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Sequential excavation, NATM and ADECO: What they have in common and how they differ

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ABSTRACT

Rabcewicz (1964, 1965) maintained that "*tunnels should be driven full face whenever possible*". ADECO, which stands for "Analysis of Controlled Deformations in tunnels", now allows us to fulfill Rabcewicz's dream in any stress–strain condition. In order to achieve that dream and its consequent control over cost and schedule, however, NATM must be abandoned for the ADECO. The paper traces the history of the sequential excavation, NATM (as first conceived) and Analysis of Controlled Deformations (ADECO) with the aim of shedding light on the *unavoidable* use of sequential excavation in "soft ground", and of highlighting advances in tunnel design and construction that have occurred in Europe after and as alternates to the NATM. The paper presents the basic concepts in the ADECO approach to design, construction and monitoring of tunnels together with some case histories, including: full face excavation for Cassia tunnel (face area > 230 m^2) in sands and silts under 5 m cover below an archeological area in Rome, Italy; Tartaguille tunnel (face area > 140 m^2) advanced full face in highly swelling and squeezing ground under 100 m cover where NATM led to catastrophic failure, France; and 80 km of tunnels (face area > 140 m^2) advanced full face in highly squeezing/swelling ground under 500 m cover for the high-speed railway line between Bologne and Florence, Italy (turnkey contract).

1. Introduction

Several generations of New Austrian Tunneling Method (NATM) consultants have us believe that NATM necessarily uses sequential excavation. Was this the original Rabcewicz's (1964, 1965) intent? On the other hand, in many countries, such as the United States, sequential excavation is currently used to indicate soft ground tunneling without a tunnel boring machine (Romero, 2002). Many points of view on and definitions of the NATM have been proposed (Kovári, 1994) and reviewed by Karakuş and Fowell (2004). Brown (1981) and Romero (2002) suggest to differentiate NATM philosophy:

- The strength of the ground around a tunnel is deliberately mobilized to the maximum extent possible.
- Mobilization of ground strength is achieved by allowing controlled deformation of the ground.
- Initial primary support is installed having load–deformation characteristics appropriate to the ground conditions, and installation is timed with respect to ground deformations.
- Instrumentation is installed to monitor deformations in the initial support system, as well as to form the basis of varying the initial support design and the sequence of excavation.

from NATM construction method:

- The tunnel is sequentially excavated and supported, and the excavation sequences can be varied.
- The initial ground support is provided by shotcrete in combination with fiber or welded-wire fabric reinforcement, steel arches (usually lattice girders), and sometimes ground reinforcement (e.g., soil nails, spiling).
- The permanent support is usually (but not always) a cast in place lining.

This paper traces the history of the sequential excavation, NATM (as first conceived) and Analysis of Controlled Deformations (ADECO) with the aim of shedding light on the *unavoidable* use of sequential excavation in "soft ground", and of highlighting advances in tunnel design and construction that have occurred in Europe after and as alternates to the NATM.

2. Sequential excavation: a 200 year old approach

In his 1963 book entitled "The History of Tunneling", Sandström talks about the tunneling methods devised when the canal era and

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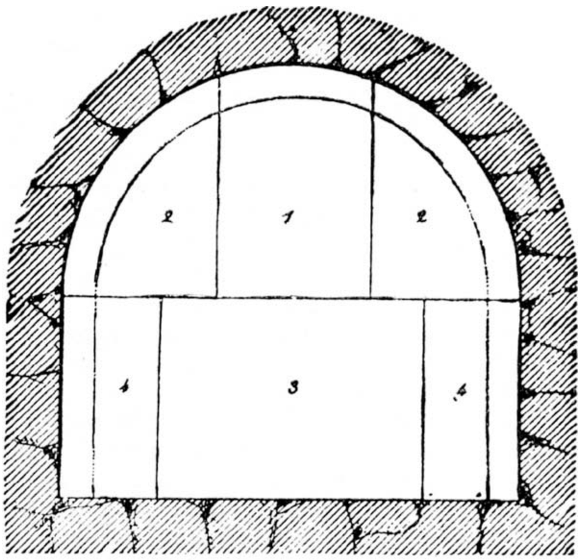


Fig 48. An early sketch indicating the sequence of excavation according to the Belgian System.

Fig. 1. Belgian system used in the 1800s. From Sandström (1963).

the railroad era developed in the first half of the 1800s: yes, this is 200 years ago! Since the book was published in 1963 and Rabcewicz's papers on NATM were published in late 1964 and early 1965, there is little doubt that what Sandström describes are methods that preceded the NATM. Let us here from Sandström (pages 113 and ff):

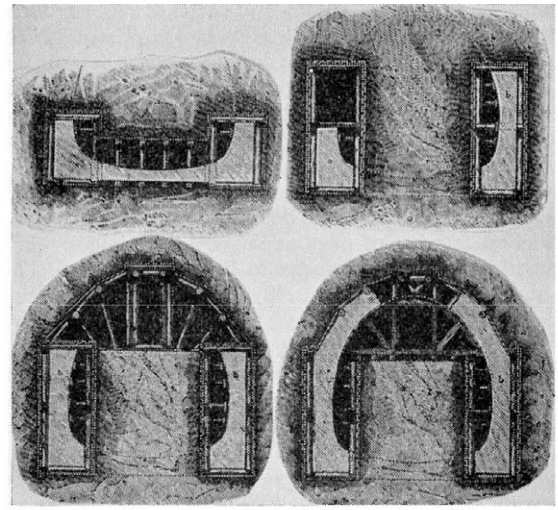


Fig 31. The Köningsdorf Tunnel on the Dresden–Leipzig line was driven in 1837. In this tunnel the foundation for the lining was placed first, after which the masonry lining was put in. With the lining in place the central core was removed.

Fig. 3. German system used in the 1800s. From Sandström (1963).

"*An old-time mining tunnel, or drift, seldom exceeded an area of 10 × 10 ft., whereas a single-track railway tunnel used to be given an area of 16 × 22 ft., and a double track 28 × 22 ft. (modern tunnels are larger). The conventional practice used to be to advance a small pilot heading first in the forepoling manner described – if in heavy ground – and subsequently expand it to full size in some other way*.

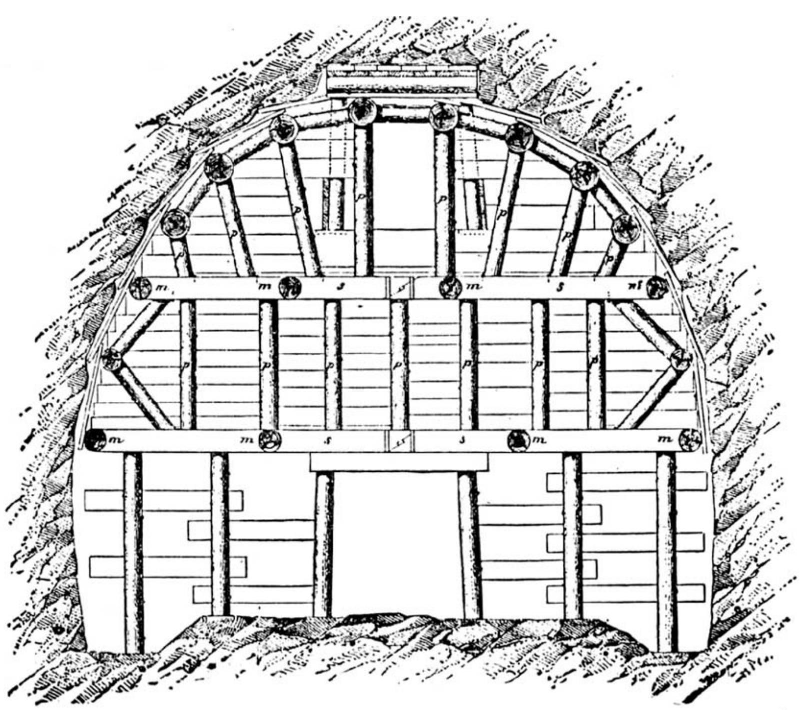


Fig 33. The first Swiss tunnel was the 8,198-ft.-long Hauenstein Tunnel on the central railway between Bâle and Olten. This 25·6 × 19·7 ft. tunnel was built 1853–8 by the famous British railway contractor Thomas Brassey.

Fig. 2. British system used in the 1800s. From Sandström (1963).

The method of breaking out from a safe, wholly enclosed pilot tunnel is one of the central problems in tunneling and was endlessly debated throughout the last century. As a matter of fact it is still an issue that has to be argued as a preliminary to any tunneling scheme, because if it is not correctly settled beforehand men will lose their lives and the contractor his capital.

During the last century, a number of different tunneling systems were evolved which derived their names from their national origin. These were the English system, the Belgian System, the Austrian system, German (actually French) system, and the Italian so-called Cristina system. The Americans also laid claim to an independent system".

And on page 130: "... , *the interesting feature of these early American railway tunnels is that most of them were driven full face, i.e. the entire tunnel area was excavated, although in poor ground the top half was taken out to the full width and the roof secured with rafter timbering and lagged*".

The methods are illustrated in Figs. 1–4, and the reader is referred to Sandström's book for excellent details.

Take home:

- The "sequential excavation method" is 200 years old and was well known when the NATM was coined in 1964.
- The "sequential excavation method" was developed 200 years ago by miners that had to adapt their mining techniques to the needs of civil engineering works.
- Power is defined as work/time, i.e. (ability to do work)/time.
- When the "sequential excavation method" was devised, tunnels were driven without electricity and compressed air, i.e. the available power was very small, mainly manpower.
- Breaking out from the pilot tunnel is one of the central problems in tunneling; if it is not correctly settled beforehand men will lose their lives and the contractor his capital.
- Early American tunneling was full face.

3. And Rabcewicz said "tunnels should be driven full face whenever possible

In his abstract to the first 1964 paper on NATM, Rabcewicz refers to the NATM as: "a new method consisting of a thin sprayed concrete lining, closed at the earliest possible moment by an invert to a complete ring – called "an auxiliary arch" – the deformation of which is measured as a function of time until equilibrium is

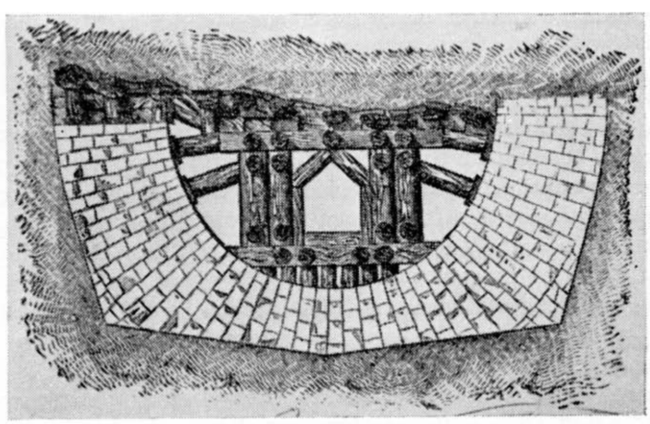


Fig 59. The fully developed Cristina System of tunnelling. The excavated section was filled with ashlar, beginning with the invert, as soon as the clay was removed.

