ADECO-RS GUARANTEES OBSERVANCE OF TIMES AND COSTS IN THE CONSTRUCTION OF UNDERGROUND WORKS

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Italy, which together with Japan is the nation that has constructed the most kilometres of tunnels by far, has long abandoned the NATM completely in favour of ADECO-RS. By adopting this innovative and universal approach to design and construction, hundreds of kilometres of tunnels have been completed, often successfully bringing to conclusion works that had long been abandoned using the NATM, as they were apparently impossible. Memory illustrates the scientific evidence that led to the definition of ADECO-RS and the highly significant results that have been attained so far in terms of industrialization, production and safety of excavations.

Keywords: ADECO-RS, NATM, industrialization

GENERAL

ADECO-RS is a universal approach to the planning and construction of underground works, which stands apart from all previous methods for having always sought to attain the observance of the times and costs of completing works, independently of the excavation system used to produce them, whether it be mechanized or traditional.
Moreover, observance of the times and costs of producing works is in the interests of Clients and the Constructors alike, and it is possible to achieve only by means of the industrialization of the advancements.
Before the arrival of the ADECO-RS, the problems of industrialization could have been considered as solved only for mechanized excavation. For several years, various types of TBM have been available, suitable for tackling wholly stone materials as well as decidedly softer materials, above or below the water table.
In Italy, for example, roughly ten TBMs are operating or have recently operated in wide-ranging geomechanical contexts in the construction of tunnels for underground rail lines, railways and motorways. Worthy of note among these, in the demanding geological-geomechanical context of the Apennines, between Bologna and Florence, is the EPB TBM "Martina", currently the largest EPB TBM in the world with its 15.62 m diameter (fig. 1), which is excavating the "Sparvo" motorway tunnel. The progress of all these works, which is perfectly in line with the forecasts, testifies to the great reliability that has been achieved in mechanized excavation.
The story is different and more complex as regards traditional excavation: we all know the difficulties and the risks that Clients, Constructors, Designers and Workers are often forced to deal with when the ground, the stress states involved, and even the geometry of the works necessitate excavation using traditional systems.
Still today, we frequently encounter very delicate situations, such as excavations in soft ground in urban areas, being tackled by partializing the section with the same criteria that were laid down in the NATM more than 50 years ago. With the persistence of this situation, which can only be defined as severely backward, it is no wonder that disasters continue to occur with a certain frequency, such as that which happened in Pinheiros in 2007.
To guarantee the industrialization of tunnel excavation even when forced to opt for traditional excavation, around thirty years ago in Italy theoretical and experimental research began into the stress-strain behaviour of a tunnel during the excavation phase. At the same time, on the basis of the evidence that was emerging from the research, innovative construction technologies were being developed (horizontal jet-grouting, full-section mechanical pre-cutting, strengthening of the core face with fibre-glass structural elements, etc.), and these were rigorously tested in the field. One of these, horizontal jet-grouting for advancing excavations in inconsistent ground, was also successfully tested by the author in Campinas in 1987, during the construction of the road underpass at the railway yard (fig. 2).

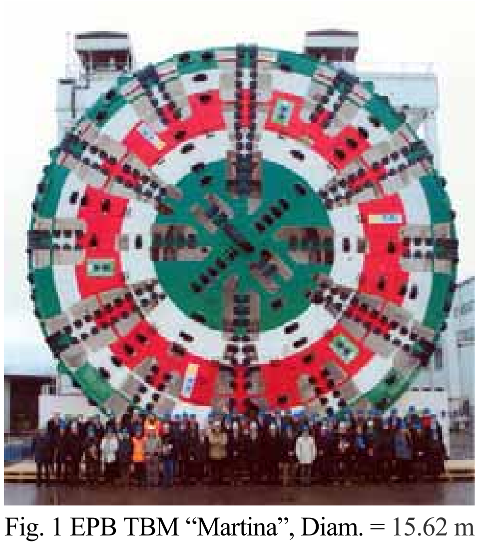

Fig. 1 EPB TBM "Martina", Diam. = 15.62 m

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After having verified, during the construction of some sample tunnels, the new principles derived from the results of the research, which were often in stark contrast with those still taught today by the NATM, a new design and construction approach was adopted, known as ADECO-RS. Having demonstrated in the field that it could effectively guarantee the accomplishment of the works, even in the most difficult situations, safely and fully observing the foreseen times and costs, it was promptly adopted by the specifications of all the major Italian Administrations. It must be remembered that, together with Japan, Italy is the nation that has by far the most kilometres of tunnels excavated in the world, and that, compared with Japan, Italy unquestionably has more experience of tunnels dug in challenging ground using conventional systems. In the last twelve years in Italy, hundreds of kilometres of tunnels have been constructed using ADECO-RS, often successfully completing works that had long been abandoned using the NATM as they were apparently impossible. The successes attained have attracted a lot of interest abroad, where, by applying ADECO-RS, seemingly impossible situations have been resolved rapidly and effectively (see for example Tartaiguille tunnel in France in fig. 3). Adopting ADECO-RS means changing your way of thinking, abandoning taboos and theories that have never been scientifically proven, and consequently modifying your specifications, as was done in Italy in the 1990s. It is an effort that, sooner or later, every country must make and which already many countries (particularly the Eastern nations that are currently paying a great deal of attention to the problems of industrialization) are preparing to do, bearing in mind that the book on the ADECO-RS system published in an Italian edition in 2006 has already been translated and published in English, in Chinese and in Korean, while translation is underway for Russian, German and Spanish editions.

Figure 2. Protection of the core-face with full-section horizontal jet-grouting - Road underpass of the Campinas Railway yard (Diameter = 14.9 m, Ground: sandy, Coverage 2 - 4 m)

ADECO-RS

ADECO-RS (Analysis of Controlled Deformations in Rocks and Soils) is a design philosophy which, differently from previous approaches, places at the centre of designing underground works the deformations that manifest in the medium in which the excavation proceeds, analyzing them in depth so as to then identify the most effective systems for controlling them.

