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Full face excavation in difficult ground

This paper describes the evolution of full face excavation from the mid 1980s to the present. During this time, more than 1,000 km of tunnels have been designed, excavated and completed using full face excavation, with cross sections ranging in size from 120 to 220 m^2, in different geological and geotechnical conditions, near the ground surface or at depth.
Starting from the basic concepts of the approach (ADECO-RS) applied at the tunnel design stage and during construction, the experience gained and the lessons learned are summarised. It is shown how full face excavation has been developed and improved through the experience gained from the construction of both road and railway tunnels in the past thirty years.
In order to highlight the current stage of development, with new materials, technologies, modelling methods and increased capacity in observation and real-time monitoring of tunnel behaviour becoming available, the case of the Sochi Tunnel in Russia is presented and a comparison with the New Austrian Tunnelling Method (NATM) is illustrated.

1 Introduction

Between the end of 1980s and the start of 1990s, no established method was available for the design and excavation of tunnels in difficult ground conditions and for different models of ground behaviour. It must be recognised however that in order to meet the needs posed by new means of transportation and the increasing demand for mobility, spectacular tunnels were excavated and completed.

One may mention the excavation of the Frejus and Simplon railway tunnels through the Alps and "La Grande Galleria dell'Appennino" through the Apennines (the "Direttissima" railway line between Bologna and Firenze) as examples. This was achieved despite a number of workers losing their lives for the sake of reaching the objective. In the absence of established methods, different methods of tunnelling were applied such as the Belgian, Austrian and Italian methods, etc. which were essentially characterised by significant differences in the choice of the starting point for excavation.

With the exception of the introduction by Someiller of the first drilling machine driven by compressed air for the excavation of the Frejus tunnel, it was only between 1920 and 1960 that landmark contributions in tunnelling were made by *Terzaghi* (the "rock load" due to the weight of broken ground resulting from the excavation of the tunnel), *Kastner* and *Fenner* (the development of a "plastic zone" in the rock mass surrounding the tunnel), and *Rabcewicz* (the New Austrian Tunnelling Method), to mention a few.

In line with the session topic of the 38th Geomechanics Colloquy, we can recognise the great merit of Rabcewicz who pointed out: *(1) the importance of conserving and mobilising the inherent strength of the ground surrounding the tunnel, (2) the need to minimise 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, to gain information about tunnel stability and optimise 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 behaviour. Use was still made of ground classes and the analyses to understand ground behaviour were performed in two-dimensional conditions and limited to the tunnel cross-section. No sophisticated and advanced three-dimensional computational tools, as are now used, were available at that time. 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...."* [1]. It is indeed in this context that in the mid 1980s *Lunardi* [2] 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 tunnelling in difficult ground conditions. Of significant importance in doing this was the evidence derived from a unique deformation phenomenon observed during the excavation of the Frejus road tunnel (1975) and the experimental research studies performed thereafter on the tunnel response during excavation.

2 The ADECO-RS approach

The ADECO-RS approach, which stands for "Analysis of controlled deformations in rock and soil", shares 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 always driving the full face of the tunnel in every ground and stress-strain situation.
- The importance of the invert in difficult ground conditions (i.e. the need of "closing the ring").
- The relevance and value of stress-strain monitoring during face advance.

Without going into a detailed description of the approach, which can be found in the tunnelling literature [3], it is important to highlight how the above concepts are the fundamental components of ADECO-RS. These were agreed upon and further developed. Where possible, the inherent weaknesses associated with NATM, mainly due to the limited knowledge at the time of development, for the control of the ground response during excavation were corrected.

The characteristic features of the approach are:

- The importance of the ground deformational response during face advance (which is strictly linked to the formation of a short and long term arching effect, which is needed for the underground excavation to achieve stability). The tunnel engineer is to analyse it and make appropriate design predictions with reference to the "extrusion" of the face, the "pre-convergence" and the "convergence" of the tunnel perimeter, before starting excavation. From this point of view, one essential component of the approach is the full understanding of the tunnel behaviour in three-dimensional conditions. Essential in this approach is the control of the core deformation, from which originate both the "pre-convergence" of the tunnel contour ahead of the face and obviously the "convergence" of the tunnel behind it.
- Tunnel excavation is to be always carried out full face, even in difficult ground conditions, when stresses and strains develop in the tunnel surround including the "core" ahead of the advancing tunnel face; this is intended to be the main means of reaching stability of the tunnel (by using the designed pre-confinement, stabilisation and reinforcement measures as appropriate). The ADECO-RS approach is characterised by having found for the first time the technologies for "protecting" and

