The underground as a resource and reserve for new spaces; ADECO-RS as an effective tool to be able to realize them (part 1).

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ABSTRACT: In ancient times, the underground was used much more wisely and intensively than it is today, especially considering the differences in technology available. This is mainly caused by modern distrust towards building underground works due to the inability of the approaches used in the recent past (and used also today) in design and construction to guarantee the success of investments and the certainty of the construction times and costs in the same manner as overground works. This distrust is no longer justifiable after the introduction, in 1980, of the new ADECO-RS approach, which is the fruit of rigorous scientific research and has been tested in building tunnels for more than 1000 km in different and often difficult conditions.

1 INTRODUCTION

At the start of the nineties, The Quarta Dimensione (fourth dimension) project was set up by entrepreneurial and industrial groups at the head of companies which had been working in the field of underground construction for years. Its goal was to mobilize the resources necessary to sensitize the public awareness towards the need of using the underground in a systematic way. This “fourth dimension” consisted of a new space which, to this day, remains mostly untouched. The “Quarta Dimensione” project started by looking towards the past, and especially towards the ancient past: our ancestors, considering the tools at their disposal, used the underground intensively. Not only did they use this resource for plumbing and for roads (or even for building vast residential areas for technical, climatic, religious, urban or military reasons), but they also had an advanced and sophisticated culture of underground construction, which we have today completely lost and must recover immediately!

The incredible underground cities of Cappadocia are a clear example of this, they were built thousands of years ago and extended in depth for 7 or 8 levels, and were connected by long tunnels (Fig. 1). The Bulla Regia is just as extraordinary, a Roman city of pre-consular Africa, the habitations of which (built between the II and IV century A.D.) almost all possessed a vast subterranean floor, containing not only service and storage rooms, but a complete reproduction of the

Figure 1. The underground city of Derinkuyu (Turkey, VII-I century B.C.)

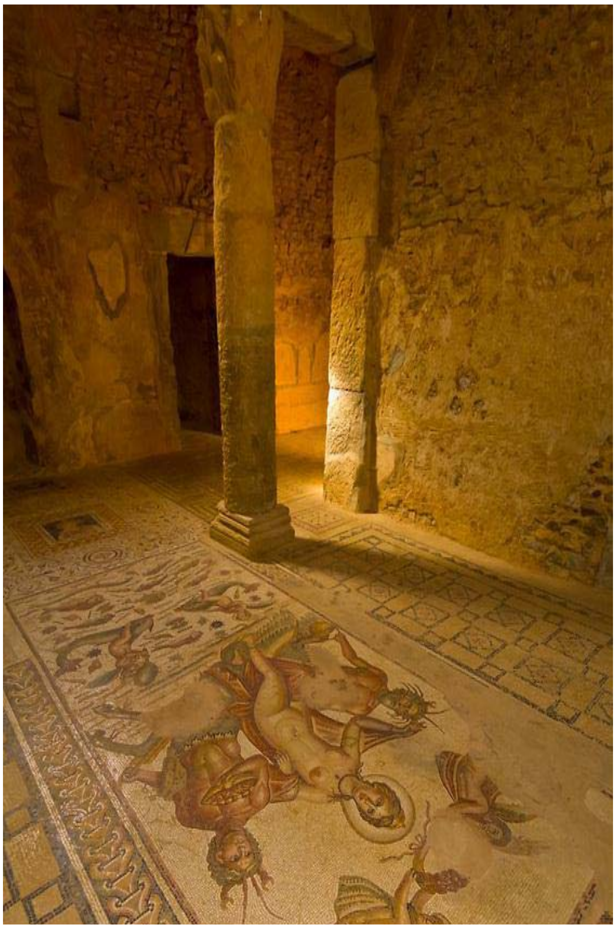

Figure 2. Underground room of a Bulla Regia Roman building (Tunisia (II-IV century A.D.)

ground floor: a luxurious area covered in mosaics and in paintings, often with working fountains (Fig. 2).

Nowadays, in different parts of the world, the underground has been used, in accordance with the geomorphologic and geomechanical characteristics, for different types of structures: transportation, industry, military structures etc. Putting aside the urban underground transportation lines, which are built mainly underground in almost all major cities, Scandinavian cities offer a few very interesting example of underground usage: in Stockholm, for example, and entire wing of the Royal National Library has been built underground. If it had been built overground, it would have visibly disturbed the main parks of the city. Instead, the books are stored in underground rooms directly connected to the library by way of elevators, leaving the overground park intact and creating unlimited possibilities for future development. The city centre also contains a storage area for foodstuffs that must be kept at a low temperature (at about -24°C) for a total of about 16000 cubic metres. Producers fill the great urban storage area and the sales points restock from it: this is a clear example of a policy which takes into account transportation needs, distribution costs and energy saving. Indeed, the refrigeration structure allows a high level of energy conservation thanks to the thermal inertia of the rock mass, and is advantageous if the cooling system should stop for a period of time.

In Italy, the great underground laboratory of the INFN was built during the eighties at a depth of 1400 metres in the Gran Sasso Mountain, and is well known for the groundbreaking nuclear physics research that it is used for Fig. 3).

Despite these and other modern examples of efficient usage of the underground around the world, this resource remains much less used than it was in the past due to that distrust which influences the choice of engineers, city planners, architects and public servants in general.

This distrust has no reason to exist if we consider:

- the availability of new design systems which allow us to approach underground works in the same manner as a work of civil engineering, in foreseeing its times and costs and in guaranteeing investments;
- the availability of technology capable of drastically reducing these times and costs;
- the need, especially in urban contexts, to find new space (as the ground space has been almost completely depleted).

These facts notwithstanding, the common distrust towards using new underground spaces continues, due to the fact that underground works (such as tunnels) are anomalous engineering works.

2 THE ANOMALY OF UNDERGROUND WORKS AND ITS SOLUTION

Figure 3. An INFN laboratory cave in construction at a depth of 1400 metres under Gran Sasso (Italy)

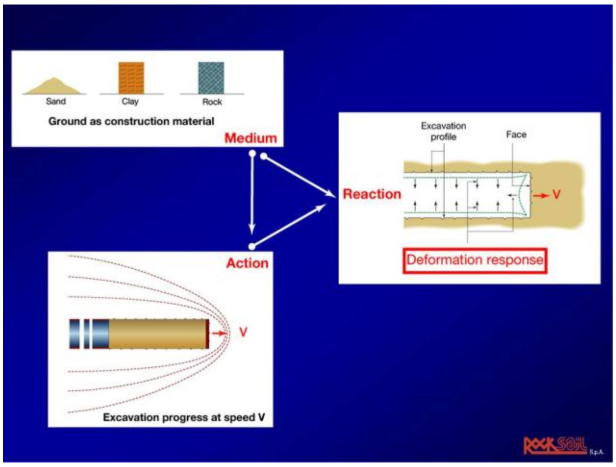

Figure 4. The “ingredients” of an underground work

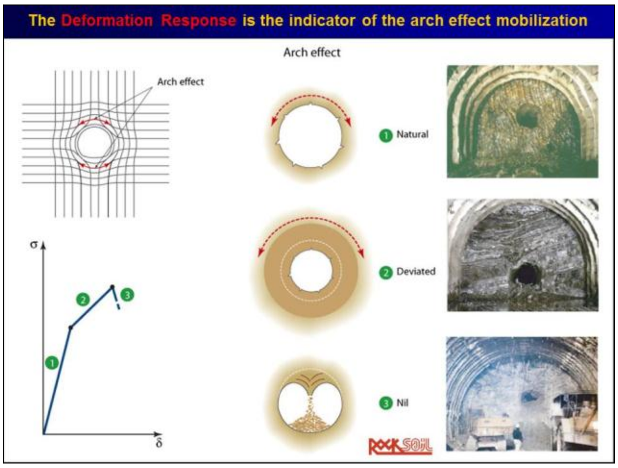

Figure 5. The deformation response is an indicator of the triggering and mobilizing of the arch effect

Underground works are considered anomalous in that, unlike similar overground works:

• they are built subtracting, rather than adding material;

• the properties of their construction material (earth) are not as clearly defined;

• the load on the structures are not known beforehand, nor is known how the work will respond in terms of resistance and deformability.

Furthermore, even today, the project and construction approaches proposed and followed are often unable to guarantee the construction times and costs, and therefore the success of the investment.

