Proceedings of the World Tunnel Congress 2014 – Tunnels for a better Life. Foz do Iguaçu, Brazil.

The reinforcement of the core-face: history and state of the art of the Italian technology that has revolutionized the world of tunnelling. Some reflections.

P. Lunardi
Lunardi Geoengineering, Milan, Italy

R. Bindi, G. Cassani
Rocksoil Spa, Milan, Italy.

ABSTRACT: Systematic reinforcement of the core-face of a tunnel using glass-fiber elements as a structural component to stabilize it in the long and short term is a practice developed in ltaly that has been used for over twenty-five years.
During this period significant developments for core-face reinforcement technique have occurred in design approach, construction technologies and materials. This paper illustrates these developments and goes deeply in the very origin and reason of core-face reinforcement using fiber glass elements.
What has in fact to point out, after decades of studies and application, is that this practice is not to be intended just as a simple stabilization tool, as often considered starting from limit equilibrium models, but above all as an instrument to control deformation and induced settlements.

1 INTRODUCTION

If strengthening of the core-face using fiber glass reinforcement is considered just as an occasional roof bolting intervention to prevent fall in from the face, then it is difficult to put a date on the first use of the practice in tunneling.

If instead strengthening of the advance core by means of fiber glass elements is seen more generally as a construction technology to be used systematically when driving a tunnel, then its introduction to tunneling practice can be dated with certainty as occurring in 1985, almost thirsty years ago. It was in Italy during the construction of some tunnels of the new high speed railway line between Florence and Rome (the Talleto, Caprenne, Tasso, Terranova, Le Ville, Crepacuore and Poggio Rolando tunnels) for a total length of about 11,0 km.

2 THE ADECO – RS APPROACH

The idea began to make headway in the authors' mind as part of the effort to develop the ADECO–RS approach to tunnel design and construction at the beginning of the '80s.

ADECO–RS approach is based on two main concepts:

- the centrality of the deformation response of the ground during excavation, which the tunnel engineer has to be able to fully analyze and then control;
- the use of the advance – core of the tunnel as a stabilization tool to control deformation response and to get a prompt stability of the excavation.

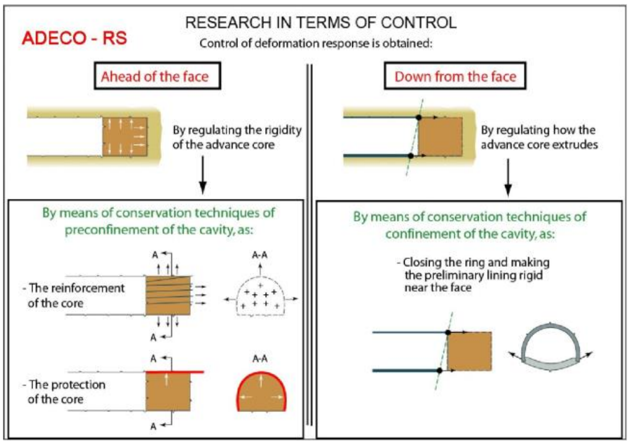

Figure 1. The ADECO–RS approach for tunneling

After more than 30 years it has been widely demonstrated that it is possible to safely and efficiently drive tunnel in every geomechanical and in situ stress context, even in the most critical conditions, working full face and reinforcing in different ways the core - face of advance.

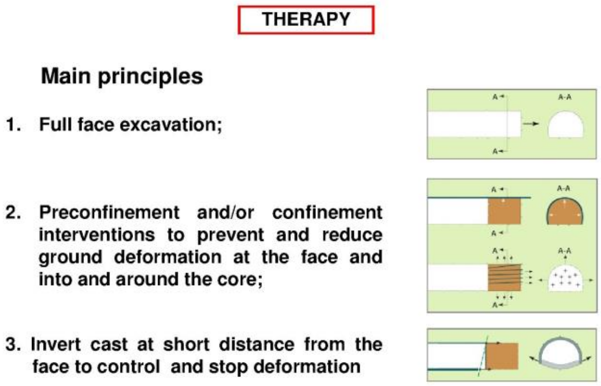

Figure 2. ADECO–RS main principles

Main advantages of this approach are:

- industrialization of the works

one of the great innovation of ADECO-RS is the simplification and cleanliness of the construction operations to be realized to drive a tunnel. With comparison to the past tunnel practice, there are always few workers working into the tunnel (not more than six person in each stage of construction), with few and powerful machines and equipments to be used (because of the important spaces given by the full face section), with a clear sequence of operations.