Table 1. Selected projects (see Figure 1)

Project	Length [m]	Ground type	Overburden [m]	Diameter [m]	Advance rate [m/d]
Milan-Rome high-speed railway line [1987] 6 tunnels between Florence and Arezzo	11,900	Sandy silts, lacustrine deposits	80	13.5	1.6
Caserta-Foggia railway line [1991] San Vitale Tunnel	2,500	Clay-shales	100	12.50	1.6
Ancona-Bari railway line [1993] Vasto Tunnel	5,000	Silty clays	135	12.20	1.6
TGV Mediterranée Marseille-Lyon [1993] Tartaiguille Tunnel	900	Swelling clays	110	15.00	1.4
Rome-Naples high-speed railway line [1994] 22 tunnels	21,987	Clays, pyroclastic and vulcanic rocks, lava, clay shales, sandstone, limestone	114	13.5	2.0
Milan-Rome high speed railway line [1996] 9 tunnels between Bologna and Florence	73,000	Silty clays, marls, flysch, sandstone, limestone	560	13.5	2.5
Large Open Ring, Rome [2000] Appia Antica twin tunnels	2 × 620	Pyroclastic rock	18	20.70	2.3
SS106 "Jonica" [2012] twin tunnel	2 × 13,265	Silty clays	120	13.0	1.8
Marche-Umbria [2013] 11 twin tunnels	2 × 20,000	Soil deposits, Limestone, marly limestone, marl	350	14.00	2.7
"Pedemontana Lombarda" [2013]) 3 twin tunnels	2 × 2,910	Gravel and sand, conglomerates, sandstone, marly sandstone	70	16.00	2.0
SS 212 "Val Fortòre" [2014] 4 tunnels	3,000	Flysch	36	14.6	1.5
Autostrada A1 "Variante di valico" between Bologna and Florence [2014] 8 twin tunnels	2 × 45,000	Flysch, scaly clays, sandstone	150	15.7	1.8

"reinforcing" the core ahead of the advancing tunnel face, whenever needed (with the use of fibreglass elements, sub-horizontal jet-grouting columns, mechanical pre-cutting full face, etc.).

- The transition from the confinement action due to the "core" ahead of the advancing tunnel face to that of the support along the tunnel perimeter is to take place in the most uniform and gradual way possible, by taking the invert in the near vicinity of the face, if needed. The key component of the approach is to minimise the extrusion surface which coincides with the tunnel perimeter and extends longitudinally, from the point of contact between the ground and the support at the crown and at the invert respectively.
- The validation and the simple and immediate calibration of the design during excavation is to be carried out in line with the longitudinal and transversal sections and the possible variability of them defined at the design stage, on the basis of continuous performance monitoring and comparison of the predicted and the measured three dimensional displacement components, in line with the iterative observational approach.

The most significant advantages of working in accordance with the ADECO-RS approach are:

- Industrialisation of the works (with reference to both time and cost), with few specialised workers in the tunnel (maximum six people per stage), a limited number of large and powerful multi-purpose machines and equipment, given the space which is made available with the full face method, with a clear sequence of operations.
- Safety of the workers (the accidents at the tunnel face are nearly zero), due to their limited number at each stage, given that fewer men means better safety.
- Excellent production rates as demonstrated by the minimum mean daily face advance of 1.5 m/d in a completed tunnel with a cross-section of about 160 m^2. This is possible in the most difficult ground, including low cover conditions, with significantly reduced construction time.

After more than 30 years of application of the approach and the excavation of significant tunnel lengths (more than 1,000 km), with cross-sections ranging in size from 120 to 220 m^2, in different ground conditions, near the surface or at depth, it is well demonstrated that it is possible to safely and efficiently drive a tunnel in difficult ground conditions and complex behaviour, by excavating the tunnel full face, according to *Rabcewicz* intention, by reinforcing the "core" ahead of the advancing tunnel face

Fig. 1. Photographs showing the face of a few selected tunnels (see Table 1)

and, if needed, around the tunnel perimeter with the most suitable pre-confinement, stabilisation and reinforcement measures.