How can we therefore solve the distrust that this anomaly has caused?

We cannot act on those natural parameters which do not depend on us (construction material, structural load), we must therefore act on the design approach, which much be correct and capable of going beyond those uncertainties and that lack of precision which has caused many past failures, penalizing underground works in favour of overground ones.

For this reason, it is absolutely necessary to know what the “ingredients” of an underground work are (Fig. 4):

• the **medium** in which operations take place;

• the **action** that is taken to excavate;

• the **reaction** (or Deformation Response) that the action will cause.

The **medium** is the ground, meaning the **construction material** of which the tunnel is composed. In depth, it is subject to triaxial states of stress, dependent on the lithostatic loads (linked to the overburden), on the tectonic loads and on the presence of natural agents. From a geological point of view, its natural consistency (sandy, clayey or stony) will change in depth in accordance with the states of stress. From a geomechanical point of view, its behaviour depends on simple compression tests, direct shear tests and triaxial cell tests.

The **action**, which is produced by the advancement of the excavation face moving at a certain speed V, causes a stress disturbance both transversally and in longitude (in all three dimensions), altering the pre-existing stress states. The importance of the disturbance is determined by the velocity of advancement V, which also depends on the excavation system used (mechanical or traditional). High velocity advancement reduces the spread of the disturbance, and therefore the entity of the reaction or the Deformation Response of the medium to the action of excavation.

The **reaction** is the Deformation Response to the advancing of the excavation face, and the result of the following variables:

• type and structure of the ground;

• the stress field that it is subject to;

• the excavation system and the advance speed.

If there were no Deformation Response, all underground works would be naturally stable and the tunnel designer would have nothing to do!

Instead, he is given the delicate task of ensuring their stability.

It is therefore important that the designer know that the Deformation Response (and therefore the stability of the work) is a clear indicator of the triggering and mobilizing of the arch effect, where the pre-existing stresses of the mass are being deviated by the opening of the cavity and channelled around it, creating zones of increased stress on the walls of the excavation (Fig. 5).

Channelling can be produced, depending on the size of the stresses in play and the strength and deformation of the ground, as follows:

1) close to the excavation face;

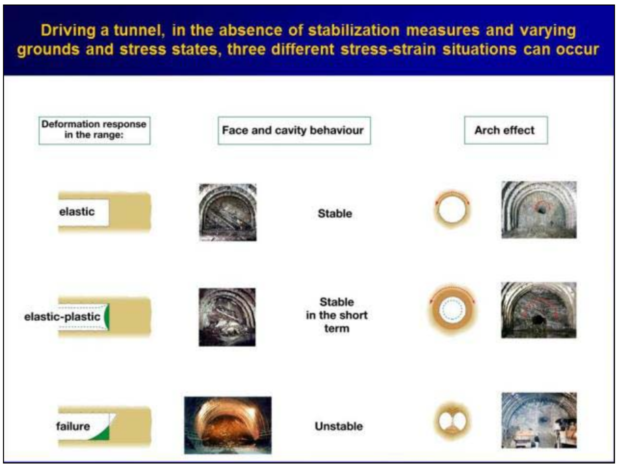

Figure 6. Excavating a tunnel, in the absence of stabilising procedures and with the variation of grounds and stress conditions, three different stability behaviours can take place.

2) far from the excavation face;
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 process. 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 the excavation walls 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 the 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

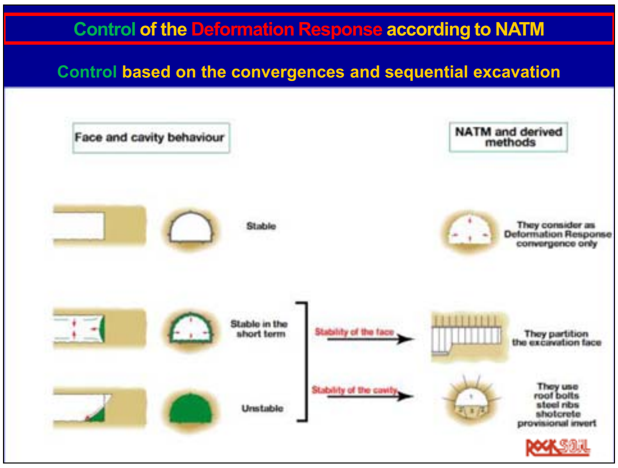

Figure 7. Past design and construction approaches such as the NATM treat situations of instability by working on a Deformation Response which is based on convergence and partitioning the excavation face.

artificial means, by acting appropriately on the ground before it is excavated.

It is the tunnel designer’s job:

1) to insure the short and long term stability of the underground work, to study if and when the arch effect will take place during the tunnel’s excavation process and then calibrating so as to favour its triggering, taking into account the different stress-strain situations, the excavation techniques used and the stabilization operations;

2) to choose the best excavation system (mechanical or conventional) necessary to guarantee the success of the process, also from an **industrial point of view**.

In order to be successful in his task, he will need to carefully study (theoretical forecasting in the design phase and experimental verification during the actual excavation) the Deformation Response of the medium, subject to excavation action, in terms of **Analysis** and **Control**.

2.1 *Analysis and control of the Deformation Response*

Excavating a tunnel, in the absence of stabilising procedures and with variations of the types of ground and the stress conditions, as seen in the previous paragraph, three different stability situations can take place (Fig. 6):

1) the Deformation Response of the excavated medium takes place in an elastic field; the arch effect consequently takes place near the excavation walls and the work will be naturally stable, both in the short term and in the long term;

2) the Deformation Response takes place in an elastoplastic field, the arch effect therefore finds its

balance deeper inside the mass, far from the walls of the excavation and the work results to be stable only in the short term;
3) the Deformation Response of the excavation medium takes place at a breaking point; the arch effect cannot take place and the work will be unstable.
The first situation is of little interest as all methods, with different levels of performance, can bring the work to a successful conclusion.
It is instead interesting to see how the situations 2 and 3 have been faced in the past and how they are faced today in terms of Analysis and Control of the Deformation Response.

2.1.1 Past procedures

In terms of Analysis, the NATM and the methods derived from it – quite popular up to 1980, and still today frequently proposed – base the study of the Deformation Response on the so-called geomechanical classifications (Bieniawski, Barton, etc.). The underground work is split up into sections which are then empirically classified according their "excavation class": the most probable geomechanical parameters, the necessary attack systems, the foreseeable convergence values and the section types to use; in any case, the final dimensioning must be decided afterwards during the construction phase, on the base of the really observed convergence values of the cavity.
In terms of control, they only take into consideration the convergence of the cavity, and on the base of these values they face (Fig. 7):
- the instability of the excavation face, partitioning it into two or more parts;
- the instability of the cavity and stabilizing it, more or less intensively, with: bolts, steel ribs, shotcrete and inverts that are to a greater or lesser degree temporary.
The result is then controlled by measuring the real evolution of the convergence and comparing the values found with those suggested by the geomechanical value foreseen in the design phase.
If the observed situation (as often happens) is different from that foreseen, the work is redesigned on the base of the real deformation behaviour.
This procedure, which continues to be used in many countries, presents many problems:
- the times and costs of the works cannot be correctly assessed, as these are actually being designed while the process is in action;
- production levels cannot be kept constant, especially in heterogeneous grounds and in non-

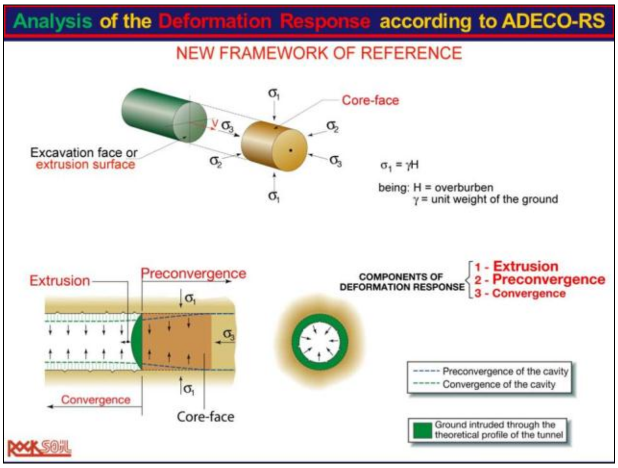

Figure 8. In order to study the Deformation Response in terms of analysis, ADECO-RS needed to find new references

standard conditions, as there is no previously completed project, with all possibilities foreseen;
- safety and stability of the excavation can likewise not be assured in difficult conditions due to the presence of poor ground or serious bonds (e.g. the entity of settlements allowed on the ground level in an urban area);
- it is also impossible, due to the small space available after partitioning, of conveniently taking advantage of the great tunnelling machines available today; both for increasing production and safety levels, and reducing the number of workers necessary to advance the face.