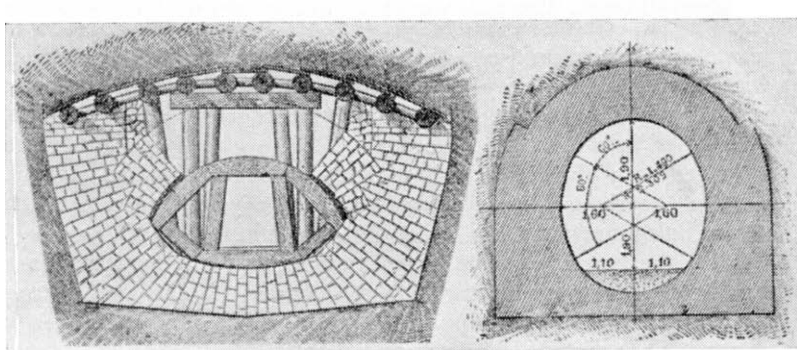


Fig 60. By filling in the excavated space with stone, leaving only a small pilot tunnel open in the centre, the Italian tunnellers finally succeeded in stabilizing the ground (left). The finished Cristina Tunnel is merely a small opening enclosed by a tremendous stone structure. But even this structure did not prove wholly stable and it became necessary to trim the sides to enable a train to squeeze through the tunnel.

Fig. 4. Cristina (Italian) system used in the 1800s. From Sandström (1963).

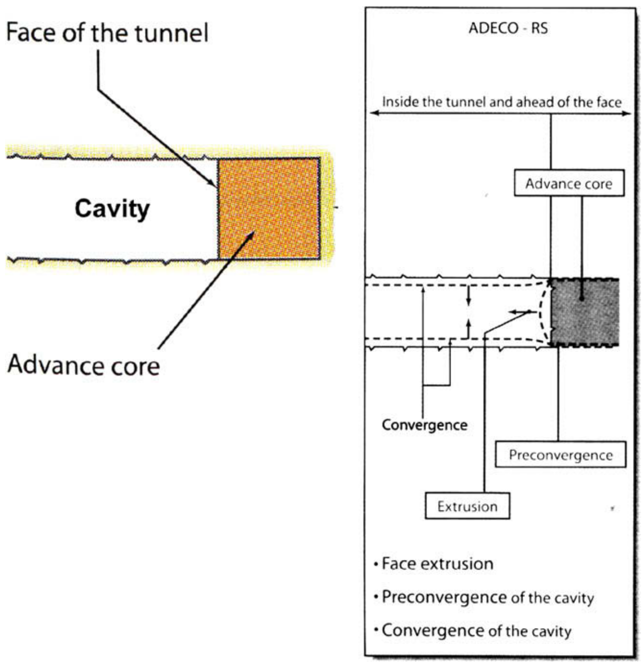


Fig. 5. Nomenclature. After Lunardi (2008).

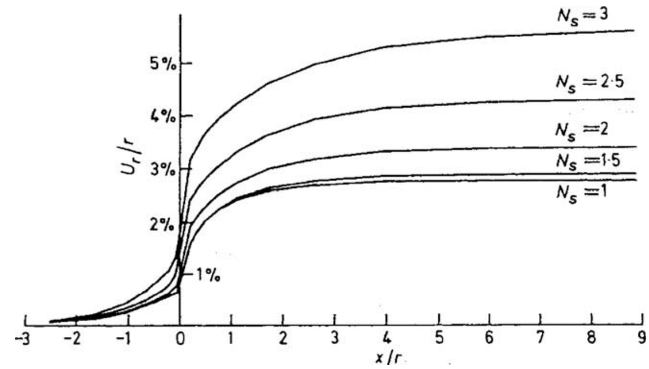


Fig. 6. Preconvergence and convergence vs. distance to the tunnel face for tunnels in clays, undrained conditions. $N_s = p_0/s_u$; p_0 = *in situ* hydrostatic stress, s_u = undrained shear strength. After Panet and Guenot (1982).

obtained". In the same paper, on page 454, Rabcewicz states that "One of the most important advantages of steel supports is that they allow tunnels to be driven full face to very large cross-sections. The resulting unrestricted working area enables powerful drilling and mucking equipment to be used, increasing the rate of advance and reducing costs. Nowadays, dividing the face into headings which are subsequently widened is used only under unfavourable geological conditions". On page 457, Rabcewicz continues on this topic: "There are still some difficulties to be overcome in normal methods of construction, as inverts are still usually built last of all, leaving the roof and sidewalls of the lining to deform at will. In the meantime, experience has taught us that it is by far more advantageous from all points of view, and frequently even imperative, to close a lining to a complete ring at a short distance behind the face as soon as possible. To comply with this requirement, tunnels should be driven full face whenever possible, although this cannot always be done, particularly in bad ground, where it often becomes necessary to resort to heading and benching. In the most difficult cases it may even be necessary to drive a pilot heading before opening it out to full section. An auxiliary arch executed in the upper heading (Belgian roof arch) though fairly effectively preventing roof loosening, represents an intermediate construction stage, which is still subject to lateral deformation. Such instability has to be removed as soon as possible by excavating the bench and closing the lining by an invert".

Take home:

- NATM has nothing to do with sequential excavation.
- Rabcewicz realized that tunnels should be driven full face.
- Rabcewicz realized that full face allows for the use of large equipment i.e. deployment of large power at the face, which translates into fast tunnel advance and reduced costs.

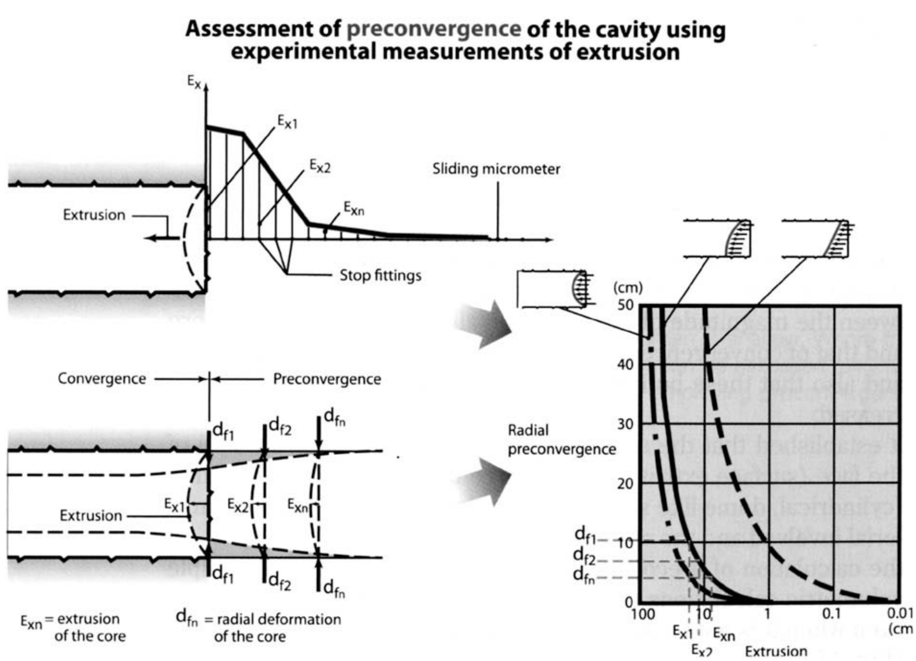
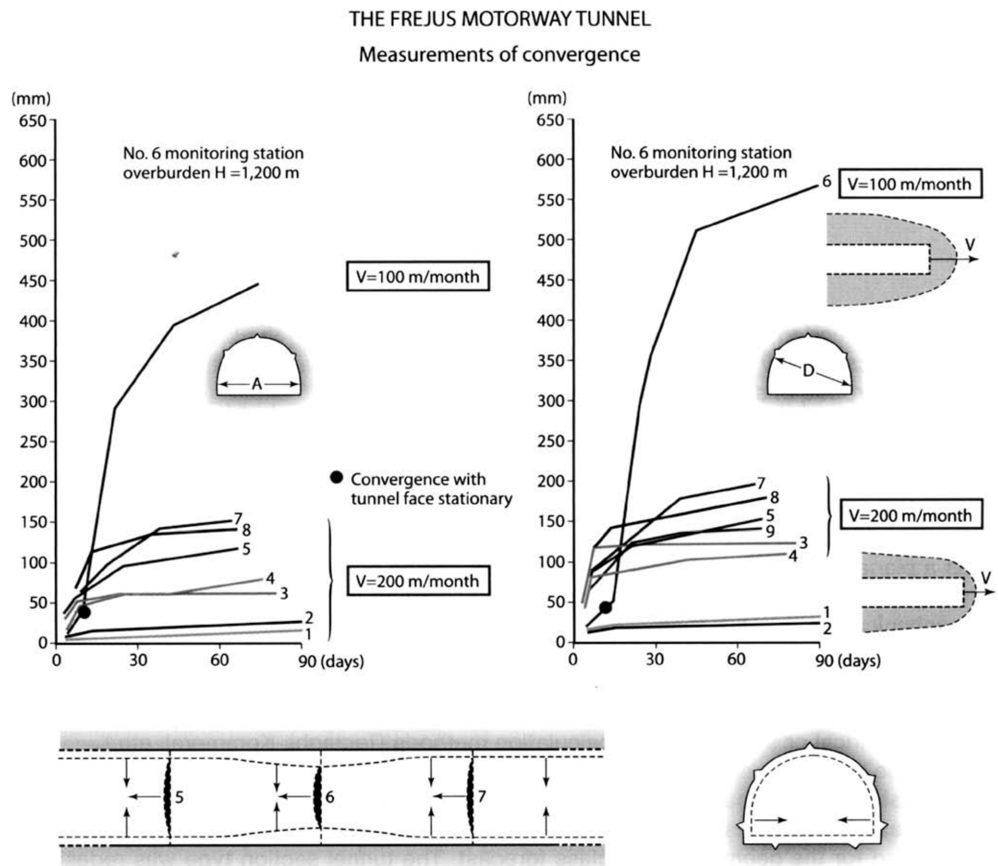


Fig. 7. Measurement of extrusion with sliding micrometer and relationship between extrusion and pre-convergence. After Lunardi (2008).



Monitoring stations	1	2	3	4	5	6	7	8	9
Chainage (m)	845	861	2772	3954	4507	5172	5533	5915	6066
Overburden (m)	490	500	580	590	740	1200	1400	1530	1640

Fig. 8. Convergence measurements in the Frejus highway tunnel, 1970s. After Lunardi (2008).

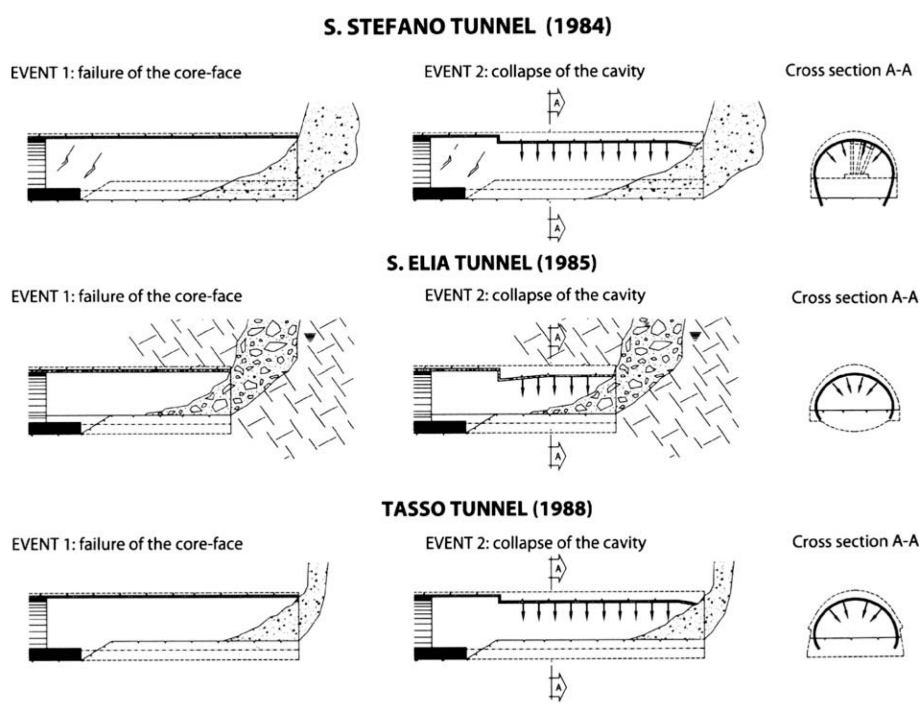


Fig. 9. Case histories of tunnel collapses. After Lunardi (2008).