Deformations according to the ADECO-RS

Deformations are simply the Deformation Response that is produced in the medium in the wake of excavation; if there were no response, the tunnel designer would have nothing to do!

Hence, ADECO-RS focuses attention on the study of the Deformation Response and, in order to understand its characteristics, in terms of origin and evolution, considers (fig. 4):

- the <u>medium</u> within which the work is performed;
- the <u>action</u> that is performed to operate the excavation;
- the <u>reaction</u> (or Deformation Response) that is produced in the medium in the wake of excavation.

The <u>medium</u> is the ground; that is, the construction material of the tunnel. Deep down, it is subject to triaxial stress states, which depend on the lithostatic loads associated with the coverage involved and the presence

Figure 3. “Tartaiguille” tunnel (France), (Diam. = 15.30 m, Ground: swelling clay, Max. coverage: 150 m.

Some comments from French technical publications:

“Lorsqu’elle en prend les moyens, l’Italie peut réaliser des travaux à faire pâlir les entreprises françaises ......” (Le Moniteur, 20 février 1998);

“Le creusement du tunnel de Tartaiguille a été très difficile, en raison notamment de convergences inattendues du terrain, qui ont nécessité un changement de méthode en cours de chantier: le professeur italien Pietro Lunardi a convaincu la SNCF de travailler à la pelle en pleine section dans les argiles, en boulonnant le front sur 24 m ......” (Le Moniteur, 7 août 1998).

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of natural agents. From the geological point of view, its natural consistency (sandy, clayey or stony) changes deep down, according to the stress states. From the geomechanical perspective, its behaviour is principally characterized by means of simple compression tests, direct shear tests and triaxial tests.

The action, which is produced by the advancing of the excavation face at a certain velocity V, causes stress perturbation in the surrounding ground, both in a transverse direction and longitudinally (hence, in three dimensions) altering the pre-existing stress states.

From the point of view of the behaviour of the tunnel as the face advances, it is important to consider the advance core (fig. 5), defined as the volume of ground ahead of the excavation face, which is more or less cylindrical and with transverse and longitudinal dimensions in the order of the diameter of the tunnel: upon the arrival of the excavation face, the advance core passes from a triaxial stress state to a biaxial or uniaxial one, and following this stress perturbation, may manifest behaviour characterized by stability, short-term stability or instability, depending on the magnitude of the lithostatic loads and the stress fields involved, but also depending on the velocity of advancing V, which is closely linked to the excavation system used (mechanized or conventional, half-section or full-section): high advance velocities reduce the propagation of perturbation, significantly influencing the behaviour of the advance core, or the Deformation Response. It can thus be seen that the choice of excavation system directly conditions the ground's Deformation Response to the action of excavation, hence the success of the engineering work in terms of times and costs of construction.

Finally, the reaction is the ground's Deformation Response to the advancing of the excavation face: according to ADECO-RS, the designer must concentrate all his or her attention on the research (theoretical forecasting during the design stage and experimental verification during the course of the works) in terms of Analysis and Control.

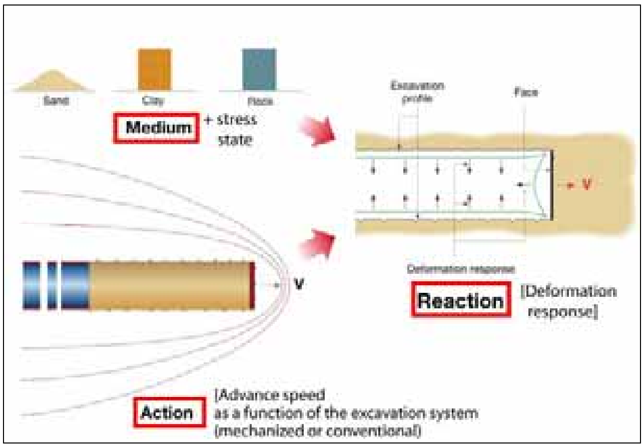

Figure 4

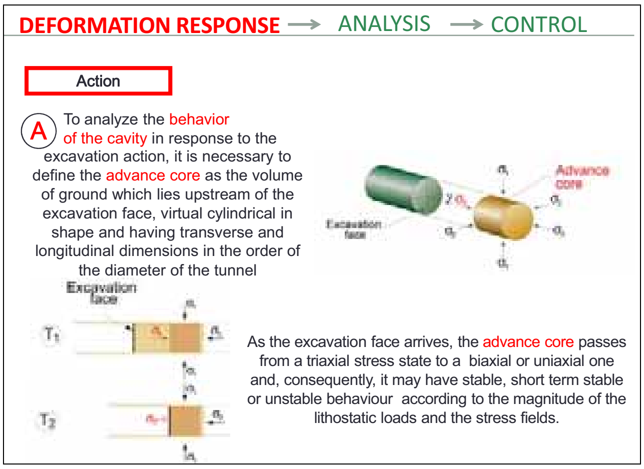

Figure 5

Analysis of the Deformation Response according to ADECO-RS

Contrary to the NATM, which identifies the medium's Deformation Response to excavation as convergence alone, on the basis of the evidence that emerged from scientific research, ADECO-RS recognizes some three different components of the Deformation Response (fig. 6):

- extrusion, identified as its primary component, 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; it is measured experimentally by means of special tools inserted longitudinally in the advance core (sliding micrometer);
- preconvergence, the secondary component of the Deformation Response, is identified as the convergence of the theoretical excavation profile ahead of the excavation face; it is evaluated analytically by means of the preconvergence calculation tables;
- convergence, which, as the third component of the Deformation Response, is identified as the convergence of the theoretical excavation profile downstream of the excavation face, is measured

