Evolution of design and construction approaches in the field of tunnelling: the results of applying ADECO-RS when constructing large underground works in urban areas

Pietro Lunardi[1]

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In the last 25 years in Italy, over 1000 km of tunnels have been constructed in urban and extra-urban areas. Despite being constructed in very complex and difficult grounds; generally these were completed (from the design stage to the construction and actual opening of activity) with industrial methods, and within the technical times and costs foreseen by the design laid out by the tenders. This extraordinary result has been made possible since the public administrations have adopted modern design and construction approaches in their contract specifications, based on strictly scientific criteria and which leave nothing to the typical vagueness of those design and construction systems from the twentieth century, which remedied cavity instability solely by means of partitioning the excavation face. Today we know that full-face advancement is all the more necessary the more difficult the excavation conditions are. Memory serves to illustrate the criteria that helped define modern design and construction concepts and an example of their application for constructing a great twin tunnel (258 m^2 + 258 m^2 in section) in the urban area of Rome.

1. THE ANOMALY OF UNDERGROUND WORKS AND ITS SOLUTION

Italy is a mostly mountainous country, bearing grounds which make it quite difficult to dig tunnels. At the same time it presents the highest development of constructed tunnels worldwide (more than 6,000 Km), a high percentage of which in urban areas (more than 800 km in the last 15 years).

This result is due to the fact that over twenty years ago the Italian school of tunnelling recognized the anomaly of underground construction compared to traditional overground construction, and thus did away with the imprecise design and construction approaches of the past in favour of new ones. These were based on a rigorously scientific base and allowed the construction of large underground projects, even in difficult stress-strain conditions, in line with projected times and costs, with an effective management of geological risk and great benefit towards both clients and constructors.

But what is this anomaly between overground and underground construction?

Underground works are anomalous because, unlike similar overground works (fig.1):

- they are built by subtracting, rather than adding material
- the properties of the construction material (ground) aren't as well defined or known
- the loads on their structures aren't previously known, nor is the response of the work in terms of resistance or deformability

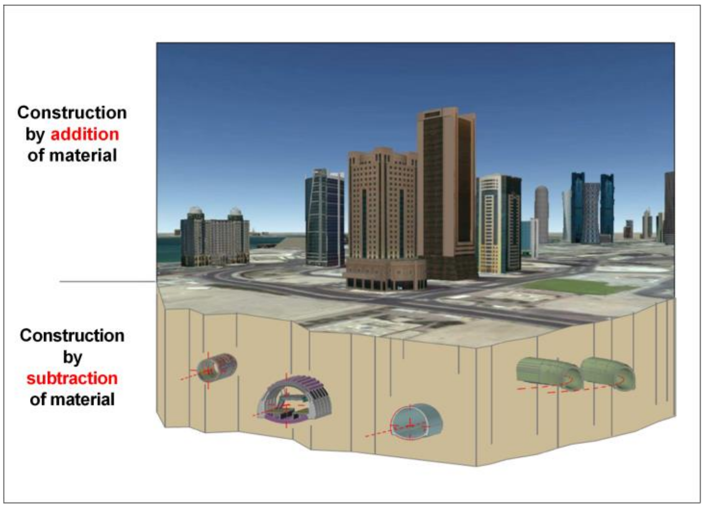

Figure 1: Difference between overground and underground constructions.

Overcoming this anomaly was made possible by changing the design approach, and using a strictly scientific focus to eliminate the uncertainties and imprecisions of past approaches which had been the cause of many (also recent) past failures and thus penalized underground works in favour of overground ones [1].

To this aim we needed to start from the knowledge of those that are the main "ingredients" of an underground work (fig. 2):

- the **medium** through which construction takes place
- the **action** taken in order to accomplish the excavation

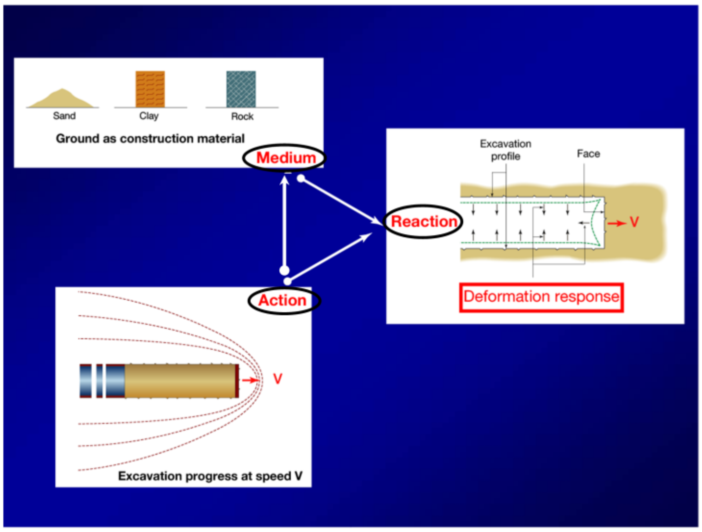

Figure 2: The "ingredients" of an underground work.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