It is important to remark that significant efforts have been made during this time to improve the technologies adopted for achieving these objectives [4]. For example, the 30 to 40 mm diameter pipes, which made it difficult to reach lengths of the core greater than 15 m, were replaced with fibre glass bands of different cross-sectional profiles. With the flexibility gained in this way, which made rolling and easy transportation possible, core lengths of 24 m could be reached.

With the understanding that the core-face reinforcement is more effective if the adhesion between the grout and the ground is increased, a significant effort has also been made to test the use of expanding mortars by means of expanding agents to be mixed with the cement in the grout to be injected. Also, more recently, the PER ground element was introduced by adopting fibre glass corrugated pipes coated by an expandable sheath, with the intent of recompressing the ground.

Different methods for measuring the face extrusion have been used such as the incremental extensometer with significant advantages, when combined with the more traditional convergence measurements, for the understanding of the deformational response of the core ahead of the advancing face and of the ground surrounding the tunnel. This, together with careful three-dimensional modelling developed with attention to the realistic simulation of the excavation/construction stages and of the ground behaviour, contributed significantly to the understanding of the tunnel response in different conditions.

3 Selected projects and the Sochi tunnels

A great number of tunnels have been completed according to the ADECO-RS approach in difficult conditions and for different ground behaviour, with due attention to the work schedule and the costs anticipated at the design stage. Some of these tunnels, which have been selected with the purpose of conveying the wide spectrum of such conditions, are given in Table 1 (Fig. 1).

In addition to major railway, motorway and road tunnels in Italy, also included in the table is the very difficult "Tartaiguille" Tunnel in France, which was excavated in swelling clays along the "TGV Mediterranée" railway line inside the predicted time and cost [5].

It is of interest to point out that more recently the approach has been applied in Russia for the excavation of the T8 and T8A tunnels of the Sochi motorway ring, one of the projects developed for the XXII Winter Olympic Games. These tunnels are of interest given that the other tunnels on the same motorway ring were excavated in similar ground conditions according to the NATM. For the first time, one is therefore in position to work out a comparison between the two methods based on real and therefore reliable data.

Figure 2 shows the tunnels of the Sochi motorway bypass. The T8 and T8A tunnels, excavated using ADECO-RS, are shown in red and the NATM tunnels are shown in light blue. It is relevant to point out that the first two tunnels, in addition of being longer than the others, are of a more significant size ranging from 120 to 220 m^2 (Figure 3). It should be noted that the 220 m^2 cross section is in the proximity of the North Portal (in a landslide zone) where a junction of the new with the old road network is

