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An innovative approach in tunnel planning and construction through 30 years of experience

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ABSTRACT: Analysis of controlled deformation in rocks and soils is a universal approach in planning and construction of underground works (named A.DE.CO), which stands apart from all previous methods for having always pursued to attain the respect of times and costs of completing works, independent of the excavation system used, whether it be mechanized or traditional. Additionally, respecting times and costs of production works is in the interests of Clients and the Contractors alike, and can be achieved only by means of industrialization of the excavation. The starting point of the approach is the reinforcement -in poor geotechnical conditions- of the tunnel core-face of the excavation by means of fiber glass elements. The practice, which started almost 30 years ago in Italy, has proven to be suitable in the most complex geological contexts, in clays, in soft grounds and in rocks and for whatever stress state conditions and tunnel dimensions.

1 INTRODUCTION

Analysis of controlled deformation in rocks and soils approach represents a universal approach to planning and construction of underground works. This method was developed in the '80s in Italy by Professor Pietro Lunardi to deal with heterogeneity of soils and difficult ground conditions. Its introduction to tunneling practice can be dated to 1985, almost thirty years ago, when it was introduced for the construction of some tunnels of the new High Speed railway line from Florence to Rome (the Talleto, Caprenne, Tasso, Terranova, Le Ville, Crepacuore and Poggio Rolando tunnels) for a total length of about 11,0 km.

Italian country is characterized by a very complicated geological and geomechanical contexts: difficult ground conditions like landslide, heterogeneity of soils like flysch, clays and claystones, low strength ground parameters. At the same time Italy presents the longest network of tunnels worldwide (more than 6000 Km). A high percentage of them is in urban area (more than 800 Km in last 15 years). Over 1000 Km of tunnels have been constructed in urban and extra-urban areas. Even though being constructed in very complex and difficult ground conditions, generally they were completed (from the design stage to the construction and actual opening of activity) with industrial methods and respect to the foreseen construction times and costs. Today we know that full-face advancement is all the more necessary the more difficult the excavation conditions are.

The paper summarizes the innovative approach for the design and construction of tunnels through the important experience gained during the design and construction of the biggest infrastructural projects developed in Italy during the last 30 years.

The significant knowhow was fundamental to outline the criteria that helped to define modern design and construction concepts through the experience of:

– High Speed Railway System - Milan to Naples Railway Line: Bologna-Florence Section (Total underground excavation 104,3 km)
– High Speed Railway System - Milan to Naples Railway Line: Rome-Naples Section (Total underground excavation 28,3 km)
– High Speed Railway System - Milan to Genova Railway Line (Total underground excavation 106 km)
– Highway A1 Milan-Naples: Bologna - Florence Section (Total underground excavation 62,2 km)

The method has been traded in Europe, too. Tartaguille, Visnove and Sochi Tunnels are the best known examples.

2 ANALYSIS OF CONTROLLED DEFORMATION IN ROCKS AND SOILS APPROACH

The idea began to make headway in the authors' mind as part of the effort to develop the Analysis of controlled deformation in rocks and soils approach to tunnel design and construction at the beginning of the '80s.

This kind of approach is based on the following two main concepts:

– the significance of the deformation response of the ground during excavation, which the tunnel engineer has to be able to fully analyse 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.

After more than 30 years it has been widely demonstrated that it is possible to safely and efficiently drive tunnel in whatever geomechanical and in situ stress context, even in the most critical ground conditions, working full face and reinforcing in different ways the core - face of advance. Main advantages of this approach are the industrialization of the works: one of the great innovation of Analysis of controlled deformation in rocks and soils approach is the simplification and cleanliness of the construction operations into the tunnel. With comparison to the past tunnel practice, there are always few workers moving into the tunnel (not more than six persons in each stage of construction), with few and powerful machines and equipment to be used), with a clear sequence of operations. There is never a superposition of different kind of interventions or operations. All these aspects lead to an increase in safety conditions and to an industrialization of the work into the tunnel:

– there is a direct relationship between the number of workers and of the machinery and safety: the less they are, the greater is the safety;
– excellent production rates - in whatever ground and overburden it is possible to ensure 1- 4 m/day of advance rate in tunnels with a cross section of about 160 sq.m.