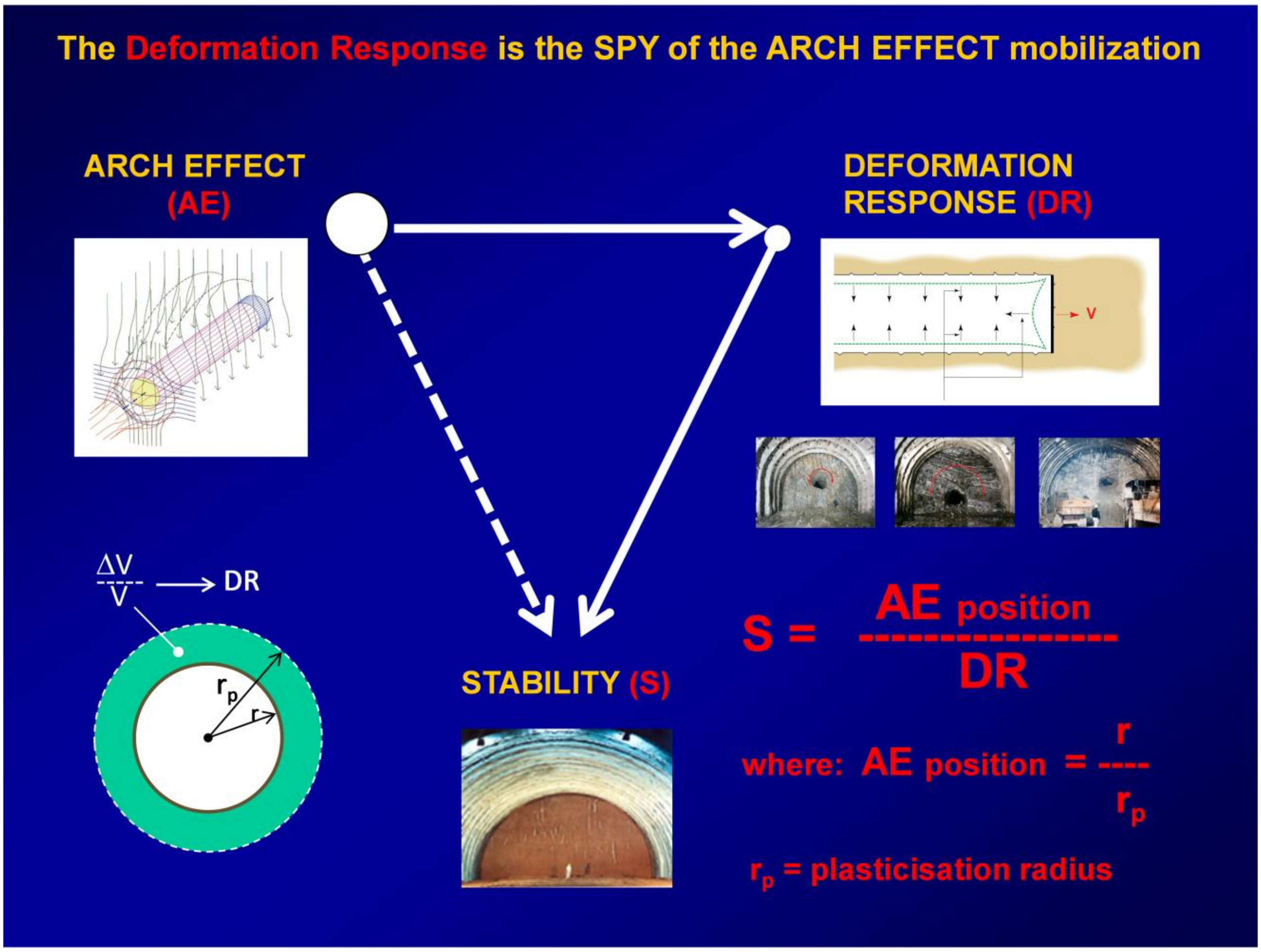

Figure 3: The arch effect and Deformation Response determine stability conditions of a tunnel.

- the **reaction** (or Deformation Response) produced following the above-mentioned action.

The **medium** is the ground, or the construction material of the tunnel. In depth it is subject to triaxial stress states, depending on gravitational loads, on lithostatic loads (depending on the coverages), on tectonic loads and on the presence of natural agents. From a geomechanic point of view the behaviour of the medium changes in depth according to its consistency (sandy, clayey, stoney) and can mostly be determined by unconfined compression tests, direct shear tests and triaxial cell tests.
The **action** is that which is produced by advancement through the medium at a speed V, and causes a disturbance of the stress field in the surrounding area, both transversally and longitudinally (in three dimensions), that changes the previous stress balance. The level of the disturbance is caused by the advancement speed V, which in turn depends on the excavation system used (mechanical or traditional).
The **reaction** is the Deformation Response of the ground to the disturbance caused by face advancement and depends:

- on the geomechanic and structural traits of the ground
- on the field of pre-existing natural stress
- on the spread in the medium of the stress field disturbance produced by the advancement action of the face (excavation system, advancement speed)

In particular, as mentioned before, high advancement velocities reduce the spread of the disturbance, and thus the entity of the reaction or the Deformation Response of the medium to excavation action.
Clearly, if the Deformation Response were zero then all underground works would be naturally stable and the tunnel designer would be out of a job! Instead, he's responsible for guaranteeing their stability. It is important that the designer be aware that the Deformation Response is the **"spy"** of the **arch effect** around the cavity (that is the channelling of stresses deviated from the opening of the cavity to its outline) which causes the formation of overly-stressed areas at the excavation walls. This effect is what really allows the cavity to remain stable (fig. 3).
The channelling of stresses, or the arch effect, is not always produced naturally (more or less near the excavation walls) ensuring the work's stability. It depends on the entity of the stress states in relation to the resistance and deformability of the ground.
The tunnel designer must ensure the short and long-term stability of the underground work, and he will is able to do so in the following manner:

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

1) studying if and how the arch effect can be induced naturally while excavating and also, when necessary, having it come about artificially by calibrating excavation methods and stabilization measures accordingly to the stress-strain situation
2) choosing the best excavation method (mechanical or traditional) for the stress-strain situation to be tackled in order to guarantee its success in **industrial terms** as well

He is able to successfully undergo this task by accurately studying (theoretically foreseeing during the design stage and experimentally verifying while works are underway) the **Expected Deformation Response** of the medium to the excavation action, in terms of **Analysis and Control** (fig. 4).

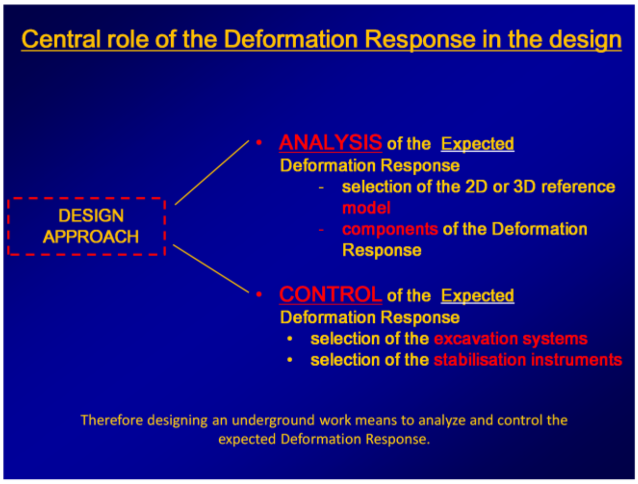

Figure 4: Designing an underground work means analysing and controlling the Expected Deformation Response.