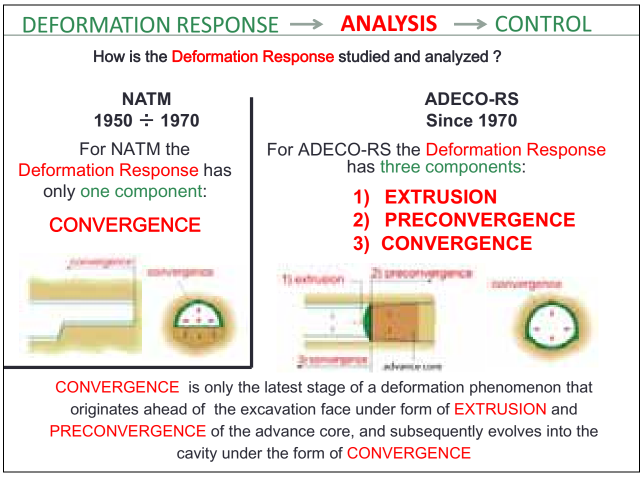

Figure 6

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experimentally by means of tape extensometers or topographical plotting on optical targets applied to the perimeter of the cavity.

According to ADECO-RS, hence, convergence is merely the final stage of a quite complex deformation phenomenon, which originates ahead of the excavation face in the form of extrusion and preconvergence of the advance core, to then evolve downstream of it in the form of convergence of the cavity.

Control of the Deformation Response according to ADECO-RS

Contrary to the NATM, which is mistakenly considered capable of resolving any difficulty by partializing the section 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 envisages always advancing in full-section and stabilizing the excavation by intervening primarily on the ground upstream of the excavation face (fig. 7). For this purpose ADECO-RS uses the advance core as the principal upstream "controlling instrument", suitably reinforced and/or protected if necessary, and, as the downstream controlling instrument, the immediate closure of the pre-lining with the invert, which, for this purpose, must be cast close to the face.

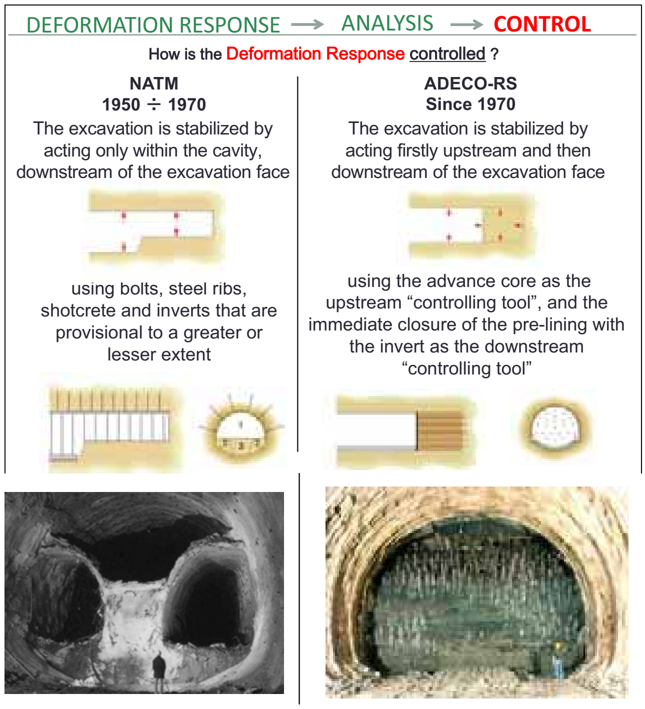

Figure 7

Operating on the rigidity of the advance core with suitable protection and reinforcing operations, it is possible to avoid the annulling of the minor principal stress σ_3 upon the arrival of the excavation face, and the advance core consequently passing from a triaxial stress state to a biaxial or uniaxial state (fig. 8); in this way it is possible to control the deformability of the advance core and hence the emergence and development of the Deformation Response upstream of the excavation face (extrusion, preconvergence) and, consequently, also its evolution downstream of it (convergence of the cavity).

It is interesting to note how Rabcewicz, the father of the NATM, in a number of his papers [Rabcewicz 1964 and 1965] expressed his conviction several times that all tunnels, especially if difficult, ought to be tackled in full section, if only suitable technology existed for doing so. Almost a century later, it is impossible not to note that today, despite availing of the technologies Rabcewicz hoped for, his nostalgic pupils and followers, who are more involved in marketing than in the progress of research, have made no advances along the path indicated by the master, and by limiting themselves to replicating the solutions he proposed more than 50 years ago, they have transformed NATM into a self-referential and futureless approach.

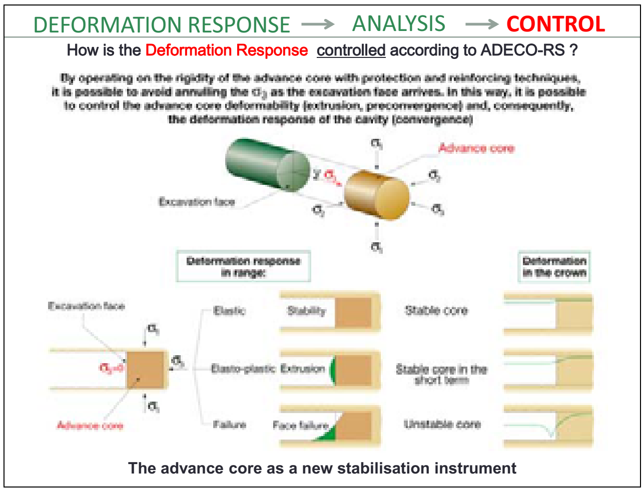

Figure 8

It is pure illusion to believe that it is possible, as the NATM still teaches today, to stabilize a tunnel in difficult stress-strain conditions by partializing the section and concentrating all efforts only on fighting convergence, that is, that part of the Deformation Response that occurs downstream of the excavation face. Using this method, in fact, nobody has ever managed to avoid situations of collapse, it not being possible to control the Deformation Response, which, on the contrary, one is forced to endure. Convergence, as the "final stage" of a quite complex deformation process that occurs ahead of the excavation face, is actually an uncontrollable phenomenon, associated with the plasticization of the ground around the cavity which, as is known, cannot be reversed once it has been allowed to develop significantly. ADECO-RS, having understood the true genesis and evolution of the Deformation Response, concentrates all its efforts on controlling extrusion (the advance core as a new stabilizing instrument) which, being the "initial stage" and the source of the deformation process, if suitably maintained within the elastic range, evolves towards phenomena of preconvergence and convergence also in the elastic range, thus allowing the pressure on the linings to be kept to a minimum in the short and long term.