- Rabcewicz never cared about nor mentioned the ground ahead of the tunnel face or ground support/reinforcement ahead of the tunnel face.
- Rabcewicz wanted but could not find a way to advance full face in difficult stress–strain conditions. His inability to proceed full face in all stress–strain conditions in 1964 was caused by a technological limitation in the normal methods of construction of those days.

4. Quantification of pre-convergence

Let us establish the nomenclature illustrated in Fig. 5, where cavity is the opening already excavated, and advance core is the ground ahead of the tunnel face and comprised within the future tunnel profile. In 1982, Panet and Guenot (1982) quantified the radial displacement of the ground at the future tunnel profile that occurs ahead of the tunnel face (pre-convergence) in an unlined tunnel (Fig. 6) excavated in an elastic or elasto-plastic ground (no time-dependent behavior was considered). At the face, about 30% of the final convergence has already occurred. Other researchers have quantified the pre-convergence and convergence with and without the effect of the installed lining (e.g., Corbetta et al., 1991; Bernaud and Rousset, 1992, 1996; Nguyen-Minh, 1994; Nguyen-Minh et al., 1995; Nguyen-Minh and Guo, 1993a,b, 1996; and Guo, 1995). In particular, these studies show that a stiff lining may significantly reduce the convergence at the face, and thus pre-convergence.

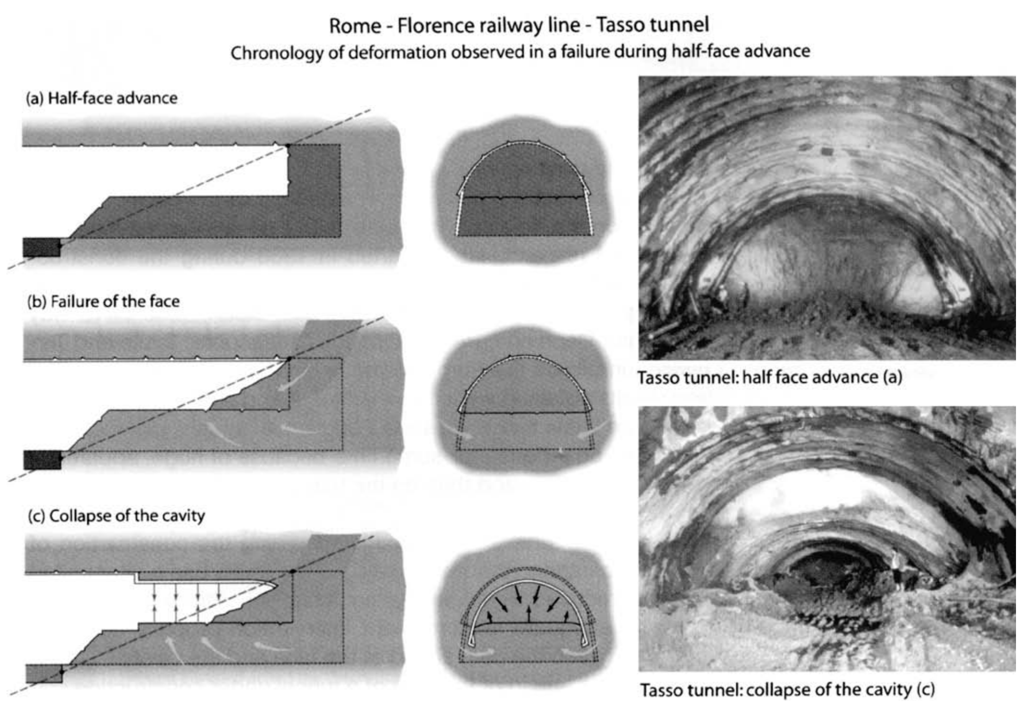


Fig. 10. Failure at Tasso tunnel excavated top heading and benching, 1988. Notice 2 m convergence in top heading. After Lunardi (2008).

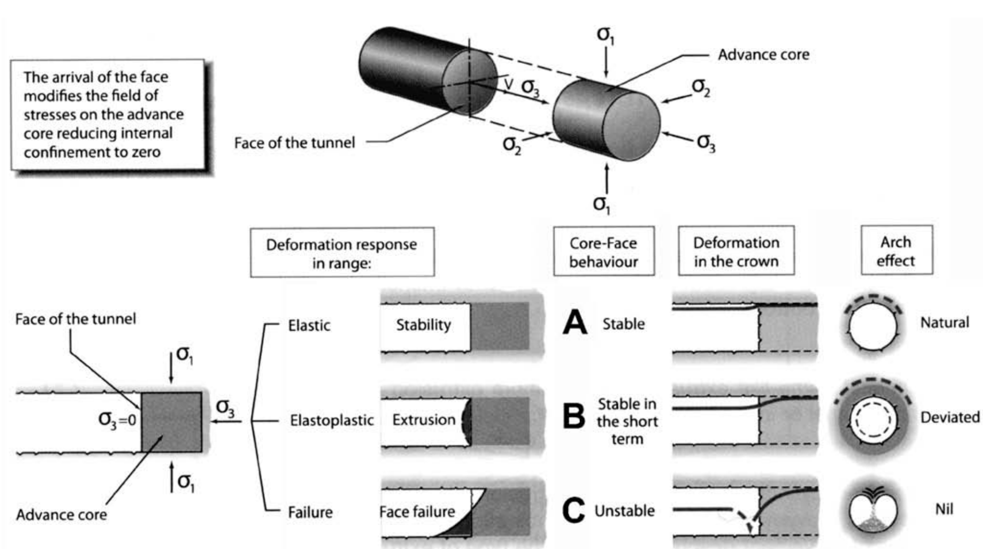


Fig. 11. Tunnel behavior categories based on face-core behavior. After Lunardi (2008).

5. Italian advances in pre-support

The micropile umbrella-arch (also known as pipe-arch umbrella) consists of sub-horizontal micropiles made up of steel pipes grouted in place at high pressure to improve the ground all around the perimeter of the excavation. In 1975, micropiles at different angles were used to tunnel through a collapsed zone (Carrieri et al., 2002), and in 1976 the first umbrella was designed as integral part of the support system for the S. Bernardino tunnel along the Genova-Ventimiglia railway line (Piepoli, 1976). By 1982, 15 tunnels in

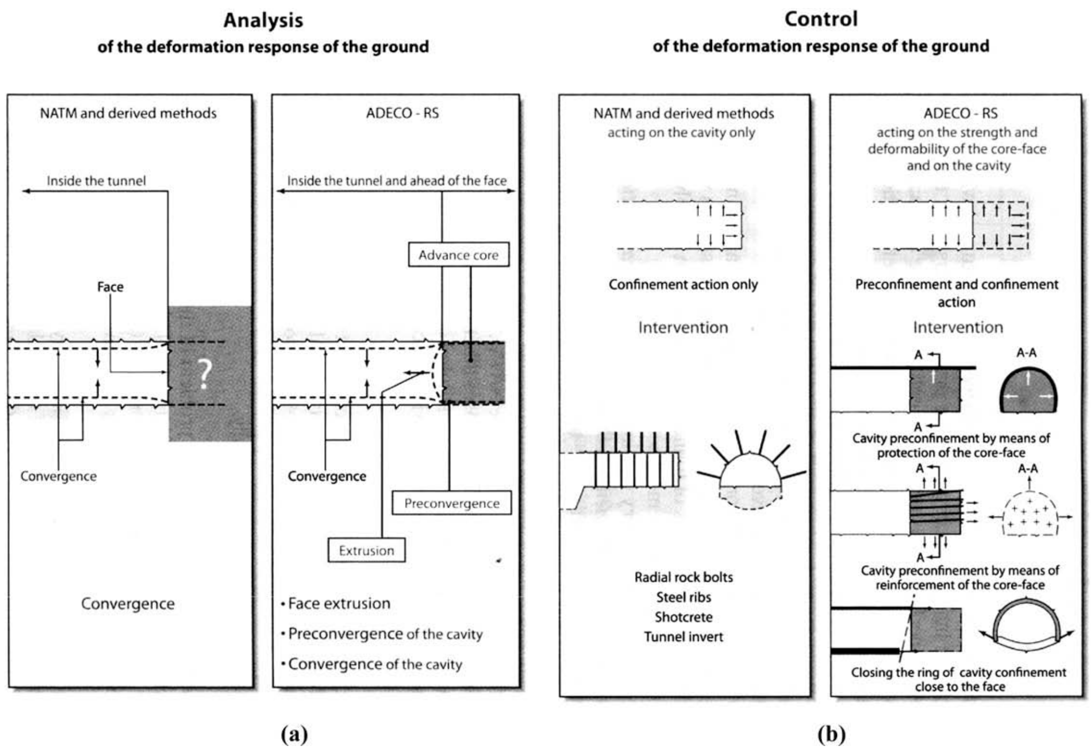


Fig. 12. NATM vs. ADECO. After Lunardi (2008).

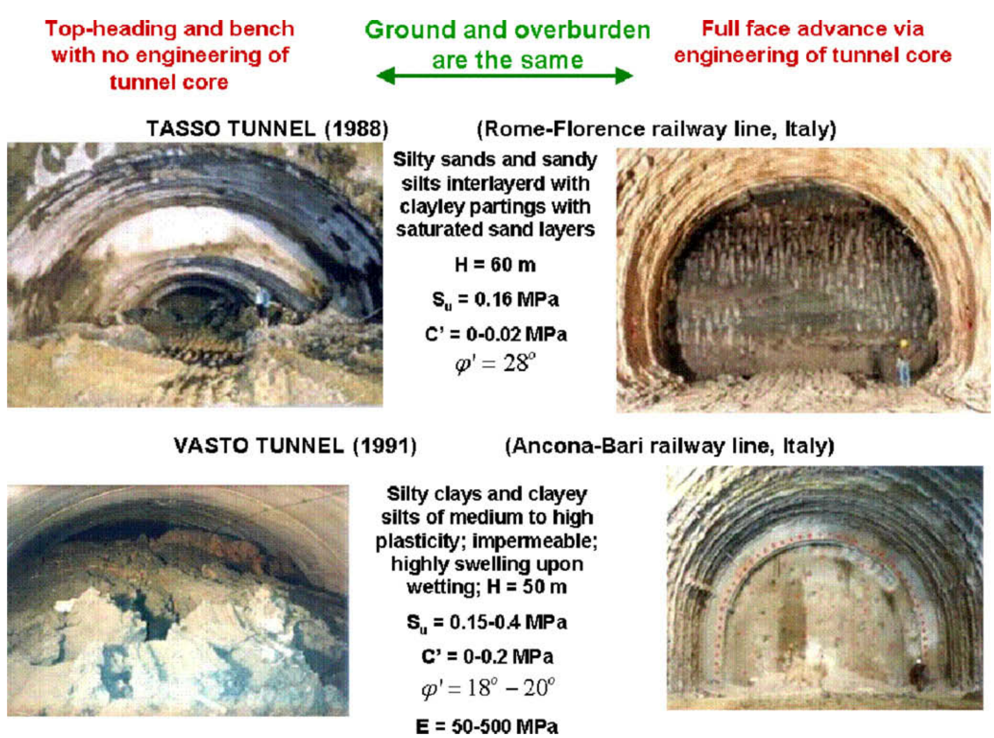


Fig. 13. Tunnels failed when the core was not used as a stabilization method (left-hand sides of Fig. 12a and b); and re-excavated by using the core as a stabilization measure (right-hand sides of Fig. 12a and b).