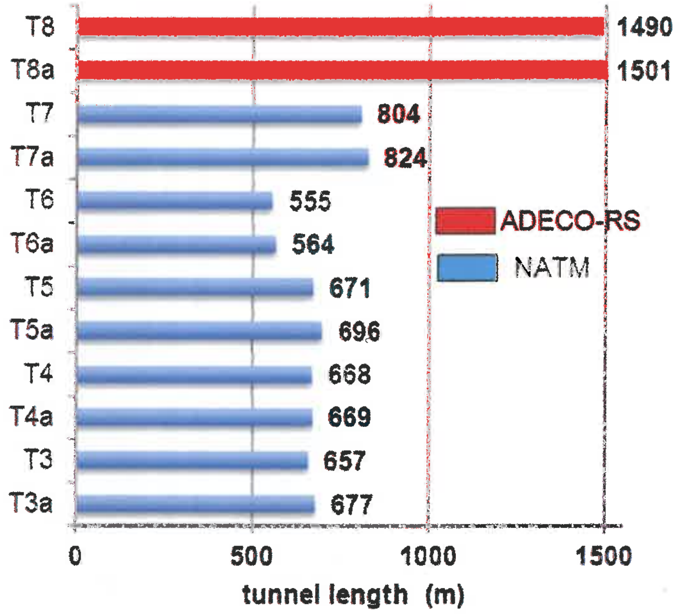

Fig. 2. Tunnels along the Sochi motorway ring

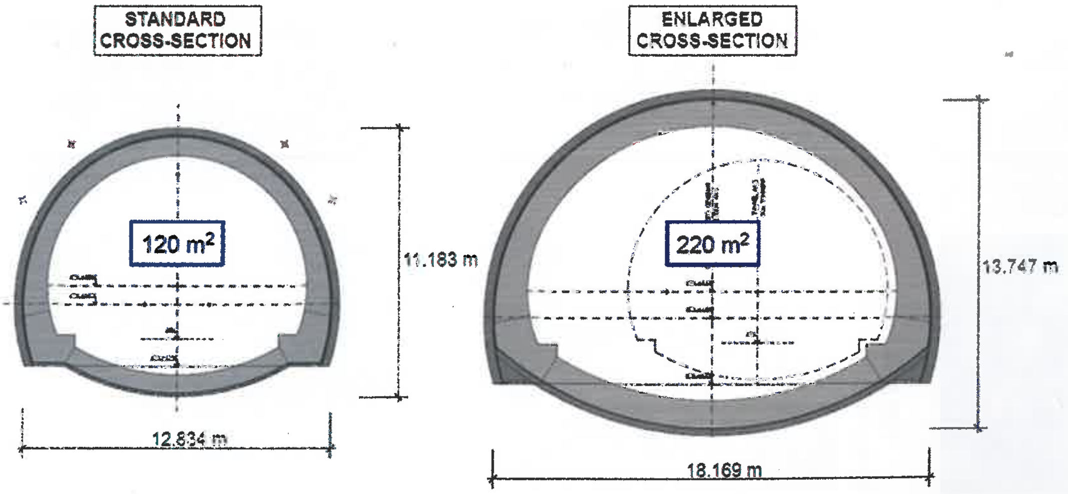

Fig. 3. Cross sections of the T8 and T8A tunnels

located. Another point of relevance is the lower cover of the tunnels, which were excavated in densely inhabited areas as shown in Figure 4.

From a geological point of view, the Sochi motorway by-pass is located along the shore of the Black Sea, which is characterised by hilly and heavily vegetated countryside. As illustrated in the longitudinal geological profile in Figure 5, the T8 and T8A tunnels cross the "Sochi Formation", composed of claystones and silty clays, and the Mamai Formation", with marly flysch with a scaly type structure. The two formations are intersected by faults. Also to be highlighted is the presence of colluvial-alluvial sedimentary covers met near the tunnel portals and in low overburden zones, where there are also active landslides.

Fig. 4. View of the Sochi North Portal showing densely inhabited areas

In line with the predictions based on ADECO-RS, the T8 and T8A tunnels were excavated along their entire length in stable in the short term or unstable core face conditions (types "B" and "C" behaviour categories). As shown in Figure 6, the excavation took place full face by using the necessary protective and/or reinforcing measures of the "core-face" and by keeping the kickers and the invert of the final tunnel lining in close proximity to the advancing tunnel face (less than 1 ∅). It is noted that in all cases, for the cross-sections where the core-face reinforcement could be avoided, this last stabilising measure has always been adopted due to the presence of a significant in-situ horizontal stress component. Figure 7 gives a view of the tunnel face with the stabilisation measures completed.

As illustrated in Figure 8, the T8 and T8A tunnels were excavated with a rate of excavation of 40 to 90 metres per month, except when under-passing the landslide zone at the North Portal, where the same rate fell to 20 m per month, also due to the large tunnel cross section adopted (220 m^2). It is noteworthy that, apart from difficulties of various kinds met with organisation and adopting the novel technologies which characterise the ADECO-RS approach for the first time in the country, the productivity of the excavation process was soon up to expectations, also due to the gradual gain of experience in the application of the approach by the contractor.