2. ANALYSIS AND CONTROL OF THE DEFORMATION RESPONSE

2.1. Design and control approaches of the past

In terms of Analysis, the approaches of the past, such as NATM and derivatives [2, 3], based their study of the **Expected Deformation Response** on the so-called geomechanic classifications (Bieniawski, Barton, etc.), and almost exclusively on two-dimensional models. Consequently, the Deformation Response was believed to be representable by one component only: cavity convergence (fig. 5).
In terms of Control they taught to control the Deformation Response acting downstream the excavation face only. Specifically:

- excavation face instability was tackled by partitioning the excavation face in two parts or more
- cavity instability was tackled by stabilizing with: bolts, steel ribs, shotcrete and (more or less provisory) inverts

This procedure, still used in many countries, has many problems:

- it is clearly incapable of guaranteeing advancement safety and excavation stability in stress-strain situations which cannot be faced by means of sole partitioning of excavation face, be it due to poor ground quality and/or severe constraints (e.g. acceptable surface settlements in the case of urban areas).
- due to the narrow space available after partitioning the face, it may never take advantage of the power of the great modern tunnelling machines, both for increasing production and excavation safety, thus reducing the number of workers required to advance the face.
- especially in heterogeneous and non-standard conditions, it can't reach an acceptable constancy of production due to the lack of an acceptable design of reference which foresees all possible situations.
- in the end, it cannot accurately foresee the work's times and construction costs as these, in difficult conditions, are **designed and decided while the work is underway.**

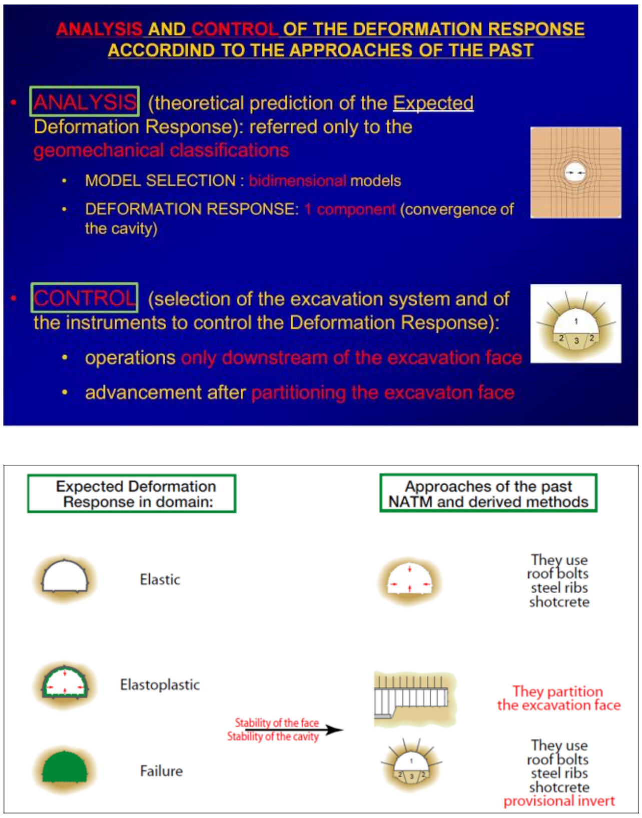

Figure 5: Approaches of the past based Analysis and Control of the Deformation Response on sole cavity convergence and on partitioned-face advancement, stabilizing solely downstream the face itself.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

2.2 Modern design and construction approaches

Unlike past approaches, modern ones base their study in terms of Analysis and Control of the **Expected Deformation Response** according to three-dimensional models, as it is deemed impossible to reduce complex stress-strain situations that develops upstream the tunnel excavation face (and thus also downstream) to simple two-dimensional models without losing data and essential relations (fig. 6).

To this aim it was necessary to find and define **new references** (fig. 7):

- **the advance core** or **core-face**, as the volume of ground that is upstream the excavation face, shaped cylindrically and presenting a width/length of the order of 1.5 times the tunnel diameter
- **extrusion**, as the primary component of Deformation Response, mostly developing inside the core-face and presenting itself through the excavation face surface, longitudinally and parallel to the tunnel's axis
- **pre-convergence**, as the secondary component of the Deformation Response, identified in the convergence of the theoretical profile upstream the excavation face.

Unlike the approaches of the past, which identified the Expected Deformation Response of the medium to the excavation solely in the convergence, the most updated design construction approaches for underground constructions understand that convergence is solely the last stage of a more complex deformation phenomenon, that starts upstream the excavation face as extrusion and pre-convergence of the core-face and then evolves downstream as convergence of the cavity.

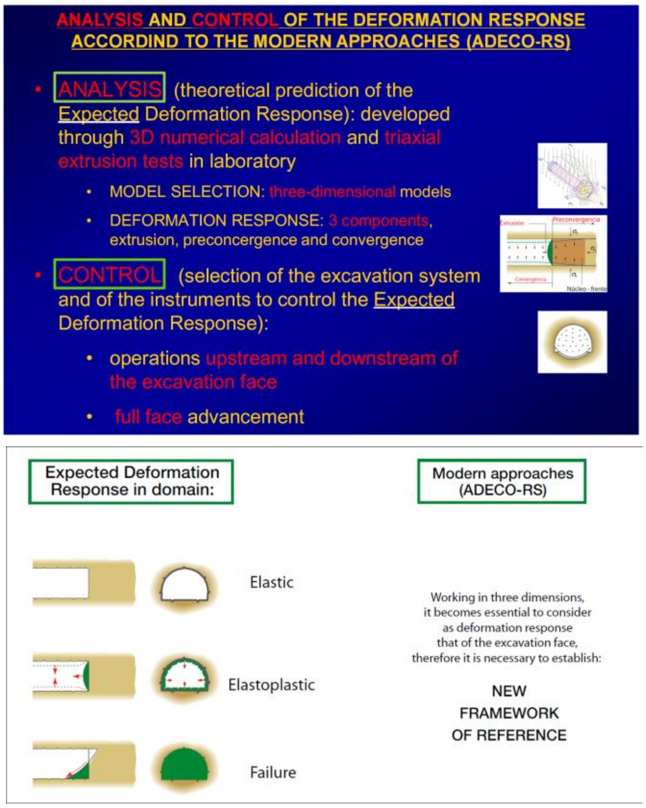

Figure 6: Modern approaches, based on the Analysis of COntrolled DEformation in Rocks and Soils (ADECO-RS), work in 3D and give utmost importance to the Deformation Response of the advance core-face, thus making it necessary to fix NEW REFERENCES.

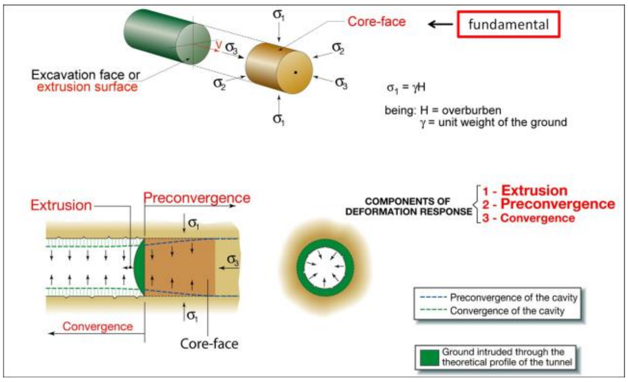

Fig. 7: The new references for the Analysis and Control of the Expected Deformation Response according to modern design and construction approaches are: the core face, extrusion, and pre-convergence.