Italy had been driven by using a micropile umbrella (Barisone and Pelizza, 1982). Unfortunately, in many countries a pipe-arch umbrella is erroneously thought of being part of the NATM. In Italy, other major technological advances were made in the 1980s as a consequence of Lunardi's basic observations on and improved understanding of tunneling. Let us see what they were.

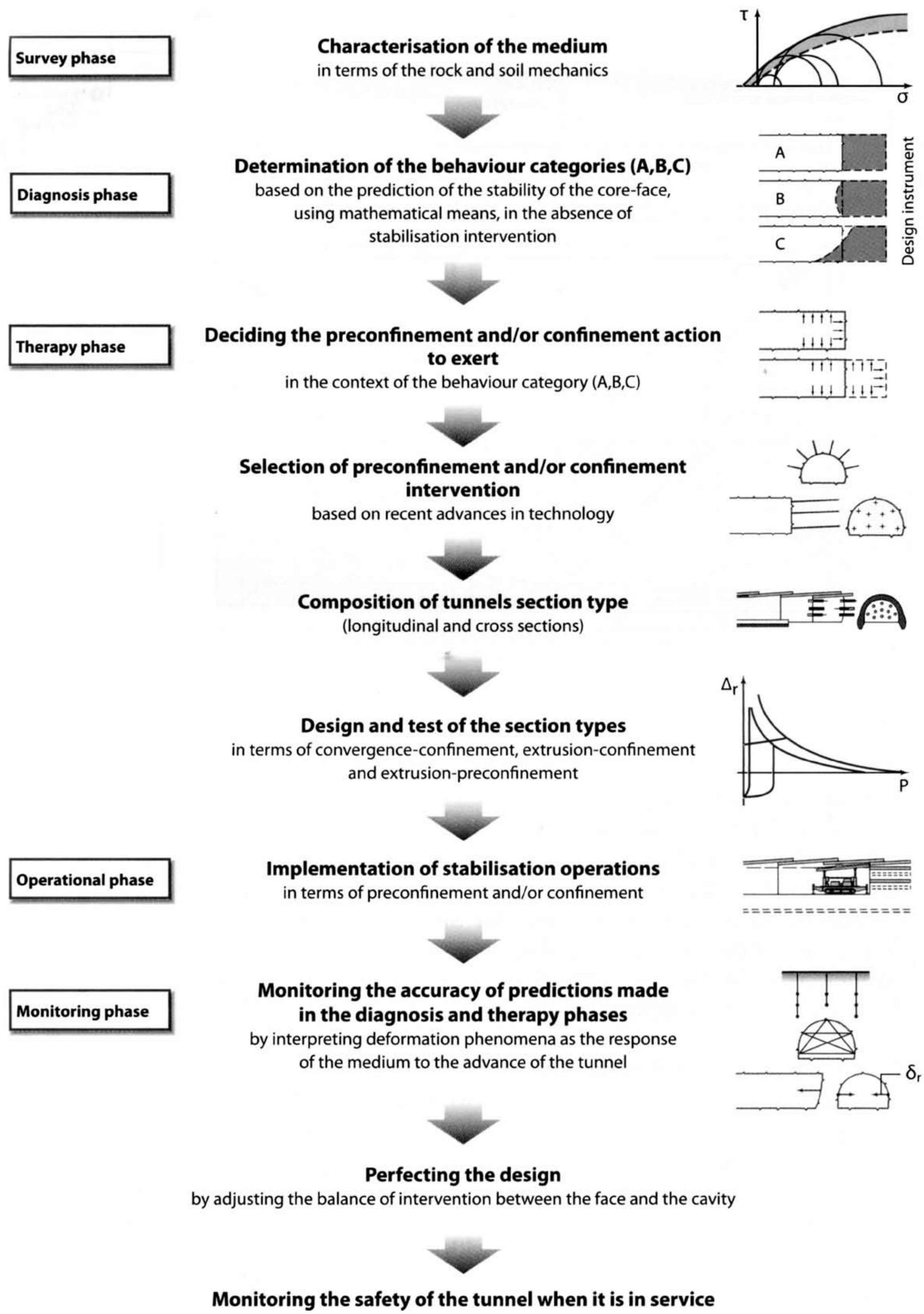


Fig. 14. ADECO workflow. After Lunardi (2008).

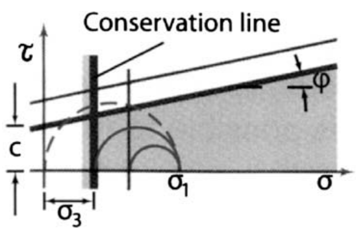


Fig. 15. Mohr-plane explanation of approaches to stabilize/stiffen the core. After Lunardi (2008).

6. Lunardi's basic observations on tunnel behavior

The same way as Rabcewicz conceived of the NATM in the 1960s by observing tunnel behavior, in the 1970–1980s Lunardi made the following basic observations in the tunnels that he designed and/or built:

(1) Convergence (radial displacement of cavity wall, Fig. 5) is only the last manifestation of ground deformation. The convergence is always preceded by and is the effect of the deformation of the advance core: pre-convergence = radial displacement of ground at the future tunnel perimeter, and extrusion = horizontal displacement of the core.
(2) Extrusion can be measured *in situ* and is related one-to-one with the pre-convergence (Fig. 7).
(3) In squeezing ground, everything else being the same, the deformation (convergence) of the cavity increases as the speed of tunnel advance decreases. This is illustrated in Fig. 8, which gives the convergence measured in the calcshists of the Frejus tunnel. When the tunnel advanced 100 m/month (Section 6), the convergence in the cavity was three times as large as the convergence measured when the tunnel advanced 200 m/month. When advancing 100 m/month, it was observed that the ground in the tunnel core deformed much more than when advancing 200 m/month.

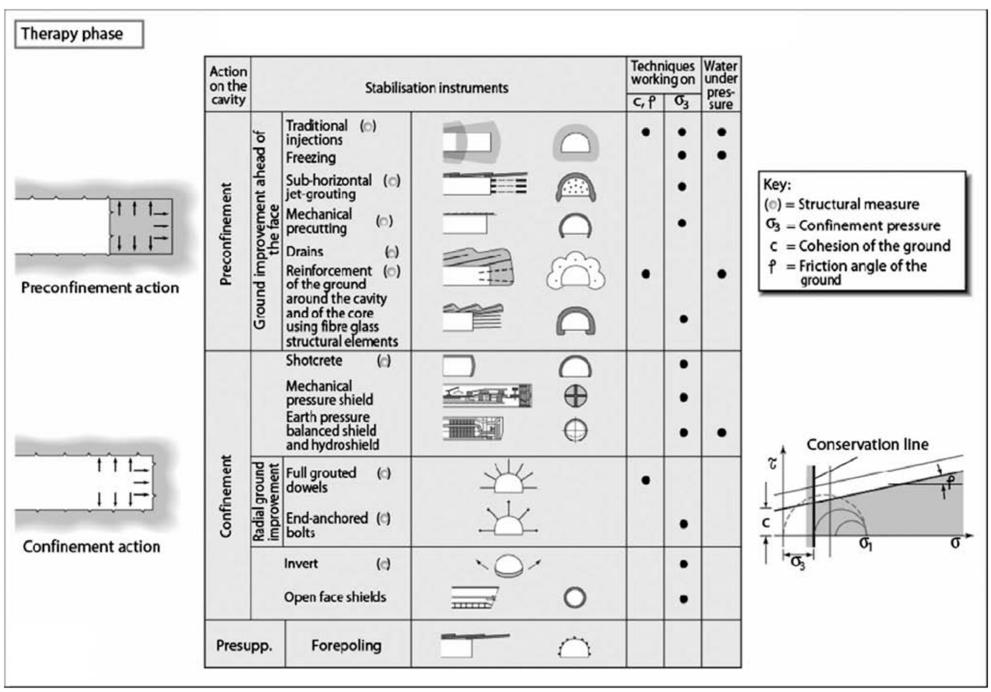


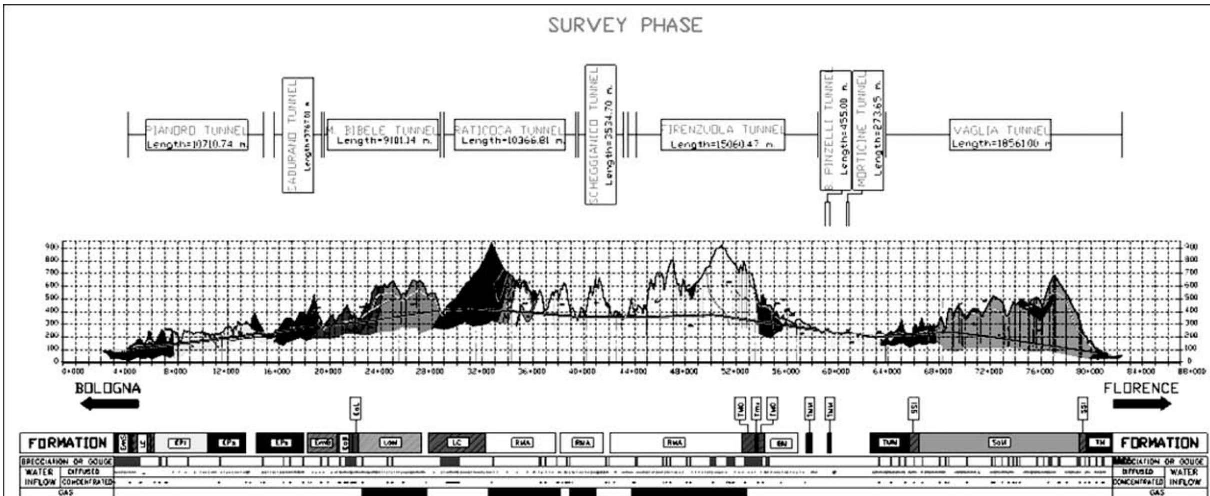
Fig. 16. Subdivision of stabilization tools based on their action as pre-confinement or confinement. After Lunardi (2008).

