The Evolution of Reinforcement of the Advance Core Using Fibre-Glass Elements

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Die Entwicklung der Verstärkung des Bereichs vor der Ortsbrust mittels Glasfaserelementen

Die systematische Verstärkung des Bereichs vor der Ortsbrust eines Tunnels mittels Glasfaserelementen zur kurz- und langfristigen Stabilisierung des Tunnels ist eine Bauweise, die in Italien entwickelt wurde und dort seit mehr als 18 Jahren angewandt wird. Während dieser Zeit wurden bedeutende Weiterentwicklungen in der Planung dieser Bauweise, bei den Bauverfahren und bei den Materialien gemacht. Der vorliegende Beitrag stellt diese Entwicklungen vor.

Systematic reinforcement of the advance core of a tunnel using fibre-glass elements as a structural component to stabilize it in the long and short term is a practice developed in Italy that has been used for over eighteen years. During this period significant developments have occurred in the design techniques used for this tunnelling technique, in the construction technologies and in the materials. This paper illustrates these developments.

Systematic reinforcement of the face of a tunnel which is then demolished may seem a strange contradiction and it is perhaps precisely because of this that eighteen years after it was first tried, the technology of reinforcing the advance core with fibre-glass structural elements is viewed by some with suspicion and is often poorly understood and badly performed even by experienced underground design engineers despite the successes the technique has enjoyed.

A true and genuine construction system of this method was made which is a part of the tunnel design and construction approach known as ADECO-RS. As such it is one of the conservation techniques and exerts a preconfinement action on the cavity (9). It has shown considerable potential and has in fact been employed to industrialize the construction of tunnels for the first time with extraordinary results, even in grounds which were impossible to tackle adequately before now.

A short illustration of the technology

The technology in question consists of dry drilling a series of holes into the face of a tunnel. They must be evenly distributed and at an angle just off parallel to the centre line of the tunnel. Special fibre-glass reinforcement is then inserted into the holes (Figures 1 and 2) and then immediately injected with grout. When, after tunnel advance, the remaining length of the reinforcement in the face is insufficient to guarantee sufficient preconfinement of the cavity (a situation which is immediately identified by careful measurement of extrusion), a new series of reinforcements is placed.

Length, density, overlap, cross-section area and geometrical distribution of the reinforcement constitute the parameters that characterize this reinforcement technique. The technology can be employed in cohesive, semi-cohesive ground and, with a little extra intervention to ensure the sta-

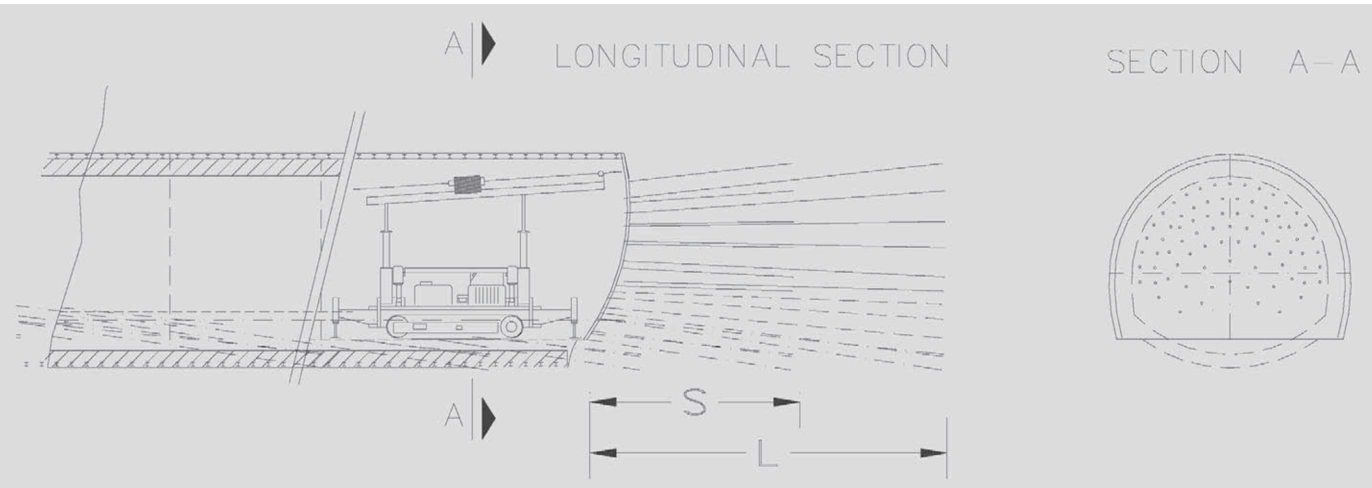

Fig. 1 Reinforcement of the advance core with fibre-glass reinforcement (FGR).
Bild 1 *Verstärkung des Bereichs vor der Ortsbrust mit Glasfaserbewehrung.*

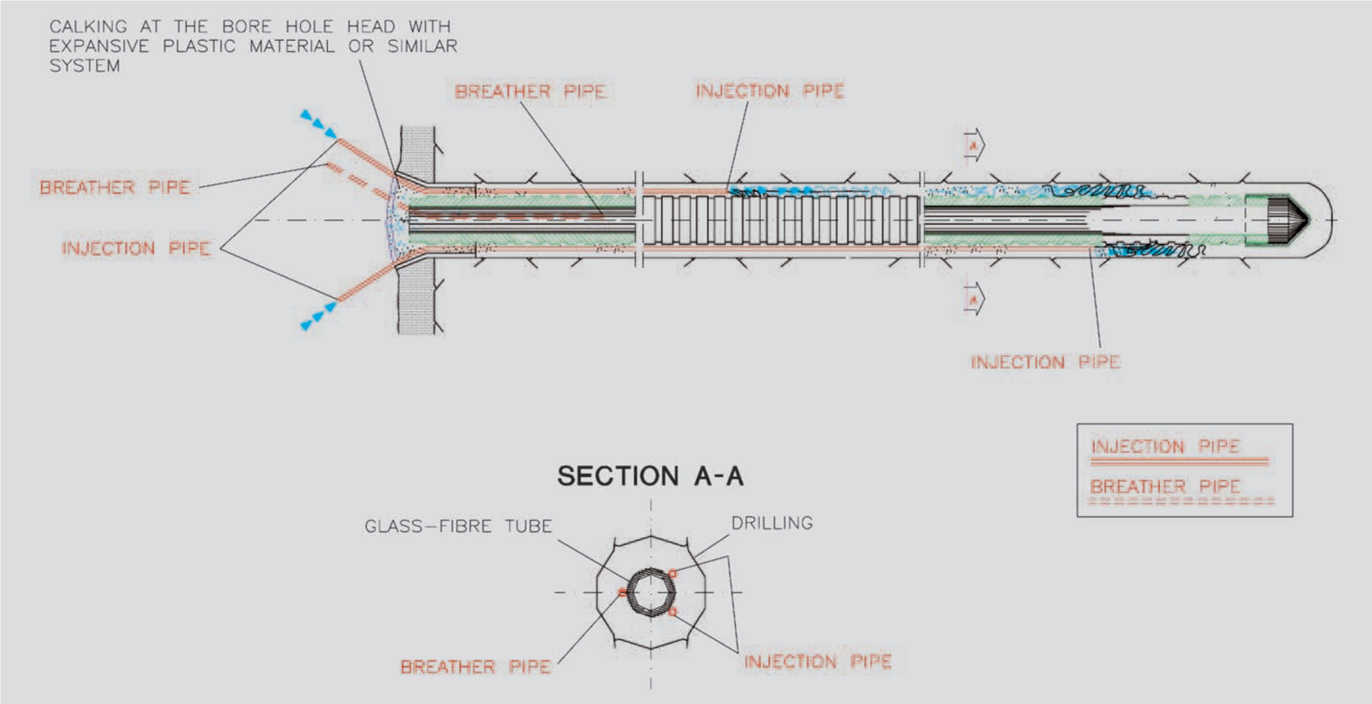

Fig. 2 Sketch of a tubular fibre-glass element.
Bild 2 *Aufbau eines rohrartigen Glasfaserelements.*

bility of the hole, even in ground with poor cohesion. If the technique is designed and performed well, it improves the strength and deformation characteristics of the ground in the advance core of a tunnel considerably and results in the development of effective preconfinement action. Clearly the idea of using fibre-glass for the reinforcement constituted the key to the success of the technology because this material combines high strength properties with great fragility. Consequently it is easy to break reinforcement made of this material with the same bucket that is used for excavating the ground (Figure 3).