2.1.2 Modern procedures

In order to resolve these difficulties and to give underground projects the same dignity and trust of overground projects – which are first designed and then built, guaranteeing worker safety, and clear times and costs – the present author, in the eighties, developed the ADECO-RS (Analysis of Controlled Deformations in Rocks and Soils) approach in Italy (well known for being one of the countries with most underground infrastructures). This approach, based on scientific evidence collected over 20 years and more than 1000 km of excavated tunnels (and on the control and monitoring of over 100,000 excavation faces), realised that new references needed to be considered in order to correctly study the Deformation Response in terms of Analysis and Control (Fig. 8):

- **advance core** or **core-face**, meaning the volume of ground ahead of the excavation face, cylindrically shaped, and transversally and longitudinally dimensioned according to 1 – 1.5 times the diameter of the tunnel;

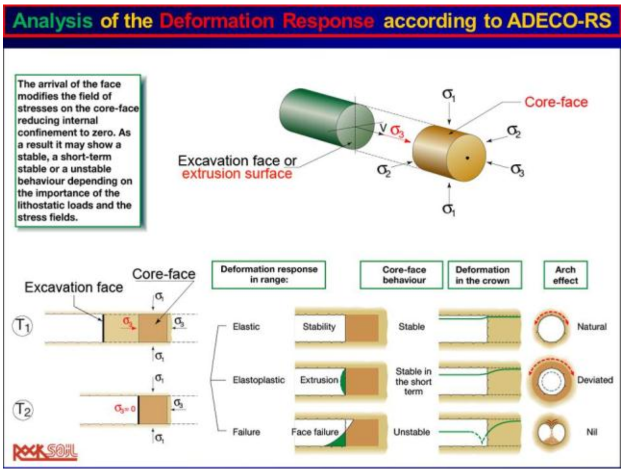

Figure 9. Arrival of the face changes the stress-strain state by cancelling σ_3, the tunnel will therefore present one of three stability conditions.

• **extrusion**, identified as the primary component of the Deformation Response, is mainly developed within the advance core and is manifested in correspondence with the surface delimited by the excavation face, longitudinally to the axis of the tunnel;

• **preconvergence**, the secondary component of the deformation response, is identified as the convergence of the theoretical excavation profile ahead of the excavation face;

• **extrusion surface**, identified as the excavation face, and extending longitudinally with the advancement, from the point of contact between the ground and the upper front extremity of the pre-lining , to the front extremity of the invert.

Unlike NATM and the past methods derived from it (which limit themselves to identifying the Deformation Response of the excavation medium in the convergence alone) ADECO-RS recognizes how the convergence is only the final stage of a much more complex deformation phenomenon, which originates ahead of the excavation in the form of extrusion and pre-convergence of the core-face, and then evolves downstream of the core-face as the convergence of the cavity.

Therefore, by focalising our attention on the Deformation Response of the medium affected by the excavation, we can see how the advance core, when the face arrives, passes from a triaxial stress state, to a biaxial or monoaxial stress state (Fig. 9). This stress disturbance will either result in a stable behaviour; a short-term stable behaviour, or an unstable behaviour in accordance with the entity of the lithostatic loads and stress fields in play. As well as in accordance with the advance speed V, closely linked to the excavation system being used

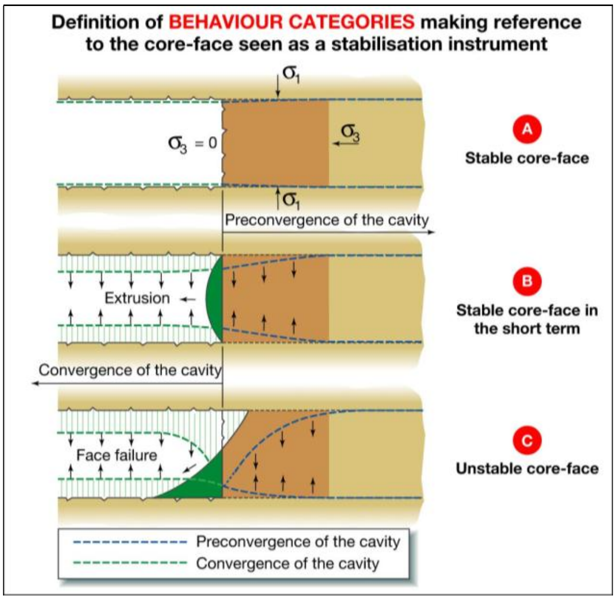

Figure 10. The ADECO-RS stress-strain behaviour categories.

(mechanized or conventional, half-face or full-face).

In terms of analysis, during the design phase, ADECO-RS studies the stability of the core-face, in the absence of stabilizing procedures, in terms of extrusion - pre-convergence. This is done using the most efficient 3D numerical models and with lab tests on reduced scale models, the behaviour is then categorized according to its stress-strain behaviour (Fig. 10):

Category A: stable core-face;

Category B: stable core-face in the short term;

Category C: unstable core-face.

The studies in terms of analysis continue during the construction stage by analysing experimentally and analytically the extrusion, the pre-convergence and the convergence. In particular, the analysis of the first of these three – measured experimentally by means of special tools inserted longitudinally in the advance core (sliding micrometer) – ADECO-RS has always avoided those dangerous structural failures in urban areas which are so common in the history of NATM (Heathrow 1994, Pinheiros 2007, Cologne 2009, to mention but the most recent and most catastrophic).

In terms of control, contrary to the NATM and the approaches of the past - which are mistakenly considered capable of resolving any difficulty by partitioning the face and trying to stabilize the excavation with bolts, ribs, shotcrete and inverts that are to a greater or lesser degree temporary, operating only downstream of the excavation face and within the cavity - ADECO-RS approach always take into account the potential instability of the face and therefore of the cavity. It always advances in full-

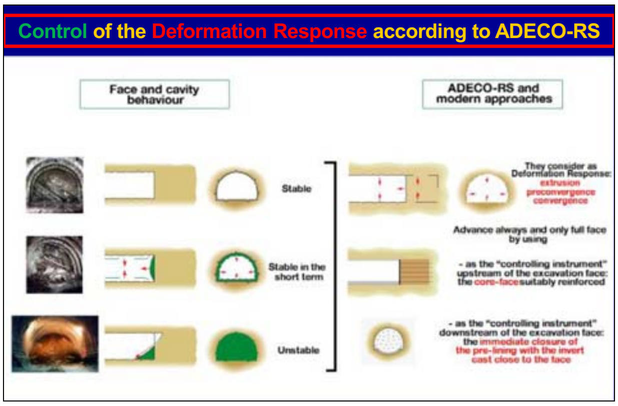

Figure 11. Control of the Deformation Response according to ADECO-RS

face and uses the core-face as the main upstream "control tool", suitably reinforced and/or protected if necessary; and, as the downstream control tool, the immediate closure of the pre-lining with invert, which, for this purpose must be cast close to the face (Figs. 11, 12a and 12b).

Operating on the rigidity of the core-face with suitable protection and reinforcing operations, it is possible to avoid the cancelling of the minor principal stress $\sigma 3$, and to avoid the core-face passing from a triaxial stress state to a biaxial or uniaxial state; in this way it is possible to control the deformability of the core-face and hence the emergence and development of the Deformation Response upstream of the excavation face (extrusion, pre-convergence) and, consequently, also its evolution downstream of the same (the convergence of the cavity).