There is never a superposition of different kind of interventions or operations. All these aspects lead to an industrialization of the work into the tunnel:

- increasing of the safety for the workers

there is a direct relationship between the number of the workers and of the machinery and safety: the less they are, the great is the safety;

- excellent production rates

in every kind of ground and with whatever overburden it is possible to ensure 1- 4 m/day of advance rate in tunnels with a cross section of about 160 m^2.

- certainty of costs

the deep understanding of the deformation response to be expected during excavation and the correct design of the necessary interventions to be adopted to control it, are the key point to have a good design, ensuring sure time and costs of construction for the tunnel.

Figure 3. Core-face reinforcement in the ADECO–RS approach for tunneling

To deal with all possible situations it is necessary, especially in the worst geomechanical conditions, to act as soon as possible to prevent deformation to develop around the cavity, this experimental evidence brought to concept to work with a reinforcement and strengthening of the core – face to counteract deformation at its real onset, that is usual from 1 to 2 diameter ahead of the face of excavation, deep inside the core of advance.

This is at the end the great innovation introduced by ADECO-RS with respect to other tunnel design approaches: to control efficiently deformation in bad soils (clays, sands, soft and weak rock) to act just from inside the cavity may be ineffective, a preconfinement action has to be applied.

Preconfinement of the cavity can be achieved using different techniques depending on the type of ground, the in situ stress and the presence of water. For instance sub horizontal jet grouting, fiber glass elements, injections by TAM (*Tubes A Manchettes*), etc. may be used to get an efficient reinforcement of the core and face.

In the ADECO–RS approach interventions put in place ahead of the face to prevent relaxation and deformation of the ground are defined as “conservative”.

There are two different kind of interventions:

1) protective conservation is the one realized in advance working around the perimeter of the cavity to form a protective shell around the core able to

reduce deformation on the core-face system;

2) reinforcement conservation is the one realize directly into the core of advance to improve its natural strength and deformation parameters.

Systematic fiber glass reinforcement of the advance core is a typical conservative measure introduced by ADECO–RS in tunneling practice.

This intervention is not to be seen simply as a traditional soil nailing dimensioned at equilibrium limit, its aim in fact is not just the stabilization of the face as in traditional tunnel face bolting, but also the reduction of deformation of the ground by improving the characteristics of strength and elasticity of the ground. In several discussion the authors had on ADECO–RS all around the world in the last years this was the less understood point of the approach. Face grouting is not be dimensioned just as a stabilizing element but as a tool to reduce ground deformation at the necessary intent, that stays as close as possible to the elastic limit.

3 FIBER GLASS REINFORCEMENT

The technology mainly consists of dry drilling a series of holes into the tunnel face; fiber glass elements are then inserted in the holes and injected by cement mortar. It may be applied in cohesive o semi cohesive soils and in soft rocks and combines great strength properties of the material with high fragility, never becoming an obstacle for excavation.

Figure 4. Core-face reinforcement in clayey materials

Length, number, overlap, cross – section area and geometrical distribution of the reinforcement constitute the parameters that characterize this reinforcement technique.

Starting from its first application in 1985 there was some sort of evolution with respect to these parameters: this evolution came out first of all from design and construction experience and then from the evolution of the fiber glass elements themselves, but also of the machines used to drill and to install the reinforcement.

Figure 5. Core-face reinforcement in cemented sand

For instance in 1985 the usual length of these elements was 15 m and the overlap between one grouting intervention and the other could vary between 5 and 6 m. Nowadays, thanks to the improvement of the equipments to be used for fast horizontally drilling into the tunnel, it is possible to reach 24 m of length for the fiber glass elements and the overlapping may vary between 6 and 12 m. This innovation allowed a best control of deformation of the core – face, especially in tunnels with a great diameter, and a further increase in the rate of advance of excavation: the longest the fiber elements are, the less it is necessary to stop to perform a new grouting intervention.

Figure 6. Core-face reinforcement in soft rock

In the years these machines became very fast in drilling: in about 20 minutes it is possible to drill, insert and inject one fiber glass element 24 m long. This means that usually an intervention of grouting realized at the face with fiber glass elements for a tunnel with a cross section of about 160 m^2 with 90 – 100 elements 24 m in length may last between 18 and 24 hours.

This big improvement in realizing the grouting interventions, allows for instance in clays and soft rocks, for the above described section, to reach a production of 35 – 40 m/month. This production includes also the final lining casting and may be intended as the rate to get the completion of the tunnel (grouting, excavation and final lining).