Fig. 3 View of a reinforced face.
Bild 3 *Ansicht einer verstärkten Ortsbrust.*

The ADECO-RS approach context

In order to understand and use fibre-glass reinforcement technology properly it is important to keep in mind two concepts that lie at the base of the ADECO-RS approach of which it forms part:

- The centrality of the deformation response of the ground to the action of excavation (Figure 4). The design engineer must give maximum attention to this, firstly to analyse it and then to control it (9).
- The use of the advance core of the tunnel (stiffened with of course fibre-glass reinforcement or protected with advance rings of improved ground or of fibre reinforced mortar) as the key to interpretation (for analysis) and as a structural stabilization element (for control) of the deformation response mentioned above during excavation and construction (Figure 5).

It has been demonstrated (7) that it is possible to tackle full face excavation of tunnels even under the most difficult stress-strain conditions by

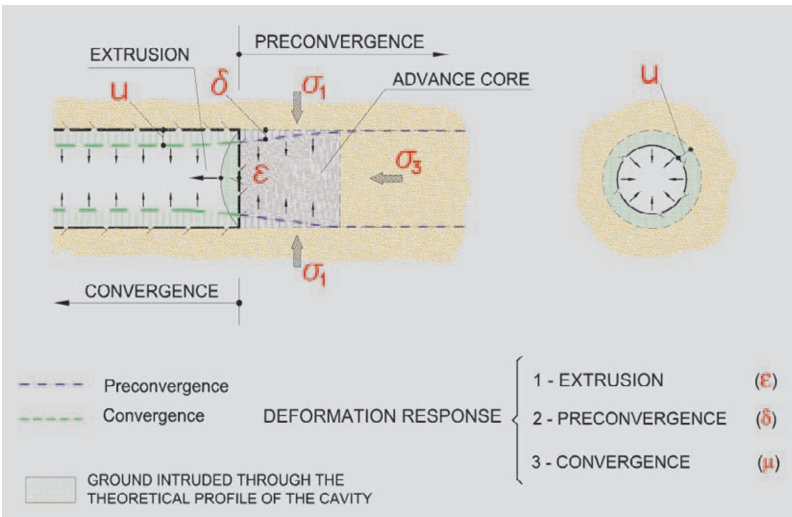

Fig. 4 The three components of the deformation response.
Bild 4 *Die drei Komponenten des Verformungsprozesses.*

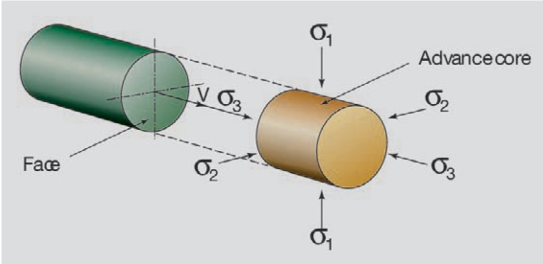

Fig. 5 Definition of the advance core.

Bild 5 *Definition des Bereichs vor der Ortsbrust .*

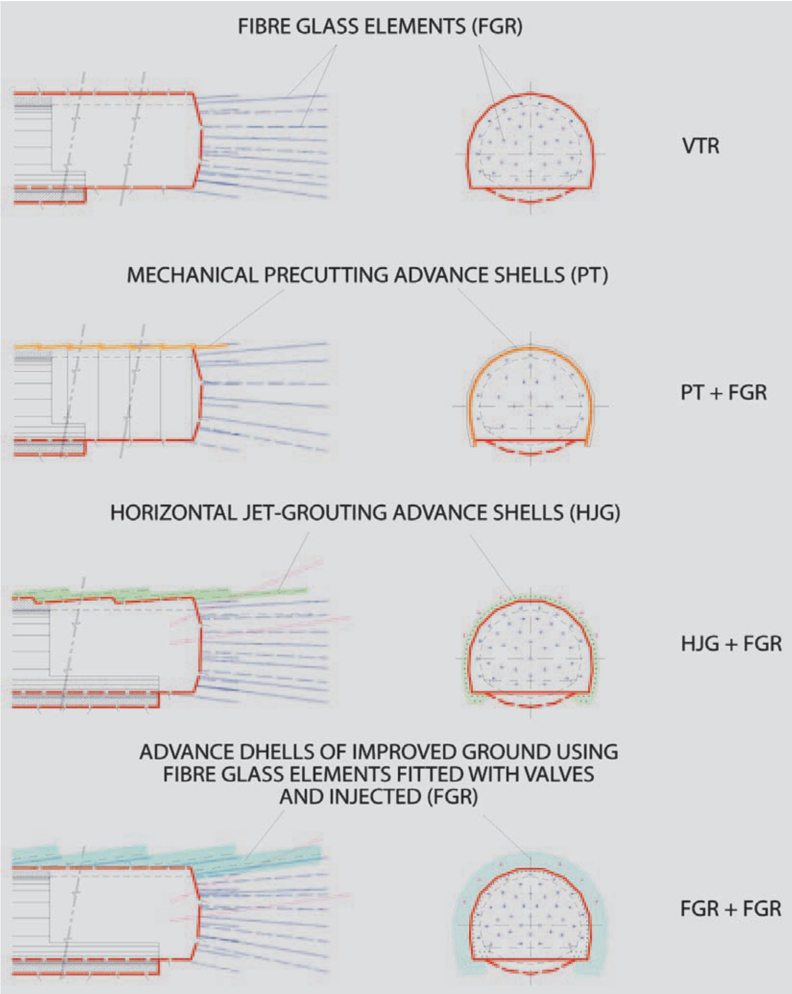

Fig. 6 Types of advance core reinforcement using fibre-glass elements.

Bild 6 *Möglichkeiten der Verstärkung des Bereichs vor der Ortsbrust mittels Glasfaserelementen.*

applying these concepts. There is also the advantage of being able to plan tunnel advance in all types of ground by industrializing works (observance of time schedules and costs) and applying even the most rigid quality assurance regulations.

In the ADECO-RS approach, the conservation techniques for preconfining the cavity were designed to deal with all those situations where tunnel advance is not possible or possible only with great difficulty using traditional methods because of the huge deformation that would be triggered at the face and around the cavity. The main advantages of the method are:

- Full face advance always with obvious benefits in terms of site organisation and the elimination of the delicate phase when bench has to be excavated,
- Site cleanliness and safety even at the face,
- Industrialized tunnel advance; excellent production rates, constant and above all certain,
- Certainty concerning costs, which are often lower, when work is finished, than what the project would have cost using traditional technology,
- High flexibility; a wide range of different types of grounds can be tackled with one set of equipment (Figure 6).

Reinforcement of the advance core part of preconfinement of the cavity

Preconfinement of the cavity can be achieved using different techniques depending on the type of ground (natural consistency), the stress states in question and the presence of water. Intervention that takes place ahead of the face (designed to prevent relaxation and loosening of the ground and to conserve the principal minor stress σ_3 at levels above zero) is defined as "conservation" intervention as already mentioned. The types are as follows:

Fig. 7 Reinforcement of the advance core with fibre-glass elements: examples of use.