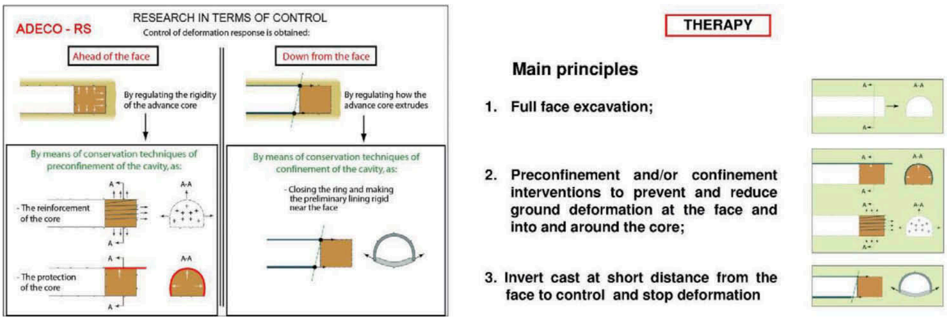


Figure 1. The analysis of controlled deformation in rocks and soils approach for tunnelling – main principles.

– 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, are the key point to have a good design, ensuring sure time and costs of construction.

To deal with all possible situations it is necessary, especially in the worst geomechanical conditions, to act as soon as possible to prevent deformation around the cavity, this experimental evidence brought to the concept to reinforce and strengthen the core – face to counteract deformation at its real onset, that is usual at 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 the new approach 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. 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.

There are two different kind of interventions:

– protective conservation is the one set 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;
– reinforcement conservation is the one set 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 the approach in tunneling practice. This intervention is not to be seen simply as a traditional soil nailing dimensioned at equilibrium limit. It means 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. This assumption is very important: face grouting is not to be dimensioned just as a stabilizing element but as a tool to reduce ground deformation as close as possible to the elastic limit. Very often this concept has been the less understood point of the approach. 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. 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 a 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, and of the machines used to drill and to install the reinforcement.

Figure 2. Core face reinforcement in clayey materials, cemented sand, soft rocks.

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 equipment to be used for fast horizontally drilling, 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 make a new grouting intervention. This way it has been possible to reach a production rate of 35 – 45 m/month for a section of about 160 sq.m. in clays and soft rocks. This production rate also includes 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 fiberglass profiles were tested and adopted. The first element to be used was a 40/60 mm pipe; this showed to be very good but had sometimes problem of transportation with length greater than 15 m.

Figure 3. Fiber glass element profile Core face reinforcement execution insertion and execution drilling of the fiber glass element.

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; it must be considered that tubular elements always have a considerable shear resistance that the above mentioned elements do not have; this aspect must be considered in the design of the intervention. 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 thanks to the adherence between the grout itself and the ground. The greatest is the adherence, the most effective is the core-face reinforcement. 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 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.

Approximately in 2010 a new ground element has been introduced in the Italian market, in order to improve adherence characteristics: it is a fiber glass element constituted by a corrugated pipe. It is proven that these new elements give very good results about adherence characteristic.

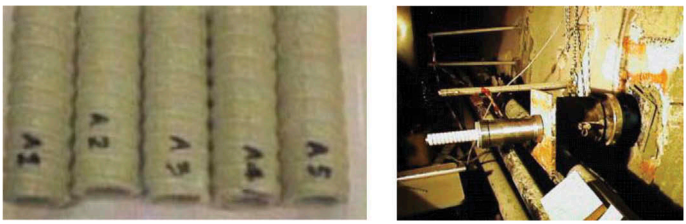


Figure 4. Corrugated ground elements and Fiber glass extraction test.

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).