The designer will therefore be able to do his job and guarantee the stability of the underground work in the short and the long term by operating of the core-face with conservative action, by pre-confining and confining the cavity. He will take care (in order to favour the development of longitudinal arch effects) to constantly keep the excavation face concavely shaped. To this aim – operating on the core-face and therefore **upstream the excavation face** – he will be able to use (Fig. 13):

- reinforcement of the core-face by means of fibre-glass structural elements, devised by the present author and tested in Italy for the first time during a tunnelling project in 1985, during the construction of a short hydraulic tunnel of 5 m in diameter for the floodway of the Citronia river in Salsomaggiore Terme (Italy), and subsequently used extremely successfully for the full-face excavation in soft ground of tunnels of even more than 20 m in excavation diameter ("Appia Antica" tunnel, GRA ring road – Rome);
- protection of the core-face with the use of **full-face** mechanical pre-cutting, a technique that was perfected and tested by the present author in Italy in 1985 during the construction of a tunnel for the Sibari-Cosenza railway line in very soft clay, between the stations of S. Marco Roggiano and Mongrassano-Cervicati. The technology was also successfully applied in the excavation in soft cohesive soils of underground station tunnels (Baldo degli Ubaldi Station on line A of the Rome Underground; ground: clay, excavation diameter: 21,5 m, overburden: 15-18 m);
- protection/reinforcement of the core-face with the use of full-face horizontal jet-grouting, devised by the present author and tested for the first time in the world in Italy in 1983, during the construction of the "Campiolo" tunnel, for the Udine-Tarvisio double-track railway line, within rubble-slopes and with overburdens varying between 0 and 70 m.

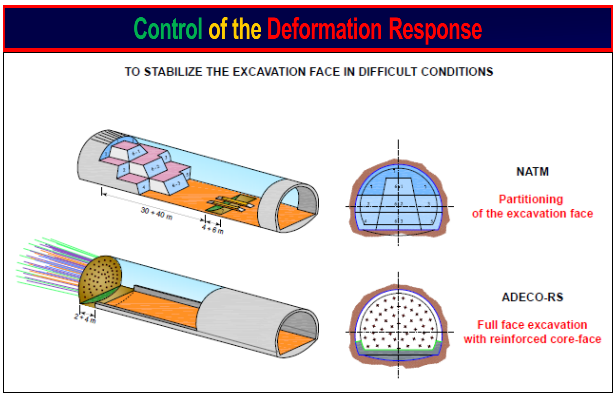

Figure 12a.

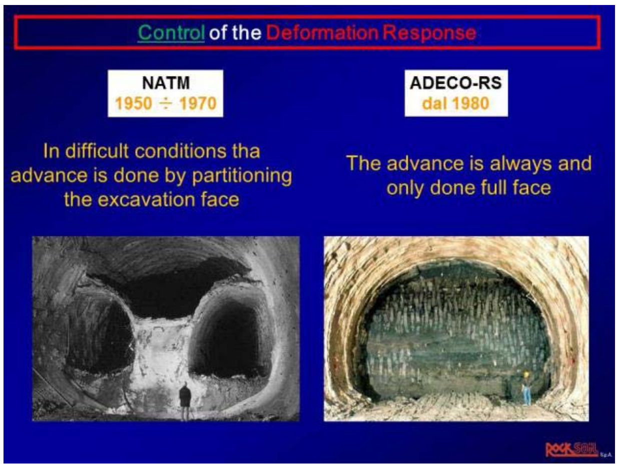

Figure 12b. No more words are needed to express the difference between the old and the modern approach to difficult situations!

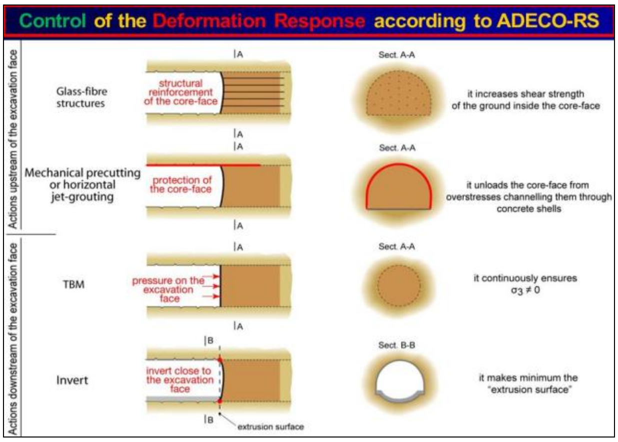

Figure 13. Controlling the Deformation-Response according to the ADECO-RS approach: actions that can be performed on the excavation face.

Instead, in order to work on the **excavation face downstream**, he will be able to use:

• TBM mechanical excavation, which insures (when correctly sized geotechnically) a constant confinement pressure on the face which avoids the cancelation of the main minor stress σ_3. In difficult situations, EPB technology is today available also for great excavation diameters - such as the present author's experience in boring the "Sparvo" motorway tunnel (2.6 Km in length); in the difficult geological and geomechanical context of the Apennines, between Bologna and Florence, the TBM EPB "Martina" – currently the world's biggest EPB TBM, with a diameter of 15.62 m (Fig. 14) – is excavating the second barrel of the tunnel, after having completed the first at an average speed 13.20 m/d;

• the immediate closure of the invert lining, which must be carried out closer to the face according to the necessity of intervening on the hardening of the advance core.

It is indeed of the utmost importance that the passage from the pre-confinement of the cavity operated upstream from the excavation face and the confinement of the cavity operated downstream from the same take place both coherently and continuously.

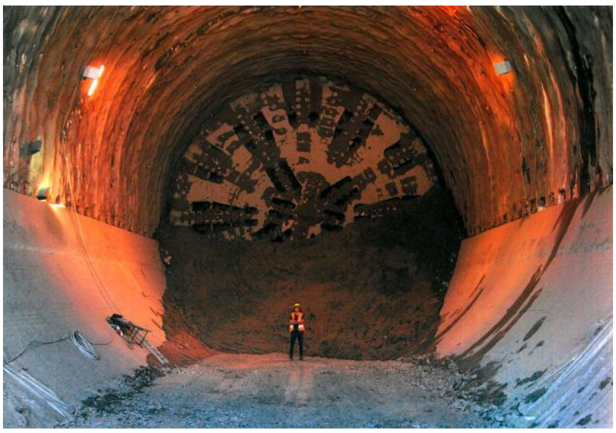

Figure 14. The EPB TBM "Martina" (15.62 m in diameter) has just completed the excavation of the first barrel of the "Sparvo" tunnel (A1 motorway between Bologna and Florence).

This necessity – which is often difficult to explain to constructors, since it requires a different organization than the bad habits of the past – was brought to light through careful observation and numeric interpreting of collapses in the past, and of the development of the Deformation Response that had taken place beforehand.

In particular, it has been noted that the extrusive phenomenon - when produced - takes place through an ideal surface called **extrusion surface**, which extends from the point of contact between the ground and the upper-front edge of the pre-lining, to the point of contact between the same ground and the front edge of the invert Fig. 15). The lifting of the trench bottom, which occurs in difficult conditions when excavating in half-face, is not convergence deformation, as is generally believed; rather, it is the result of a Deformation Response, the regime of which is not correctly regulated in its extrusion component.

Casting the invert nearer to the excavation face, progressively reducing the extrusion surface, produces an equally progressive diminution of the extrusion phenomenon (which tends to develop more symmetrically on the height of the face) and hence also pre-convergence and convergence.

Observing Figure 15, which graphically illustrates that which is explained above, it is also absolutely clear that casting the invert farther away from the excavation face means increasing the amplitude of the extrusion surface, and consequently the volume of the core-face; the extrusion will soon become impossible to control and the cavity will collapse, with consequences similar to advancing in half-face. As shown in the photographs in Fig. 15, casting the invert near the excavation face is possible and, if the site is properly organized, does not affect production; rather, it guarantees an important increase in safety.