Bild 7 *Anwendungsbeispiele für die Verstärkung des Bereichs vor der Ortsbrust mit Glasfaserelementen.*

REFERENCE PROJECT		TUNNEL LENGTH	TYPE OF	Max overburden	Ø	FEATURES OF THE ADVANCE CORE REINFORCEMENT					
WORK	TUNNEL	[m]	GROUND	[m]	[m]	TIPOLOGY	TYPE OF ELEMENTS	LENGTH [m]	NUMBER	INTENSITY [n/sq.m]	MATERIAL
	Talleto	2700	Sandy silts	60	7	PT + FGR	Tubular	15	25	0,35	Fibre glass
ROME-FLORENCE	Caprenne	2700	Sandy silts	60	7	PT + FGR	Tubular	15	25	0,35	Fibre glass
HIGH SPEED	Poggio Orlandi	850	Sandy silts	60	13	FGR	Tubular	15	50	0,43	Fibre glass
RAIL LINE	Crepacuore	700	Sandy silts	50	13	FGR	Tubular	15	50	0,43	Fibre glass
[1988]	Tasso	2000	Sandy silts	90	13	FGR	Tubular	15	60	0,51	Fibre glass
	Terranova Le Ville	2600	Lacustrine deposits	90	13	FGR	Tubular	15	60	0,51	Fibre glass
CASERTA-FOGGIA RAIL LINE [1991]	S. Vitale	2500	Scaly clays	100	12	FGR + FGR	Tubular	18	49 + 50	0,41	Fibre glass
ANCONA-BARI RAIL LINE [1993]	Vasto	5000	Silty clays	135	12	HJG + FGR	Tubular	18	55	0,45	Fibre glass
ROME METRO LINE A [1997]	Baldo degli Ubaldi	120	Clays and sandy silts	22	22	PT + FGR	Flats	25	47	0,37	Fibre glass
T.G.V.MEDITERRANEE MARSIGLIA-LIONE "G.V." RAIL LINE [1998]	Tartaiguille	900	Over-consolidated clays	110	15	FGR	Flats	24	90	0,5	Fibre glass

- Protective conservation, when the stresses around the advance core are channelled to produce a protective action that ensures that the natural strength and deformation characteristics of the core are conserved (e.g. shells of ground improved by means of sub-horizontal jet-grouting, shells of fibre reinforced mortar of concrete created by means of mechanical pre-cutting);
- Reinforcement conservation, when the action is applied directly to the consistency of the advance core to improve its natural strength and deformation characteristics by appropriate reinforcement techniques (e.g. reinforcement of the core using fibre-glass structural elements).

It is important to make it clear that this intervention must be considered as complementary to the traditional techniques of simple confinement of the face and cavity, since their effectiveness depends on the continuity and regularity of the passage from preconfinement of the cavity (ahead of the face) to confinement of the cavity (in the tunnel, back from the face).

Concentrating on those preconfinement techniques based on improving the advance core with fibre-glass reinforcement (FGR), it is interesting to observe that this technique comes in four different types, depending on the type of ground and the stress-strain situation to be tackled (see Figure 4):

- Fibre-glass reinforcement (FGR): simple reinforcement of the core by means of fibre-glass reinforcement (indirect conservation technique),
- Pre-cutting plus fibre-glass reinforcement (PT + FGR): strengthening of the advance core by means of fibre-glass reinforcement and simultaneous protection of the core by means of advance shells of shotcrete around it by means of mechanical pre-cutting (mixed conservation technique),
- Horizontal jet-grouting plus fibre-glass reinforcement (HJG + FGR): strengthening of the advance core by means of fibre-glass reinforcement and simultaneous protection of the core by means of advance arches of improved ground around it by means of horizontal jet-grouting (mixed conservation technique),
- Fibre-glass reinforcement plus fibre-glass reinforcement (FGR + FGR): reinforcement of the core by means of fibre-glass reinforcement and simultaneous protection of the core by means of advance shells of improved ground around it using fibre-glass elements, fitted with valves, inserted ahead of the tunnel and injected with grout (mixed conservation technique).

For each of these types an example of its use can be found in the table in Figure 7 where it was tried out for the first time or some change was made to it. It is perhaps worthwhile at this point looking at the history of the technology.

Fig. 8 Florence-Arezzo High Speed Rail Line, Terranova Le Ville Tunnel: view of the face reinforced with fibre-glass structural elements.

Bild 8 *Hochgeschwindigkeitsstrecke Florenz-Arezzo, Tunnel Terranova Le Ville, Ansicht der mit Glasfaserelementen verstärkten Ortsbrust.*

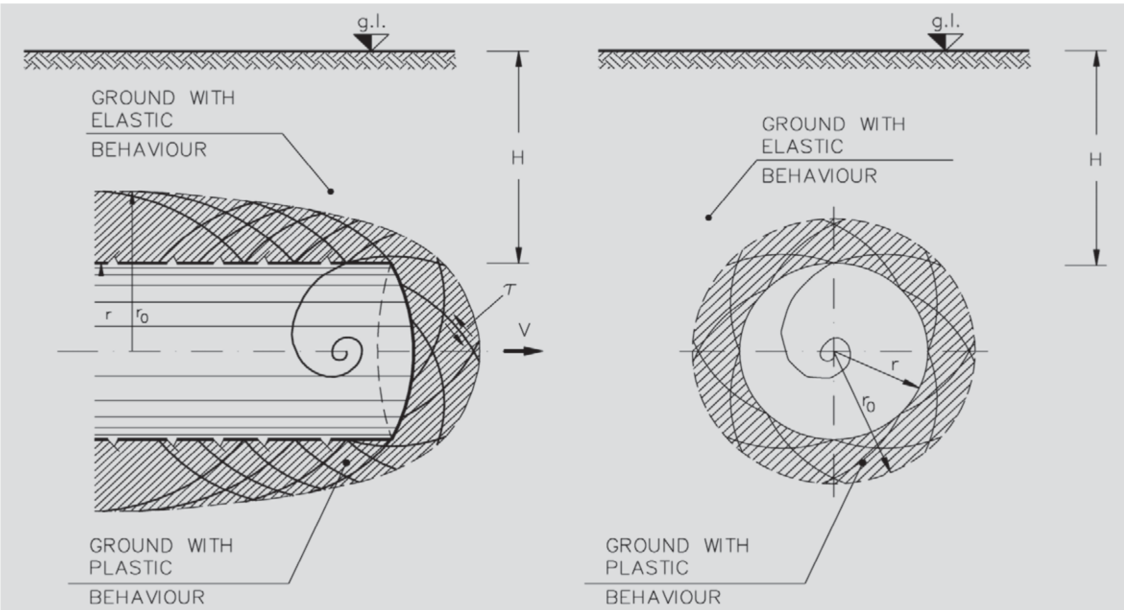

Fig. 9 Mathematical model for calculating dimensions for advance core reinforcement technique.

Bild 9 *Mathematisches Modell für die Dimensionierung der Verstärkung des Bereichs vor der Ortsbrust.*

Fig. 10 Samples of fibre-glass tubes.

Bild 10 *Bauarten von Glasfaserröhren.*

History

If strengthening of the face using fibre-glass reinforcement is considered on the same level as any other roof bolting intervention used occasionally for brief stretches of tunnel as a countermeasure to prevent fall-in from the face, then it is difficult to put a date on the first use of the practice.