At the lead of this modern approach towards design and construction of tunnels and underground works, is the Analysis of COntrolled DEformation in Rocks and Soils (ADECO-RS), set up starting from the Eighties in Italy by the here-present Author, after observing certain phenomena during the Frejus excavation, which were clearly in contrast with the then-common design and construction approaches [4]. The following in-depth scientific Research in three stages that followed (figure 8), and then lasted over 20 years for more than 1,000 Km of finished tunnels and hundreds of thousands of monitored excavation faces demonstrated that:

- there is a strict correlation between the extrusive behaviour of a tunnel at the core-face and between that which happens downstream it, in the cavity.
- the extrusive behaviour of the core-face always and inevitably conditions the cavity's behaviour.
- by controlling the extrusive behaviour of the core-face it's also possible to control the cavity behaviour.

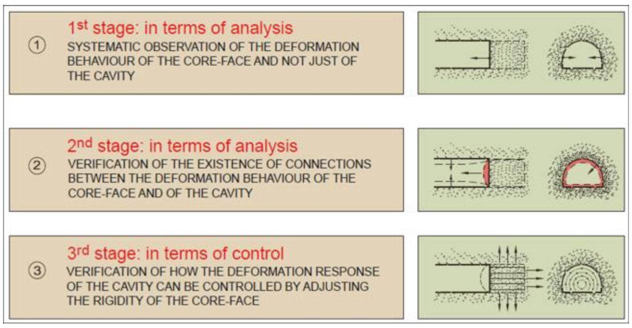

Figure 8: Research in three phases on the Deformation Response conducted by the Author from the Eighties onwards, which brought about the Analysis of COntrolled Deformation in Rocks and Soils (ADECO-RS).

For these reasons, modern design and construction approaches considers the role of convergence reduced as the last stage of the Deformation Response to the excavation action, that starts upstream the excavation face from the extrusive behaviour of the core-face.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

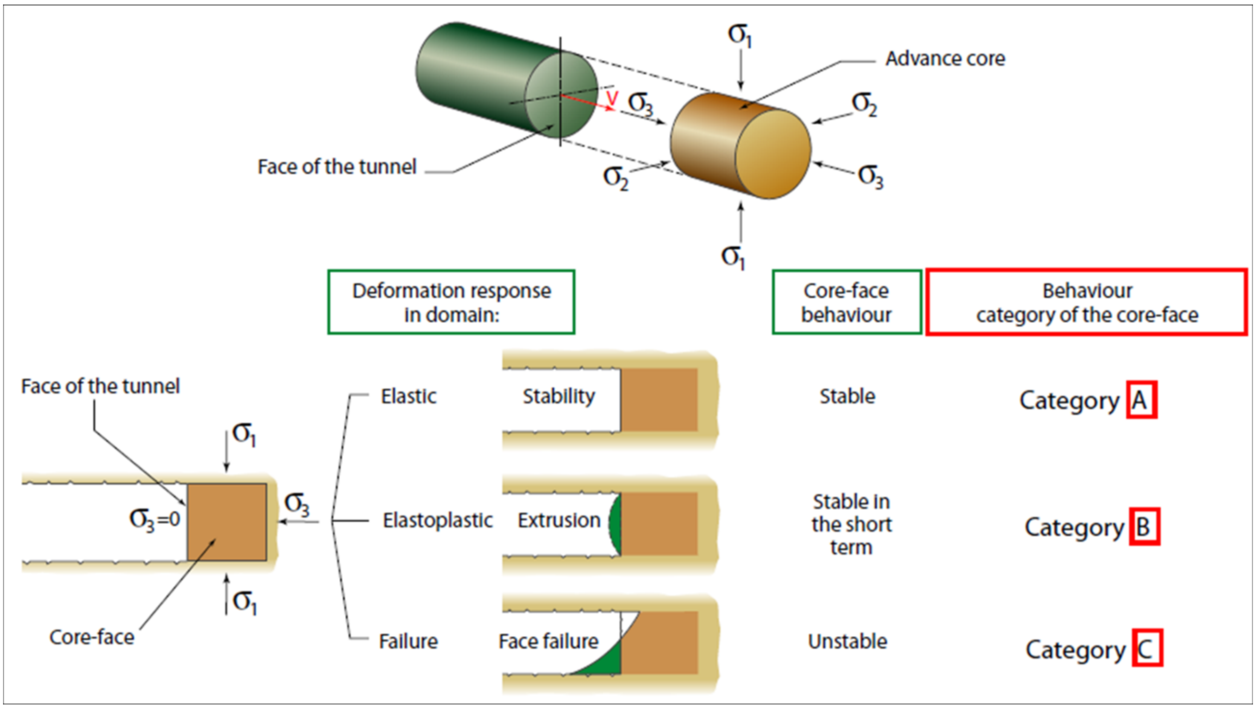

Figure 9: In function of several different stress-strain states, reducing to zero the main minor stress σ_3 due to the face advancement, the behaviour of ground upstream the excavation face can be indicatively traced back to three different situations: stable core-face (elastic domain), stable core-face in the short-term (elastic-plastic domain), unstable core-face (failure domain), which can be associated to three main fields of behaviour: A, B and C.

When focalizing on the Expected Deformation Response of medium to the excavation in three dimensions, it's immediately clear that the advance core will pass from a triaxial stress state, to a biaxial or monoaxial one (fig. 9) and, following stress disturbance, may bring about a behaviour which is stable, stable in the short term or unstable according to the lithostatic loads and the stress fields in play (in elastic, elastic-plastic or failure domain), but also according to advance speed V, which is strictly linked to the excavation system being used (mechanical or conventional, half-face or full-face) [5].