3 DESIGNING AND CONSTRUCTING A TUNNEL IN ACCORDANCE WITH ADECO-RS

It has been seen how ADECO-RS (Analysis of the Controlled Deformations in Rocks and Soils) concentrates the designer's attention on the analysis and the control of the Deformation Response, which is understood as a reaction of the medium to the action of excavation, and how the rigidity of the

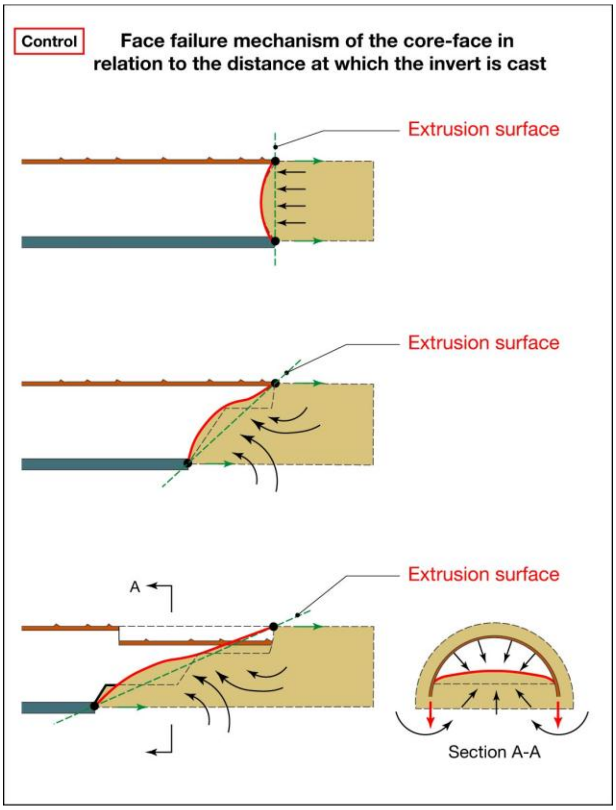

Figure 15. Casting the invert away from the excavation face increases the extrusion surface.

advance core is a natural instrument for controlling extrusion and hence the pre-convergence and the convergence of the cavity, components of the Deformation Response itself, which, as is known, conditions the industrialization of the excavation and consequently the observance of the times and costs of construction. In this perspective, the analysis and the control of the Deformation Response play a fundamental role as indispensable steps for correctly planning and constructing underground works:

• **Analysis**, aimed at predicting the deformation phenomena that will occur following the excavation, must be performed theoretically, using analytical or numerical calculation instruments, at the "design stage", during which, on the basis of the forecasts made (categories A, B, C), the designer also makes the necessary operating decisions, in terms of systems, phases, excavation rates, pre-confinement and confinement of the cavity.

• **Control** of the Deformation Response, however, occurs during the "construction stage", when, as the excavation proceeds, the planning decisions are implemented and verified through the measurement of the Deformation Response of the medium to the actions implemented.

It follows that, for correctly planning and constructing underground works, it is essential:

Figure 16. Invert cast near excavation face – Raticosa (Ø = 13.90 m, Ground: scaly clays, Overburden: 500 m) and Tartaiguille tunnel (Ø = 15.30 m, Ground: swelling clays, max overburden: 150 m.

• **at design**:

- to have in-depth knowledge of the medium that is to be operated in, from a geological and geomechanical perspective, with particular regard to its resistance and deformability properties.

- to study in advance the stress-strain behaviour (Deformation Response) of said medium to excavation (categories A, B, C), in the absence of stabilizing operations.

- to define the type of pre-confinement or confinement actions necessary for regulating the regime of - and controlling - the Deformation Response of the medium to excavation.

- to choose the type of stabilizing operation from among those currently available thanks to existing technologies, on the basis of the pre-confinement or confinement actions that each type is able to guarantee.

- to compose the section types, according to the foreseen behaviour of the medium to excavation, by defining the phases, rates and times of their implementation, in addition to the most suitable stabilizing operations for the context in which the work is expected to take place.

- to size and test the operations chosen, by means of mathematical calculation, so as to obtain the desired behaviour of the medium to the excavation and the necessary safety coefficient of the work, also foreseeing its stress-strain behaviour thus stabilized;

• **during construction**:

- to verify, during the course of the work, that the stress-strain behaviour of the tunnel during excavation corresponds to that foreseen theoretically in the design stage;

- to then proceed with the finalization of the project, balancing the proportion of the operations between the core-face and the perimeter of the cavity.

In order to frame the design and the construction of underground works in a correct and universally valid manner, the ADECO-RS approach divides them into two chronologically separate moments (Fig. 17):

• a **design stage** consisting of:

- a **survey phase**, referred to the geological, geomechanical and hydrogeological knowledge of the medium and to the analysis of the existing natural equilibriums;

- a **diagnosis phase**, referred to the analysis and the theoretical forecasting of the behaviour of the medium in terms of Deformation Response, in the absence of stabilizing operations, according to the stability conditions of the core-face (categories A, B and C);

- a **therapy phase**, referred, firstly, to the definition of the methods of excavating and stabilizing the medium for the purposes of regulating the regime of the Deformation Response, in agreement with the categories of behaviour A, B and C; and subsequently, to the theoretical evaluation of the effectiveness, in this regard, of the solutions chosen; in this phase the section types are composed according to the application and the possible variability depending on the actual deformation behaviour of the tunnel in the excavation phase, which will be measured during the operating phase;

• **a construction stage** consisting of:

- an **operational phase**, referring to the actual construction of the tunnel, in which the application of the stabilizing instruments for controlling the Deformation Response is implemented.

- **a monitoring and final design adjustment phase** during the course of the work, referring to the measurement and experimental interpretation of the actual behaviour of the medium to excavation in terms of Deformation Response, for the finalization and the balancing of the stabilizing systems implemented between the core-face and the excavation perimeter, and for checking the chosen solutions by means of comparing actually measured deformations with the ones that are expected theoretically.

Stage	Phase	Description
Design	– Survey	– Analysis of existing natural equilibriums
	– Diagnosis	– Analysis and prediction of deformation phenomena (*) in the absence of stabilisation measures
	– Therapy	– Control of deformation phenomena (*) in term of stabilisation systems chosen
Construction	– Operational	– Application of the stabilisation instruments for controlling deformation phenomena(*)
	– Monitoring	– Control and measurement of deformation phenomena(*) as the response of the rock mass during tunnel advance (measurement of extrusion at the core-face and of convergence at the contour of the cavity and at varying distance from it, inside the mass of the ground)
	– Final design adjustments	– Interpretation of deformation phenomena(*) – Balancing of stabilisation systems between the core-face and the perimeter of the cavity

(*) Deformation phenomena in terms of extrusion at the core-face and of convergence at varying distance from it, inside the mass of the ground

Figure 17.

Contrariwise to the NATM, the project is therefore checked and adjusted during the course of the work by comparing uniform parameters (Deformation Response expected by calculation with the Deformation Response measured during the course of the work). In this way, it is possible to avoid errors, not to mention horrors, such as that of comparing, during the construction of a tunnel, the convergences measured during the advancement phase with the convergence intervals correlated arbitrarily with geomechanical classes.

(continued in part 2)

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The underground as a resource and reserve for new spaces; ADECO-RS as an effective tool to be able to realize them (part 2).

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ABSTRACT: ADECO-RS approach is not merely a design and construction method that can be used to solve a few complex situations where the face is unstable. It is a complete technological system to produce a reliable design for safe industrialised tunnel construction (on schedule and to budget). This is what has been demonstrated in Italy by the abundant evidence and final data obtained from the construction of more than 100 km of tunnel on the new high speed/capacity railway line between Bologna and Florence.

4 100 KM OF TUNNELS THROUGH THE APENNINES

In excess of 100 km of tunnels were excavated between 1996 and 2005 in the Bologna - Florence section of the new Milan-Rome-Naples high-speed railway line, and they are a fine example of the application of the ADECO-RS approach and its ability to attain the full industrialization of excavations even in grounds that are very difficult by their nature and owing to the stress fields involved (Fig. 18).
The overall length of the layout is more than 78.5 km, of which 70.6 (about 90 % of the total length) are in natural double-bore tunnels. The design of the section comprised the construction of:
• 9 line tunnels of about 140 m2 of section varying in length between 528 m and 18,561 m;
• 14 access tunnels for 9,255 m overall;
• 1 service tunnel for 10,647 m overall;
• 2 connecting tunnels and passage way tunnels for 2,160 m overall; for a total of approximately 104 km of tunnels to be excavated.
The detail and construction design of all these works were undertaken on the basis of the ADECO-RS approach. The project and the construction were hence developed in two absolutely separate moments, from the chronological point of view; more specifically, by means of:
• at the design stage: a survey phase, a diagnosis

Figure 18. Localization of the tunnels built under the Tuscan-Emilian Apennine for the new high-speed/high capacity railway line between Bologna and Florence.

phase and a therapy phase;

- at the construction stage: an operational phase and a monitoring phase during the course of the work.