If, however, in the light of what has been said, strengthening of the advance core by means of fibre-glass reinforcement is seen more correctly as a true and genuine construction technology to be applied systematically in average to extreme stress-strain conditions to obtain complete control over deformation phenomena (and of the subsequent surface subsidence when necessary), then its introduction to tunnelling practices can be dated with certainty as occurring in 1985 when it was tried out for the first time in the world by the authors during the construction of some tunnels on the Florence-Arezzo section of the new high speed railway line between Rome and Florence (the Talleto, Caprenne, Tasso, Terranova Le Ville (Figure 8), Crepacuore and Poggio Orlandi tunnels).

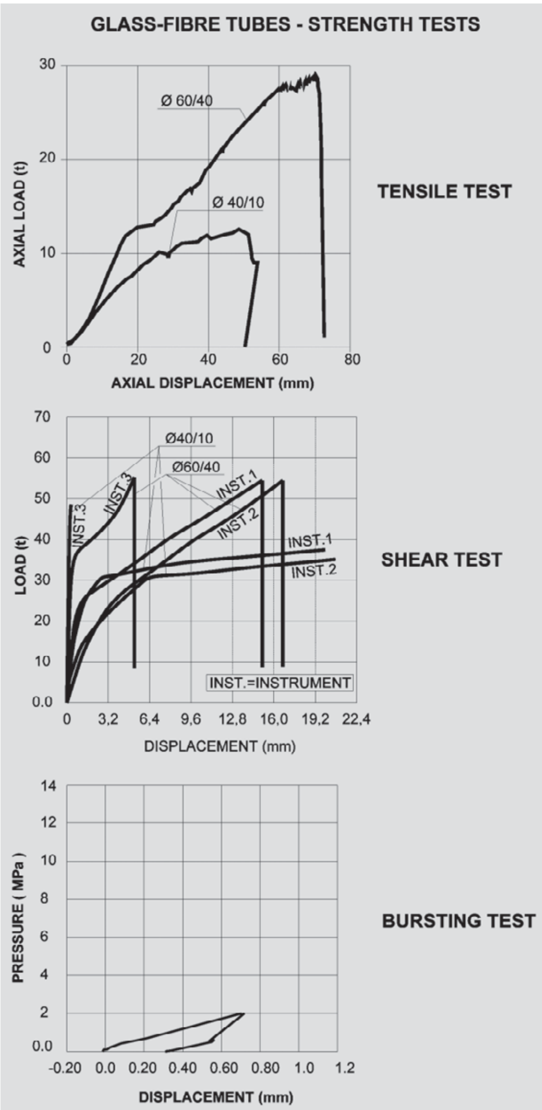

Fig. 11 Strength tests of smooth and corrugated fibre-glass tubes.

Bild 11 *Festigkeitsuntersuchungen an glatten und profilierten Glasfaserröhren.*

The idea began to make headway in the authors´ minds as part of the effort to develop the ADECO-RS approach (which, as has been said, is based on an analysis and on the control of the deformation response of the ground to excavation, and is practised by adjusting the rigidity of the advance core) after resort was made with success to placing roof bolts in the face to counter fall-in phenomena which occurred without fail after work halted each weekend, during the construction of tunnels through clay on Sibari-Cosenza rail line (1984).

On that occasion the intervention consisted of simply pushing a certain number of steel roof bolts, Ø 24 mm and 4 m in length, into the face using the excavator bucket and a small cross piece was attached to the end of them. The work which was then completed with the placing of a small mantle of shotcrete turned out to be very effective since when work recommenced on Monday, it was sufficient to pull out the bolts gripping them by the cross piece and resume tunnel advance with no problems.

The authors were convinced of the importance of the rigidity of the advance core for controlling deformation in the tunnel. It was a conviction that had developed with positive confirmation from experimental observation of the stress-strain behaviour of a few difficult tunnels driven full face with core protection only (horizontal jet-grouting, mechanical pre-cutting) beforehand. The authors started to study the possibility of artificially increasing the rigidity of the core until the desired level of strength was reached. Reinforcing the advance core with special systematic bolting capable of ensuring significant increases in the strength and deformation of cores treated, but not hindering demolition during excavation, seemed a project worth studying.

Once fibre-glass was identified as the most suitable material for all the purposes considered, operational methods were studied to implement the technology checking its effectiveness against a store of original mathematical modelling methods on computers (Figure 9). At this point the new technology needed to be tried out in the field.

Tunnels on the new high speed Rome-Florence rail line (1985)

The chance presented itself soon when the poor quality of the geological formations through

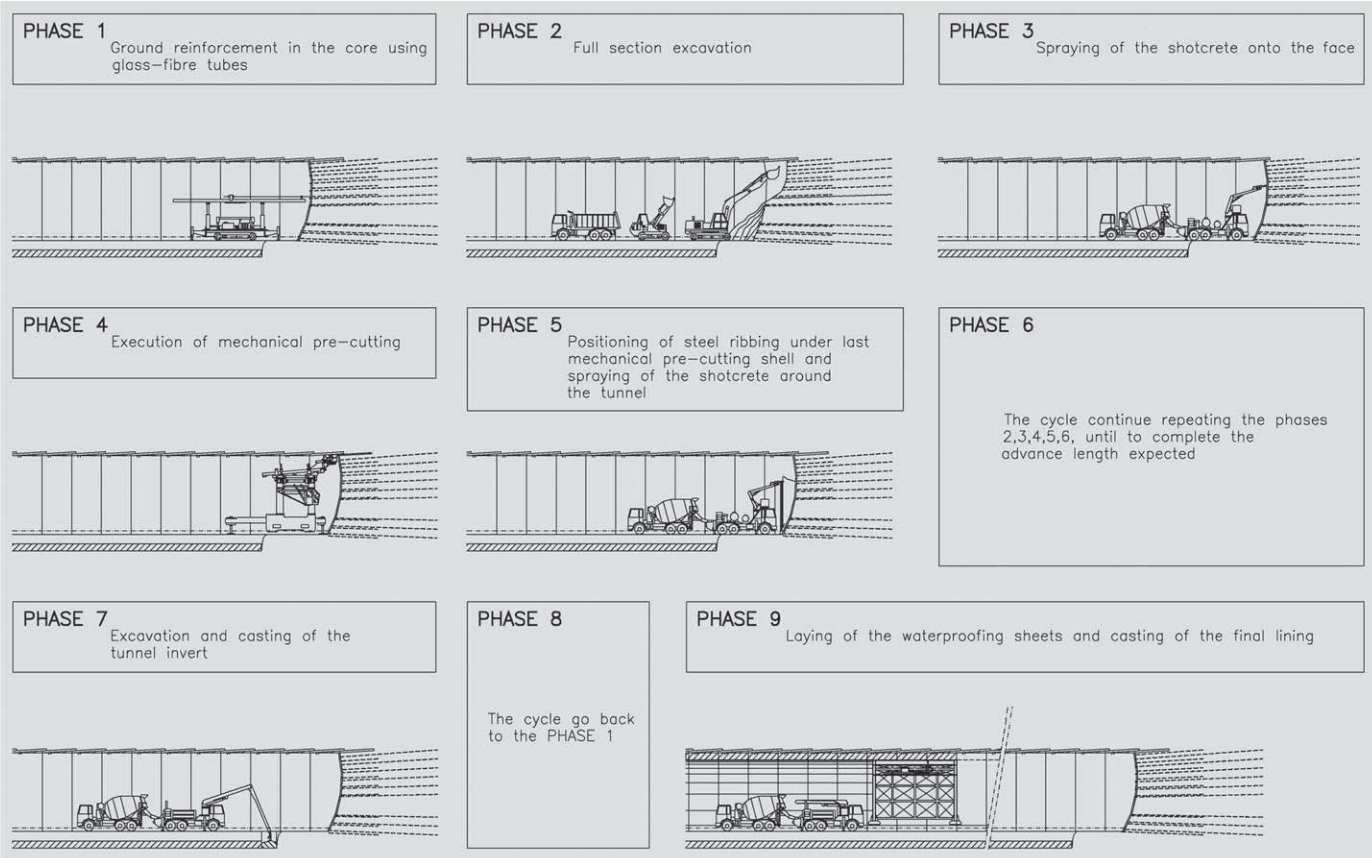

Fig. 12 Work cycle adopted for the Caprenne and Talleto tunnels.
Bild 12 *Arbeitsablauf in den Tunneln Caprenne und Talleto.*

which tunnels on the new high speed Rome to Florence rail line were to pass caused serious problems resulting in the halt of works and the redesign of the works.