In the years several fiber glass profile were tested and adopted. The first element to be used was a 40/60 mm pipe; this showed to be very good but had a big problem of transportation and it was very difficult to have elements with length greater than 15 m, because to transport longer pipes would be very much expensive requiring a non standard shipping.

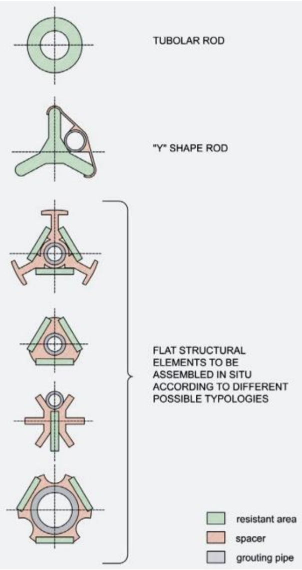

Figure 7. Fiber glass element profiles

To solve this problem and to reduce the final cost on site of the fiber glass elements, special profiles were introduced using band of fiber glass differently composed together. These elements are more flexible than pipes and can be rolled and transported in length up to 24 m. They are then assembled on site.

Another important issue to be treated talking about the execution of a core-face reinforcement using fiber glass elements is cementation. When inserted into the hole, the element is then cemented to fill the drilling hole. The system works using the adherence between the grout itself and the ground. The greatest is the adherence, the most effective is the core-face reinforcement.

Figure 8. Core-face reinforcement execution – insertion of the fiber glass element

Figure 9. Core-face reinforcement execution – drilling

Several efforts were made in these almost thirty years to improve adherence: one of the most important was the use of expanding mortars. The expansion is obtained using several agents to be mixed together with the cement in the injected grout. These new mortars had a great success in the middle of the '90s because of the increase of adherence they are capable of. The first systematic application was in the some tunnels of the Bologna – Florence High Speed railway line in 1997.

These mortars are constituted mixing on site cement and an alluminate expanding agent: this operation requires to be realized very carefully to get the expansion when the hole is completely filled by the grout and not before. Otherwise the intervention should become completely ineffective. It has also to be noted that an excess of expansion would produce an immediate reduction of the strength of the mortar. For this reason expanding mortars need very careful application and skilled specilized workers, but they offer to reach very good results in term of adherence increasing, which in very difficult geomechanical condition may become indispensable.

More recently the P.E.R. ground element was introduced in the Italian market: this element is a fiber glass element constituted by a corrugated pipe coated by an expandable sheath designed to hold the injected mixture inside the drilled hole and to exert an effective recompression of the soil. Also with this element is proven to get very good results with regards to adherence.

Figure 10. P.E.R. ground elements

Numerous in situ tests and measurements were performed during tunnel advance for in – depth study of both the nature of the interaction between the fiber glass elements and the surrounding ground (extraction tests, strength and deformation tests) and the effect of the reinforcement of the core-face in these three decades (extrusion and convergence measures).

Figure 11. Fiber glass extraction test

Different methods of measuring extrusion were developed and are now widely used in tunneling along with the more traditional convergence measurements.

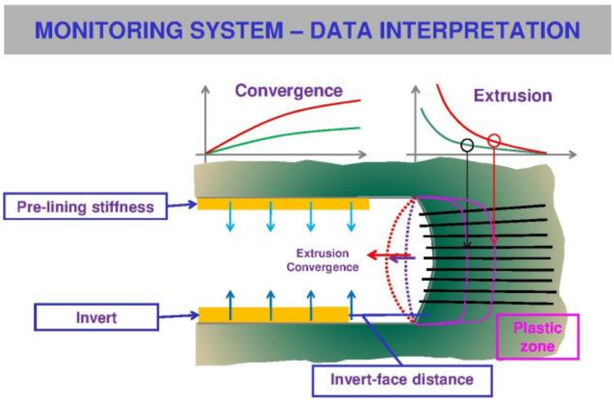

Figure 12. Monitoring data interpretation

These measures were realized inserting incremental extensometers into the core. The results of extrusion, preconvergence and convergence measurements taken allowed to increase the theoretical knowledge of the stress – strain behavior of a tunnel at the face considerably and they confirmed the effectiveness of the new technology in controlling deformation.