Section Types	Geology	Convergence (cm)	Extrusion (cm)
A	Monte Modino Sandstones	2-3	Negligible
B0		3-5	Negligible
B0V		5-10	< 3
B2	Scaly Clays	8-12	< 6
B2V		6-10	< 5
C2		10-14	< 10
C6		8-12	< 8

Section Types	Intervention	Variabilities		
		Minimum	*Nominal*	*Maximum*
C2	Steel rib step	1.2 m	1.0 m	0.8 m
	N° VTR face	50	70	90
	VTR face overl.	10.0 m	12.0 m	14.0 m
	Excavation	14.0 m	12.0 m	10.0 m
	Invert-face (°)	< 2.0∅	< 1.5∅	< 0.5∅
	Crown-face	< 3.0∅	< 5.0∅	< 7.0∅

Fig. 17. Displacement predictions and design guidelines. After Lunardi et al. (2008).

(4) The collapse of the cavity is always preceded by the collapse of the face-core system (Fig. 9).
(5) In top heading and benching, the tunnel face starts at the crown of the top heading and ends at the invert of the bench (Fig. 10).
(6) The arrival of the tunnel face reduces the confinement in the core and increases the major principal stress, giving rise to three basic face-core behaviors: A = stable; B = stable in the short term; C = unstable (Fig. 11).



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

Fig. 18. Bologne–Florence high-speed railway tunnels. After Lunardi (2008).

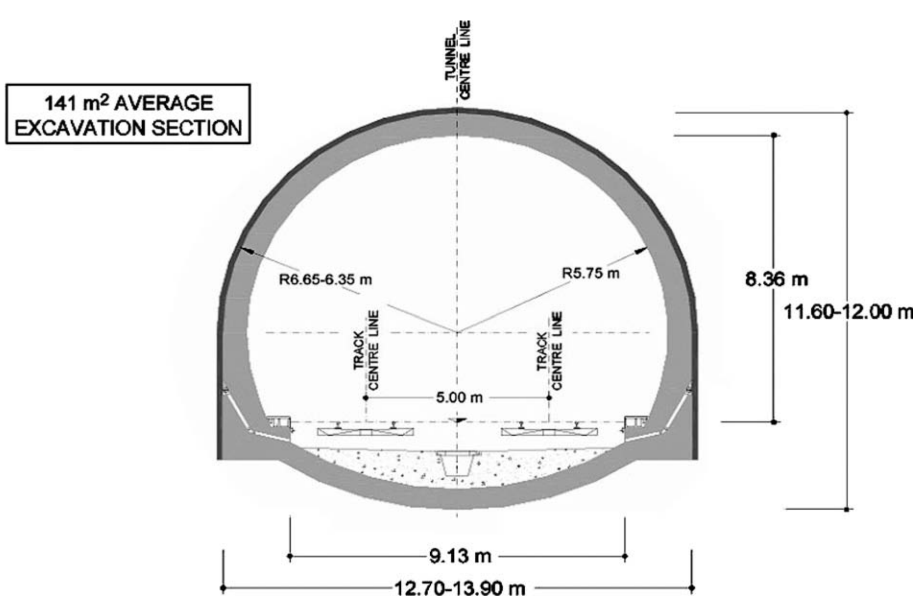


Fig. 19. Bologne–Florence high-speed railway: typical cross-section. After Lunardi (2008).

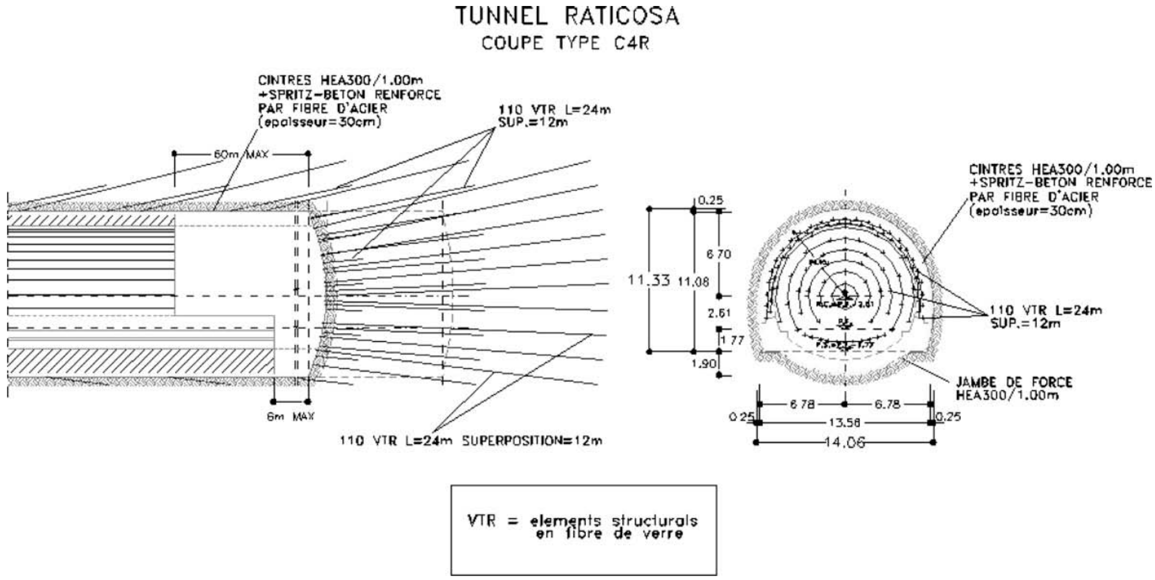


Fig. 20. Raticosa tunnel for the Bologne–Florence high-speed railway: Longitudinal and transverse cross-sections for highly squeezing scaly clays. After Lunardi (2008).

Take home (Fig. 12):

- The ground behavior around the cavity and the convergence in the cavity at a given tunnel chainage X are controlled by the deformation and the behavior of the ground in the tunnel core when excavating the tunnel at chainage X (what Rabcewicz did not understand and could not do in 1960s).
- In difficult stress–strain conditions, counteracting convergence is not feasible. One needs to control pre-convergence and extrusion, i.e. the deformations in the core ahead of the tunnel face (what Rabcewicz did not understand and could not do in 1960s).
- Sequential excavation extends the tunnel face even if the top heading is lined (same as Rabcewicz "*An auxiliary arch executed in the upper heading ... represents an intermediate construction stage, which is still subject to lateral deformation*") and increases the volume of ground in the core that, by deforming, controls the behavior of the cavity (what Rabcewicz did not understand).
- If the extent of the face and of the core must be minimized, one has to proceed full face (same as Rabcewicz "*tunnels should be driven full face whenever possible*").

These results led Lunardi to the idea of engineering the core in order to use the core as a stabilization method for the cavity, the same way as rockbolts, shotcrete and steel sets are used to stabilize the cavity. One of the most striking proofs of the central role of the core is given by the re-excavation of tunnels that failed when the core was ignored: Fig. 13 offers two of many examples. The idea of engineering the core was implemented by developing new technologies, such as:

- Sub-horizontal jet-grouting (Campiolo tunnel, 1983).
- Pre-cut with full face excavation (Sibari-Cosenza railway line, 1985, evolution of the pre-decoupage used in the top heading in the Lille Metro, France).
- Fiberglass reinforcement of the core as a construction technology to be used systematically in full face tunnel advance (1985, high-speed railway line between Florence and Rome), and not only as an ad hoc means to overcome unpredicted tunneling problems.

The ADECO is the culmination of these observations, experiments, and new technologies. The new technologies introduced with the ADECO can thus only be understood and properly used within the context of the ADECO approach.

Fig. 21. Raticosa tunnel for the Bologne–Florence high-speed railway: full face excavation under 500 m of cover in highly squeezing scaly clays. After Lunardi (2008).

Fig. 22. Raticosa tunnel for the Bologne–Florence high-speed railway: preparing for pouring the final invert under 500 m of cover in highly squeezing scaly clays. After Lunardi (2008).

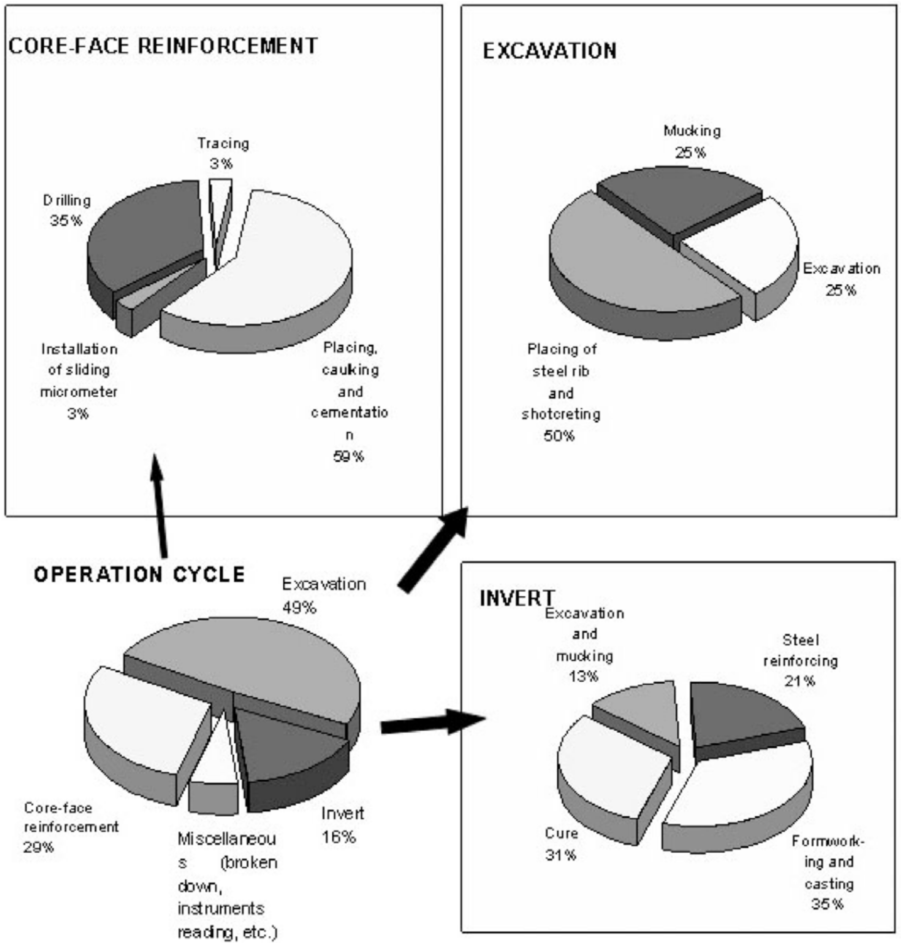


Fig. 23. Raticosa tunnel for the Bologne–Florence high-speed railway: breakdown of construction operations. After Lunardi (2008).