Thanks to the courage and farsightedness of Ferrovie dello Stato (Italian state railway) officials and of the contractors (Ferrocemento S.p.A. and Fondedile S.p.A.) and to the trust they obviously placed in Professor Lunardi, it was decided to try out the new technology that had been proposed to them and so the whole line under construction between Florence and Arezzo became a huge experimental tunnelling site.

It is interesting to look briefly at the principal characteristics of these first works, not to mention the tests, the monitoring and the most significant measurements that were carried out or that started to be developed in that pioneering construction site.

Fibre-glass structural elements

There was no choice but to select the fibre-glass structural elements from among those on the market, taking account also of transport considerations. A tube shape was chosen with 60 mm outer diameter, 10 mm thick and a length of 15 m. Both smooth tubes and corrugated tubes were tried for better adherence to the mortar cement (Figure 10).

Figure 11 gives a summary of the results of the strength tests performed at the time. They were indispensable for deciding the dimensions

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of the intervention (shear and tensile strength) and for establishing the operating parameters to use for the mortar injections (bursting strength).

Geometry and parameters for characterizing reinforcement of the advance core

The first reinforcement was performed with the following parameters (see Figure 1):

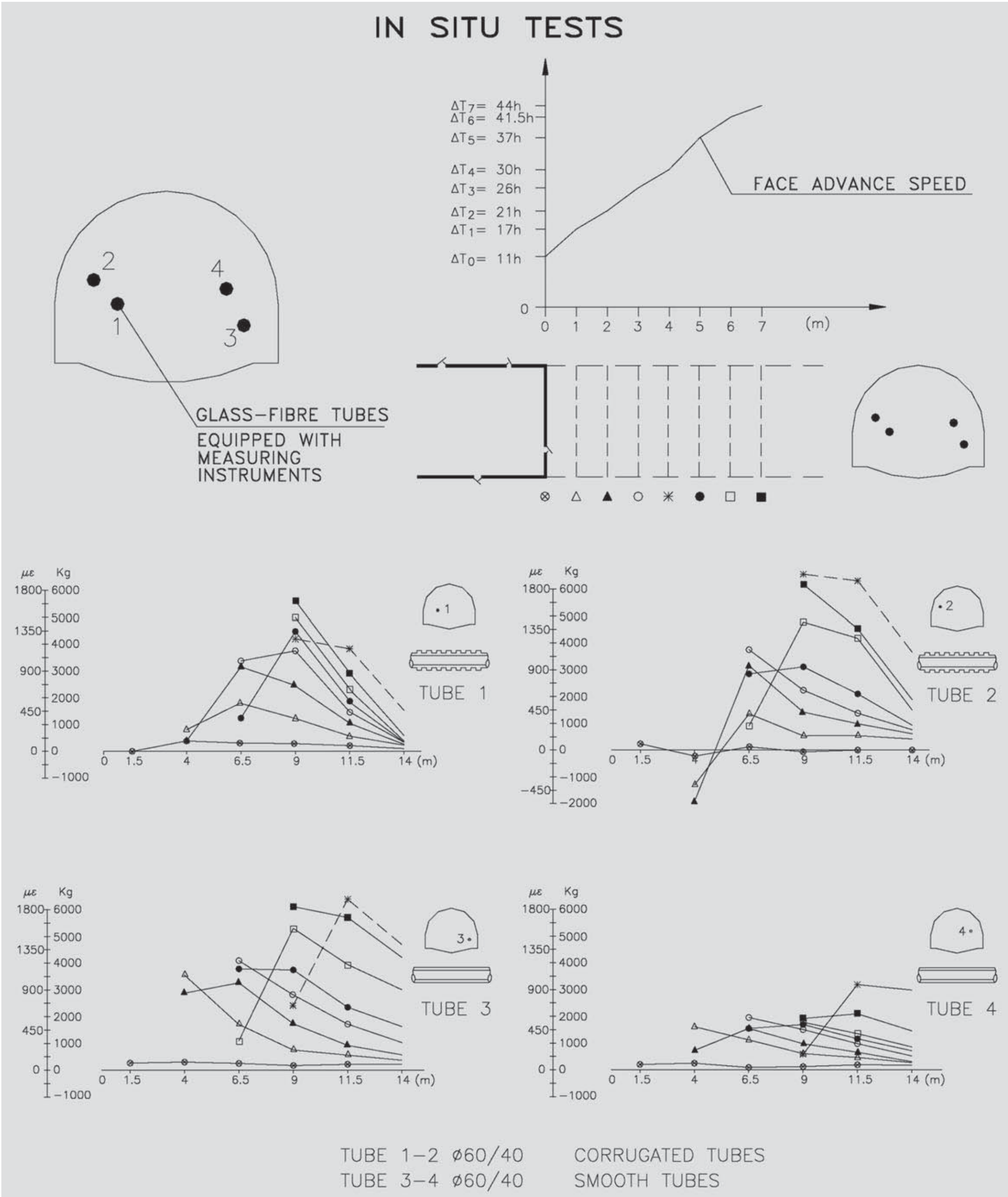


Fig. 13 Poggio Orlandi tunnel: results of strain measurements in instrumented fibre-glass tubes.

Bild 13 *Ergebnisse von Dehnungsmessungen an instrumentierten Glasfaserröhren im Tunnel Poggio Orlandi.*

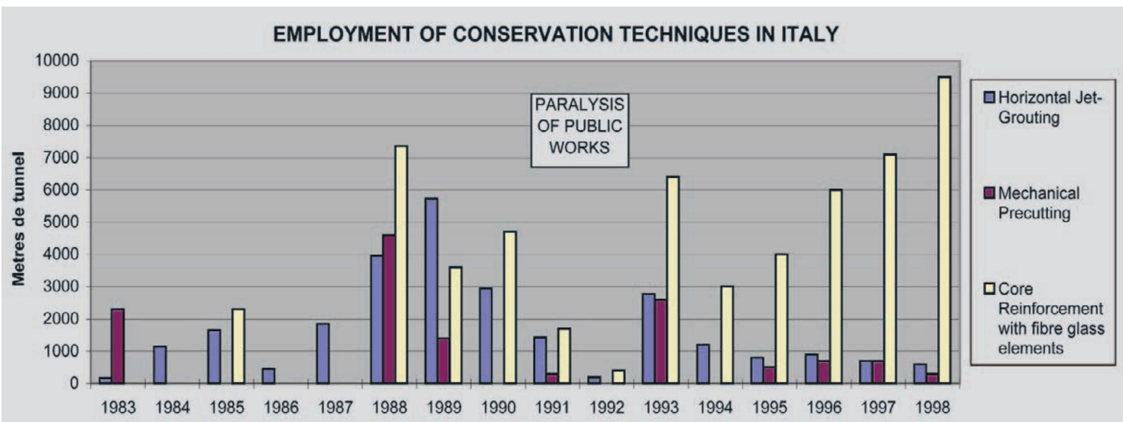


Fig. 14 The use of technology involving advance core reinforcement in Italy.

Bild 14 *Anwendung der Verstärkung des Bereichs vor der Ortsbrust in Italien.*

- Length of each reinforcement advance step: L = 15 m,
- Resistant cross section of fibre-glass elements: Ø = 60/40 mm,
- Density of the reinforcement: I = 0.35 to 0.51 elements/m²,
- Overlap between advance steps: S = 5 m.

