THE ADECO RS APPROACH AND THE RECENT EUROPEAN APPLICATION EXPERIENCES

P. Lunardi

Lunardi Geoengineering, Milan, (Italy)

G. Cassani

Technical Director, Rocksoil S.p.A., Milan, (Italy)

M. Gatti

Project Manager, Rocksoil S.p.A., Milan, (Italy)

C.L. Zenti

Consultant, Rocksoil S.p.A., Milan, (Italy)

ABSTRACT: The main feature of the ADECO-RS approach is that the design Engineer focuses primarily on the deformation response of the ground to the action of excavation. Thisdeformation response is first analysed and predicted using a variety of instruments (full scaleand laboratory tests, mathematical models), then it is controlled by using appropriate stabilisation measures. The ADECO-RS approach investigates the deformation response very thoroughly, right from its onset where it starts ahead of the face, as opposed to traditional approaches, that only consider deformation behind the face. The approach controls the deformation response acting first and foremost ahead of the face, usingpreconfinement action, and not just ordinary confinement action as in traditional approaches.In this way the ADECO-RS approach is able to successfully tackle any type of ground and stress-strain conditions, especially in the most difficult ones.The ADECO-RS Approach has been applied in Italy, for the first time, in 1988 to Tasso Tunnel and then to San Vitale and Vasto tunnels. The first application outside of Italy was in 1997 with the Tartaiguille tunnel (high speed rail line between Marseille and Lyon in France). In this paper the authors describe the two real cases by which it is possible to start to make a direct comparison between ADECO-RS and NATM. The Sochi Case reports the main differences observed in terms of production and of safety between the two different approaches used during excavation the DublerKurortnogoProspekta tunnels (ADECO-RS and NATM). The Visnove Case reports the different production related to the different excavation faces of the double tube tunnel. For each tube the construction started from the East and West portals with NATM and then changed into ADECO RS. The production benefit introduced by ADECO-RS will be highlighted into the paper.

1. INTRODUCTION

Between the end of ‘800 and the beginning of ‘900 no established method was available for the design and excavation of tunnels in difficult ground conditions. It must be recognized however that, in order to meet the needs posed by the new transportation means and the increasing mobility requests, spectacular tunnels were excavated and completed, such as Frejus and Simplon railway tunnels through the Alps and “La Grande Galleria dell'Appennino” through the Apennines between Bologna and Firenze. This was achieved although a number of workers lost their lives for the sake of reaching the objective. In the absence of established methods, different ways of tunnelling were applied such as the Belgian, Austrian and Italian methods, etc. It was only between 1920 and 1960 that landmark contributions in tunnelling took place by Terzaghi (the “rock load” due to the weight of the broken ground resulting from the excavation of the tunnel), Kastner and Fenner (the development of a “plastic zone” in the rockmass surrounding the tunnel), and Rabcewicz (the New Austrian Tunnelling Method), to mention a few.

It has to be un underlined the great merit of Rabcewicz who pointed out: (1) the importance of conserving and mobilizing the inherent strength of the ground surrounding the tunnel, (2) the need to minimize ground loosening and excessive deformations by means of a primary support system, flexible rather than rigid, and placed to remain in physical contact with the ground and deform with it, (3) the installation of instrumentation to monitor tunnel deformation and build-up of load in the support, for gaining information on tunnel stability and optimizing the load bearing rock mass ring. Naturally, the tools available to Rabcewicz were those of the time when his “approach or philosophy” was developed, by integrating the principles of rock mass behaviour and the monitoring of this behavior. Use was still made of ground classes (Lauffer-Pacher,Bieniawski and so on) and the analyses to understand the ground behavior were performed in two-dimensional conditions and limited to the tunnel cross section. No sophisticated and advanced three dimensional computational tools were available at that time as presently adopted. To control tunnel stability during face advance, the only option was to adopt sequential excavation. Rabcewicz was well aware of the need to improve the way of thinking of the time, when he pointed out that “Tunnels should be driven full face whenever possible, although (today) this cannot always be done...” (Rabcewicz, 1964). It is indeed in this context that in the mid ‘80s Lunardi (2008) pointed out the importance of the stability of the “core-face” and conceived the ADECO-RS approach. He suggested that understanding and controlling the behaviour of the “core” ahead of the advancing tunnel face is the secret to successful tunneling in difficult ground conditions (Lunardi P. et al 2015).

2. THE HYSTORICAL BACKGROUND: THE FIRST APPLICATIONS

After several years of researches and studies it has been formalized the A.DE.CO. RS Approach (Analysis of controlled deformations in rock and soil) which shared the concepts of Rabcewicz by applying them to the “extreme”:
- the ground considered as a construction material
- the importance of the ground deformational response during excavation
- the advantage of driving the tunnel always full-face in every stress-strain situation
- the importance of the invert in difficult ground conditions (to “close the ring”)
- the relevance and value of stress-strain monitoring during face advance.