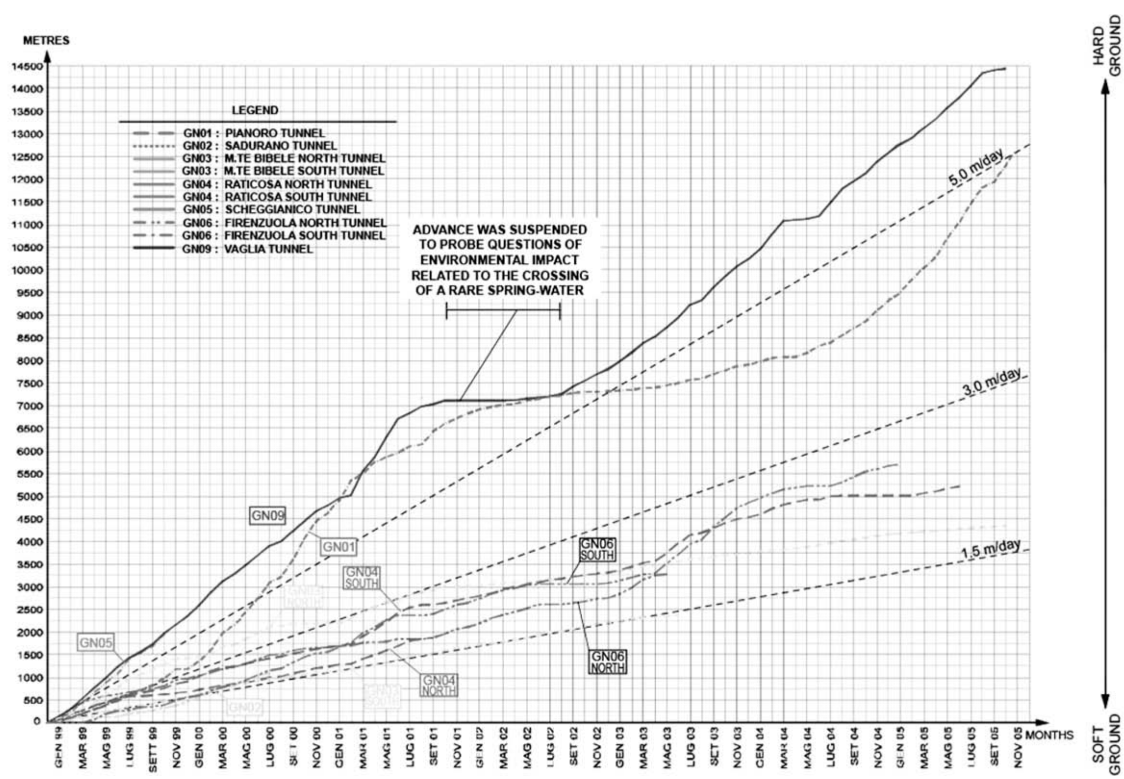


Fig. 24. Production data in the Bologne–Florence high-speed railway tunnels. After Lunardi (2008).

7. ADECO approach

The Analysis of Controlled Deformations (ADECO) workflow is illustrated in Fig. 14. In the Diagnosis Phase, the unlined/unreinforced tunnel is modeled in its *in situ* state of stress with the aim of subdividing the entire alignment into the three face/core behavior categories: A–C; these depend on the stress–strain behavior of the core (ground strength, deformability and permeability + *in situ* stress), not only on the ground class. The site investigation must be detailed and informative enough to carry out such quantitative analyses: this clearly defines what the investigation should produce.

In the Therapy phase, the ground is engineered to control the deformations found in the Diagnosis Phase. For tunnel category A, the ground remains in an elastic condition, and one needs to worry about rock block stability (face and cavity) and rock bursts; typically, rock bolts, shotcrete, steel sets and forepoling are used to this effect. In categories B and C yielding occurs in the ground; an arch effect must be artificially created *ahead* of the tunnel face (pre-confinement) when a large yielded zone forms in category B, and in all cases in category C. By looking at the Mohr plane (Fig. 15) two courses of action clearly arise:

- Protecting the core by reducing the size of the Mohr circle: this can be achieved either by providing confinement (increasing σ_3) or by reducing the maximum principal stress (reducing σ_1).
- Reinforcing the core, thereby pushing up and tilting upwards the failure envelope.

The rightmost column in Fig. 12 depicts the actual implementation of these two ideas as pre-confinement actions. The third line of action consists of controlling the convergence at the face by using the stiffness of the lining (preliminary or even final, if needed), which may also longitudinally confine the core. It is only in this context that the different technologies currently available and listed in Fig. 16 take their appropriate role. Notice that, at differ-

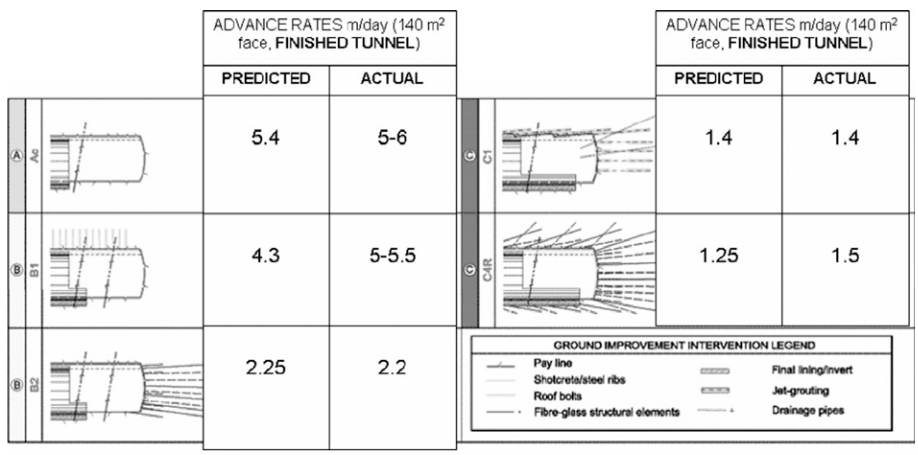


Fig. 25. Predicted vs. actual production rates in the Bologne–Florence high-speed railway tunnels. Reconstructed after Lunardi (2008).

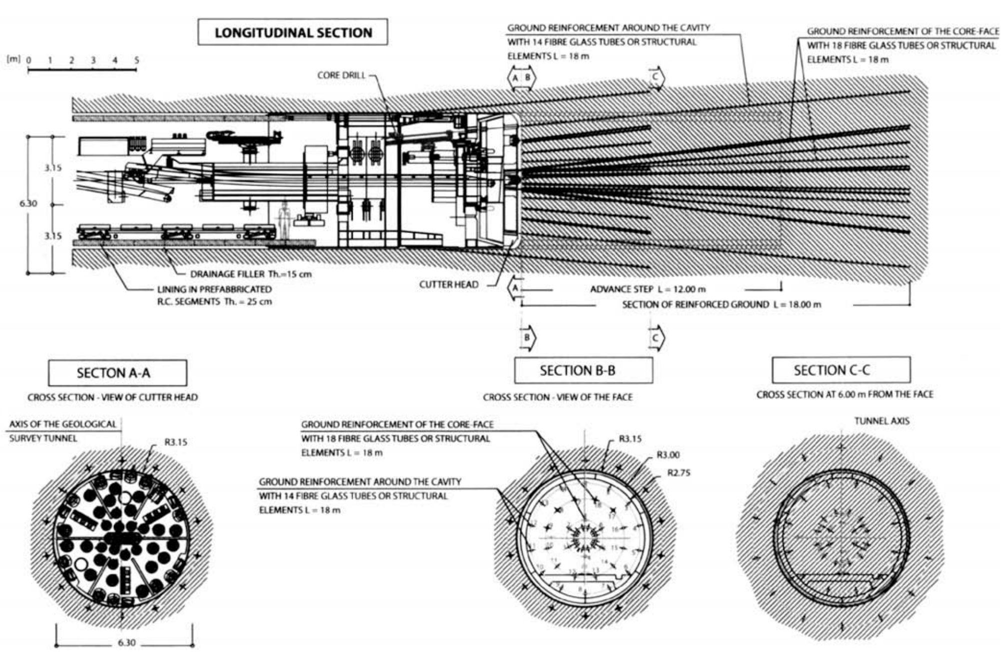


Fig. 26. Bologne–Florence high-speed rail: TBM used in the Ginori tunnel. After Lunardi (2008).

ence with the NATM, the ADECO embraces tunnels excavated with and without a tunnel boring machine.

Once the confinement and pre-confinement measures have been chosen, the cross-section is composed both in the transverse and longitudinal directions, and then analyzed. In all cases, full face advance is specified in all stress–strain conditions, thus fulfilling Rabcevicz's dream.

For each cross-section, displacement ranges are predicted in terms of convergence and extrusion (Fig. 17). Besides plans and specs, construction guidelines are also produced during the design stage. The construction guidelines are used at the construction site to make prompt decisions based on the displacement readings. If the readings are in the middle of the predicted ranges, then the nominal cross-section in the plans and specs is adopted; if reading

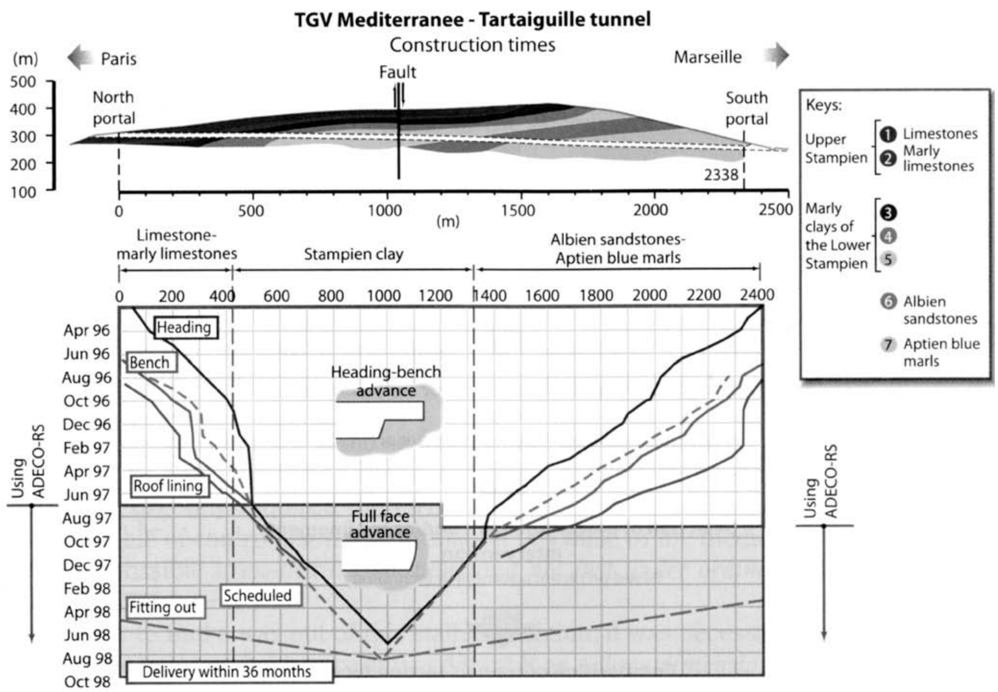


Fig. 27. Tartaguille tunnel construction time versus geology. After Lunardi (2008).