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To provide tunnel designers with adequate tools for controlling the Deformation Response, ADECO-RS, after having analyzed the stability of the core-face of the tunnel with experimental and mathematical models, refers to the advance core, which is seen as the principal instrument for stabilizing the excavation, identifying three categories of basic stress-strain behaviour (fig. 9):

- category A or behaviour with a stable core-face
- category B or behaviour with a core-face that is stable in the short term
- category C or behaviour with an unstable core-face.

It is hence evident that to stabilize a tunnel in the short or long term during the excavation phase, it is necessary to bring B- and C-type behaviours back to category A, by intervening, firstly, on the rigidity of the advance core. This is the principal task of the design engineer, who may perform it successfully by operating on the advance core with suitable conservation (or reinforcing or protecting) techniques to preconfine the cavity, and subsequently, so as not to lose the result attained upstream, by adjusting the core-face's manner of extruding downstream of the excavation face, by means of conservation techniques to confine the cavity, such as closing and stiffening the first-phase lining near the face with the invert (fig. 10).

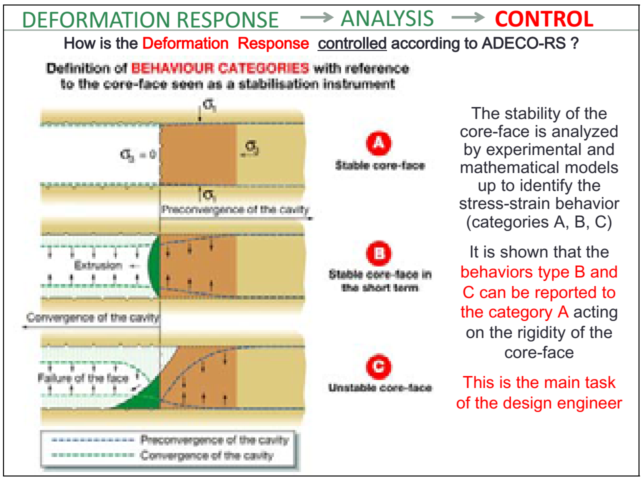

Figure 9

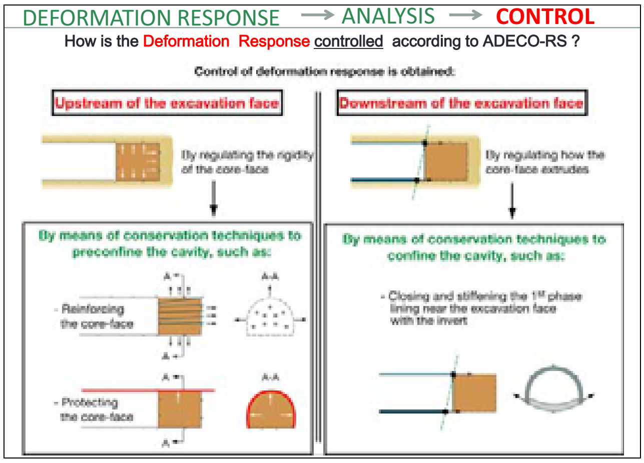

Figure 10

Technologies for controlling the Deformation Response ahead of the excavation face according to ADECO-RS

Given that the operations are said to be:

- reinforcing, when they act directly on the consistency of the advance core, improving its natural properties of resistance and deformability through appropriate ground improvement techniques;
- protective, when they produce the canalization of the stresses outside the advance core carrying out a protective action, which guarantees the conservation of its natural resistance and deformability properties;

among the conservation technologies for reinforcing the core-face able to perform an effective controlling action of the Deformation Response ahead of the excavation face, mention is made of:

- the reinforcing of the core-face by means of fibre-glass structural elements, devised by the author and experimented in Italy for the first time in the exercise of tunnelling 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-section excavation in soft ground of tunnels of even more than 20 m in excavation diameter ("Appia Antica" tunnel, GRA ring road – Rome in fig. 11).

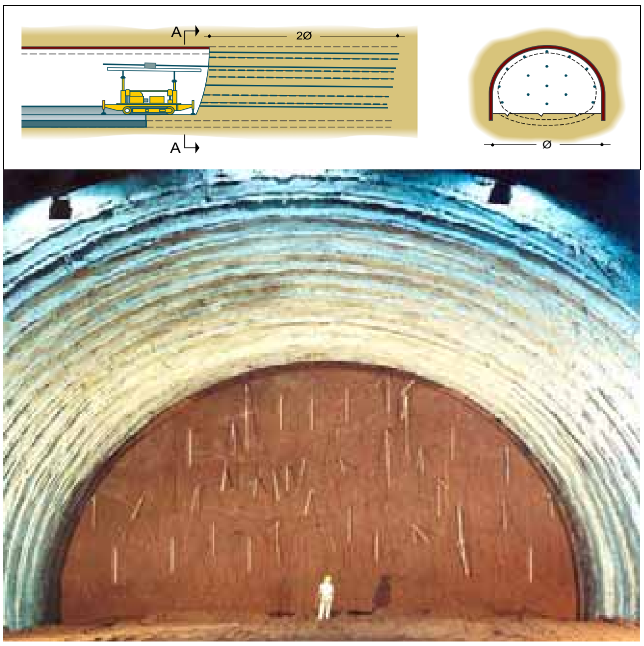

Figure 11. Reinforcing the core-face with fibre-glass structural elements – Appia Antica Tunnel - (Diam. = 20.65 m, Ground: pyroclastites, Coverage: 4 - 18 m)

Among the conservation technologies for protecting the core-face able to perform an effective controlling action of the Deformation Response ahead of the excavation face, particular mention is made of:

- full-section mechanical pre-cutting, devised by the author and experimented for the first time in the world in 1985 in Italy during the construction of a tunnel for the Sibari-Cosenza railway line in very

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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 in fig. 12, ground: clay, excavation diameter: 21.5 m, coverage: 15-18 m).