It is important to highlight how the above concepts are the fundamental components ofADECO-RS. These were agreed upon and further developed. The “inherent”weaknesses associated with NATM, mainly due to the limited knowledge, at the time ofdevelopment, on the control of the ground response during excavation were “corrected”.The Deformation Response of the ground and rock-mass,subject to excavation action, in terms of “Analysis and Control” should be carefully studied(theoretical forecasting in the design phase and experimental verification during the actualexcavation). Deformation response is complex and involves not just the tunnel cavity, but alsothe volume of ground that lies ahead of the face, virtually cylindrical in shape, withdimensions quite similar to that of the diameter of the tunnel to be excavated. This region,called the “advance core”, is affected by a primary component of the deformation response:“extrusion”, which manifests on the surface of the face along the longitudinal axis of thetunnel (bellying or rotation of the face), and “preconvergence” of the cavity, i.e. theconvergence of the theoretical profile of the tunnel ahead of the face (Figure 1). These primarycomponents depend on the relationship between the strength and deformation properties ofthe advance core and its original stress state (Lunardi, 1997).The ADECO-RS Approach has been applied in Italy for the first time to Tasso Tunnel (1988) and then to San Vitale (1990) and Vasto tunnels (1991). Starting from its very beginning the A.DE.CO.-RS approach has aroused considerable interest and rapidly established itself as an advantageous alternative to those employed to date. The first application outside of Italy was in 1997 the Tartaiguille tunnel (high speed rail line between Marseille and Lyon) in France.

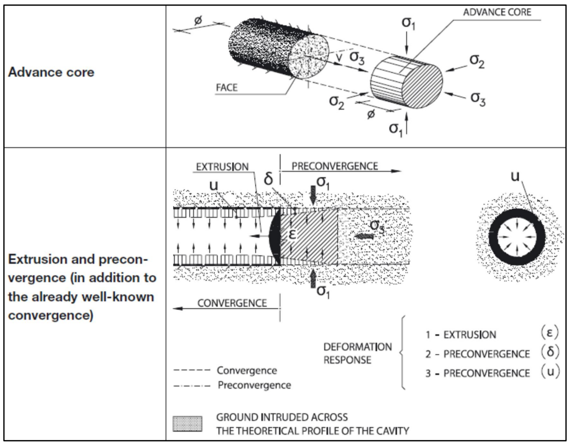


Figure 1: The influence of advance core

2.1 THE TASSO TUNNEL (ITALY, 1988)

The “Tasso” tunnel is one of a series of tunnels excavated towards the end of the 1980’s for the new “High Speed” Rome to Florence railway line. The original design involved half face advance, stabilising the walls with arches and shotcrete. The arches were anchored at the feet with sub-horizontal tie bars and given a foundation of micropiles or columns of ground improved by jet-grouting. Initially excavation proceeded with no appreciable deformation phenomena either at the face or in the tunnel. As the overburden increased, and therefore also the stress state of the medium, and given also the poor geomechanical characteristics of the ground, conditions of face stability rapidly changed to those of an unstable face. Following the failure of the face despite half-face advance, approximately 30-40 m of already excavated tunnel also collapsed during the course of one single night with convergence in the order of 3-4 m (see Figure 2.a-b).The deformation of the advance core of a tunnel was the true cause of the whole deformation process in all its components (extrusion, preconvergence and convergence) and then, as a consequence, the rigidity of the core played a determining role in the stability of a tunnel both in the long and short term. The rigidity of advanced core can be regulated by different technologies: fibre glass elements (GFRP), horizontal jet grouting, chemical and cement injections. In case of Tasso Tunnel, after the collapse, has been decided to reinforcing the advance core using fibre glass (Figure 2.c).