In terms of Analysis, during the design stage ADECO-RS and modern approaches study the stability of the core-face, **in absence of stability operations**, by using the most efficient 3D numerical models and lab experiments on models in a reduced scale (fig. 10), and thus categorise its behaviour according to one of three following stress-strain behaviours:

- **Category A: stable core-face**
- **Category B: stable core-face in the short-term**
- **Category C: unstable core-face.**

It is thus clear that in order stabilize in the short and long term a tunnel under excavation, behaviours B and C must be brought back to category A, specifically by focusing on the resistance and deformability of the advance core. This is the designer's main task, and it can be successfully undergone by studying the Expected Deformation Response **in terms of Control**, in order to choose which excavation systems and which tools are best to use to control it. Past approaches operated solely within the cavity in order to control the Deformation Response, downstream the excavation face, with bolts, ribs, shotcrete and somewhat temporary inverts, in the mistaken belief that any problem could be solved by partitioning the face. Instead, modern underground design and construction approaches, based on ADECO-RS, cure the potential instability of the core-face and of the cavity **advancing solely in full face** and using:
- as main control instrument upstream the face, the core-face properly reinforced/protected if necessary
- as control instrument downstream the face, in the case of excavation by conventional systems, immediately

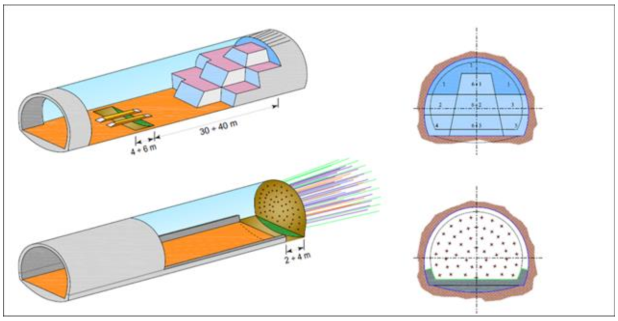

Figure 10: Advancement according to approaches of the past and according to approaches of today (ADECO-RS)

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

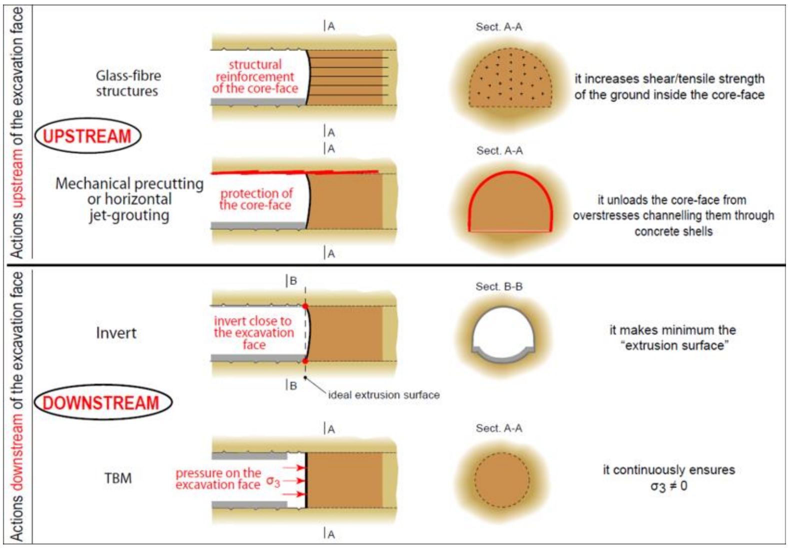

Figure 11: Methods for controlling the Deformation Response according to modern approaches, inspired by ADECO-RS, which give priority to the deformation response of the face core.

closing the pre-lining with the invert at the face itself (fig. 10).

In this manner, modern approaches avoid the main minor stress σ_3 cancellation caused by the advance face arrival and that, consequently, the core-face passes from a triaxial stress state to a biaxial or mono-axial one. So its deformability can be controlled and situations potentially in Category B or C brought back to Category A. It is thus possible to keep under control the start and development of the Expected Deformation Response upstream the advance face (extrusion, pre-convergence), and therefore its evolution downstream (cavity convergence).

Upstream the advance face, in order to reinforce and/or protect the core-face the designer has (fig. 11):

- operations to reinforce and/or protect, such as:
    - core-face reinforcement with fibreglass structural elements. This technology was devised by the Author and tested in Italy for the first time in tunnelling in 1985, when constructing a short hydraulic tunnel (5 metres in diameter) for the floodway of the Citronia torrent at Salsomaggiore Terme (Italy) and since then used most successfully for full-face excavation in soft grounds of tunnels even greater than 20 metres in diameter (e.g. "Appia Antica" tunnel, GRA – Rome)
    - core-face protection with **full face** mechanical pre-cutting, a technology which was perfected and experimented for the first time in the world by the Author in 1985 in Italy while building a tunnel through very soft clay for the Sibari-Cosenza rail line, between the stations of S. Marco Roggiano and Mongrassano-Cervicati. The technology was also successfully applied for excavation (through soft cohesive and layered grounds under watertable) of subway station tunnels (e.g. Baldo degli Ubaldi station of the Rome subway A line, grounds: clays, excavation diameter: 21.5 m, coverage: 15-18 m)
    - core-face protection/reinforcement by means of horizontal full-face jet-grouting. This technology was devised by the Author and tested for the first time in Italy in 1983, while constructing the "Campiolo" tunnel, for the two-track railway line of Udine-Tarvisio, through rubble-slope and under a coverage varying between 0 and 70 m.

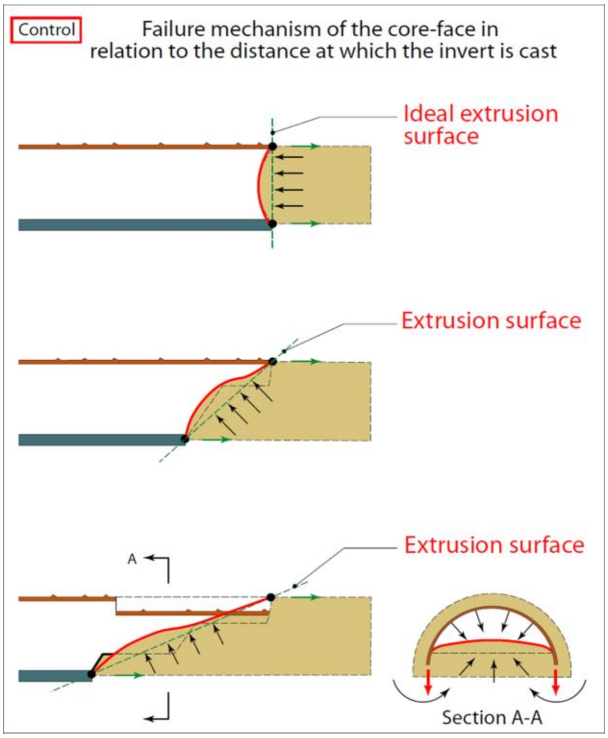

Figure 12: The extrusion surface.

As well as preparing these operations, the designer must also guarantee short and long-term stability of the underground work taking care that longitudinal arch effects in the ground are always favoured, by ordering the builder, in the design specification, to keep the open surface of the excavation face constantly concavely shaped.