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

Extrusion measures were done inserting incremental extensometers into the core. The results of extrusion, preconvergence and convergence measurements allowed to increase the theoretical knowledge of the stress – strain behavior of a tunnel at the face and they confirmed the effectiveness of the new technology in controlling deformation. Monitoring data represents an important tool to fine tuning the face reinforcement intervention, 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 different ground conditions. In worst geomechanical conditions this tool is absolutely indispensable and effective to avoid any possible trouble into the tunnel, including collapses. Fitting all this information it is practically impossible to be found unprepared to unforeseen geological and geotechnical variations.

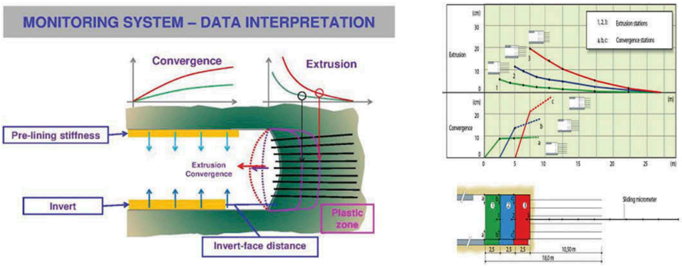


Figure 5. Monitoring data – combined extrusion and convergence measurements.

The results obtained directly from the tunnels advance are the ones that better give the opportunity to support the success of the ADECO – RS approach when using fiber glass elements as reinforcement of the core – face of advance.

Different parameters control the core – face deformation when driving a tunnel:

a. Ground parameters (cohesion, friction angle, 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).

A good 3D FEM or DEM model, able to produce results comparable with the ones collected on site during excavation, may help the tunnel engineer to make several sensitive analyses and to guide the final choose of the distribution and length of the fiberglass elements at the face and into the core. 3D models are useful to give evidence of the behavior of the reinforced core; if we compare the analyses of a tunnel at low overburden with those of a tunnel at high overburden, in absence and presence of core-face reinforcement, it is proven 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. 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 important, too, 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.

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

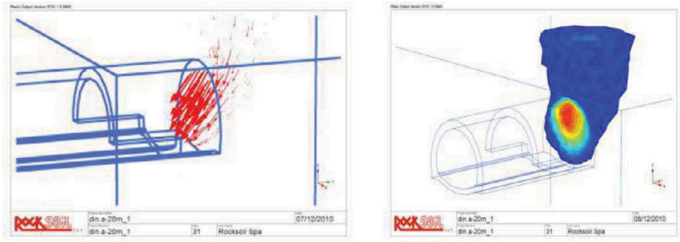


Figure 6. Numerical analysis of a tunnel at low overburden (20 m).

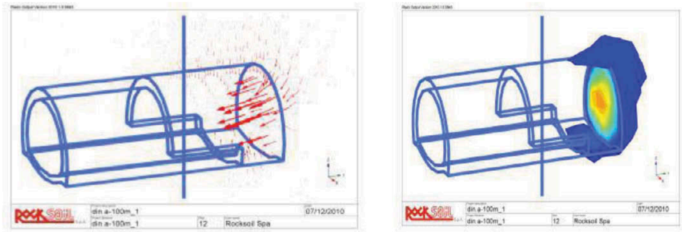


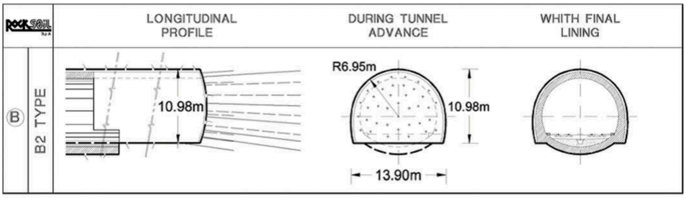
Figure 7. Numerical analysis of a tunnel at high overburden (100 m).

3 CASE HISTORIES

ADECO-RS approach has been adopted in the most complicated geological and geomechanical contexts. A tough geological study of the area interested by the future infrastructure is the starting point of an efficient and successful underground project. The following road and rail tunnels represent the consolidation of the of ADECO-RS approach.