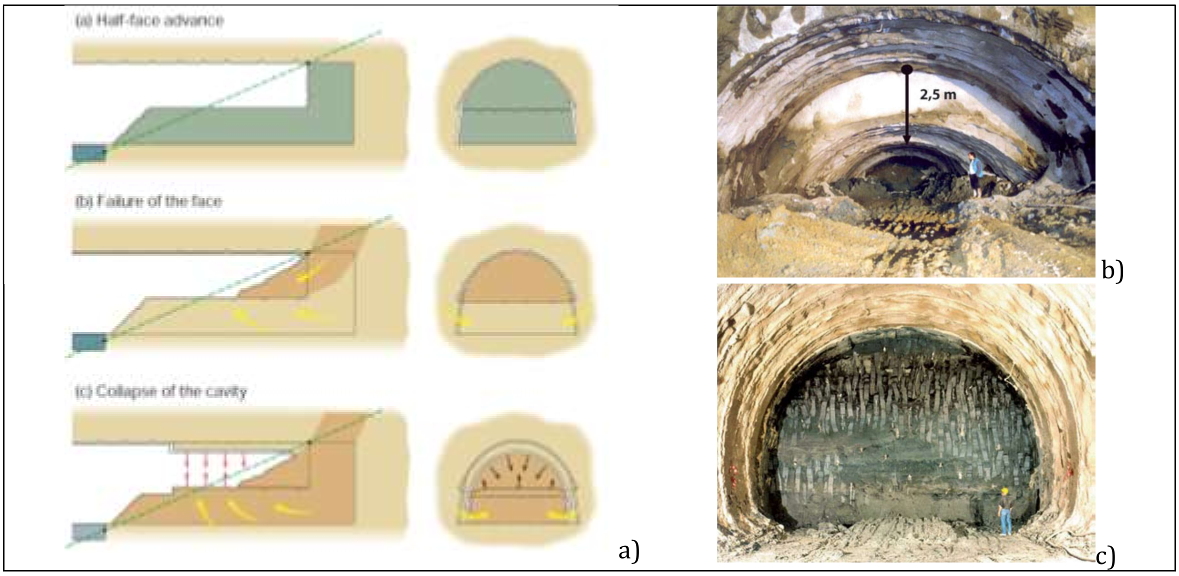


Figure 2: Rome to Florence railway line – Tasso Tunnel: a) Chronology of observed deformation in a collapse during half-face advance; b)collapse during half face advance (NATM); c) full face advance after reinforcing the advance core with fibre glass tubes

2.2 THE VASTO TUNNEL (ITALY, 1990)

The "Vasto" tunnel is located along the railway line Ancona-Bari. The works began in 1984 at the North portal and continued slowly between repeated and serious incidents until April 1990. The original design involved half face excavation, immediately protected with a temporary lining of shotcrete, steel arches and welded steel mesh reinforcement. The final lining made by reinforced concrete characterized by a thickness of 1,0 m was cast straight behind the face and still in the presence of the core. The side walls of the tunnel were cast subsequently for underpinning and the casting of the tunnel invert completed the work. After the first serious incident of tunnel deformation, an attempt was made to resume tunnel advance employing several methods, which all, however proved to be completely inadequate. Finally a disastrous cave-in occurred at chainage Km. 38+075 under an overburden of 38 m., which involved the face (Figure 3) and then a section of approximately 40 m behind it. It produced deformation of enormous size (greater than one meter) in the final lining and it was impossible to continue working.

Figure 3: Vasto Tunnel (Italy, Ancona to Bari Rail Line, ground: silty clay, overburden: 135 m, tunnel diameter: 12.20 m.). The extrusion of the ground through the face during heading and bench excavation (according to NATM principles)

Three alternative tunnel section types (Figure 4) have been designed to be adopted according to the homogeneity and consistency of the ground encountered during tunnel advance. The only difference between the three types was the type of treatment (preconfinement) to be applied ahead of the face around the future cavity, while the method of ground reinforcement performed in the advance core was the same for all three. The choice of technique to be applied around the core was strictly dependent on the nature and the acquired consistency of the ground to be tunnelled. In granular ground or where cohesion was poor, characterised by weak shear strength, horizontal jet-grouting was specified. The most appropriate technology to create strong shells ahead of the face in cohesive, compact and homogeneous ground, able to guarantee the mobilisation of an “arch effect” is mechanical precutting.