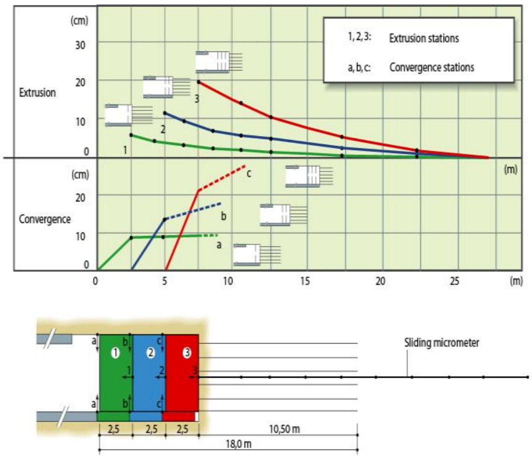

Figure 13. Combined extrusion and convergence measurements

Carefully using these data it is possible to fine tuning the face reinforcement intervention, eventually increasing or diminishing the overlapping and increasing or diminishing the number of elements to be applied into the face. The approach is in this way very flexible and guarantees to work always at the maximum production rate allowable by the ground conditions. In very bad geomechanical conditions this tool is absolutely indispensable and effective to avoid any possible problem into the tunnel, including collapses. Fitting all these information it is practically impossible to be found unprepared to unforeseen geological and geotechnical variations.

3.1 *Numerical models*

If the results obtained directly from the tunnels advance are the ones that better give the opportunity to underline the success of the ADECO – RS approach when using fiber glass elements as reinforcement of the core – face of advance, it has to be said that there was also a great work made with numerical modeling starting from 1985.

These models were very useful to better understand the behavior of the core – face in different stress conditions, giving evidence of the different behavior of the reinforcement at low and high overburden. On site and numerical evidences are guiding even today the design of core-face reinforcement.

A lot of different parameters control the core – face deformation when driving a tunnel:

a) Ground parameters
   Cohesion, friction angle (peak and residual values), modulus of elasticity, pore pressure, water flow, overburden, stress state, ground constitutive model, stratigraphy and strata inclination
b) Tunnel parameters
   Dimension and geometry
   Construction stages and sequences
c) Reinforcement parameters
   Number of elements into the face, position/distribution, inclination, length, overlapping, area, tensile strength, shear strength, Young modulus, diameter of the drillings. Bending stiffness is not taken into account. Fiber glass elements are just tension and shear resistant.

A good 3D FEM or DEM model, able to produce results comparable with the ones collected on site during excavation, may help a lot the tunnel engineer, allowing several sensitive analyses to guide the final choose of the distribution and length of the fiber glass elements at the face and into the core.

3D models are very useful to give evidence of the behavior of the reinforced core; it is quite clear for instance, comparing the analyses of a tunnel at low overburden with those of a tunnel at high overburden, in absence and presence of core-face reinforcement, that the use of core-face reinforcement produces the effect to create a similar behavior of the tunnel at low overburden with the one at high. In fact the stress redistribution induced by the reinforcement during excavation is generally more homogeneous on the height of the tunnel and the displacements of the core-face are reduced. This is very important to control the risk of potential collapses starting from the crown in tunnels at shallow overburden. This is a crucial issue in urban areas, where important interferences with existing buildings and underground utilities have to be considered and preserved. But it is nevertheless essential, to have not significant stops of the tunnel during construction, to avoid any kind of collapse even in less sensible areas. These stops should cause in fact major time and cost.

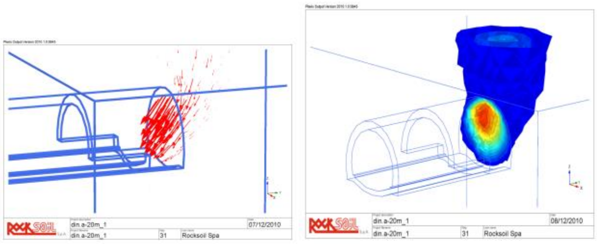

Figure 14. Numerical analysis of a tunnel at low overburden (20 m)

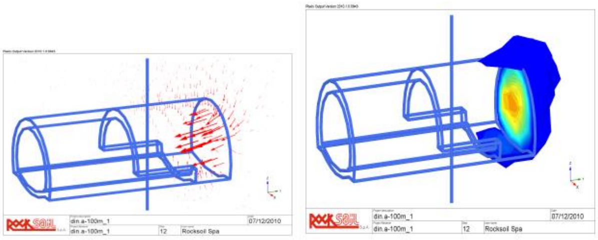

Figure 15. Numerical analysis of a tunnel at high overburden (100 m)