3.1 *High Speed Railwayy system – Milan to naples Railway Line-Florence Section*

The new railway line between Bologna and Florence is part of the Italian Milan-Rome-Naples route of the High Speed/Capacity Train which constitutes the southern terminal of the European rail network. The total length of the alignment is more than 78.5 km, constituted by twin track underground tunnel. This was a pilot experience for the whole of the major infrastructure sector and not just because the project was awarded to a single general contractor for the first time in Italy, but also because of the technical difficulties that had to be overcome. The geological and geotechnical context appeared to be, and so it was, one of the most difficult and complex in the world. A wide and heterogeneous variety of grounds had to be tunnelled, affected by groundwater and gas at times and under overburdens ranging from nil to very deep. A new design and construction approach was selected to tackle the heterogeneity of the materials and conditions, which is based on the "Analysis of the COntrolled DEformation in Rocks and Soils" (ADECO-RS). By using this approach, which is based on a clear distinction between the design stage and the construction stage of tunnels, it was possible to reliably estimate construction costs and times for the project in advance and this in turn made it possible to award contracts for the work on a lump sum "turnkey" basis for the first time in the history of underground works for projects of these dimensions and difficulty. Tunnel construction on the Apennines section between Bologna and Florence of the new Milan-Rome-Naples high speed/capacity railway line finished after less than six years since the first excavation of the running tunnels started. Today the route from Bolognas to Florence with more than 70 km of twin track tunnel, which has a cross section of 140 sq. m. is under traffic. The exceptional complexity of the grounds to be crossed was well known. It had already been tackled with great difficulty for the construction of the "Direttissima" railway line inaugurated in 1934 and currently still in service. It was then decided to invest a sum of € 84 million, 2% of the total cost of the project in the geological survey campaigns required for detailed design of the new high speed/capacity railway line. This provided a geological-geomechanical characterisation of the ground to be tunnelled that was very detailed and above all accurate. The formations are primarily of flyschoid, clay and argillite formations and loose grounds, at times with substantial water tables, accounting for more than 70% of the underground alignment, with overburdens varying between 0 and 600 m.



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

Figure 8. Section type variability as a function of the actual response of the ground to excavation.

The contract for the entire section of the railway between Bologna and Florence was awarded on a rigorous lump sum basis (€ 4,209 million) by FIAT S.p.A., the general contractor, which accepted responsibility for all unforeseen events, including geological risks on the basis of the final design as illustrated above. It subcontracted all the various activities out to the CAVET consortium (land expropriation, design, construction, testing, etc.). Immediately after the contract was awarded, the construction design of works began at the same time as excavation work (July 1996). Additional survey data and direct observation in the field generally confirmed the validity of the detailed design specifications, while minor refinements were made in the construction design phase.

3.2 *High Speed Railway System – Milan to Naples Railway Line-Naples Section*

The new Rome-Naples railway is part of the High Speed Train Milan-Naples line which in turn represents a southern terminal of the European High Speed network. The total length of the line is 204 km and 28.3 km of this (equal to 13% of the total length) runs underground. Rocksoil designed 22 tunnels for a total length of 21.8 km. The underground route runs through ground which can basically be classified as having two different types of origin: pyroclastic ground and lava flows, generated by eruptions of the volcanic complexes of Latium, of Valle del Sacco and of Campania; sedimentary rocks of the flyschoid and carbonatic type (marly and limy argillites) belonging to the Apennine system.

The overburdens vary greatly but never exceed 110 m., while they are often very shallow at the portals. The final and construction design of the tunnels was performed using the Analysis of Controlled Deformation in Rocks and Soils approach (ADECO-RS).

3.3 *High Speed Railway System – Milan to Genova Railway Line*

The Terzo Valico is the new high-speed, high capacity railway line that will improve connections between the Liguria port system and the main railway lines of Northern Italy and the rest of Europe. The Terzo Valico represents one of the strategic projects of national interest and is part of the Rhine-Alpine Corridor, one of the main corridors of the trans-European strategic transport network (TEN-T core network) connecting Europe's most densely populated and most important industrial regions. The total length of the alignment will be approximately 53 km.