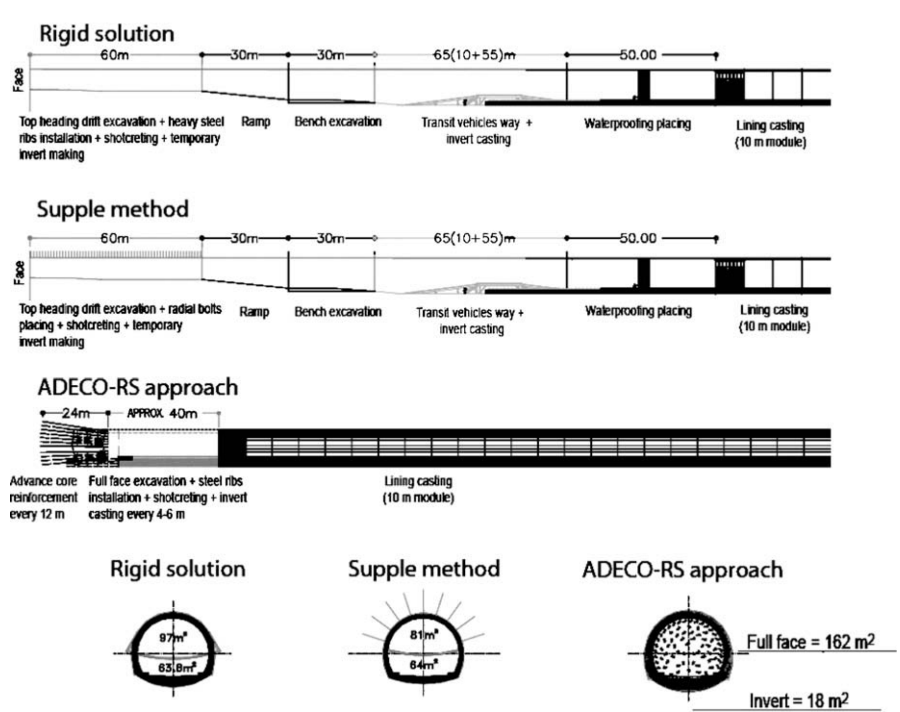


Fig. 28. Tartaguille tunnel: the three proposed solutions to advance in the Stampien clays. After Lunardi (2008).

values fall to the lower end of the predicted displacement ranges, then the minimum quantities specified in the guidelines are adopted for the stabilization measures (Fig. 17). Likewise, if reading values are on the upper end of the predicted displacement ranges, then the maximum quantities specified in the guidelines are adopted. Finally, if the readings are outside the predicted displacement ranges, the guidelines specify the new section to be adopted. In this way, ADECO clearly distinguishes between design

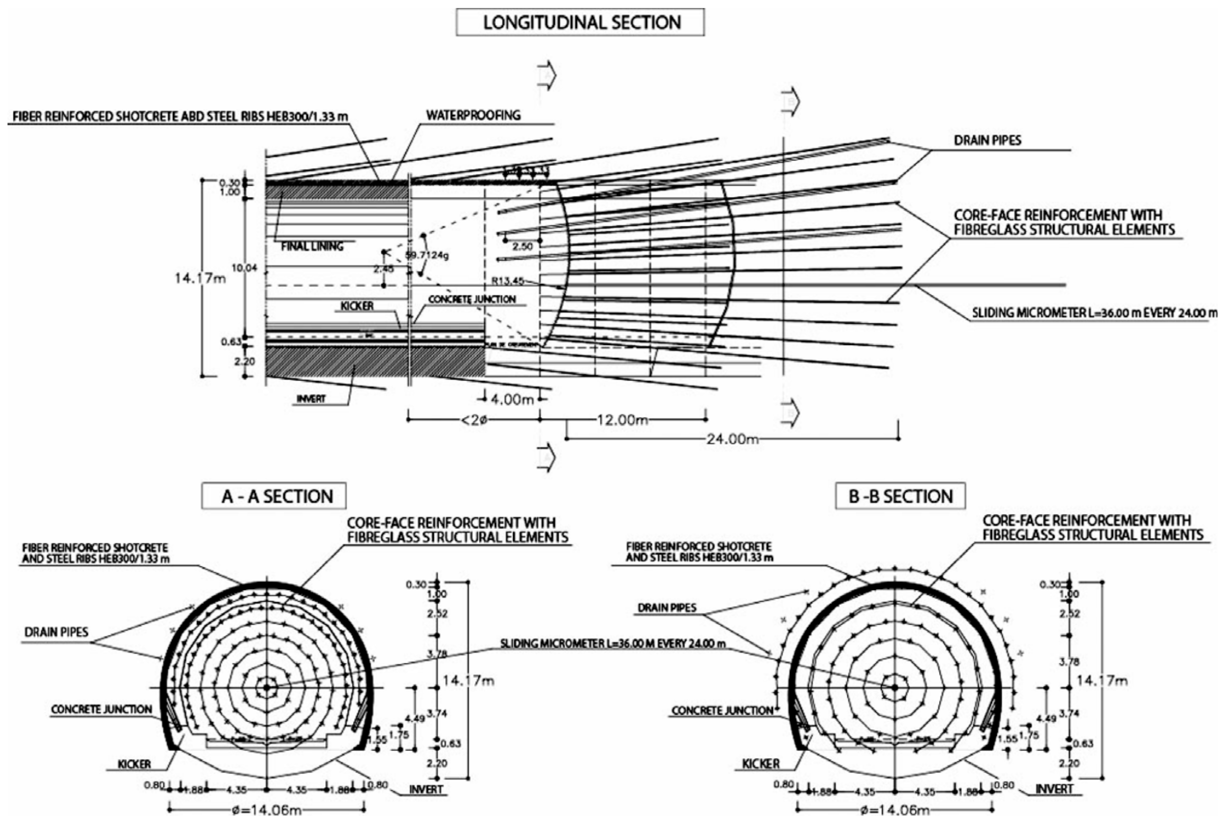


Fig. 29. Tartaguille tunnel: adopted ADECO solution in Stampien clays. After Lunardi (2008).

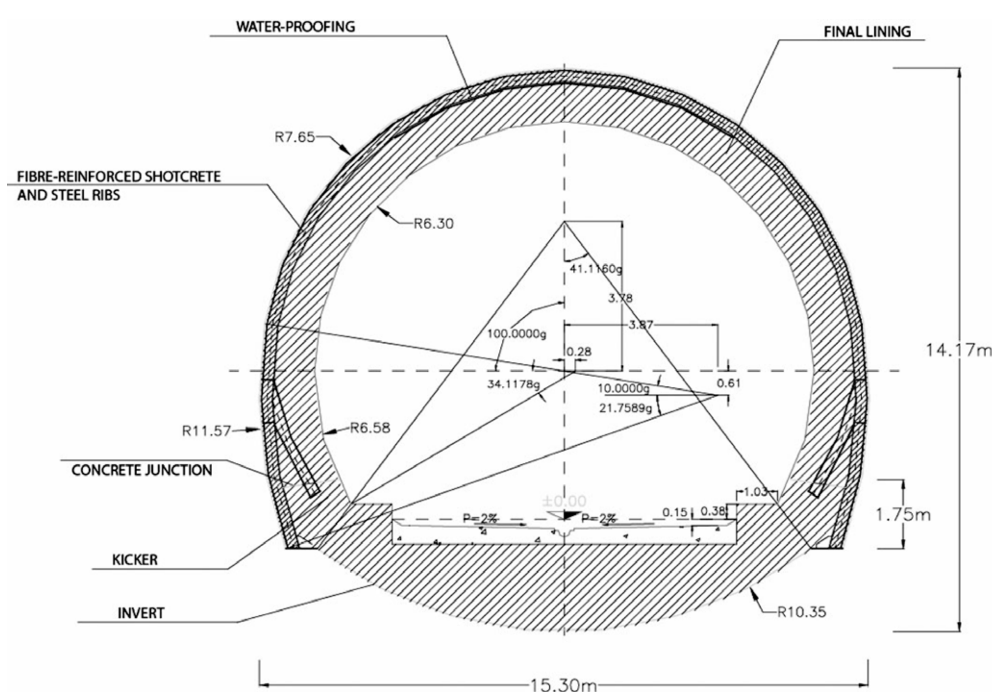


Fig. 30. Tartaguille tunnel: cross-section showing primary lining and final lining. After Lunardi (2008).

and construction stages because no improvisation (design-as-you-go) is adopted during construction.

Monitoring plays a major role in the ADECO, but with two main differences with respect to the NATM:

- In categories B and C, not only convergence but also extrusion is measured because the cause of instability is the deformation of the core, and because stability of the core by pre-confinement actions is a necessary condition for the stability of the cavity.

Fig. 31. Tartaguille tunnel: installation of fiberglass elements in the core: notice the kickers and the final invert against the face. After Lunardi (2008).

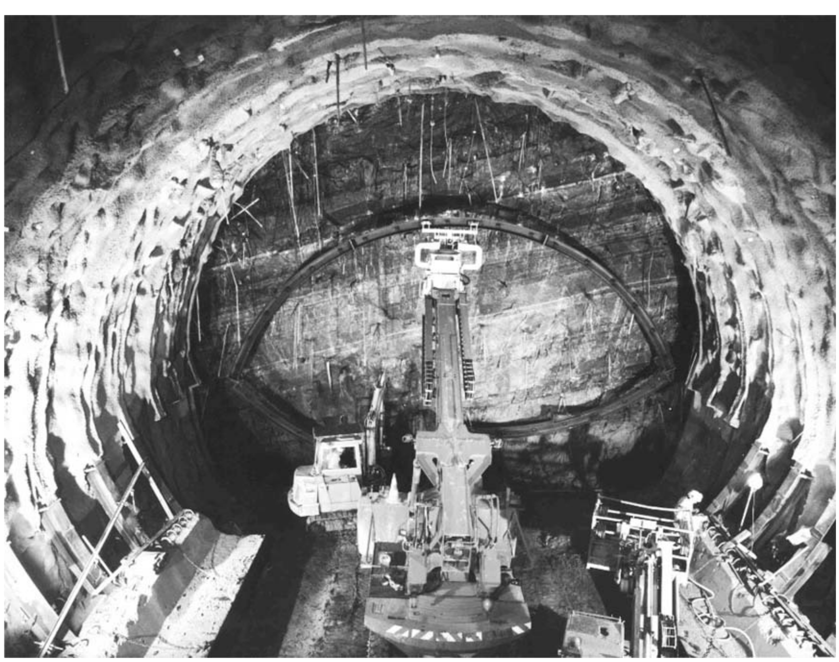


Fig. 32. Tartaguille tunnel: erection of a steel rib. After Lunardi (2008).

- Monitoring is used to fine tune the design, not to improvise cavity stabilization measures, so that construction time and cost can be reliably predicted.

Tunnels are thus paid for how much they deform, which, unlike rock mass classifications carried out at the face, is an objective measure void of any interpretation. In addition, rock mass classifi-

Fig. 33. Tartaguille tunnel: the steel rib is erected. After Lunardi (2008).

Fig. 34. Tartaguille tunnel: waterproofing and formwork are placed before pouring the final invert against the tunnel face. After Lunardi (2008).

cations are inapplicable to soils and complex rock mass conditions not included in classifications' databases. Experience in over 500 km of tunnels indicates that, when the ADECO has been adopted and tunnels were paid for how much they deformed, claims have decreased to a minimum.

8. Case histories

8.1. Bologne–Florence high-speed railway, Italy

The largest tunnel construction project ever implemented in the world entailed 84.5 km of running tunnels with a cross-section of 140 m^2 and additional 20 km of service tunnels for a total of about 13 million m^3 of excavated material (Figs. 18–25). Because of the difficult tunneling conditions, all running tunnels were excavated *without* a tunnel boring machine. Indeed, the route passed through the highly squeezing conditions of the Apennines with covers varying form zero to 550 m. Once the ADECO design was complete, the E 4.209 billion lump sum contract was won by FIAT, who took all risks including the geological risks. Construction started in 1996 and finished in time and on budged in 2006: a maximum of 26 faces were open simultaneously with a production of 1600 m/mo. Figs. 20–23 exemplify the case of a C category section designed for highly squeezing scaly clays in the Raticosa tunnel. Scaly clays are extremely sensitive to stress–relief, and lose all of their cohesion if confinement drops to zero. It was thus of utmost importance to pre-confine the core and to adopt a stiff preliminary lining with very stiff final invert that was always kept very close to the tunnel face. Despite the heavy ground improvement and the final invert poured at the tunnel face, production rates were constant and equal to 1.5 m/day: a clear indication of the benefits in using the core as a stabilization measure and of the industrialization achieved with the ADECO.