Tunnel advance was full face with the tunnel invert and the kickers placed at a maximum distance from the face of 1.5 times the diameter of the tunnel. The face was concave in shape to favour the natural mobilization of a longitudinal arch effect.

Figure 12 shows the operating cycle adopted for the excavation of the Caprenne and Talleto tunnels in the sections where face reinforcement was combined with mechanical pre-cutting (PT + FGR).

In situ tests and measurements

Numerous in situ tests and measurements were performed during tunnel advance for in-depth study of both the nature of the interaction between the fibre-glass elements and the surrounding ground (deformation and extraction tests, Figure 13), and the effect of the reinforce-

Fig. 15 Caserta to Foggia rail line, San Vitale tunnel: reinforcing the advance core using tubular fibre-glass elements.

Bild 15 *Tunnel San Vitale auf der Eisenbahnlinie Caserta-Foggia: Verstärkung des Bereichs der Ortsbrust mit röhrenartigen Glasfaserelementen.*

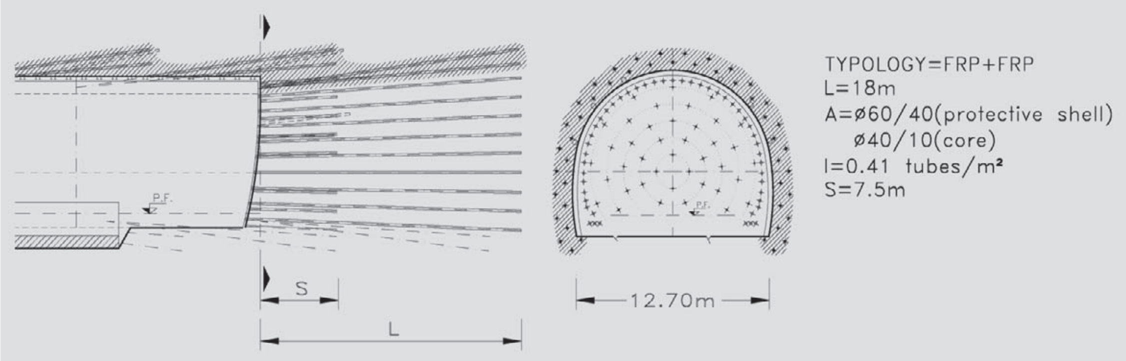
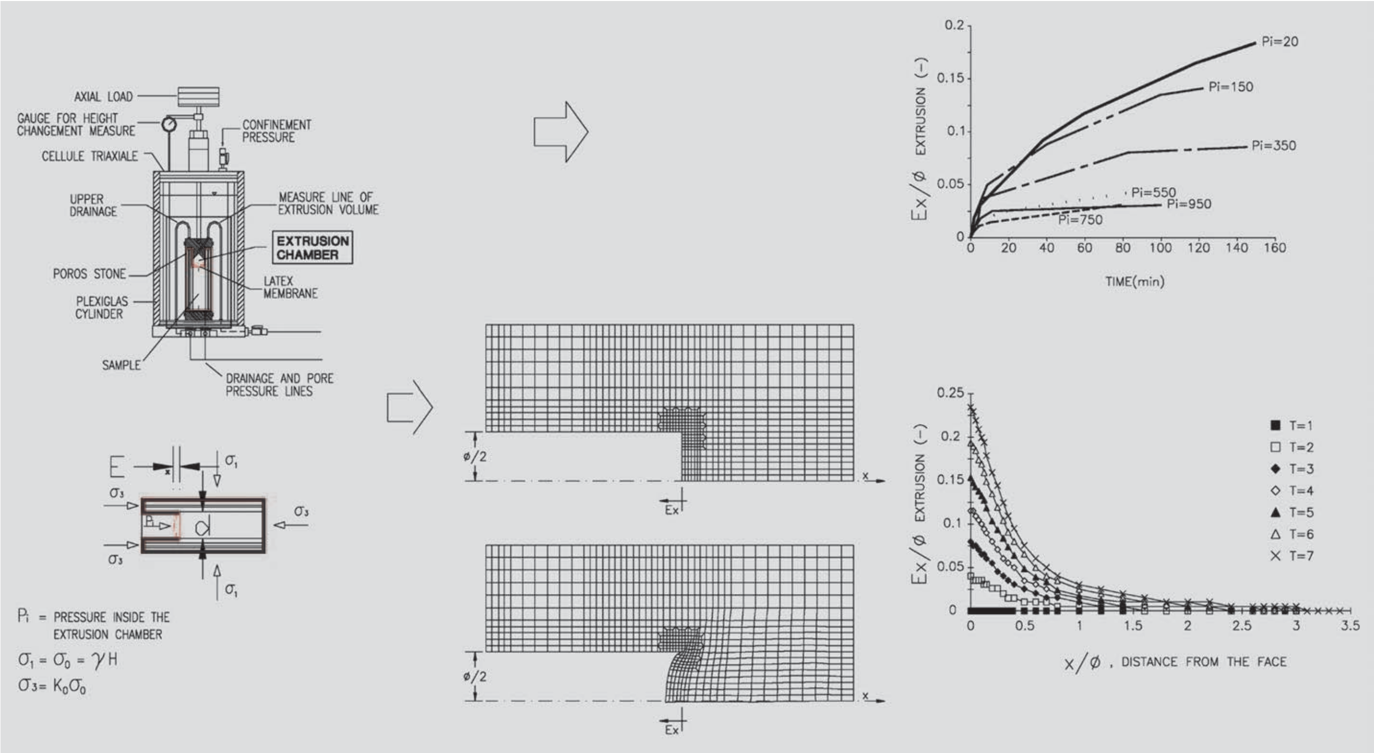


Fig. 16 San Vitale tunnel: longitudinal and cross section.

Bild 16 *Tunnel San Vitale: Längs- und Querschnitt.*

Fig. 17 Analysis of an extrusion test.