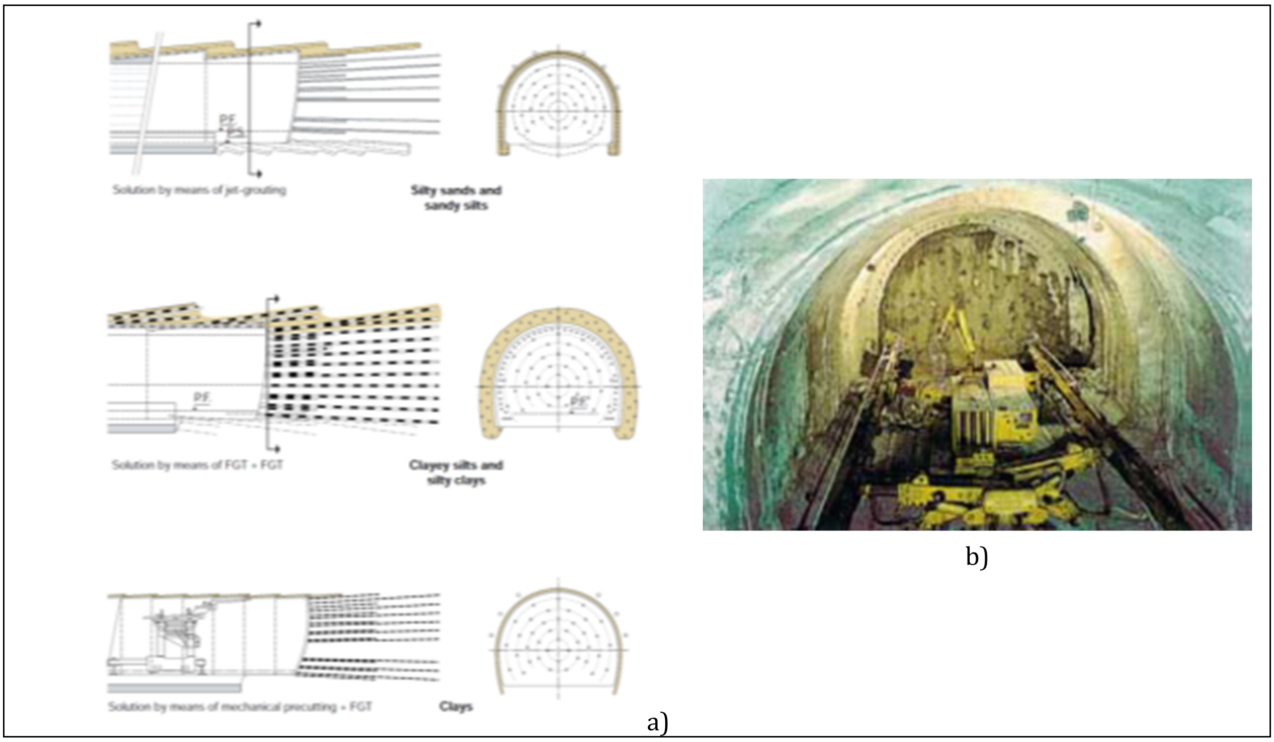


Figure 4: Vasto Tunnel: a) Full face excavation section types; b) reinforcing of the advance core with fibre-glass tubes during full face excavation (according to A.DE.CO.-RS principles)

2.3 NEW HIGH SPEED RAIL LINE BETWEEN MARSEILLE AND LYON: THE TARTAIGUILLE TUNNEL (FRANCE 1997)

Excavation of the Tartaiguille tunnel (180 m^2 in section), for the new railway line “TGV Méditerranée” Lyon – Marseille, began for both entrances (North and South) in February 1996. The initial approach consisted of advancing in partitioned face, excavating the heading and the bench about 200 m back. At the end of September 1996, while excavating the Aptien marls, convergence at the southern face raised well-above the expected values. This caused fissuring and cracking in the shotcrete pre-lining. Soon, excavation needed to face the worst stretch on both sides: 900 m through the feared “Lower Stampien” formation, which alternated strata of marls, clays and silts, with a high percentage (75%) of montmorillonites which were highly sensitive to air humidity and at risk of swelling (c' = 0.05 Mpa , φ' = 18°). Those in charge were quite worried and had therefore conducted an integrative geognostic campaign. The revision of the initial project proved that the excavation systems used previously were inadequate for the Stampien clays. These systems required partitioning of the excavation face which would have caused in that case unacceptable deformation phenomena. In order to solve the problem, in 1997 the SNCF (Societè National du Chemin de Fer), formed a study group (“Comité de pilotage”) with the technicians of the French Railways themselves, the G.I.E. TARTAIGUILLE consortium, the Coyne et Bellier consultants, the Terrasol-Simecsol consortium geotechnicians and the CETU. Said group started consulting the greatest European tunnelling experts and invited them to present a design solution capable of facing the clayey stretch both in safety and in line with the contracted timetable. In March 1997 a solution which adopted ADECO-RS approach has been proposed with a detailed design of the 860 m of tunnel which needed to be constructed. The new design solution radically changed the traditional design criteria: full-face advancement (with control of deformation phenomena by means of the reinforcement of the core-face used as a stabilisation instrument), casting of the final invert at the face and final lining within 20 ÷ 40 m. (see Figure 5). G.I.E. TARTAIGUILLE recommenced advance works on the tunnel in July 1997, under strict supervision of the designer, who kept a trusted engineer on the site for the full duration of the work. The new advance system respected the contractual timetable of the works with an industrialised production of 1.7 m/day, which was even above the design phase prediction of 1.4 m/day. The tunnel was completed after just a year after recommencing with the full-face system, about 1 month and a half ahead of schedule.