Downstream the excavation face, on the other hand, as well as traditional tools such as radial bolts, ribs and shotcrete, in order to operate the necessary actions the designer has:

- immediate closing of pre-lining with the invert, which in order to minimize the "extrusion surface" (fig. 12), must be built as close to the face as the measures operated to stiffen the advance core require. It's indeed of the utmost importance that transition from the cavity pre-confinement action operated upstream the excavation face to that

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

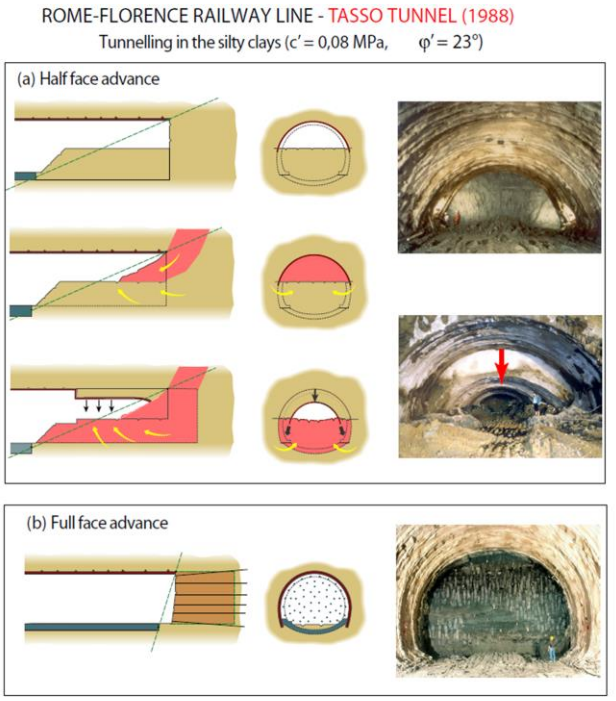

Figure 13. In difficult stress-strain conditions, advancement in full section with invert cast at the excavation face is fundamental to avoid instable situations as shown here.

operated downstream take place coherently and with continuity.

This need is often difficult to explain to builders as it requires a different organization of the construction site than the bad habits of the past, but is clearly evident when careful observing and interpreting, also by numerical methods, the collapse events occurred in the past and the modes of development of Deformation Response that had preceded them (fig. 13).

In particular it has been observed that when the extrusion phenomenon takes place, it does so through an ideal surface, defined extrusion surface, which extends from the point of contact between the ground and the upper-forward extreme of the pre-lining, to the point of contact between the same ground and the forward extreme of the invert (fig. 12). Despite common belief, when the bottom of the excavation raises during difficult half-face excavations (fig. 13), this does not take place due to deformation of convergence, but as the result of Deformation Response which hasn't been correctly controlled in its extrusive component.

By approaching the invert at the excavation face, the ideal extrusion surface is progressively reduced and this produces a equally progressive reduction of the extrusive phenomenon, which tends to develop more symmetrically on the entire surface of the face.

Figures 12 and 13 graphically present what has just been said, and clearly show that the more the casting of the invert is delayed the more the extrusion surface extension increases and so does consequently the volume of the core-face, the extrusion of which becomes no longer controllable leading the cavity to the collapse, just as in the case of half-face advancement.

The photographs in fig. 14 show that casting the invert at the excavation face is possible and will not hinder production if the construction site is correctly managed, indeed it will even bring about a great increase in worker safety.

Figure 14. Invert cast at the excavation face – Raticosa Tunnel (Ø = 13.90 m, Ground: scaly clays, Coverage: 500 m) and Tartaiguille Tunnel (Ø = 15.30 m, Ground: expanding clays, max Coverage: 150 m.

- mechanical TBM excavation, where the correct geotechnical sizing of the machine assures constant pressure against the face, such as to avoid cancelling out the main minor stress σ_3. It must here be said that EPB technology can today be used for extremely difficult situations, even on great excavation diameters, as can be proven by the Author's experience when building the "Sparvo" motorway twin tunnel (2.6 km in length). For this work the TBM EPB "Martina" (biggest in the world; 15.62 in diameter) excavated the two tunnel tubes through the difficult geological-geomechanical context of the Apennines, at an average advancement speed of 13.50 m/day of completed tunnel.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

3. DESIGNING AND CONSTRUCTING UNDERGROUND WORKS ACCORDING TO MODERN DESIGN AND CONSTRUCTION APPROACHES

To summarise, it has been seen above that:

- modern approaches, derived from ADECO-RS, focus the designer's attention on the Analysis and Control of the Deformation Response, intended as a reaction of the medium to the excavation action

- the rigidity of the advance core is a natural instrument for controlling the extrusive phenomenon and therefore the extrusion of the entire Deformation Response which, as is known, influences the industrialization of excavation and consequently the respect of construction times and costs.

Analysis and Control of the Deformation Response therefore play a fundamental role as indispensable steps for designing and constructing an underground work successfully (fig. 16).

During the design stage:

- **Analysis** means first of all researching the medium to be tunnelled from a geological and geomechanic point of view (**survey phase**), especially by taking into consideration its resistance and deformability, and later forecasting by means of analytical and numeric instruments, what sort of stress-strain behaviour will take place (Expected Deformation Response) when excavating (Categories A, B, C), **in the hypothetical lack of stability operations (diagnosis phase).**
- **Control** of the Expected Deformation Response may come about by (**therapy phase**):
    - defining the type of pre-confinement actions or confinement actions that are necessary to manage and control the Expected Deformation Response of the medium to excavation
    - choosing the type of stabilization operations from those available with todays technology, on the base of pre-confinement and confinement actions that each one is capable of guaranteeing
    - the composition, in function of the foreseen behaviour of the medium during excavation, of typical sections, defining the best type of stabilization operations for the expected operative context as well as phases, cadences, timing of implementation and any possible variability.
    - sizing and verification, by means of mathematical models, of the operations chosen to reach the medium's desired behaviour under excavation with the necessary safety coefficient
    - a forecast, again using mathematical models, of the medium's stress-strain behaviour under excavation when so stabilised.

During the construction stage, that is at the moment in which the design decisions are actually implemented (**operational phase**):

- **Analysis** means **verification** while the work is underway, by monitoring the Real Deformation Response (with systematic measure of extrusion, pre-convergence and convergence) and taking care that the tunnel's stress-strain behaviour during excavation corresponds with the theoretical one foreseen during the design stage. The project is then verified and measured during the work by comparing homogeneous parameters (Expected Deformation Response, **foreseen** by means of calculation, with Real Deformation Response, **measured** while the work is ongoing). By this way, mistakes are avoided, such as the typical one of the old approaches, of comparing, during tunnel construction, the convergences measured during face advancement with intervals of convergences linked arbitrarily, during the design stage, with geomechanic classes.
- **Control**, on the other hand, is developed by **perfecting the design** balancing on the base of the results of Analysis and in the field of the possible variabilities that have already been planned in the design stage, the weight of operations to stabilize the core-face, without modifying criteria, advancement systems and tools.