Among the conservation technologies for protecting/reinforcing the core-face that are capable of performing an effective controlling action of the Deformation Response upstream of the excavation face, finally, remember:

- full-section horizontal jet-grouting, devised by the author and experimented 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-slope and under coverage varying from 0 to 70 m. As was mentioned in the introduction, the same technology was also used in 1987 in Campinas (fig. 2), for the construction of the double-bored road underpass of the embankment of the existing rail yard (ground: heterogeneous sand, excavation diameter: 14.9 m, coverage varying between 2 and 6 m).

Lastly, as regards controlling the Deformation Response ahead of the excavation face, it is important to highlight how ADECO-RS, always with a view to favouring the formation of longitudinal arch effects in the ground, considers it vital while advancing to keep the exposed surface of the excavation face constantly concave-shaped (fig. 13).

Technologies for controlling the Deformation Response downstream of the excavation face according to ADECO-RS

With regard to controlling the Deformation Response downstream of the excavation face, ADECO-RS insists on the necessity of the designer paying the greatest attention to passing from the preconfinement action of the cavity performed upstream of the excavation face to the confinement action of the cavity performed downstream of it, which must take place consistently and continuously.

This means that, contrary to the practice taught by the NATM, which ignores the true nature of the Deformation Response and allows it to develop upstream of the excavation face, obliging the implementation of flexible linings to encase the deformation phenomena already triggered (a practice which, in truly difficult stress-strain conditions, leads only to disasters), ADECO-RS, when advancing in the presence of a stiffened core, unavoidably requires the implementation of proportionately rigid linings.

To this end, it is vital that, downstream of the excavation face, the more important the stiffening operation is that has been performed on the advance core, the nearer to the face should the closure of the lining with the invert be made (fig. 10).

This necessity, which is often difficult to convince constructors of because it requires different organization

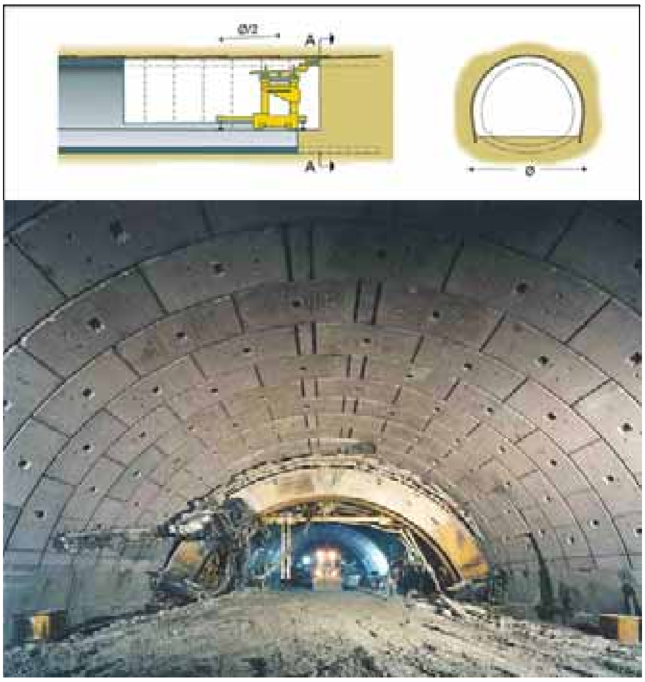

Figure 12. Mechanical pre-cutting – Baldo degli Ubaldi Station - (Diam. = 21.5 m, Ground: clay, Coverage: 15 - 18 m)

Figure 13. Excavation face shaped with a concave profile – tunnel of Baldo degli Ubaldi Station - (Diam. = 21.5 m, Ground: clay, Coverage: 15 - 18 m)

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of the site than the bad habits acquired in the past, is precise evidence that emerged from careful observation and from interpretation, including by mathematical means, of the collapses that occurred in the past and the development processes of the Deformation Response that preceded them.
In particular, it was seen that the extrusion phenomenon, when it is produced, occurs through an ideal surface, defined as the 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 ground itself and the front edge of the invert (fig. 14). The lifting of the trench bottom, which occurs in difficult conditions when excavating in half-section, is not convergence deformation, as is generally believed; rather, it is the result of a Deformation Response whose regime 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 preconvergence and convergence.
Observing figure 14, 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, with consequences similar to advancing in half-section.
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.