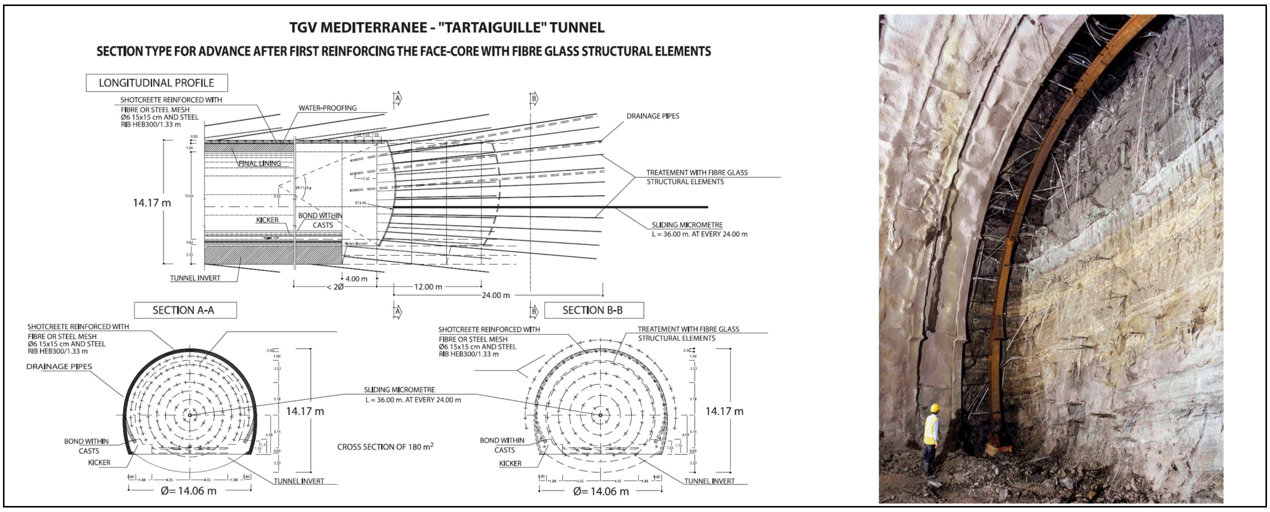


Figure 5: Section types and cavity preconfinement after reinforcement of the core-face with fibre glass reinforcement: detail of the reinforced face (TGV Méditerranée, Lyon-Marseilles railway line, Tartaiguille tunnel, 1997, ground: clay, max. overburden: ~ 110 m)

3. THE ADECO RS APPROACH: THE RECENT EUROPEAN APPLICATIONS

3.1 THE SOCHI CASE: T8 AND T8A (RUSSIA, 2011-2014)

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 web. 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.

Construction of the new artery, which remained of decisive and strategic importance, presented many obstacles, especially regarding the short time slot available. Indeed, the project required the construction of eight double-bore natural tunnels, as well as open-cut sections, embankments and bridges for a total length of 16 kilometres (Figure 6). 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. Of these, the T8 and T8A were the most difficult due to the geological context faced as well as considering the reduced times available to design, construct and open the works due to the length of the underground layout (1,550 m for the T8 tunnel and 1,523 for the T8A tunnel) and due also to size of the excavation faces, which could vary from 120 m^2 up to 220 m^2. 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). Illustrated below, the two approaches are compared both in terms of average production and in terms of "bored volume/month" and in terms of "metres 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. Indeed, the 8-8a tunnels occupy a harsh geological context and measure excavation sizes between 120 m^2 and 220 m^2, (see Figure 7) while the tunnels bored using the NATM passed through better contexts with excavation sizes just equal to 113-115 m^2.

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 (Figure 8.a). 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 8.c).