Bild 17 *Analyse eines Extrusionsveruchs.*



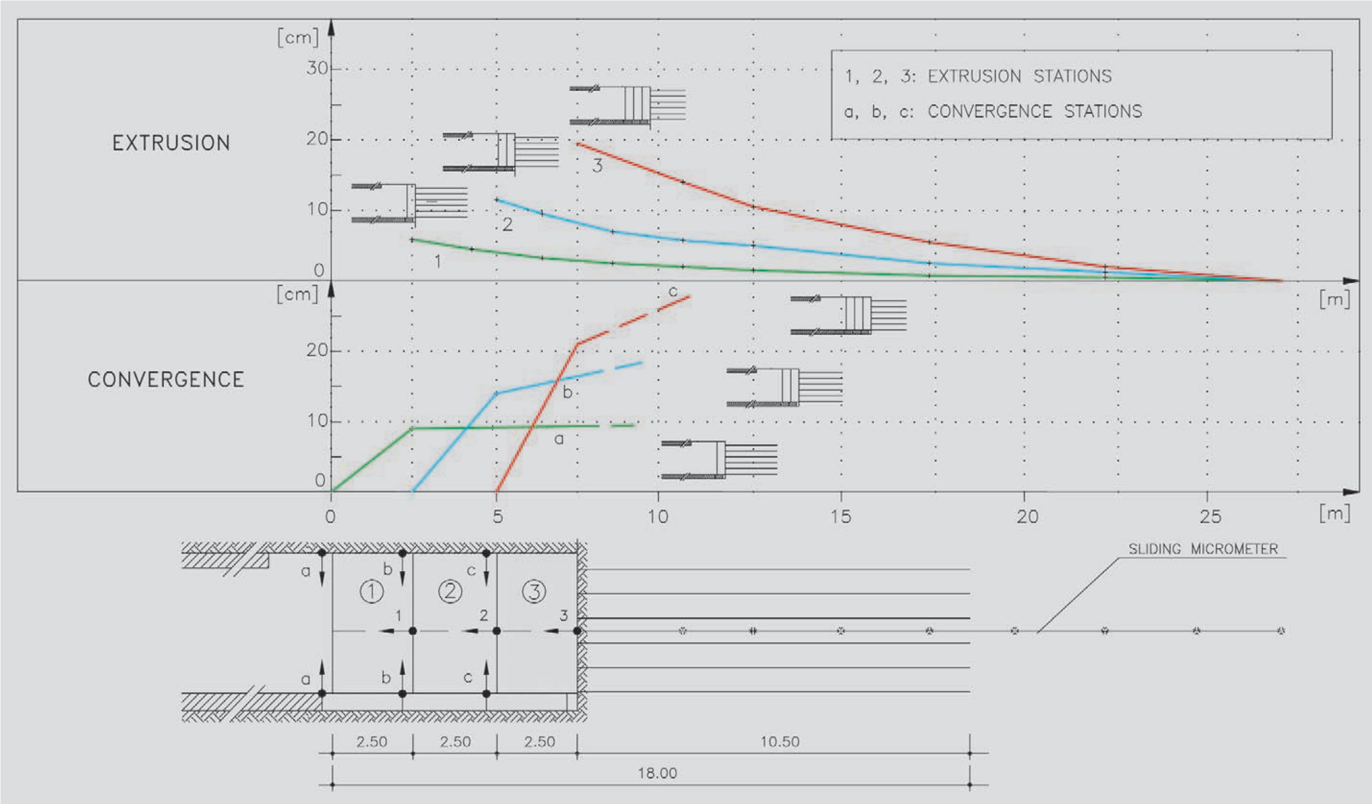


Fig. 18 San Vitale tunnel: combined measurements of extrusion and convergence.

***Bild 18** Tunnel San Vitale: Kombinierte Messungen von Längsverformungen und Konvergenz.*

ment of the advance core on the stress-strain behaviour of the cavity as it advanced under different degrees of reinforcement. Methods of measuring extrusion were developed precisely for this last purpose and were later to become widely used in tunnelling along with the more traditional convergence measurements. These measurements were performed by inserting incremental extensometers, 15 m in length, into the face, with measuring bases placed at intervals of 1 m.

The results of the extrusion, preconvergence and convergence measurements taken allowed to increase the theoretical knowledge of the stress-strain behaviour of a tunnel at the face considerably and they confirmed the effectiveness of the new technology in controlling deformation.

Spread of the technology

The successes achieved on the Florence-Arezzo line in driving more than 11 km of tunnel under

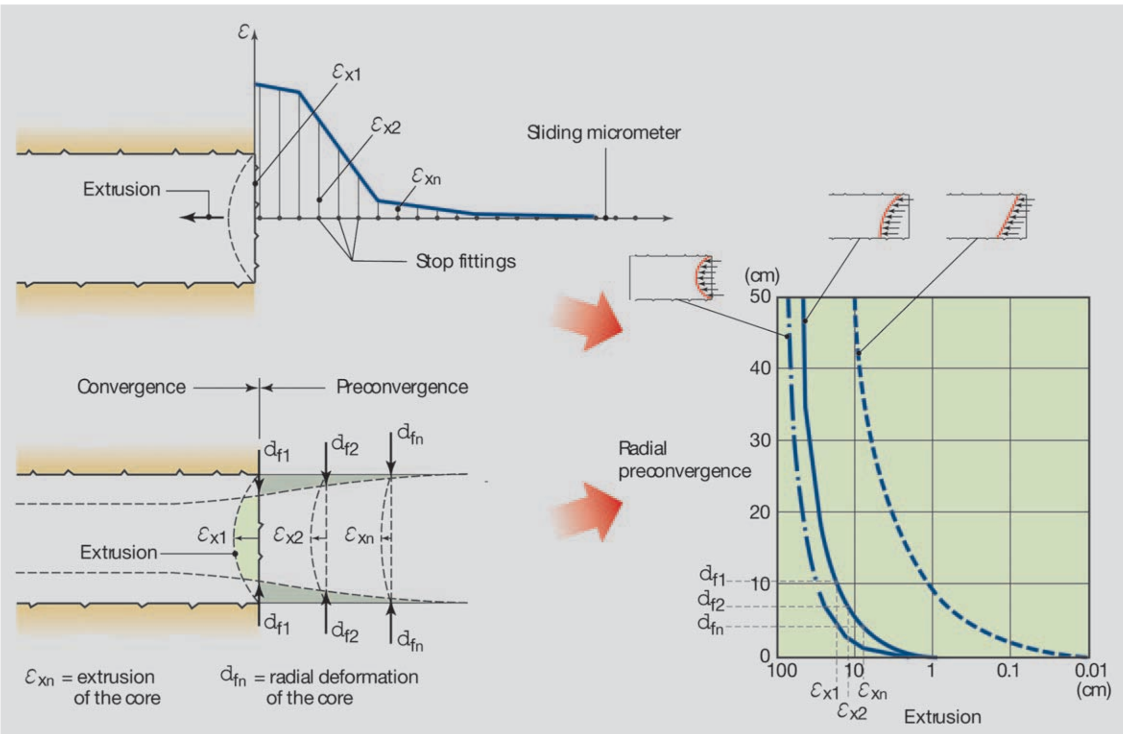


Fig. 19 San Vitale tunnel: calculation of pre-convergence.

***Bild 19** Tunnel San Vitale: Berechnung der Vorkonvergenz.*

objectively difficult conditions confirmed the complete reliability of the principles of full face advance in the presence of a rigid core through soft ground. This decreed the rapid spread of conservation methods for preconfinement of the cavity and, above all, of strengthening of the advance core with fibre-glass reinforcement as one of these (Figure 14).

Evolution of the technology

Since this technology of strengthening the advance core using fibre-glass reinforcement was first tried out it has evolved significantly in terms of design instruments, materials, different types and operating techniques. The main stages of this evolution are given below with reference to design examples (see Figure 7).

The San Vitale tunnel

The San Vitale tunnel (Caserta to Foggia State Railway line) (5) was driven in 1991 through the Argille Scagliose (scaly clays) in which traditional tunnelling methods had failed completely (Figure 15). The application of tunnel advance principles using a rigid core (ADECO-RS) made it possible to save the tunnel, which had been abandoned for over two years, and complete it with average advance rates of 50 m/month. Figure 16 gives a summary of the reinforcement and ground improvement parameters.

The difficulty of the task not only constituted a severe test for in-depth exploration of all the possibilities of the new technology, but also an opportunity for the development of new operating methods, new types of laboratory and in situ measurements and new three dimensional mathematical models capable of correctly simulating the effect of operations in the face-core zone on the stress-strain behaviour of the tunnel and on the entity of the long and short term loads on the linings:

- As regards operating methods, the type FGR + FGR (grouted fibre-glass in the face plus valved and injected fibre-glass in advance around the core) was introduced as opposed to PT + FGR which was little suited to the ground due to the difficulty in guaranteeing a continuous pre-cut shell,
- As regard measurements, new apparatus for performing triaxial extrusion tests was studied as well as for systematic measurement of extrusion which are extremely useful: the former in the diagnosis phase for predicting the behaviour category and in the therapy phase for deciding the intensity of the reinforcement needed to counter extrusion effectively (Figure 17), the latter in the operational phase to optimize the length of the reinforcement advance steps and their overlap (Figure 18),
- As regards mathematical models, in addition to refining 2D and 3D FEM models, special tables were calculated to furnish values and distributions of preconvergence ahead of the face for the first time (Figure 19).

Fig. 20 Ancona to Bari rail line, Vasto tunnel: excavation stage.