4.1 *Design of the work*

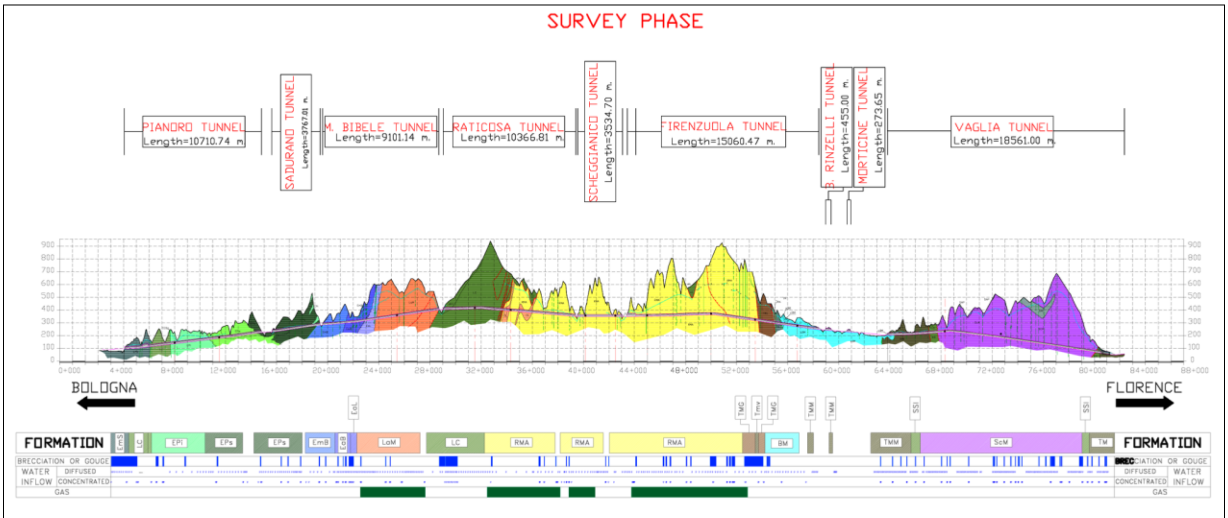
4.1.1 *The survey phase: geological-geotechnical setting*

Considering the substantial complexity of the grounds involved, which had already been tackled amid exceptional difficulties to construct the "Direttissima" railway line, opened in 1934, it was decided to invest a sum of approximately 84 million euro, 2% of the global amount of the work, in the geognostic campaigns to be performed for the purposes of the detailed planning of the new HS/HC line. This allowed a sufficiently detailed and, above all, realistic geological-geomechanical characterization of the grounds that would be involved in the excavation of the tunnels to be obtained. As is shown in Fig. 19, these are principally flysch formations, clays, shale and loose soil, sometimes the locations of major aquifer horizons, which concerned more than 70 % of the underground layout, with overburden varying between 0 and 600 m. Some formations also have the problem of the presence of gas, which is always dangerous to deal with. On the basis of the knowledge acquired, during the survey phase the layout was divided into tracts with similar geological-geomechanical properties, to which were attributed the resistance and deformability parameters to be assumed in the subsequent diagnosis and therapy analyses.

4.1.2 *The diagnosis phase: forecast of the stress-strain behaviour of the rock and soil masses in response to excavation*

On the basis of the geological, geotechnical, geomechanical and hydrogeological knowledge gathered, and the results of the stability calculations carried out using analytical and/or numerical methods, during the diagnosis phase the underground route was divided into sections with uniform stress-strain behaviour, according to the foreseen stability of the core-face in the absence of stabilizing operations:

- stable core-face (category A behaviour; deformation phenomena in the elastic range, prevailing manifestations of instability: ground fall



FORMATION		LENGTH [m]	OVERBURDEN [m]	Cohesion [Mpa] Angle of friction [°]	Modulus of elasticity [Gpa]
Marne in facies di Schlier (EmS)		2012	0 -120 (Pianoro Tunnel)	c = 0.25-0.3 φ = 28 - 30	E = 2.9 - 3.4
Pliocene Intrappenninico Superiore (EpS)		11445	0 - 245 (Sadurano Tunnel)	c = 0.5-0.7 φ = 28 - 30	E = 3.0 - 6.0
Marne di Bismantova		7055	0 -140 (Monte Bibele Tunnel)	c = 0.8-1.35 φ = 29 - 33	E = 4.0 - 6.0
Flysch di Monghidoro (LaM)		9115	0 - 290 (Monte Bibele Tunnel)	c = 0.12-0.5 φ = 23 - 35	E = 3.0 - 8.5
Complesso Caotico (LC)		11187	0 - 520 (Raticosa Tunnel)	c = 0.03-0.7 φ = 10 - 25	E = 0.1 - 1.8
Marly-Sandstone Formation (RMA)		39961	0 - 550 (Firenzuola Tunnel)	c = 2.0-2.2 φ = 24 - 38	E = 15 - 20
Clays of Mugello Basin (aBM)		7404	0 - 80 (Firenzuola Tunnel)	c'_p = 0.03 φ'_p = 26 - 28	E = 0.01 - 0.3
Monte Morello Formation (ScM)	limestones	13861	25 - 560 (Vaglia Tunnel)	c = 1.0-1.4 φ = 42 - 45	E = 7 - 15
	clays and marls			c = 0.18-0.24 φ = 28 - 33	E = 2 - 8

Figure 19.

at the face and around the cavity)

• core-face stable in the short term (category B behaviour; deformation phenomena in the elasto-plastic range; prevailing manifestations of instability: spalling at the face and around the cavity)

• unstable core-face (category C behaviour; deformation phenomena in the failure range; consequent manifestations of instability: failure of the face and collapse of the cavity)

From this analysis, it resulted that 17% of the layout would have been developed inside deposits which, at the time of excavation, would have manifested category A behaviour, 57% would predictably have been affected by deformation phenomena in the elasto-plastic range that could be traced to category B behaviour, and approximately 26%, finally, would have been characterized, in the absence of appropriate operations, by serious phenomena of instability of the core-face typical of category C behaviour.

4.1.3 *The therapy phase: definition of the excavation systems and stabilisation measures*

After having formulated reliable forecasts regarding the stress-strain behaviour of the rock and soil masses in response to excavation, for section of tunnel with uniform stress-strain behaviour, the actions (of pre-confinement and/or simple confinement) were identified that were necessary to guarantee, in every situation hypothesized, the formation of an arch effect as close to the excavation profile as possible. Consequently, the methods of advancing were planned (abatement system, length of excavation step) and the most suitable operations for producing said actions, and hence guaranteeing the stability and safety of the excavations in the short and long term.

Given that the soil variability, which was more or less pronounced in all the tunnels, discouraged the adoption of totally mechanized excavation technologies, with the exception of the service tunnel of the Vaglia tunnel, the guiding principles on which the design of the section types for the line tunnels were based were the following:

• advancing always in full-face, particularly in difficult stress-strain conditions: thanks to the static advantages it has, and to the high level of mechanization that it is possible to achieve in the large working spaces available, the use of full-face excavation after core-face reinforcement, when necessary, makes it possible to advance in safe conditions attaining excellent and above all constant advance rates, even in the most difficult situations;

• confinement, where necessary, of the alteration and the decompression of the soil caused by excavation, by means of the immediate implementation of efficacious operations to reinforce and/or protect the advance core;

• construction of a final lining of concrete, if necessary reinforced, complete with cast invert, wherever the necessity of promptly blocking the deformation phenomena was observed, near the face, for samples of reduced length.

Thus, the longitudinal and cross section types (in total 14) that were most appropriate for dealing with the diverse ground conditions were identified. The range of geological and geomechanical and stress-strain (extrusion and convergence) conditions within which they were to be applied

