE FIRST PART OF THE TABLE CONCEIVED BY BIENIAWSKI TO EVALUATE THE R.M.R. INDEX

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RANGE OF VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-load strength index (MPa)</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Uniaxial compressive strength (MPa)</td>
<td>&gt; 250</td>
</tr>
<tr>
<td>Rating</td>
<td>15</td>
</tr>
<tr>
<td>Drill core quality RQD (%)</td>
<td>90 – 100</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
</tr>
<tr>
<td>Spacing of discontinuities</td>
<td>&gt; 2 m</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
</tr>
<tr>
<td>Condition of discontinuities</td>
<td>Very rough surfaces</td>
</tr>
<tr>
<td>Rating</td>
<td>30</td>
</tr>
<tr>
<td>Inflow per 10 m tunnel length (L/min)</td>
<td>None</td>
</tr>
<tr>
<td>Rating</td>
<td>0</td>
</tr>
<tr>
<td>General conditions</td>
<td>Completely dry</td>
</tr>
</tbody>
</table>
Subsequently, during the second research stage, detailed analysis - above all in terms of timing – was performed on instability phenomena observed during the construction of at least 400 km of tunnel in an extremely wide range of ground types and stress-strain conditions. The aim was to seek a connection between the stress-strain behaviour of the core-face (extrusion and preconvergence) and that of the cavity (convergence).

Once we had established that the deformation response as a whole (extrusion, preconvergence and convergence) is systematically conditioned by the rigidity of the core of ground at the face as a function of the stress state acting on it (which is therefore the real cause of it), at a third stage, the third research stage, we worked to discover to what extent the deformation response of the cavity (convergence) could be controlled by acting on the rigidity of that core.

To do this, the stress strain behaviour of the advance core, systematically compared to that of the cavity, was analysed both in the absence and the presence of intervention to protect and to reinforce the advance core.

### 2.1.1 The first research stage

The first research stage (systematic observation of the deformation behaviour of the core-face) was conducted by using instruments and visual observation to monitor the stability and deformation behaviour of the advance core and walls of tunnels, with particular attention paid to the following phenomena (Fig. 2.1):

*We mean for instability the intrusion of material into the tunnel across the theoretical profile of the tunnel
The new Austrian method (NATM)

The New Austrian Tunnelling Method (NATM), developed between 1957 and 1965 by Pacher and Rabcewicz [5], which laid claim to the technological innovations of the Sprayed Concrete Lining or SCL Method, is a design and construction philosophy based on purely observational criteria. The starting point is a system for classifying rock masses based on a qualitative description of the conditions these present when an underground opening is made. The geomechanical parameters of the design, the excavation system (full or partial face) and the tunnel section type are associated to each rock type on an empirical basis and the final dimensions are in any case decided during construction on the basis of cavity convergence measurements.

The principal merit of the NATM is that it explained the importance of using reinforcement and active stabilisation instruments to make the rock mass contribute to the stability of a tunnel by adapting the deformation properties of linings to the deformability of rock mass. Its main shortcomings, which now make it obsolete and incompatible with new tendencies, are:

- it is impossible to perform preliminary design of construction with it in enough detail to allow estimates of construction times and costs to be made that are sufficiently reliable;
- it is inadequate for the more difficult terrains and stress-strain conditions, which it erroneously presumes can be tackled with partial face tunnel advance;
- practical implementation suffers from too much subjectivity, the result of being based on what are essentially qualitative parameters.

### Table: The New Austrian Tunnelling Method (NATM) - Rock Classification According to Rabcewicz-Pacher

<table>
<thead>
<tr>
<th>ROCK CLASSES</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARACTERISTICS</td>
<td>COMPACT MATERIAL, SLIGHTLY TO SLIGHTLY CRUSHED</td>
<td>SOFT ROCKS AND MUDSTONE</td>
<td>SEMIFRAGMENTAL TO COMpletely FRACTURED AND VERY CRYSTALLINE</td>
<td>VERY FRAGMENTAL AND COMpletely FRACTURED, SOME SUBJECT TO SQUEEZING</td>
<td>COMPLETELY SQUEEZING, SOME SUBJECT TO SQUEEZING</td>
<td>SUBJECT TO SQUEEZING</td>
</tr>
<tr>
<td>EXCAVATION</td>
<td>FULL FACE</td>
<td>FULL FACE</td>
<td>STOP AND LOOKING</td>
<td>DRILLING OF FACE 1-4</td>
<td>DRILLING OF FACE 4-8</td>
<td>DRILLING OF FACE 8-11</td>
</tr>
</tbody>
</table>

### Diagram: Active Stabilisation Cross Section Types for Tunnel Ø ~ 10.00 m

The principal merit of the NATM is that it explained the importance of using reinforcement and active stabilisation instruments to make the rock mass contribute to the stability of a tunnel by adapting the deformation properties of linings to the deformability of rock mass. Its main shortcomings, which now make it obsolete and incompatible with new tendencies, are:
a) *extrusion at the face*, which can manifest with either a more or less axial symmetric geometry (belly of the face) or a gravitational churning geometry (rotation of the face), depending on the type of material and the existing stress state;

b) *preconvergence of the cavity*, understood as convergence of the theoretical profile of the tunnel ahead of the face, strictly dependent on the relationship between the strength and deformation properties of the advance core and its original stress state.

c) *convergence of the cavity* (which manifests as a decrease in the size of the theoretical cross section of the excavation after the passage of the face).

In addition to the systematic implementation of the well known measurements of cavity convergence at the walls of the tunnel or of the ground inside the rock mass, new types of experimental monitoring were studied, developed and implemented to achieve this, which enabled the deformation response of the medium to be studied in detail for a given section of tunnel before, during and after the arrival of the face, with particular attention paid to the face zone itself.

They consisted of *pre-convergence measurements*, performed from the surface using multi-point instruments to measure deformation (extensometers), which were inserted vertically into the ground above the crown and the springline of the tunnel to be constructed whenever the morphology of the ground and the depth of the overburden permitted.

In most cases preconvergence measurements were accompanied by measurements of advance core *extrusion* performed by inserting a *sliding micrometer* horizontally into the face, supplemented with line of sight measurements targeted on marks positioned on the face.

Systematic visual observation performed inside the cavity enabled the following *manifestations of instability* (instability is intended as occurring whenever material intrudes into an excavation beyond the theoretical profile) located on the face or around it to be associated with the types of deformation mentioned above:

a) rock fall, spalling and failure of the face in the core-face system;

b) rock fall, spalling and collapse of the cavity in the roof and tunnel wall zone.

### 2.1.2 The second research stage

Once the different types of deformation and manifestations of instability that occur on the *core at the face* and on the *roof and walls of a tunnel* had been identified, we asked ourselves whether observation of the former might in some way give us an indication of what the type and size of the latter might be. The second stage of the research thus commenced [to seek *possible connections* between the deformation of the core-face (→ extrusion and preconvergence) and that of the cavity (→ convergence)]. It was performed by studying, observing and monitoring deformation at the face and in the cavity, with particular attention paid to its magnitude and the chronological sequence of it in relation to the systems, stages and rates of construction adopted at different times.

It is essential to first briefly illustrate the observations we made on a few of the tunnels we ourselves designed before presenting the results of this experimental stage.