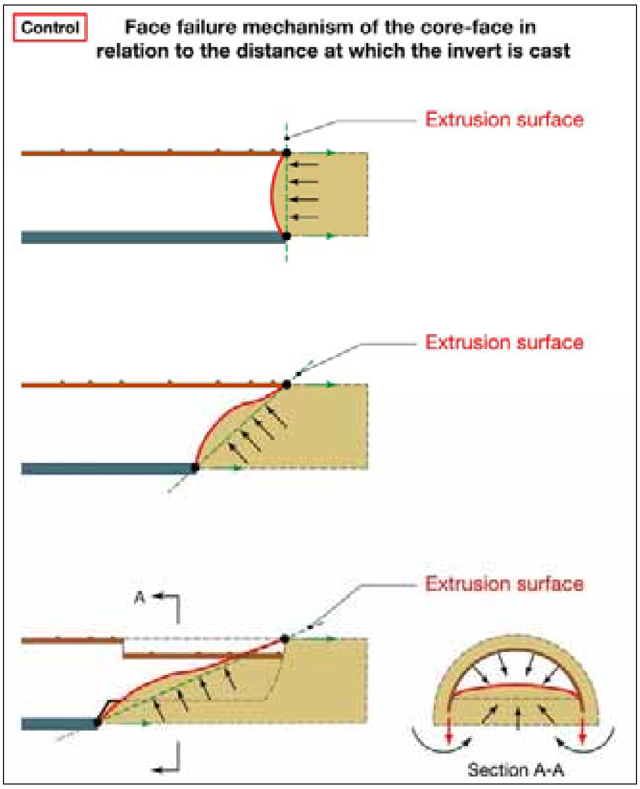

Fig. 14. Moving the casting of the invert away from the excavation face means increasing the extrusion surface

Figure 15. Invert cast near the excavation face - Raticosa Tunnel (Diam. = 13.90 m, Ground: scaly clays, Coverage: 500 m) and Tartaiguille Tunnel (Diam. = 15.30 m, Ground: swelling clays, Max. overage: 150 m.

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 advance core is a natural instrument for controlling extrusion and hence the preconvergence 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 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, the designer also makes the necessary operating decisions, in terms of systems, phases, excavation rates, and ground improvement and stabilizing instruments;

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- the 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:

- 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, in the absence of stabilizing operations;
  - to define the type of preconfinement 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 preconfinement or confinement actions each one 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 behaviour of the tunnel during excavation corresponds to that foreseen analytically in the design stage. And then to proceed with the finalization of the project, balancing the proportion of the operations between the core-face and the perimeter of the cavity.

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 16.

Thus, to frame the design and the construction of underground works in a correct and universally valid manner, the ADECO-RS approach envisages that they are divided into two chronologically separate moments (fig. 16):

- 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 balances;
  - 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 envisaging the application and the possible variability depending on the actual

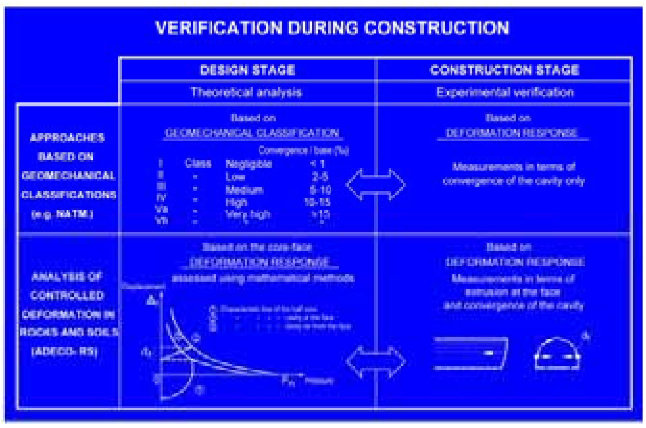

Figure 17

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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 actual deformations with expected ones.

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 convergence intervals correlated arbitrarily with geomechanical classes (fig. 17).

Figure 18.

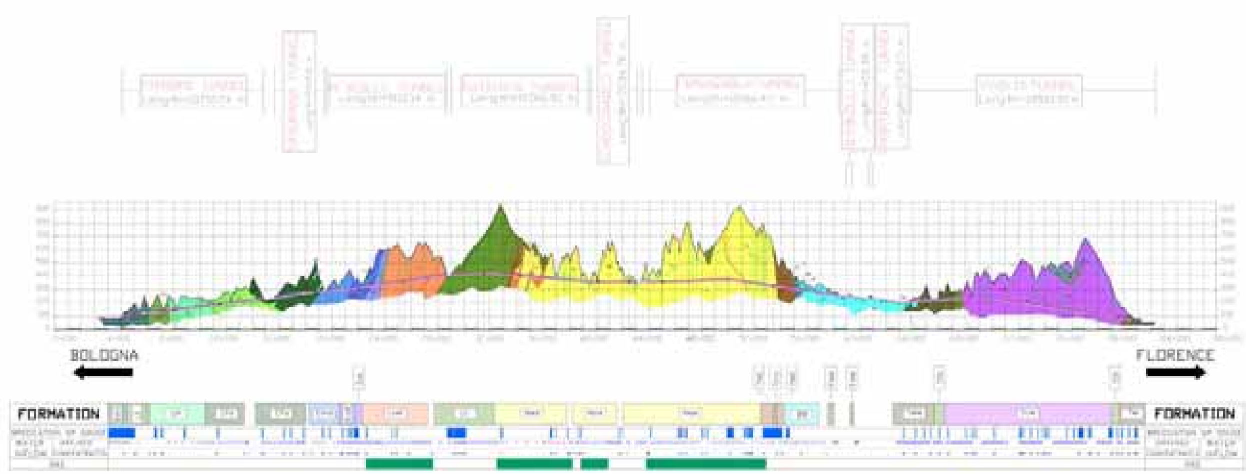
100 KM OF TUNNELS THROUGH THE APENNINES

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 m^2 of section varying in length between 528 m and 16,775 m;
- 14 access tunnels for 9,255 m overall;