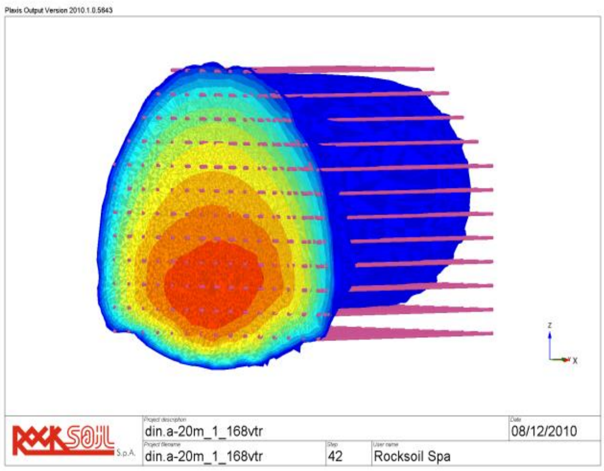

Figure 16. Stress redistribution in a tunnel at low overburden in presence of core-face reinforcement (20 m)

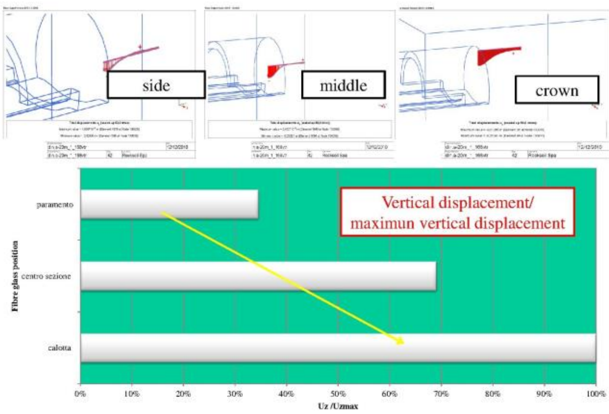

Figure 17. Shear stress distribution into the core-face reinforcement depending on the element position

Other important element to be derived by 3D numerical models is the stress distribution in the fiber glass elements in different portion of the face.

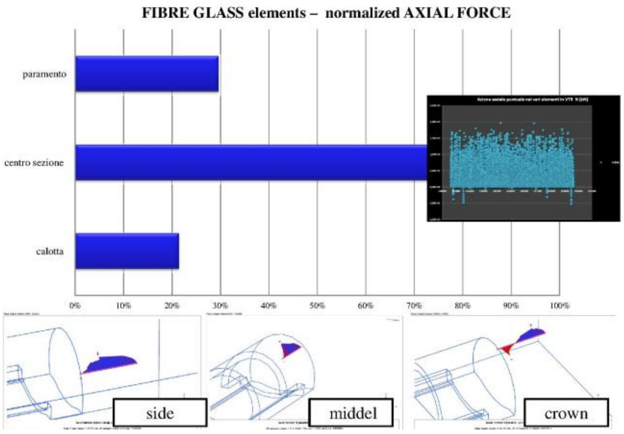

Figure 18. Normal stress distribution into the core-face reinforcement depending on the element position

In the most recent development of the Italian codes and prescriptions for public works (D.M. 20 august 2012 n. 161), fiber glass element is finally described as an inert material. This has definitively solved the environmental issue of the transportation to final landfill of the extracted material in presence of this kind of reinforcement.

4 CONCLUSION

The main principles of the application of fiber glass elements as reinforcement of the tunnel core - face of excavation according to the ADECO – RS approach have been presented. The practice, which started almost thirty years ago in Italy, has proven to be suitable in clays, soft grounds and rocks in whatever stress state condition and tunnel dimension. The development in design, material and construction of the technology has been briefly discussed.

ACKNOWLEDGEMENTS

The authors want to thank Andrea Bellocchio and Mauro Frandino of Rocksoil S.p.A. for preparing the numerical models presented.

REFERENCES

Lunardi, P. 2008. *Design and Construction of Tunnels – Analysis of Controlled Deformation in Rock and Soils (ADECO – RS).* Berlin: Springer. 576p.

Anagnostou, G. 2012. The contribution of horizontal arching to tunnel face stability. *Ernst&Sohn Verlag fur Architektur und technische Wissenschaften Gmbh & Co. KG.* Berlin – *Geotechnik* 35, Heft1

Anagnostou, G.; Serafemidis K., 2007 The dimensioning of tunnel face reinforcement, *Proceedings of the International Congress on Underground Space – The 4th Dimension of Metropolises.* Prague

Lunardi, P.; Cassani, G.; Carriero, F.; Agresti F.S. 2012. Val di Fortore State Road 212 Problems addressed in the excavation of tunnels in structurally complex formation: from design to construction, *Proceedings of the International Congress Tunnelling and Underground Space for a Global Society*. Bangkok

Lunardi, P.; Bindi, R. 2004. The evolution of reinforcement of the advance core using fibre-glass elements. *Felsbau*, no. 4/2004, p.8-19.