The project requires the construction of 36 km of tunnels running through the Apennine Mountains between Piedmont and Liguria. The full scope of underground works, including dual tube single-track running tunnels, accesses and interconnections, for a total underground excavation of about 106 Km. About 60% of the design alignment crosses the lithological unit defined as Argille a Palombini – claystone schist with limestone lens – (hereinafter aP), which therefore is particularly important for the implementation of the project.

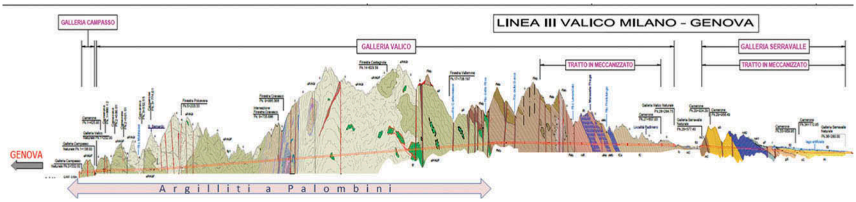


Figure 9. Longitudinal geological profile.

The excavation intersects the aP at the southern part of the alignment, along the stretch Genoa-Voltaggio (AL), thus embracing the excavation of mainline tunnels, access tunnels and interconnections with the old Voltri railway. Excavations in aP are mainly designed and executed with conventional method by full face tunnel advance and cross sections area between 75 and 400 sq.m. The only exception is the Polcevera access, which was carried out by an EPB Tunnel Boring Machine, with an excavation diameter of approximately 10 m.

Figure 10. "Argille a Palombini" Formation – claystone schist with limestone lens.

Last but not least, the project and construction for the new high speed railway line faced one of the most relevant environmental issue: safe excavation and managing of rocks, that may contain asbestos in relevant amounts. Asbestos is a group of fibrous minerals that mainly occurs in mafic and ultramafic rocks (ophiolitic sequences). This work focuses the criteria to better evaluate the amount of asbestos fibres in the metaophiolites belonging to Sestri-Voltaggio Zone (Liguria, Northern Italy), the criteria for the environmental monitoring system and management of disposal materials used by Cociv for checking asbestos risk along tunnel alignment. The Cravasco Tunnel adit section, one of the four accesses tunnels to the main tunnel of the Terzo Valico, of approx. 1,260m in length has represented the pilot experience to face tunnel excavation issues when asbestos is present. Cravasco Tunnel crosses a part of the complex geological context within the Sestri-Voltaggio Zone. This area represents the core zone of Sestri – Voltaggio area and is constituted by a large number of different lithologies: from dolomites to chalk stones, from argilloschists to metabasalts to serpentinites and ophicalcites.

3.4 *Motorway A1 Milan-Naples_ Bologna – Florence Section*

The accurate geological, geotechnical and hydrogeological model for Tunnel construction on the Apennines section between Bologna and Florence of the new Motorway A1 (total of underground excavation of about 62 Km) detected the presence of a very complex geological and geomorphological context in the area between Bologna and Florence. Complexity derived both for the presence of a heterogeneity of soil conditions (flysch, clays and claystones) and landslide soil conditions. When tunneling in presence of a landslide, the main design target should be the reduction of the disturbance caused in the ground by the excavation. The “ADECO – RS approach” to tunneling design and construction is well capable to manage this kind of difficult and delicate situations.. A detailed monitoring system should be designed in detail, highlighting the reading frequency and the criteria/flow-chart to manage the data collected and to enable corrective actions in the presence of unexpected behaviour or exceeding the thresholds defined. Some recent experiences, collected on different job sites of the Bologna–Florence Motorway, are presented in the following. Geological-geotechnical context is mainly affected by flysch consisting of argillites, siltites and clayey marls. The interaction between the underground excavations and the overlying slopes, affected by a complex system of landslides, will be focused through the exam of movement data, derived from an extensive monitoring program. Both conventional and mechanized tunneling will be analyzed to compare the results and to evaluate similitudes and differences.