Fig. 26 illustrates the application of the ADECO to a tunnel boring machine (TBM) drive for the 9.26-km long 5.6-m diameter Ginori service tunnel to the Vaglia tunnel. A TBM was chosen because the service tunnel had to be completed rapidly from only one portal, and it was necessary to keep the excavation watertight at all times. The ground, which varied from compact limestone to argillites, was excavated with a Wirth TB 630E/TS double shield TBM equipped with drilling equipment to drill through the cutter head and the shield in order to pre-confine and investigate (by georadar) the advance core. Construction finished on time and on budget with an average advance rate of 20 m/day under a maximum water pressure of 5 bar.

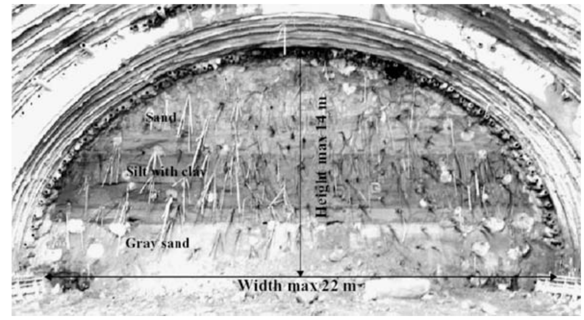


Fig. 36. Cassia 1 tunnel: dimensions and stratigraphy.

8.2. Tartaguille tunnel, France

The Tartaguille tunnel, 2.3 km in length with a cross-section of 180 m^2, is one of six tunnels on the high-speed railway line that connects Lyon to Marseille in France. The tunnel passes through Cretaceous formations, including the lower Stampien marly clays, which are 75% montmorillonite. As depicted in Fig. 27, construction started according to the original design in the Stampien clays from the North portal with top heading and benching. The top heading was equipped with temporary invert and composed of 25-cm thick shotcrete and HEB 240 steel sets at 1.5 m spacing that were founded on micropiles and on rock bolts after benching. Con-

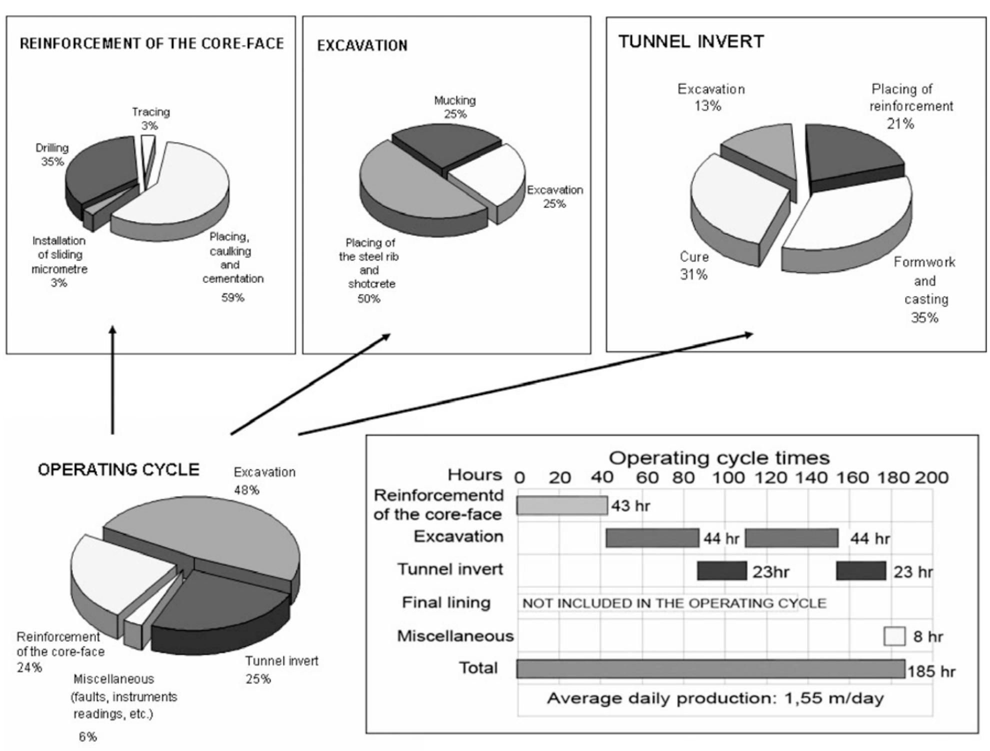


Fig. 35. Tartaguille tunnel: breakdown of construction schedule. After Lunardi (2008).

Fig. 37. Cassia 1 tunnel: jet-grouting columns in the core reinforced with fiberglass elements.

struction proceeded with great difficulties and it was much slower than anticipated. After clear signs of distress appeared in the primary lining and construction became unsafe, several solutions were proposed by eminent European consultants as illustrated in Fig. 28. Only the ADECO proposal adopted full face (180 m^2) advance and used the advance core as a stabilization measure; the other solutions tried to counteract or control convergence by advancing with sequential excavation and by installing support and reinforcement in the cavity. The flexible solution is a typical NATM solution. The French Rail (SNCF) decided to adopt the ADECO approach because the ADECO proposal was the only one that promised to finish the tunnel on budget and within schedule. Figs. 29–35 illustrate the proposed design and some construction phases. Notice:

- The large and powerful equipment deployed at the face.
- The large number of workers that can work at the face at the same time.
- The steel rib erected at the face with only two connections: this ensures quick installation, and quality control and assurance are much more simplified.
- The sheer stiffness of the preliminary lining and of the final invert meant to avoid (together with fiber glass reinforcement of the core) any decompression of the montmorillonitic clays so as to avoid any swelling.
- Construction schedule included waterproofing and pouring of the invert to the tunnel face without disruption while keeping a constant full face advance of 1.55 m/day.

The tunnel was completed one and a half months ahead of schedule and below budget. Fig. 27 shows how ADECO yielded constant production rates (industrialization), whereas the production rates obtained with the sequential excavation were not constant (lack of industrialization).

8.3. Cassia 1 tunnel, Italy

The construction of the "Cassia Tunnel" (outer lane) is part of a larger project for increasing the capacity of the external Ring Road in Rome. The tunnel is 22-m wide and 230-m long, it carries three traffic lanes plus one emergency lane. The tunnel passes through sands and silts with sand with an overburden of 5 m below a Roman archeological site. Construction advanced full face with preconfinement made up of an umbrella of overlapping sub-horizontal jet-grouting columns and sub-horizontal jet-grouting columns, in the core (Figs. 36–38).

The roto-injection technique developed by Trevi and Soilmec for this project uses a double counter-rotating system made up of a rod and a pipe. The internal rod includes the jetting system, equipped with self-drilling monitor. In the umbrella, the pipe remains permanently inserted and works as reinforcement. The spoil is directed into the annulus between the rod and the pipe, which allows one to check and control the spoil flow rate, thus preventing voids to form in the jet-grouting column.

Fig. 38. Cassia 1 tunnel: Construction stages.

9. Advantages of the ADECO approach over sequential excavation and NATM

- ADECO fulfills Rabchewicz's dream of advancing full face in all stress–strain conditions, which allows risk, cost and construction time to be minimized.
- Tunnel construction is finally industrialized in all tunneling conditions because tunneling advance is no longer subject to the ground but the ground is made what it needs to be in order to proceed as fast as possible. This is illustrated in Figs. 24–27, where production rates are constant even in the most difficult stress–strain conditions (highly squeezing, and squeezing and swelling, respectively). In Fig. 27, compare ADECO advance rates with sequential excavation rates, which are overall much smaller and are not constant.
- Industrialization entails that cost and time can be reliably predicted at the design stage. Fig. 25 shows how predicted production rates were maintained during construction of 85 km of tunnels even under the most difficult stress–strain conditions (highly squeezing). Notice that these advance rates refer to the finished 140 m^2 face tunnel (including final lining), not top heading, or pilot drift. As stated in the introduction, NATM philosophy entails designing the cavity support/reinforcement based on monitoring results, which means that construction time and cost cannot be predicted.
- Constant production minimizes ground deformation, which minimizes squeezing and thus the loading on the final lining, which becomes cheaper.
- By advancing full face under all conditions, large and powerful equipment can be used, which means that a lot of work can be done in a short time. This reduces cost and construction time.
- By concentrating all critical operations at the face, safety is greatly improved as opposed to sequential excavation, where many different (and critical, such as slashing the bench) construction operations spread out along the tunnel length.
- By advancing full face and minimizing squeezing, settlements are minimized, which, for example, is of paramount importance in urban area.
- Tunnels construction with and without a tunnel boring machine can be handled within the same approach.

Fig. 39. Typical transportation means in the early 1800s, when sequential excavation was conceived.

Fig. 40. Opening of the tunnel under the Tames in the early 1800s, when sequential excavation was conceived.

Fig. 41. 1964 Cadillac Fleetwood 60 Special Sedan, produced when the NATM was conceived.

9. Conclusions

Sequential excavation was started 200 years ago; at that time, there was no electricity, horse and buggy were commonly used to move around (Fig. 39); ladies wore crinolines and gentlemen wore top hats (Fig. 40). As originally conceived by Rabcewicz, the NATM did not necessarily embrace sequential excavation. Rather, Rabcewicz was completely in favor of full face advance but he realized that NATM did not allow him to advance full face in difficult stress–strain conditions. The research and projects carried out by Lunardi indicate the reasons why Rabcewicz could not fulfill his dream in difficult tunneling conditions. He (and all his followers to date):

- Ignored the behavior of the advance core.
- Tried to counteract only convergence, which is the effect, instead of counteracting the very cause of instability, i.e. the deformation of the advance core.
- Used deformable linings, which allow the ground to deform and provide negligible confinement to the core.
- Let the ground deform and tried to mobilize the strength of the ground. In squeezing conditions, this practice allows the ground to start creeping, which is an irreversible phenomenon and is very difficult (if not impossible) to control by acting only on the cavity.
- Did not have the technology to pre-confine the core.

Ironically, continuing using the sequential excavation was a *consequence* of Rabcewicz's choices (not Rabcewicz's choice), which led him (and all of his followers to date) to give up on full face excavation, i.e. Rabcewicz's goal itself.

We now know much more than in 1960s, we have much improved technology (in investigation, design and construction), we can deploy much more computational and construction power, and we have a complete design and construction approach that allows us to advance full face in all stress–strain conditions; it works with and without a tunnel boring machine. This approach has been proven in over 500 km of tunnels, the majority of which in difficult tunneling conditions. As for the United States, proceeding full face is just going back to the roots of early American tunneling. In the end, none of us rides horse and buggy (Fig. 39), nor wear crinolines or top hats (Fig. 40) anymore. Let us update our tunneling approach as well!

We may still listen to the Beatles, but we do not take the risk and (fuel) cost of driving a 1964 Cadillac Fleetwood (Fig. 41) across the US. Why should owners (and, eventually, taxpayers) across the US (and across most of the world) take the risk and pay the cost entailed in a 1964 tunneling approach?

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