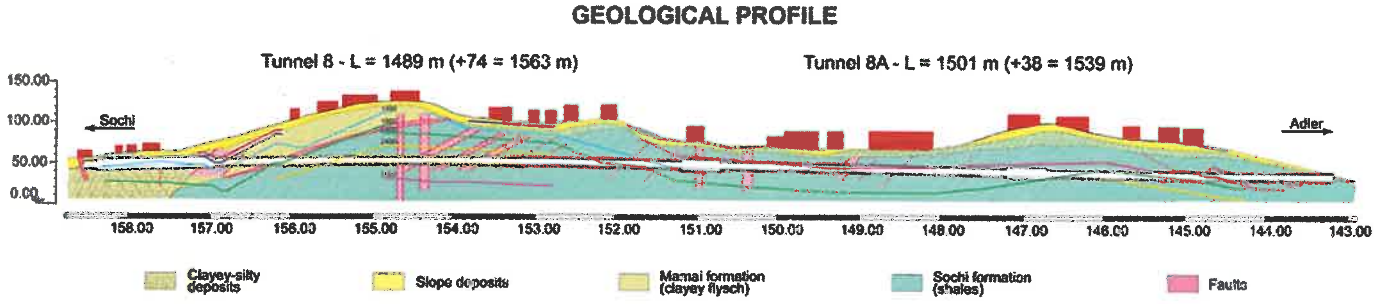

Fig. 5. Geological profile of the T8 and T8A tunnels

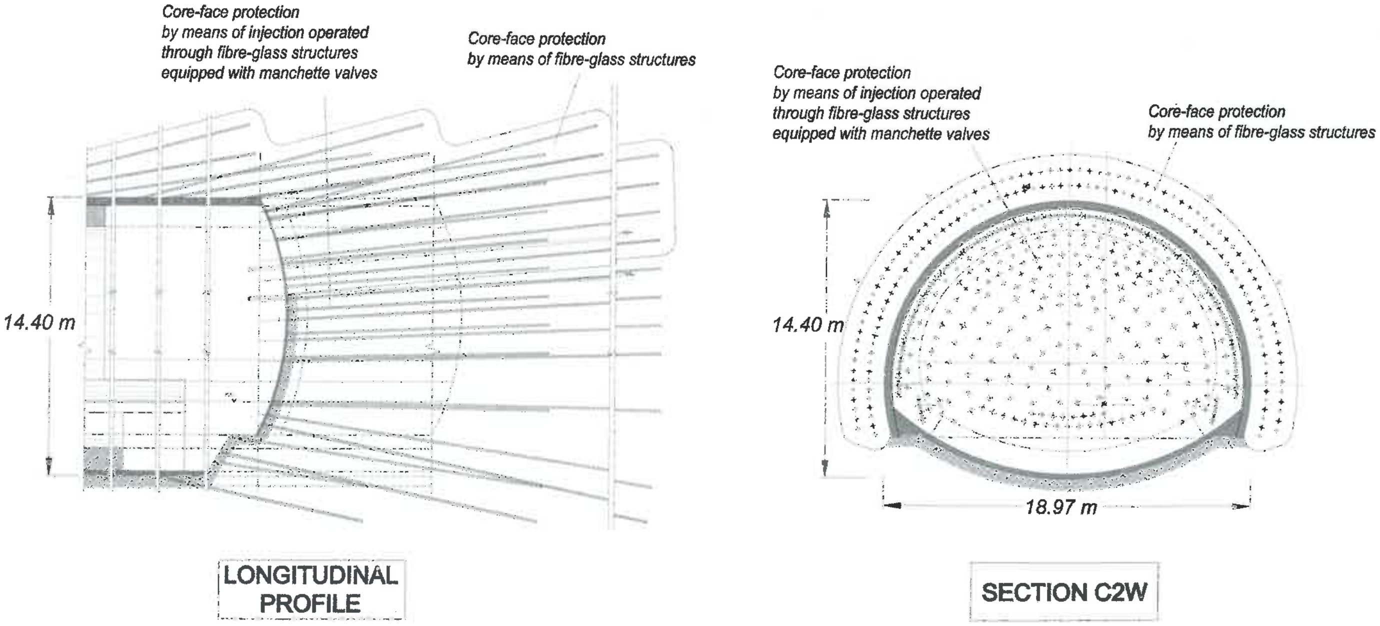

Fig. 6. Typical cross-section with the stabilisation measures of the core and of the tunnel contour ahead of the advancing face

Fig. 7. View of the tunnel face showing the core-face stabilisation measures

With the excavation of the T8 and T8A tunnels completed, it is also of interest in the light of the topic covered by the 63rd Geomechanics Colloquy to draw attention to Figure 9 where the "volume of rock excavated/month" and "metres of completed tunnel/month/face" are shown for these two tunnels and the T7, T7a,…,T3, T3a tunnels (see Fig. 2). The better performance of ADECO-RS compared to NATM in terms of these two parameters is clearly shown. The "volume of rock excavated/month" with the former approach is 2.4 times that attained with the latter approach; similarly, the "metres of completed tunnel/month/face" is 40 % greater with ADECO-RS compared to NATM.