Val di Sambro Tunnels are located at the base of a slope degrading to the Setta River, mainly consisting of deposits (silty clays and sandy silts) laying on the rock-mass (flysch of Monghidoro Formation); the thickness of the deposits is ranging between few meters up to 35-40 m, and represents a big landslide, quiescent in nature, with local active area of lower thickness (max.10-15 m). During the design stage, the alignment of the tunnels was located deep into the slope, so to present a big distance from the topographic surface and from the base of the landslide, with overburden into the range of 60-90 m. Further investigations and a new geological model were necessary. The area interested by the movement is very large, even if within the same it was possible to point out several components: the main one is connected to the deep landslide. It is located about ten meters over the tunnels alignment and with a planimetric angle of 45°. The new information about geological model and the data collected about interferences gave the possibility to redefine the design data and revalue the tunnel construction process. Once known the real geometry of the landslide, it was not possible to avoid interference with the tunnels constructions, so that it became very important to adopt a construction system able to minimize the impact with the pre-existences (the buildings and the slope itself!), minimizing the deformation inside the ground during excavation. Before the tunnels excavation was stopped, conventional system was adopted, without face support, just confining the cavity by steel ribs and shotcrete. This system was upgraded, in the spirit of ADECO Approach, according to Lunardi (2006). New pre-confinement and confinement actions were defined, in order to minimize face extrusion, convergence and settlements into the tunnel, which had reached 10-15 cm in the first stage of excavation. Several support sections were prepared according to the distance from the landslide surface, the landslide nature (active or deep landslide) and the face position with respect to the buildings location; specific “guidelines” were prepared too, in order to govern the support section application and to fine tuning the number of intervention.

Sparvo Tunnels were located in the opposite bank of the Setta River with respect to Valdisambro Tunnels; a bridge between the two tunnels crosses the river. But the slope of this bank is, at the same time, interested by several landslides, because of the poor condition of the ground, mainly represented by clays of the “Argillite a Palombini” formation, and considering the water level, which is very high. To face the tunnels excavation, a TBM-EPB was adopted; it was a very challenger project, considering the excavation diameter (15.56 m) and the TBM working parameters, such as thrust (up tp 390 MN) and chamber pressure (3.5-4.0 bar in crown, up to 7-8 bar at the base of the machine). The geotechnical dimensioning of the TBM and the construction process are described in Gatti et al. (2011) and Lunardi, Cassani and Gatti (2013). With respect to the interference with the landslides located along the tunnels alignment, similar criteria with Valdisambro Tunnels were used: the aim of the construction method was to minimize the deformation response after excavation, mainly maintaining the clays’ strength parameters closed to the peak value (elastic domain), neglecting, as much as possible, plasticization in the ground. Also this goal was achieved applying the ADECO Approach: several detailed analyses were performed to define the correct chamber pressure to properly confine the core-face. For the tunnel stretch under discussion, with overburden equal to 110-120 m, chamber pressure equal to 3.5 bar (at the top of the excavation chamber) was defined, to confine external ground pressure with low stress-strain redistribution. In this way, as assessed in Gatti (2011), it was possible to reduce the plasticization ring around the excavation profile, and consequently on one hand the friction forces on the TBM shield ("jamming risk control") and on the other the propagation of the movements towards the ground surface.