Figure 6: The "Dubler Kurortnogo Prospekta" lay-out

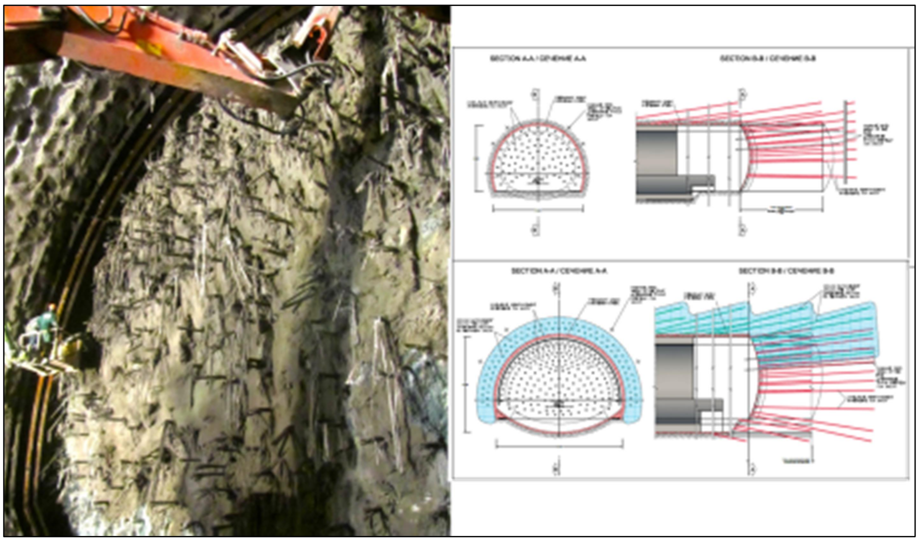


Figure 7: Enlarged cross section (220 m^2), T8 and T8A, Sochi, Russia

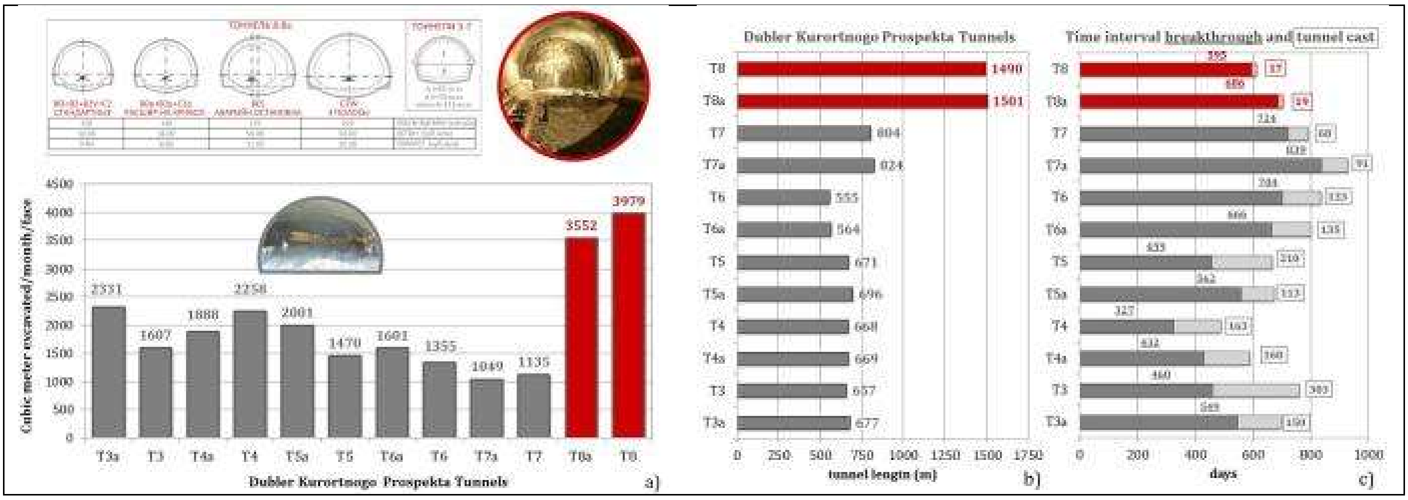


Figure 8: Comparison of ADECO-RS and NATM in the Sochi tunnels: a) "cubic meter excavated/month/face"; b)Tunnels length; c) in terms of time interval between breakthrough and tunnel cast (Lunardi G. et al, 2014)