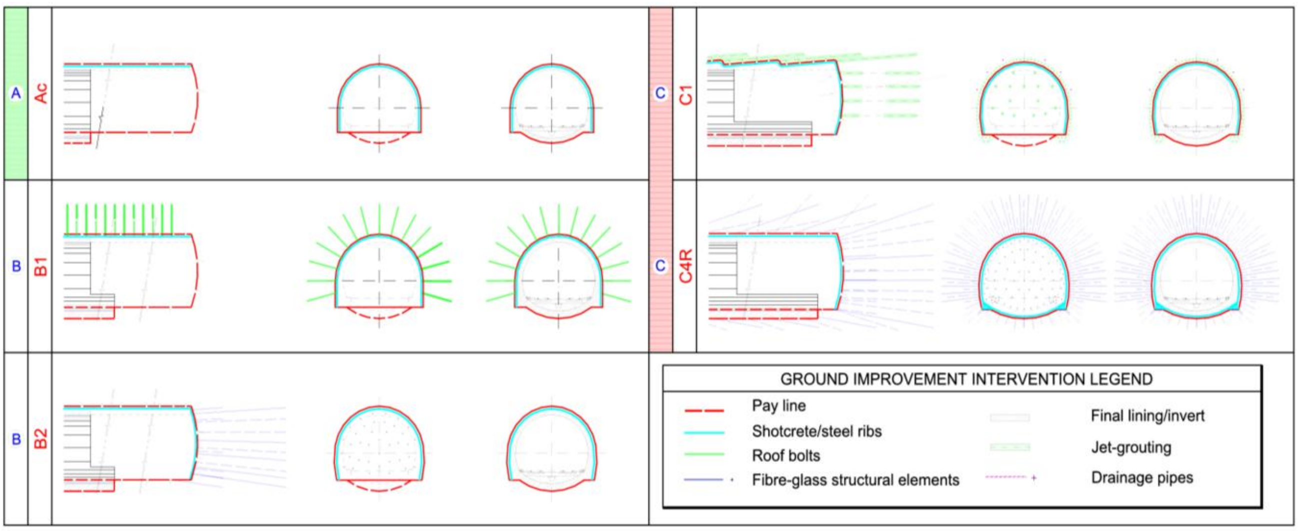


Figure 20. Main section types.

was clearly defined for each type as well as the position in relation to the face, the intensity and the phases and intervals for placing the various types of intervention (advance ground improvement, preliminary lining, tunnel invert etc.). Very reliable work cycles based on a considerable number of previous experiences were drawn up from which precise predictions of daily advance rates could be made (Fig. 20). Variations to be applied were designed for each section type for statistically probable conditions, the location of which could not, however be predicted on the basis of the available data.

The preventive identification, for each section type, of the admissible variations as a function of the actual response of the ground to excavation, always and in any case, within the deformation ranges predicted, is a fundamental part of the ADECO-RS approach. It allows highly detailed definition of the design and at the same time the flexibility required for the useful application of ISO 9001 quality assurance systems during construction without impairment of the basic principles of such systems. By employing this method, Non Conformities (i.e. differences between building and design) are avoided which oblige partial redesign each time a change in conditions is encountered even if it involves only a minor change to the design.

Each section type was analysed as a function of the loads mobilised by excavation as determined in the diagnosis phase, with regard to both the different construction phases and the final service phase by employing a series of calculations on plane and three dimensional finite element models in the elastic-plastic range.

Finally, precise specifications were formulated for the implementation of an adequate monitoring programme, which, according to the different types of ground tunnelled, would both guarantee the safety of tunnel advance and verify the appropriateness of the design and allow it to be optimized in relation to the actual conditions encountered.

4.2 *Construction of the work*

4.2.1 *Type of contract*

The contract for the entire section of the railway between Bologna and Florence was awarded on a rigorous lump sum basis (€ 4,209 million) by FIAT S.p.A., the general contractor, which accepted responsibility for all unforeseen events, including geological risks on the basis of the final design as illustrated above. It subcontracted all the various activities out to the CAVET consortium (land expropriation, design, construction, testing, etc.).

4.2.2 *The operational phase*

Immediately after the contract was awarded, the construction design of works began at the same time as excavation work (July 1996).
Additional survey data and direct observation in the field generally confirmed the validity of the detailed design specifications, while the following minor refinements were made in the construction design phase:

- To deal specifically with particularly delicate stress-strain conditions a steel strut was introduced as a variation to section types B2 and C4 in the tunnel invert to produce much more rapid confinement of deformation. This modification of the B2 section type was found to be much more versatile and appropriate even for many situations where the core-face was unstable. Use of the heavier C section types was thus limited to the more extreme stress-strain conditions.
- The effectiveness of core-face ground improvement using fibre glass structural elements was increased considerably by introducing an expansive cement mix to cement the fibre glass nails.
- As a consequence of positive results acquired during the construction of tunnels on the Rome-Naples section of the same railway line, a section type B2pr was designed for underground construction of the Sadurano, Borgo Rinzelli and Morticine tunnels originally designed as artificial tunnels.
- Finally, it was decided to replace section types B3 and C3, which involved the use of mechanical precutting with section C2 (ground improvement in the core-face and around it with fibre glass structural elements) better suited to the ground to be tunnelled.

The final result of construction design was the definition of the following percentages of tunnel section type: type A sections: 20.5 %; type B sections: 57.5 %; type C sections: 22.1 %.
Approximately 70.6 km of line tunnels were driven and lined. The average monthly advance rates were in the order of 1000 m of finished tunnel, reaching a maximum of 2000 m in March 2001 working simultaneously on 30 faces. The production graphs shown in Fig. 21 highlight the marked linearity of the productions, which reached very high absolute values in relation to the grounds tunnelled. Even in

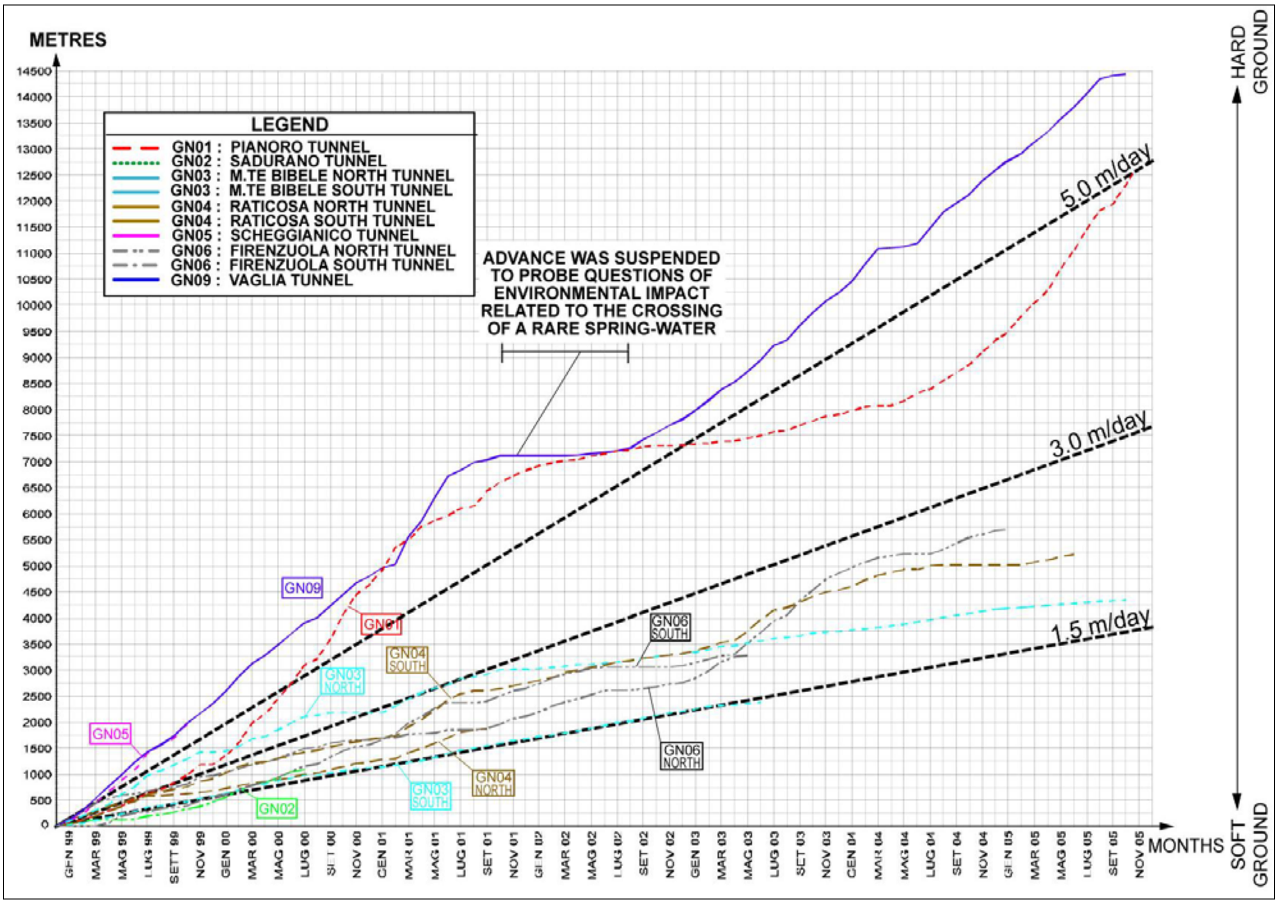


Figure 21. Production advance in different stress-strain conditions.

the Raticosa tunnel, which was driven in very difficult stress-strain conditions within the Chaotic Complex formation consisting of the much feared scaly clays, average advance rates were never less than 1.5 m per day. Table 1 gives a comparison of daily advance rates forecast by the detailed design specifications for some section types and the actual advance rates achieved.