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 15. Analysis and Control in different phases for designs and construction.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

4. A PRACTICAL EXAMPLE OF UNDERGROUND WORKS IN AN URBAN AREA DESIGNED AND BUILT ACCORDING TO MODERN CRITERIA

An excellent example of underground design and construction in a difficult urban context, built according to modern criteria and according to the times and costs expected by the final design, is the construction, by using conventional excavation, of the "Trionfale" tunnel in Rome.

4.1 The "Trionfale" tunnel on the Great Ring Road of Rome

The "Trionfale" tunnel was built between 2005 and 2007 as part of a three-lane upgrade of the Great Ring Road of Rome. It's a double tube tunnel, each one 258 m^2 in section and about 400 m in length. Due to the enormous size, low geo-mechanic quality of the grounds to be tunneled and the need to go under several habitations, the Peschiera aqueduct (the largest conveyor of Rome) and the Rome-Viterbo railway with a coverage much smaller than the diameter of excavation, made this construction very delicate and complex; using the criteria of the past it would have been surely constructed by partitioning the face in 4 parts or more. Instead the approach according to the more recent criteria suggested by the Analysis of COntrolled DEformation in Rock and Soil (ADECO-RS) made it possible to face excavation in full face. This not only greatly reduced construction times and costs, but also avoided the plasticization of ground outlining the tunnel and the subsequent surface settlements, thus protecting full integrity of the pre-existing on surface and underground structures.
In detail, the final design of the tunnel was developed before starting excavation and, in terms of **Analysis and Control**, followed these phases:

5.1.1 Survey phase for the "Trionfale" tunnel

Studying the "**Analysis**", in the survey phase, pointed out that the natural tunnel would have been excavated within a formation of fine marine sands, with layers of clays and silts (fig. 16). On the other hand, the portals would have affected the grounds above the sands, including pyroclastic deposits at the West portal and accumulated backfill material at the East portal. From a hydrological point of view, the study excluded any important aquifers, but water

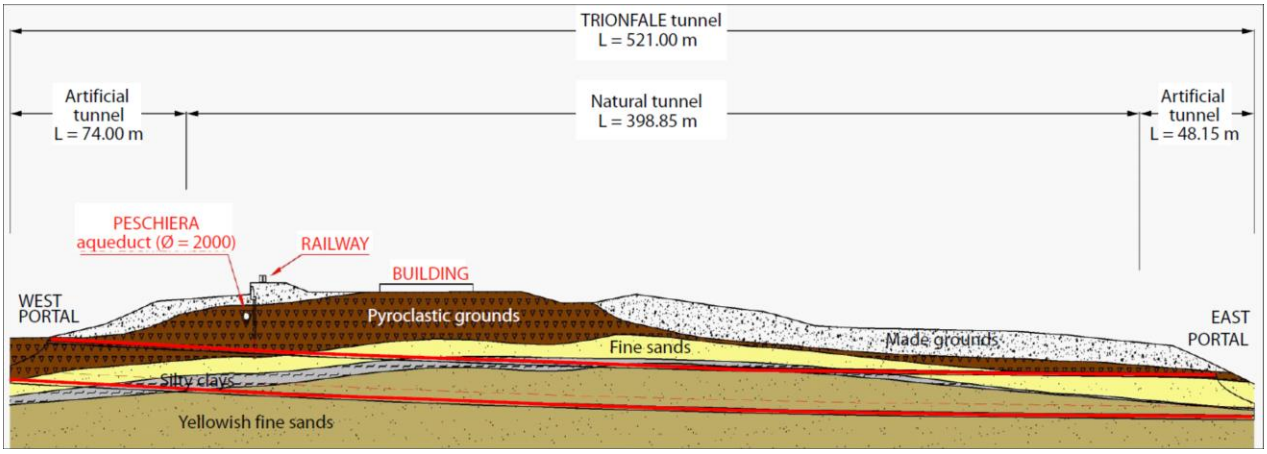

Fig. 16: Geological profile of the "Trionfale" tunnel.

infiltration couldn't be ruled out due to the known presence of drained rainwater and the permeability of sandy grounds.

5.1.2 Diagnosis phase for the "Trionfale" tunnel

Following the results of the survey phase, in accordance with the ADECO-RS approach, during the diagnosis phase the deformation response of the core-face and of the cavity was studied in terms of short/long term "Analysis" in absence of stabilization measures.
This "Analysis" study helped foresee a stress-strain behaviour of the tunnel core-face, which in absence of stabilization measures, would clearly enter category C (unstable core-face).

5.1.3 Therapy phase for the "Trionfale" tunnel

Based on the evidence coming from the "Analysis" study during the diagnosis phase, in order to guarantee the necessary conditions of tunnel stability in the short and long term, in terms of "Control" excavation and stabilization methods needed to be set in order to bring the situation from Category C (unstable core-face) to Category A (stable core-face). Since it wasn't possible to use TBM mechanical excavation due to geometrics, advancement was designed to be conventional but equally industrialized, such that it could give total assurance of protecting the overground pre-existing structures despite thin coverage.

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

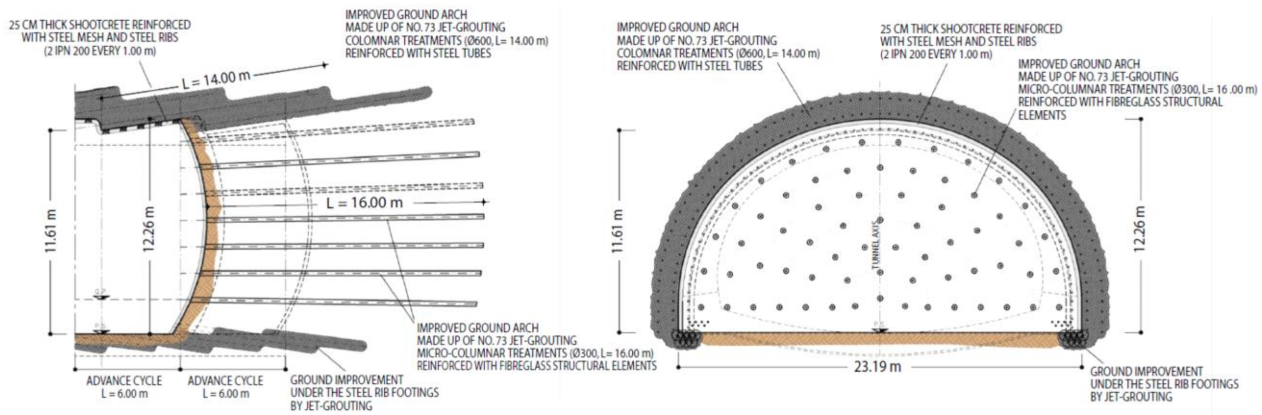

Fig. 22: Section type C1 for the "Trionfale" tunnel.