An additional interesting comparison between the two tunnelling approaches is possible by plotting, as shown in Figure 10, the time (days) between the breakthrough of a tunnel and the time the final lining was installed, i.e. tunnel stability and safety were reached. It is clear that ADECO-RS, by its own nature, is characterised by the very short time (three weeks approximately) until final lining installation compared to the NATM (from 10 weeks minimum to 43 weeks maximum).

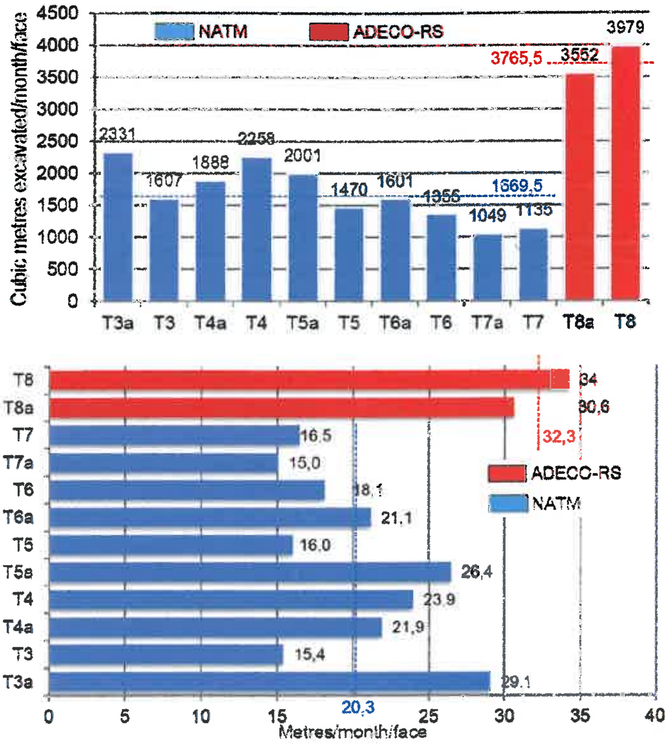

Fig. 9. Comparison of ADECO-RS and NATM in the Sochi tunnels in terms of "cubic metre excavated/month" (above) and "metre/month/face completed" (below)

It is observed that the authors are not in position to compare the two approaches from the point of view of the cost of the completed tunnel, since this data is not available for the NATM excavated tunnels. It is well understood that full face excavation of a tunnel with concomitant stabilisation measures applied to the core, typical for the ADECO-RS tunnels excavated in difficult ground,