Bild 20 *Tunnel Vasto auf der Eisenbahnlinie Ancona-Bari, Vortriebsarbeiten.*

Fig. 21 Rome Metro: Baldo degli Ubaldi station: view of the face during the excavation stage.

Bild 21 *U-Bahn Rom, Bahnhof Baldo degli Ubaldi: Ansicht der Ortsbrust während der Ausbruchsphase.*

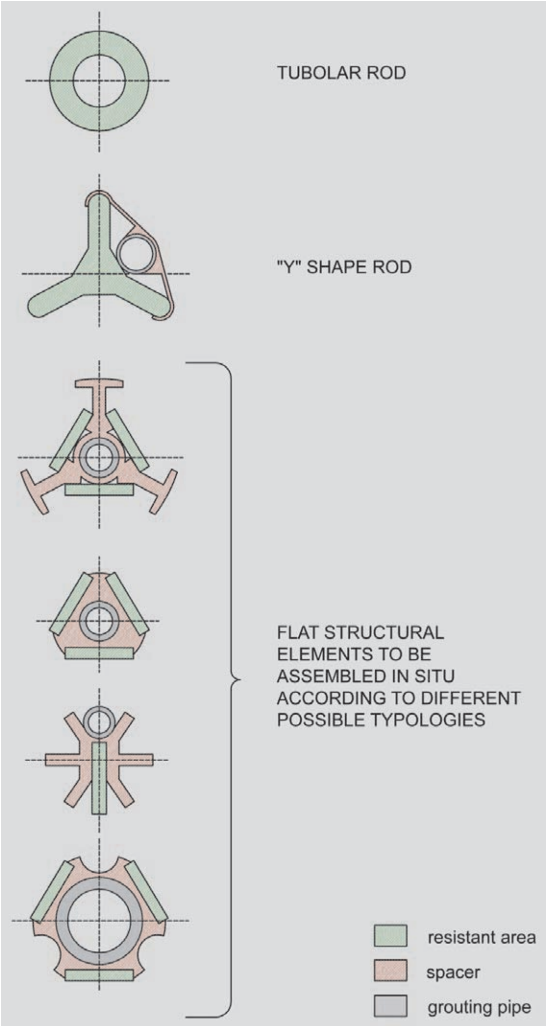


Fig. 22 Types of fibre-glass structural elements.

Bild 22 *Bauarten von Ausbauelementen aus Glasfasern.*

Fig. 23 TGV Méditerranée, Tartaiguille tunnel: View of the face reinforced with fibre-glass structural elements.

Bild 23 *Tunnel Tartaiguille, Linie TGV Mediterranée: Ansicht der mit Glasfaserelementen verstärkten Ortsbrust.*

The Vasto tunnel

The Vasto tunnel (Ancona to Bari State Railway line) (4) was driven in 1993 through a heterogeneous formation of silty clays containing sizeable sandy, water bearing, lentils. There was a passage with a shallow overburden (8 m) close to the southern portal under residential buildings. Here too, the use of traditional tunnelling methods (partial face advance and preliminary stabilization using steel ribs, radial roof bolts and shotcrete) had failed completely. Use of the ADECO-RS approach made it possible to complete the tunnel at an average speed of around 50 m/month. The combination of fibre-glass reinforcement in the face + horizontal jet-grouting in advance around the future tunnel was employed during construction for the first time (Figure 20). The Table in Figure 7 gives the reinforcement parameters.

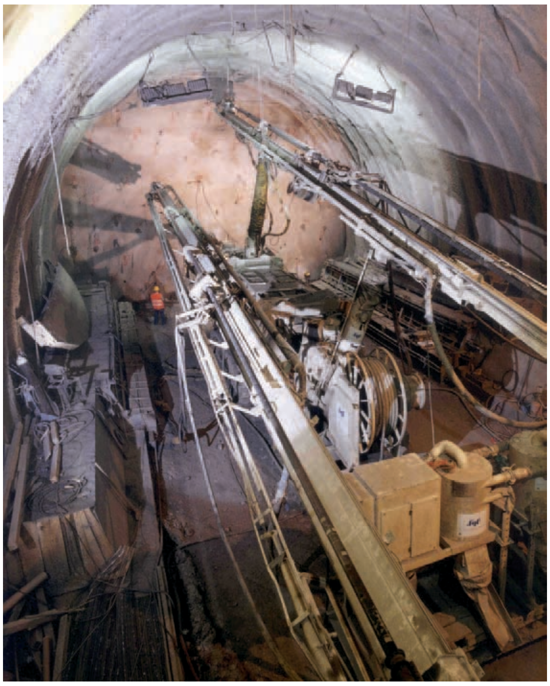


Fig. 24 Bologna to Florence High Speed Rail Line, Raticosa Tunnel: reinforcement of the advance core by using fibre-glass structural elements (ground: scaly clays of Chaotic Complex Formation, overburden: 500 m).

Bild 24 *Tunnel Raticosa auf der Hochgeschwindigkeitseisenbahnstrecke Bologna-Florenz: Verstärkung des Bereichs vor der Ortsbrust mittels Glasfaserelementen.*

The Baldo degli Ubaldi tunnel

The Baldo degli Ubaldi tunnel on the Rome Metro (a span of approximately 22 m and a cross section of 271 m^2) (6) was driven, in 1997, underground in the centre of the city through clays and sandy silts (Figure 21). Tunnel advance after first reinforcing the advance core was adopted both for the side wall drifts and for the subsequent top heading in the crown. Civil engineering works (excavation and lining of the station tunnel) required only 18 months of work at a cost of 568 EUR/m^3. Surface subsidence was practically negligible. A new innovative type of fibreglass reinforcement was adopted for this project, flat elements, which can not only be assembled in a wide variety of types (Figure 22), but are also very easy to inject and to transport, allowing reinforcement advance steps of 25 m as opposed to only 15 to 18 m with the tubular reinforcement. Table in Figure 7 gives the parameters that characterize this type of reinforcement.

The Tartaiguille tunnel

The Tartaiguille tunnel (TGV Mediterranée, Marseilles to Lyons “G.V.” Line) was driven in 1998 through the argile du Stampien, a very strongly swelling formation (75 % of the content is montmorillonite) (Figure 23). Given the increasing difficulty in advancing using traditional systems, the French railways asked leading European tunnel designers to put forward alternative proposals for completion of the remaining 900 m of tunnel (15 m outer diameter) in safety and within the deadline for the commissioning of the railway line. The almost unanimous opinion was that the tunnel could not be completed by the required deadline. The only exception was the proposal put forward by Professor Lunardi to use full face advance after first reinforcing the advance core according to the principles of the ADECO-RS approach. This proposal guaranteed completion of the tunnel on schedule and within the budget with minimum advance rates of 1.4 m/d. The tunnel was actually finished without any problems ahead of schedule with average advance rates of approximately 1.5 m/d (during the last five months with production at full speed, advanced rates actually reached 1.7 m/d). Important studies were performed during construction of the Tartaiguille tunnel on different types of extrusion and on the importance of the distance at which the tunnel invert is placed from the face when advancing with a stiffened advance core to minimise extrusion surface.

More recently advance core reinforcement and the ADECO-RS design approach of which it forms part have been and are being used with excellent results in the construction of over 100 km of tunnels in extremely varied types of ground and stress-strain conditions on the new high speed Bologna-Florence railway line (Figure 24 and 25).

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Fig. 25 Bologna to Florence High Speed Rail Line, Raticosa Tunnel: view before casting the invert near the face.

***Bild 25** Tunnel Raticosa auf der Hochgeschwindigkeitseisenbahnstrecke Bologna-Florenz: Blick in den Vortrieb vor dem Betonieren der Sohle nahe der Ortsbrust.*

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