FORMATION		LENGTH [m] to be tunnelled	already tunnelled	OVERBURDEN [m]	Cohesion [Mpa] Angle of friction [°]	Modulus of elasticity [Gpa]
Marne in facies di Schlier (EmS)		0	2012	0 -120 (Pianoro Tunnel)	c = 0.25-0.3 φ = 28 - 30	E = 2.9 - 3.4
Pliocene Intrappenninico Superiore (EpS)		0	11445	0 - 245 (Sadurano Tunnel)	c = 0.5-0.7 φ = 28 - 30	E = 3.0 - 6.0
Marne di Bismantova		0	7055	0 -140 (Monte Bibele Tunnel)	c = 0.8-1.35 φ = 29 - 33	E = 4.0 - 6.0
Flysch di Monghidoro (LaM)		0	9115	0 - 290 (Monte Bibele Tunnel)	c = 0.12-0.5 φ = 23 - 35	E = 3.0 - 8.5
Complesso Caotico (LC)		0	11187	0 - 520 (Raticosa Tunnel)	c = 0.03-0.7 φ = 10 - 25	E = 0.1 - 1.8
Marnoso-Arenacea (RMA)		0	39651	0 - 550 (Firenzuola Tunnel)	c = 2.0-2.2 φ = 24 - 38	E = 15 - 20
Clays of Mugello Basin (aBM)		0	7404	0 - 80 (Firenzuola Tunnel)	c'_p = 0.03 φ'_p = 26 - 28	E = 0.01 - 0.3
Monte Morello (ScM)	limestones	0	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.

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- 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 detailed 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:

- a survey phase, a diagnosis phase and a therapy phase, at the design stage;
- an operational phase and a verification phase during the course of the work, at the construction stage.

Design of the work

The survay 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 coverage 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.

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 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.

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 preconfinement and/or simple

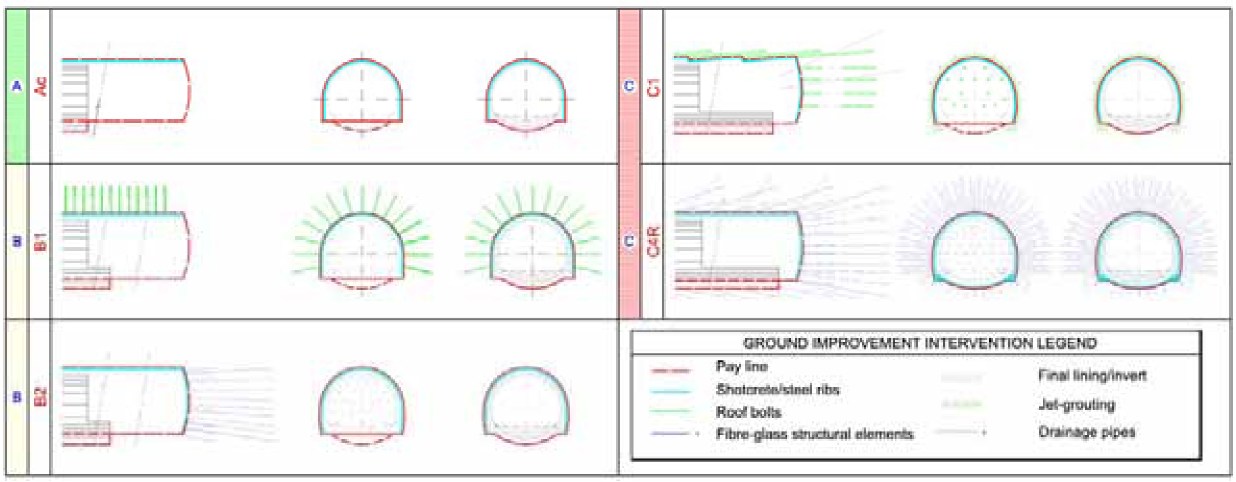

Figure 20. The principal section types.

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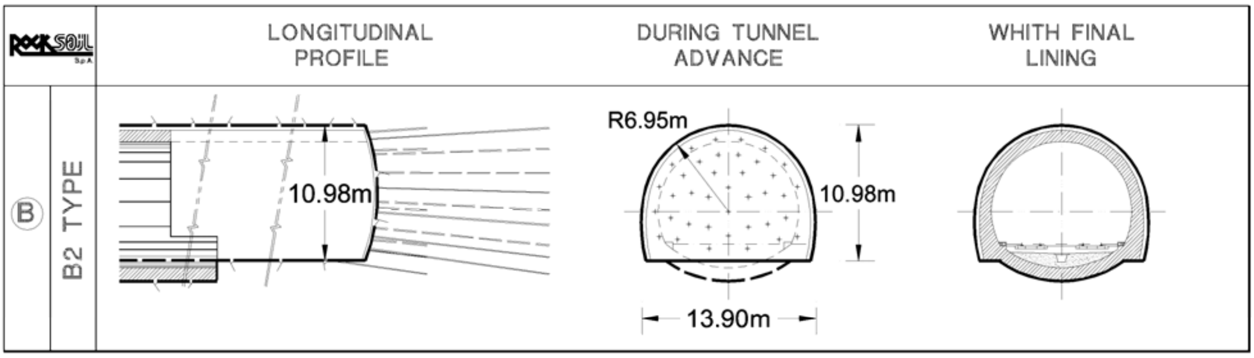

GEOLOGY	GEOMECHANICS Intrinsic band	OVERBURDEN (m) From	OVERBURDEN (m) To	DESIGN SECTION TYPES Type	DESIGN SECTION TYPES INTERVENTION Primary	DESIGN SECTION TYPES INTERVENTION Final	FORECAST DEFORMATION RESPONSE	FORECAST DEFORMATION RESPONSE	VARIABILITY INTERVENTION Primary	VARIABILITY INTERVENTION Final
Sandy-silty complexes in massive or not well stratified from slightly to moderately cemented facies. Low permeability at the mass scale.	φ=14÷32 c=0.25÷0.5 MPa E=0.5÷3.0 GPa	50	100	B2	45 fibre glass structural elements in the advance core Overlapping >5.00m Lattice steel ribs every 1.20 m Shotcrete >30cm	90 cm concrete lining 100cm invert	<10cm	5÷18cm	35÷55 fibre glass structural elements in the advance core Overlapping 5÷7m Lattice steel ribs every 1÷1.4 m Shotcrete 25÷30cm	90 cm concrete lining 100cm invert

Figure 21. Example of planned variations according to the actual behaviour of the rock and soil masses in response to excavation.