Following modern criteria, this immediately excluded any form of face partitioning during excavation in order to minimize the **extrusion surface** (fig. 12). Indeed, given the conditions, only full face advancement, after having protected and reinforced the tunnel core-face, would have been capable of blocking any deformation of extrusion-pre-convergence and thus proceed whilst guaranteeing the integrity of all overground structures. In this specific case, due to the high presence of incoherent or poorly coherent grounds, protection/reinforcement of the core-face required to use the jet-grouting technology.
Advancement was therefore planned with the following stabilisation measures:

- reinforcement of the core-face, every 6 m of advancement, with 66 jet-grouting micro-columns Ø 300, length 16 m superimposed for 10 m and strengthened by fibreglass structural elements
- treatment of the ground band around the section to be excavated, every 6 m of advancement, with an arch made of 73 sub-horizontal jet-grouting columns (double coronella) Ø 600, length 14 m and an overlap of 8 m, reinforced by steel tubes
- drainage pipes operated ahead of the tunnel face, if necessary due to water presence
- cast of a pre-lining consisting of 2IPN 200 ribs set every 1.00 m and shotcrete layer reinforced with electro-welded mesh (25 cm thick)
- excavation and cast of the invert (120 cm thick) and the kickers, within a maximum distance from the tunnel face equal to 9 metres
- put in place of water proofing in geotextile and a PVC sheath
- cast of r.c. final lining, within a maximum distance from the tunnel face of 3 excavation diameters

setting up the section type C1 shown in fig. 22 and later verifying, using a series of calculations based on 3D numerical models, the short and long-term behaviour of the so treated groundmass (**Expected Deformation Response**). Guidelines were then setup for the application of the section type so designed, which summarized the possible variabilities in the number and intensity of ground improvement operation in function to the **Real Deformation Response** observed by a comprehensive monitoring of the ground's Deformation Response during construction. To this aim the project required the following:

- systematically measuring extrusion by inserting a 40 m long slide-micrometer into the tunnel core-face, every 30 m of advancement
- systematically measuring the convergence by setting convergence stations every 6 m of advancement


Figure 23: Enacting reinforcement of the core-face for the C1 section type, it is also visible the crown treatment with compenetrated jet-grouting columns reinforced with steel tubes

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com

- systematically measuring surface settlements with topographic levelling (alignment with superficial settlement plates)
- measuring pressure under the rib footings
- measuring stress in the ribs and in the final lining by means of extensimetric bars

5.1.4 Operational Monitoring phases during construction

During construction, the extrusion measures of the core-face were of crucial importance to verify the design suitability and to allow excavation to continue with utmost safety. Indeed extrusion, which is measured within the core-face, is the first stage of the Deformation Response and is a sensitive as well as immediate indicator of instability onset, thus allowing the enactment of necessary countermeasures before the situation is compromised. Instead, convergence is the last stage of the Deformation Response and can only be measured within the cavity, thus measuring just that which is already evident and at that point unstoppable.

Figure 24: Phase of demolition of the face

Putting aside the Peschiera Aqueduct, where the installed drainages intercepted unexpected amounts of water up to 4-5 l/sec, later traced to persistent losses from the aqueduct itself (indeed, in order to proceed excavation in safety drainage wells had to be built from the ground level to the sides of the tunnel), the two tunnel tubes – despite difficult conditions and an enormous excavation section – were built seamlessly and at an average advance speed of about 1 m/day of completed tunnel, without causing significant surface settlements and without having to interrupt rail traffic on the above Rome-Viterbo line.

6. Conclusion

Modern approaches to design and construct underground works (of which ADECO-RS, which was conceived in the 1980's by the present Author and his collaborators, is the precursor) are truly capable of successfully facing any type of ground and stress-strain condition with industrial methods, both using TBMs and conventional excavation, fully respecting construction times and costs expected before starting to dig. This has been proven by the many underground works built over the last twenty years using full-face industrialized excavation in the most difficult grounds and stress-strain states [6, 7, 8].

It's foreseeable that this progress may consolidate a more hopeful approach than in the past towards using the underground as a believable resource for new usable space for man and his social life.

Bibliography

[1] Lunardi P. (2000). Design & constructing tunnels – ADECO-RS approach. Tunnels & Tunnelling International, Special Supplement, May 2000

[2] Rabcewicz L. (1964). The New Austrian Tunnelling Method, Part One, Water Power, November 1964, 453-457, Parte 2, Water Power, December 1964, 511-515

[3] Rabcewicz L. (1965). The New Austrian Tunnelling Method, Part Three, Water Power, January 1965, 19-24.

[4] Lunardi P. (2015). Extrusion control of the ground core at the tunnel excavation face as a stabilisation instrument for the cavity. Muir Wood Lecture at the ITA/AITES World Tunnel Congress on "Promoting tunnelling in see region", Dubrovnik, 22-28 May 2015

[5] Lunardi P. (2008). Design and construction of tunnels – Analysis of controlled deformation in rocks and soils. SPRINGER, Berlin Heidelberg.

[6] Martel J., Roujon M., Michel D. (1999). TGV Méditerranèe – Tunnel Tartaiguille : méthode pleine section. Proceedings of the International Conference on "Underground works: ambitions and realities" Paris, 25-28 October 1999

[7] Lunardi P. (2001). The ADECO-RS approach in the design and construction of the underground works of Rome to Naples High Speed Railway Line: a comparison between final design specifications, construction design and "as built". AITES-ITA World Tunnel Congress su "Progress in tunnelling after 2000", Milan, 10-13 June 2001, Vol. 3, 329-340

[8] Lunardi G., Cassani G., Bellocchio A. (2014). The construction of two tunnels in difficult stress-strain conditions: the results of the first real comparison between NATM and ADECO-RS. AFTES International Congress on "*Tunnels and Underground space: risks and opportunities*" – Lyon, 13-14-15 October 2014

[1] Lunardi Geo-engineering, Milan (Italy)
e-mail: pietro.lunardi@gmail.com