4 ADECO-RS APPROACH IN THE WORLD

ADECO-RS approach was successfully implemented not only in Italy. The first case history is represented by the Tartuaguille Tunnel (1997), new High Speed Rail line between Marseille and Lyon in France. More recently it was applied in Russia (Sochi Motorway, T8 and T8A tunnels) and in Slovak Republic (D1 Motorway, Visnove Tunnel). One of the most important and recent case history of application of ADECO-RS approach all over the world is represented by the Sochi Tunnels construction in Russia. During the preparation for the XXII Winter Olympic Games in Sochi (Russia) from 7 to 23 February 2014, the Russian Federation allocated important investments in fixing the city's lack of infrastructure and in strengthening its transportation network. One of these projects is the new Sochi by-pass motorway, also known as "Dubler Kurortnogo Prospekta", which runs parallel to the black sea and makes it possible to reach the Olympic sites and the Adler airport without having to cross the city. The new Sochi by-pass motorway presents two separate carriageways, each with 2 lanes per direction, adjusted for a design speed of 120 km/h. Construction required the excavation of a series of tunnels. The T8 and T8A tunnels crossed the most difficult geological context because of the presence of clays, claystones and sandstones, which are flysch conditions. Extra difficulties were represented by the reduced times available to design, construct and open the works, considering the length of the underground layout (1,550 m for the T8 tunnel and 1,523 for the T8A tunnel) and the size of the excavation faces, ranging from 120 sq.m up to 220 sq.m. The "Dubler Kurortnogo Prospekta" tunnel, is made up of 6 double-bore tunnels for a total of: 10 tunnels bored using the NATM approach (New Austrian Tunnelling Method) and 2 tunnels using the ADECO-RS approach (Tunnels 8 and 8a). It was the first time that these two approaches were directly and reliably compared to each other, in relatively similar conditions (despite the difficulty regarding those tunnels constructed using the ADECO-RS). The two approaches are compared both in terms of average production and in terms of "bored volume/month" and in terms of "meters of tunnel finished/month". The geological conditions affecting the 8-8a tunnel excavation were clearly worse than those of the other tunnels, and the excavation sizes were also greater. The tunnels bored using the NATM passed through better contexts with excavation sizes just equal to 113-115 sq.m. The comparison between the two approaches clearly exhibits extreme efficiency of the ADECO-RS system over the NATM: in terms of volume of excavation/month for single face the ADECO-RS approach produced results 2.4 times higher than the NATM; in terms of linear metres of completed tunnel, productivity was 40% greater than the NATM approach. The ADECO-RS approach is naturally fast in closing the lining, in the case of SOCHI this was completed under 3 weeks. Instead, the NATM approach showed much greater times: from a minimum of 10 weeks to a maximum of 43; such a time frame has clear repercussions on safety. From this point of view, the ADECO.RS method can complete all necessary safety measures for the tunnel in a short time frame, thus greatly limiting the deformation phenomena linked to excavation.

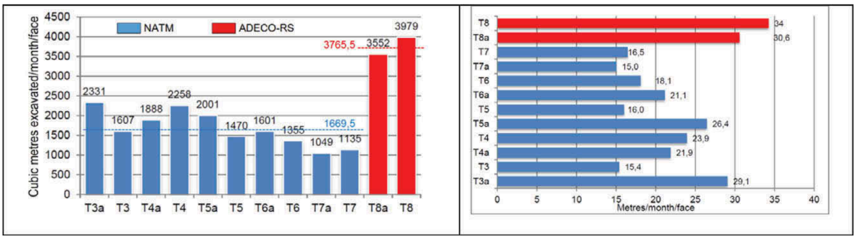


Figure 11. Comparison of ADECO-RS and NATM in the Sochi Tunnels, Russia.

5 CONCLUSIONS

The important knowhow and experience described above produced the standards for full face tunnel excavation. The first 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. The new railway High Speed/Capacity line between Bologna and Florence was a pilot experience for the whole of the major infrastructure sector because of the technical difficulties that had to be overcome. One of the most difficult and complex geological context in the world has been faced successfully with ADECO-RS method. Today we know that full-face advancement is all the more necessary the more difficult the excavation conditions are. To deal with all possible situations it is necessary, especially in the worst geomechanical conditions, to act as soon as possible to prevent deformation 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. These important results have been made possible since the public administrations have adopted modern design and construction approaches in their contract specifications, based on strictly scientific criteria.

The memory of previous experiences contributed to develop and improve the approach, that it is still an ongoing process, looking for further improvements of equipment, solutions, safety and environmental aspects.

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