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-section 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 (figure 20). The range of geological and geomechanical and stress-strain (extrusion and convergence) conditions within which they were to be applied 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. 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 (see example in fig. 21).

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 as built 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 elasticplastic range.

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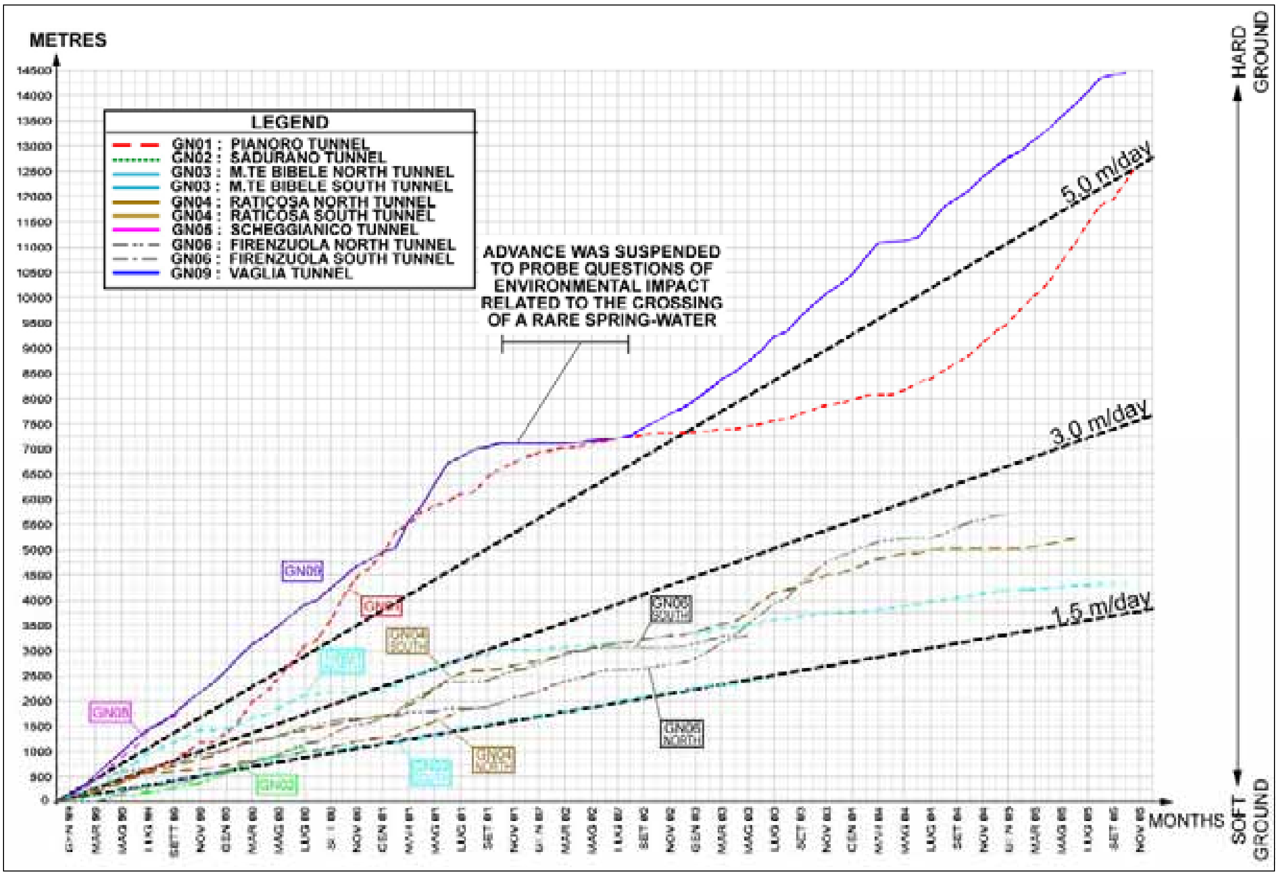

Figure 22. Advance rates obtained in the different stress-strain conditions found.

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.

Construction of the work

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.).

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;

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- 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.

Table I

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

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. 22 highlight the marked linearity of the productions, which reached very high absolute values in relation to the grounds tunnelled. Even in 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 II, 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 preconfinement methods employed even under high coverage. This was the first time they were applied with coverage of more than 500 m. However, advancing after stiffening the core-face, while deemed counterproductive by some under greater coverage, 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 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.

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 followings 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

Table II

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

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Figure 23. Monte Bibele Tunnel, the core-face reinforced with fibre-glass structural elements (ground: Monghidoro flysh).


Figura 24. Firenzuola Tunnel, the core-face consolidated with reinforced micro-jet-grouting (ground: clayey sands with pebbly intercalations).

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 works, 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 "variabiloities" 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.

CONCLUSIONS

The experience accrued with the accomplishment, which was achieved in substantial compliance of the times and costs foreseen, and with almost no injuries at the excavation face, of an exceptional project in terms of its vastness, diversity and the difficulty of the situations dealt with, such as the Apennine crossing of the new high speed/high capacity railway line between Bologna and Florence, demonstrates that the ADECO-RS approach is effectively capable of successfully tackling any type of ground and stress-strain condition, guaranteeing the observance of the times and costs of construction. The ample spaces available at the excavation face thanks to full-section advancement allow the use of powerful machinery and hence permit particularly high levels of industrial production to be attained in relation to the geological and stress-strain conditions faced. The acceptable working environment at the face and the necessity of a very small number of miners ensure very high safety levels that are far superior to those of other systems.

The apparent higher cost of a tunnel constructed with ADECO-RS compared to a similar one constructed with the NATM is amply compensated for by the much higher safety standard guaranteed at the excavation face (respect for human life), without counting the considerable financial savings consequent to the marked industrialization (observance of the times and costs of construction).

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