3.2 THE VISNOVE TUNNEL: NATM AND ADECO RS COMPARISON

"Visnove tunnel" is a double lane tunnel of the D1 Motorway "Lietavska Lucka – Visnove – Dubna Skala", about 7450 m length. It's located in the Zilina district. The tunnel width category is 2T 7.5, with maximum speed 100 km/h. Two traffic lanes, 3.5 m width, are provided with clearance 4.8 m of height. The maximum slope 3.4%. Because of the ventilation system, the tunnels present two different sections for the west and the east sides: in the east part a ceiling is present at the tunnel crown, connecting a ventilation shaft; the excavation areas are about 120 m². Geological conditions along the alignment of the tunnel were verified by a “pilot tunnel”, excavated in 1998-2002, 3.12 km from the west portal conventionally and 4.36 km from the eastern portal using a TBM; the pilot tunnel will be used as a drainage tunnel during service. The rockmass, starting from the west portal, are so defined: claystone flysch formations, mudstone–sandstone-limestone, with max overburden 90 m, limestone-dolomite and granitoids with max overburden of 250 m. From a geotechnical point of view, the data collected during the pilot tunnel excavation allowed to define seven geotechnical units, from 1 to 6a/6b, according to rock-mass properties and rock-mass discontinuities (fractured zones, faults and tectonic contacts); the 43% of the tunnels is interested by geotechnical unit 1, 2 and 3: these represent good rock-mass condition, intact or little wethered granitoid and limestone, locally fractured, with low deformation (RMR 60-100). Another 46% by the units 4 and 5, carachterised by wethered and tectonally disturbed rock-mass, fractured to strongly fractured; low rock strength due to joints with collapsing of rock from free unsupported surfaces, occasionally squeezing conditions (RMR 20-60). And finally, just 11% is related to the units 6a and 6b, mainly at the tunnel portals, where weathered and tectonically disturbed claystone sandy and sandstone (6a) and carbonatic breccias and claystone carbonatic (6b) are present; they are strongly fractured, with low interlocking and quickly subsiding (RMR<20). The first parts of the tunnels were excavated employing the NATM system; at the portal, in geo-units 6a and 6b, section types 7MP and V6-Z6 were used; for the top-heading excavation (1.0-1.3 m step), forepolings in crown were used, R32 L=3.0 m in section type 6 and Ø114 mm L=12 m in section type 7MP, coupled with self-drilling radial anchors R51 L=4.0-6.0 m; locally steel tubes R32, L=8.0 m, were placed for core-face confinement. Prelining were composed by shotcrete layer, with wire-mesh and lattice girders. Bench excavation was done for 2.0-2.6 m excavation step, with shotcrete and lattice girders. In geo-units 4 and 5 section types V4-Z4 and V5-Z5 were applied, using steel forepolings Ø28 L=4.0 m in crown (just for section type 5), radial Swellex bolts L=4.0 m, shotcrete with wire-mesh and lattice girder (top excavation for 1.3-1.7 m steps and bench excavation for 2.6-3.4 m steps). Once ready the needed equipments, the tunnels‘ excavation is now continuing by means of the ADECO-RS approach, adopting full-face excavation and face and cavity pre-confinements, where necessary. For geo-units 1, 2 and 3 core-face “stable” conditions occur (category A), the deformation exhibits mainly in the elastic domain, no convergence are expected in the range 1.0-3.0 cm; section types A0 and A1 will be provided, with D&B excavation step in the range 3.0-4.5 m, Swellex bolts, L=4.0 m, and shotcrete, reinforced by steel fibers. For geo-units 4 and 5 expected behavior of the core-face is “stable at short time” (category B): the deformation exhibit in the elasto-plastic domain, with low extrusion and expected convergence and settlement in the range 2.0-6.0 cm; plastic zone at the face is 1.0-2.5 m, and increases up to 4.0-8.0 m around the cavity. No ground reinforcements for the core-face are required, but pre-support in crown could be necessary to maintain the excavation profile and avoid local collapsing of fractured rock-mass. Section types B0 and B0V will be provided, with excavation step in the range 1.0-1.6 by mechanical system (up to 3.2 m if D&B is used for section type B0); the confinement of the cavity is supported by steel ribs: 2 IPN 160 spacing 1.0-1.6 m and shotcrete, reinforced by steel fibers. For section type B0V, steel forepoles, 88.9 mm of diameter and 12-15 m in length, cemented with grout, will be placed. Finally for geo-unit 6a and 6b core-face “stable in a short time”, or “unstable” condition (category C), in very tectonised rock-mass, could be occur.