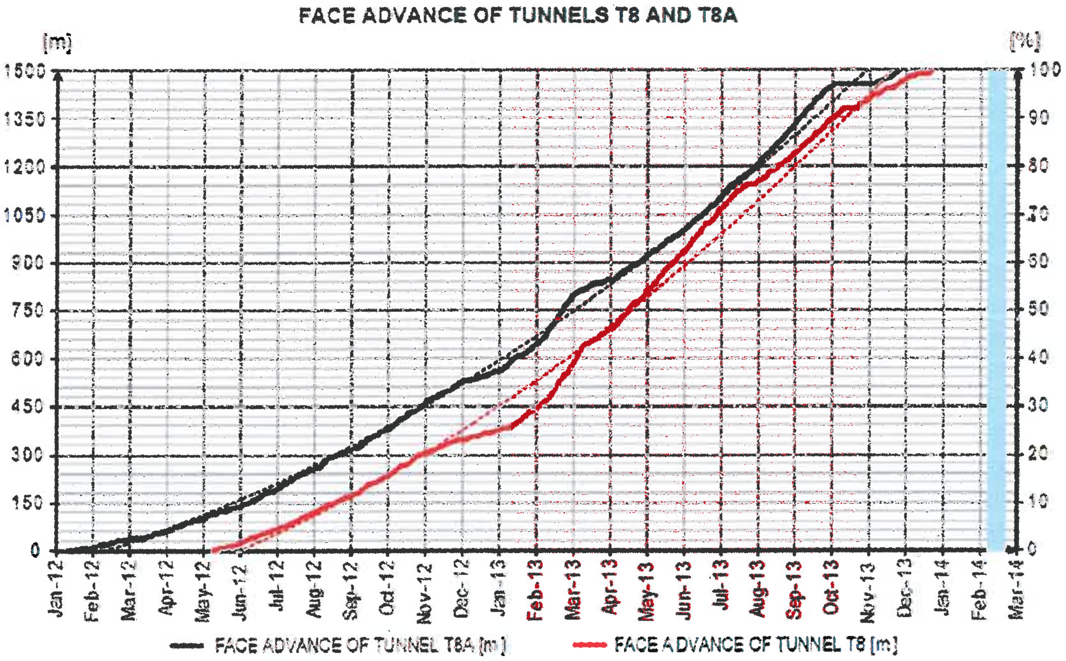

Fig. 8. Rate of excavation of the T8 and T8A tunnels

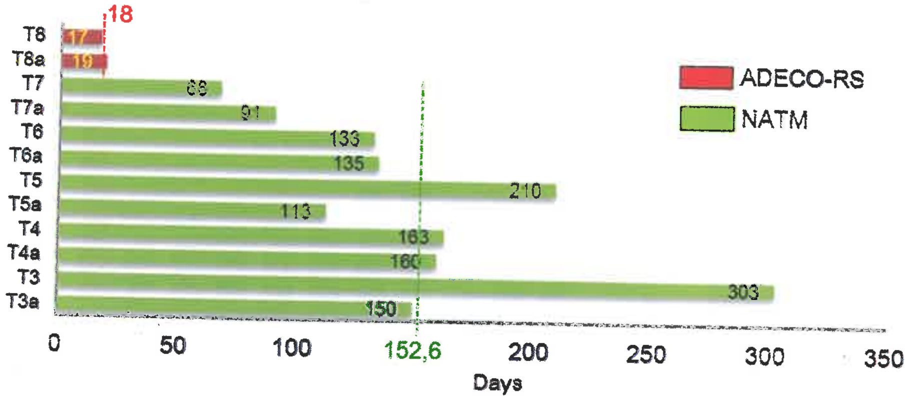

Fig. 10. Comparison of ADECO-RS and NATM in terms of the time (days) between the tunnel breakthrough and the time the final lining is installed

might be a little more costly. However, it is fair to say that if one correctly considers the other factors pointed out above, such as the time saved for tunnel completion, the reduced manpower needed at the face, the high degree of industrialisation of tunnelling, and the greater safety conditions achieved, ADECO-RS is overall thought to also be more advantageous with regard to the cost.

4 Concluding remarks

An attempt has been made in this paper to introduce the key components of the ADECO-RS ("Analysis of controlled deformations in rock and soil") approach to tunnelling in difficult ground. It has been stated that this approach, at the time of its development, agreed with many of the concepts of NATM, and then developed and deepened them, introducing the appropriate "corrections", where possible, of its "inherent" weak features with reference to the control of ground response during excavation.

A number of selected applications of the ADECO-RS approach in the last 30 years have been briefly reported, before taking as a recent case example the excavation of the tunnels of the Sochi (Russia) motorway ring, one of the projects developed for the XXII Winter Olympic Games. These tunnels are thought to be of interest given that two of them (T8 and T8A) were excavated using the ADECO-RS approach, whereas the remaining ones (T7, T7a,…,T3, T3a) were completed according to the NATM.

It has been shown that the ADECO-RS approach, when applied to tunnels in difficult ground with full face excavation with concomitant stabilisation of the core-face, as in the case of the Sochi tunnels, offers significant advantages in terms of the production rates which can be achieved, the shorter time needed for tunnel completion, the reduced manpower needed at the face, the high industrialisation of tunnelling, and the better safety conditions.

In light of the developments and the results achieved so far with the full face excavation method when properly applied with the advanced design tools and the novel technological developments that are now available, and the performance monitoring methods which can be used during face advance, the authors would like to invite their Austrian friends to find two tunnels to be excavated in their country where difficult ground conditions are expected.

A fruitful comparison between the NATM and its natural development, represented by ADECO-RS, could be carried out with the intent of progressing together, from both a scientific and a technological point of view, in the complex, challenging and fascinating world of tunnelling.

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