Table 1.

Section type	Foreseen advance [m/day of finished tunnel]	Actual advance [m/day of finished tunnel]
A	5,40	5 - 6
B0	4,30	5 - 5,5
B2	2,25	2,1 – 2,2
C1	1,40	1,4
C2	1,25	0,85
C4V	1,25	1,63

Fug. 22, in turn, gives the distribution differences of the section types between the detailed design specification and the tunnel "as built", showing a significant reduction in the application of more expensive section types in favour of cheaper ones. This result is to a large extent due to the exceptional effectiveness demonstrated by the pre-confinement methods employed even under high overburden. This was the first time they were applied with overburden of more than 500 m. However, advancing after stiffening the core-face, while deemed counterproductive by some under greater overburden, if correctly performed and ensuring the continuity of the action from ahead of the face back down into the tunnel with the placing of a steel strut in the tunnel invert, proved very effective also in these situations, requiring the adoption of heavier section types only in the most extreme conditions. Another reason for the greater use of section type A was that there are only minor differences between it and the B0 sections types such as the thickness of the final lining or the distance from the face at which the tunnel invert is cast. As a consequence, section type A was adopted in place of section types B0 or B0V, whenever the ground conditions allowed this to be done without risk (e.g. in long sections of the Vaglia tunnel where the presence of the adjacent service tunnel already built made the situation particularly clear). The differences found between the detailed design specifications and the tunnel as built did not reveal any sensational discrepancies, neither in terms of

HIGH SPEED/CAPACITY TRAIN - Milan to Naples Line - SECTION TYPES DISTRIBUTION

FINAL DESIGN

TUNNEL	Length [m]	SECTION TYPES DISTRIBUTION [m] A	B0	B0V	B1	B2	B3	B4	C1	C2	C3	C4	C4V	C5
Pianoro	10293,4		951,8			3886,4	3036		62,0	948,8	1083	310		15,5
Sadurano	3778,0	64,0	2580,8			875,0			68,0	190,3				
M. Bibele	9118,5	978,2	1094,6		4529,1	1212,2			76,0	1112,8		115,6		
Raticosa	10381,0	3043,0			972,2	758,4			40,0	786,7		4465,1		315,67
Scheggianico	3530,6	2089,9			1404,7					36,0				
Firenzuola	14311,5	3528,7			5950,4	716	412,2		227,5	511,9	2226,8	738,1		
B. Rinzelli	455,0								160		295			
Morticine	273,7								80	193,7				
Vaglia	16757,0	2017,2	3104,3	1129,8	5629,0			1151,2	692	708,5			2325,2	
TOTAL LENGTH [m]	68898,6	11721,0	7731,5	1129,8	18485,2	7447,9	3448,2	1151,2	1405,4	4488,6	3604,8	5628,8	2325,2	331,2
SECTION TYPES DISTRIBUTION [%]		17,0	11,2	1,6	26,8	10,8	5,0	1,7	2,0	6,5	5,2	8,2	3,4	0,5

AS BUILT (up to 31st March 2004)

TUNNEL	Length [m]	Tunnelled length [%]	Tunnelled length [m]	SECTION TYPES DISTRIBUTION [m] A	B0	B0V	B2	B2pr	B2V	C1	C2	C4	C4V	C6
Pianoro	10710	97	10438,0		8167,0		682,5		63,0	3,5			1522,0	
Sadurano	3767,0	100,0	3767,0	2213,1	1408,0		85	53			8			
M. Bibele	9101,0	95,0	8643,1	2935,5	2015,7		3507,9		97,9	41	45			
Raticosa	10367,0	98,1	10165,2	3578,2	686,0		857		25	85		1468	673,4	2792,6
Scheggianico	3535,0	100,0	3535,0	3517,0	18,0									
Firenzuola	15211,0	92,9	14128,0	6833,1	3194,3		3081,8		263,5	577,1	9		125,83	43,5
B. Rinzelli	528,5	100,0	528,5					303,5			225,1			
Morticine	565,5	100,0	565,5					537,0			28,5			
Vaglia	16757,0	80,3	13449,7	5287,60	5992,20	96,60	1547,0		296,70	128,25	101,4			
TOTAL LENGTH [m]	70542,3	92,5	65220,0	24364,5	21481,2	96,6	9761,2	893,5	746,1	834,8	417,0	1468,0	2321,2	2836,1
SECTION TYPES DISTRIBUTION [%]				37,4	32,9	0,1	15,0	1,4	1,1	1,3	0,6	2,3	3,6	4,3

Final design specification:
Section types: A = 17%, B = 57%, C = 26%

Tunnels as built:
Section types: A = 34.7%, B = 53.7%, C = 11.6%

Figure 22.

the overall cost of the works, which was a little less than budgeted under the detailed design specifications (~ -5%) nor with regard to construction times. While the Contractor partially benefited from the lower cost, a reward for the greater risk run by agreeing to sign a rigorously lump sum, all-in contract, the Client and citizens benefited from the punctual observance of time schedules because they will be able to use the new transport services without intolerable delays.

4.2.3 *The monitoring phase*

The particular nature and the importance of the project required a thorough monitoring programme both during construction and for the completed tunnel in service. The following were monitored during construction:

• the excavation faces of the tunnels, through accurate geomechanical surveys carried out in accordance with I.S.R.M. standards. These surveys are very useful for giving an initial indication of the characteristics of the ground to be compared with design forecasts;
• the deformation behaviour of the core-face, by measuring both surface and deep core-face extrusion. The systematic execution of this type of measurement is essential, especially when the stress-strain conditions are difficult, because they provide precise and very reliable indications on the potential evolution of the deformation phenomena, permitting the selection and implementation of any countermeasures that might be considered necessary, with providential timeliness and multiplied effectiveness;
• the deformation behaviour of the cavity by means of systematic convergence measurements;
• the stress behaviour of the ground-lining system, by means of pressure cells to be placed at the ground-lining interface and inside the lining itself, both in the first phase and final lining.

During the course of the work, the results of the monitoring guided the Design Engineer and the Work Management in deciding whether to continue with the specified section type or to modify it, if necessary, according to the criteria already indicated in the design, by adopting the "variabilities" specified in it. This method of proceeding allowed the satisfactory management of the unpredictability inherent in underground works, even with a strictly lump sum contract such as the one between CAVET and TAV.

5 CONCLUSIONS

There exists a modern distrust towards underground works that stems from the inability of the design and construction approaches of the recent past (yet still proposed today) to ensure the success of investments and to guarantee certain times and construction costs. This distrust no longer has reason exist: the experience of the construction – greatly within the foreseen times and costs, and with an almost nonexistent percentage of injury at the excavation face – of an exceptionally vast, heterogeneous and difficult work such as the new high-speed Bologna-Florence railway line crossing the Apennines, has proven that the ADECO-RS approach (which was established in 1980 by the present author and his collaborators, specifically to industrialize underground works,

Figure 23. Monte Bibele tunnel, the core-face reinforced with fibre-glass elements (ground: Monghidoro flysh, overburden: ~ 200 m).

Figure 24. Firenzuola tunnel, the core-face impreoved with reinforced micro-jet (ground: clayey sands with pebbly intercalcations, overburden: ~ 40 m).

and was intensively tested in Italy since 1990) is indeed capable of successfully handling any type of ground and stress-strain behaviour within the given times and costs. The great spaces available at the excavation face, due to full-face advance even in the most difficult situations, allows the use of big and powerful machinery capable of reaching high industrial production levels in accordance with the geological conditions and stress-strain behaviours being faced. The work environment at the face is agreeable and the need for a reduced number of miners ensures extremely high safety levels, the likes of which are unheard of with other systems. The apparent higher cost of a tunnel built using ADECO-RS is justified by the higher safety standards guaranteed at the excavation face (respect of human lives) and by the vast financial savings due to the high-level of industrialization (respect of construction times and construction costs).

ADECO-RS may be the way for a more confident approach towards the use of the underground as a possible new space for man and for his activities.

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