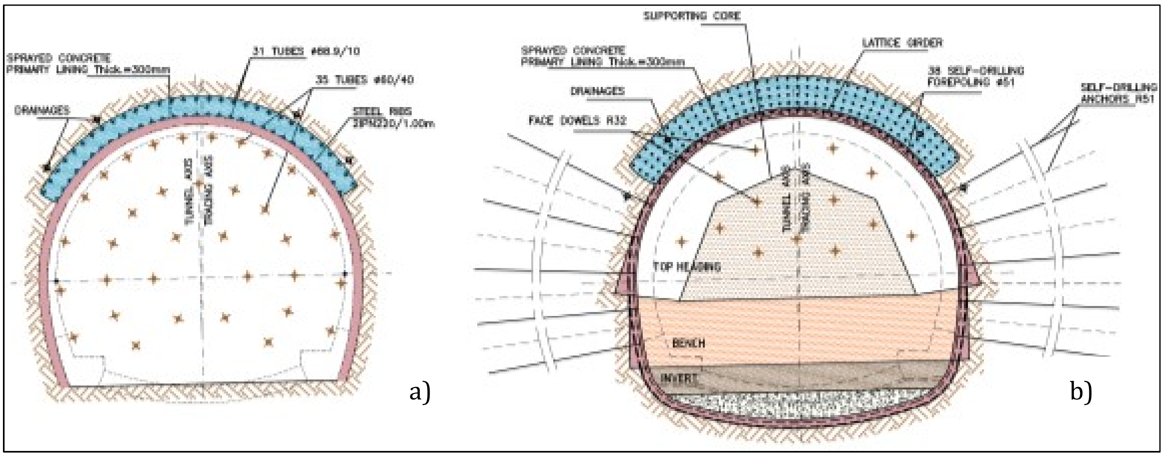


Figure 9: Visnove Tunnel Section types – a) ADECO-B2V; b) NATM-Z7

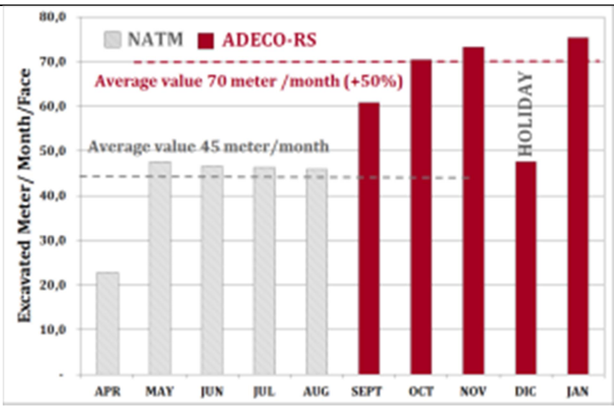
The deformation exhibit in elasto-plastic domain: extrusion is expected in the range 4-8 cm, with convergence and settlement in the range 5.0-10.0 cm. Plastic zone at the face is 2.0-4.0 m which increases around the cavity up to 9.0-12.0 m. To minimize this deformation response, pre-confinement is necessary, reinforcing the advance-core ahead

the current face with fiber-glass elements; sections B2 and B2V (Figure 9) will be provided with excavation step equal to 1.0 m: 35 cemented fiberglass structural elements, Ø60/40 type L=18 m length, overlap 8.00 m, will be placed in the core-face, steel ribs 2IPN200 spacing 1.0-1.2 m and shotcrete (10 cm shotcrete at the face).
The two excavation systems have been analysed in term of advance rates; in Figure 10 the average daily production of the main excavation section types are summurised, both for NATM and ADECO-RS system. It could be noticed that, for similar geotechnical units, the productions reached using ADECO-RS approach are greater with respect to the NATM ones, with an increase of 50-70%, despite the initial logistic difficulties in the implementation of the method. The main advantage is due to the face excavation in one step (full-face), which avoids the advance stops to allow the bench excavation. These best productions are also clearly pointed out considering the average monthly productions for face: from September, with the application of the ADECO Approch, the average face production is increased fron 45 m/month up to 70 m/month. These first data will have to be checked with the progress of the works and with the industrialization of the excavation process.

Average Daily Productions

Geo Unit	NATM		ADECO-RS	
	Section	m/day	Section	m/day
6a-b	7MP/Z6-V6	1,00	B2V/B0V	1,80
5	Z6/Z5-V5	1,50	B0	2,40
4	Z4-V4	2,50	A1-A0	4,40

a)



b)

Figure 10: Comparison of ADECO-RS and NATM for Visnove TunnelProductions: a) Daily; b) Monthly

4. CONCLUSION

The ADECO-RS Approach has been applied in Italy, for the first time, in 1988 to Tasso Tunnel and then to San Vitale and Vasto tunnels. After these successful experiences the method easily spred out and was rapidly adopted in Italy by all the Clients and introduced in their design specifications. The first application outside Italy was in 1997 with the Tartaiguille tunnel (high speed rail line between Marseille and Lyon in France). The benefit highlited from the method, in reference e.i. to the reinforcemnt of the advanced core, has been largely adopted in the last 15 years also from the NATM method. The implementation of the ADECO-RS approach in Russia has been positive, both in terms of production and in tunnelling safety. Russia has a strongly-rooted tradition towards the NATM system, but the Federal Administrations have of late been following a philosophy of deep technological innovation towards industry and production. The ADECO-RS approach enters perfectly in said new attitude and is of special interest to administrations and construction companies for its capability in tunnel construction within definite times and costs.The paper reports at the end the initial results of the most recent application of the ADECO – RS Approach in Europe, that is the Visnove Tunnel, a long motorway tunnel with a length of about 7,5 km which, for the second time in a few years after the experience in Sochi, is giving a realistic comparison of the construction features with respect to NATM.

REFERENCES

[1] LUNARDI, G., CASSANI, G., BELLOCCHIO A.The construction of two tunnels in difficult stress-strain conditions: the results of the first real comparison between NATM and ADECO-RS, Proceedings of the AFTES International Congress on "Tunnels and Underground space: risks and opportunities", Lione, 13-14-15 maggio 2014
[2] LUNARDI, P. Design and construction of tunnels, analysis of controlled deformations in rock and soils (ADECO-RS), Springer-Verlag Berlin Heidelberg, 2008.
[3] LUNARDI P.,CASSANI G., GATTI M., LODIGIANI G., FRANKOVSKÝ M., FULVIO M. The ADECO-RS approach and the full-face excavation for Visnove tunnel. Proceedings of the International Conference on "Tunnels and underground construction 2015", Žilina, 11-13 novembre 2015.
[4] RABCEWICZ, L. 1964. “The New Austrian Tunnelling Method”, Part one, Water Power, novembre, 1964.

G. Cassani: Giovanna.Cassani@rocksoil.com; M. Gatti: Martino.Gatti@rocksoil.com; C.L. Zenti: Carla.Zenti@rocksoil.com