"Val Fortore State Road 212" – Problems addressed in the excavation of tunnels in structurally complex formations: from design to construction.

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ABSTRACT

The arrival of the ADECO-RS approach (Lunardi P., 2008) in the field of tunnelling made a substantial contribution to the process of industrialising conventional excavation, making it possible, amongst other things, to construct tunnels in structurally complex contexts.
In this paper the authors illustrate the main issues addressed in the designs for the construction of tunnels on the new Val Fortore State Road 212. Tunnel excavation passes mainly through the clayey-marly and calcareous-marly flysches of the Lagonegresi Unit (Flysch Rosso) with a shallow overburden (< 15 m.).
The final design specifications prepared by the Contractor involved full face advance using fibre glass structural elements for the ground improvement of the face, while metal forepoles were specified for around the cavity. Unfortunatly, the section types employed were inadequate for tunnel advance under low overburden conditions and in grounds having very poor geotechnical characteristics. Substantial deformation of the cavity (average diametric convergence of between 200 mm. and 300 mm.) occurred during excavation of the Cerzone Tunnel (September 2008). Despite measures taken by the Contractor to contain deformation, the face fell in with rock and soil pulled down from the roof as a consequence, which the forepoles were unable to confine and this caused a crater to open at the surface. This event caused work to be suspended and a new design for tunnel advance to be drawn up by Rocksoil S.p.a.
The new tunnel section types and the on-site technical assistance provided by Rocksoil engineers by using the ADECO-RS approach enabled excavation to resume without difficulty and with limited deformation.

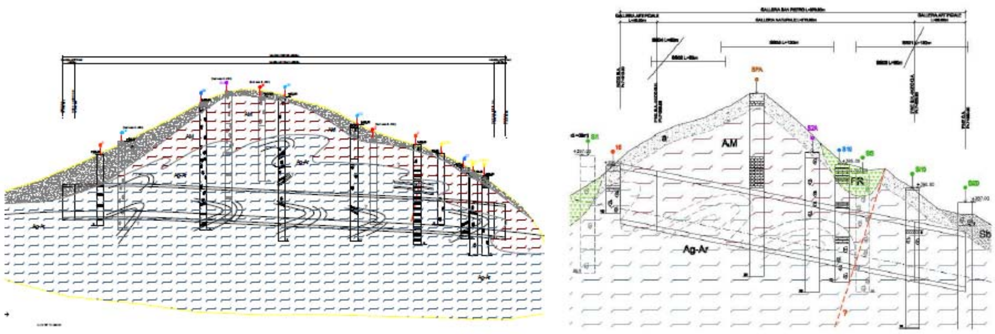
1 INTRODUCTION

ANAS's (state-owned company for the construction and maintenance of motorways and highways) intention with the project to modernise the Val Fortore State Road 212 was to create a route for fast-moving traffic between Campania and Puglia.
Studies of the route date back to the 1990s and, after various solutions were considered, a preliminary design for the entire route was drawn up with a final design for the first section approved in 2003 which was put out to tender in 2004 by ANAS with a full, design and construction, contract formula.
The contract for the first section, between the Pietrelcina junction (chainage 5+600) and the exit for S. Marco dei Cavoti (chainage 46+900 of the former State Road S. 369), was awarded to the *ATI* (temporary consortium of companies) consisting of the Consorzio Ravennate delle Cooperative di Produzione (the Lead Contractor), Intini Spa and Rillo Costruzioni Spa (Member Contractors).
The construction of the following four tunnels was programmed moving from South to North:

- Cerzone Tunnel (underground section L= 900 m.) ;

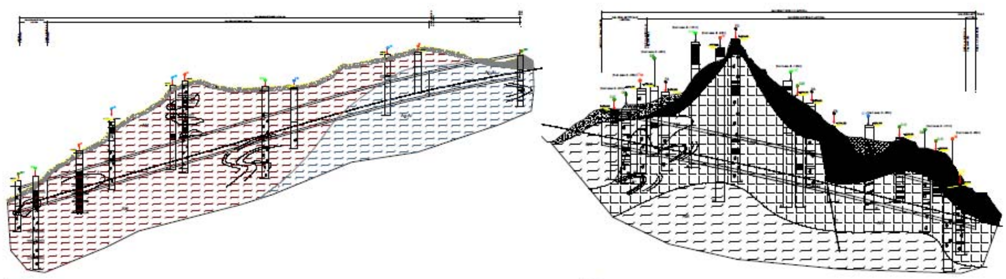
- San Pietro Tunnel (underground section L=275 m.);
- Fuciello Tunnel (underground section L= 570 m.);
- Monteleone Tunnel (underground section L= 920 m.).

The tunnel faces had a surface area of approximately 145 sq. m. and passed through the marly-arenaceous flysch formations (Sb-Ar), belonging to the complex of the Miocene deposits of the *Unità Irpina* (*Flysch di S.Giorgio*) and the clayey-marly and calcareous-marly flysches (AM and Ar-Ag) of the *Unità Lagonegresi* (*Flysch Rosso*).



(a) (b)

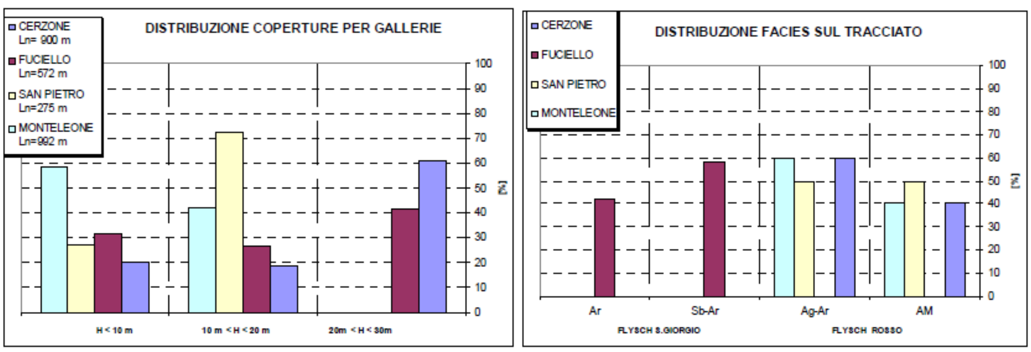
Figure 1- geological profile of the Cerzone Tunnel (a) and the San Pietro Tunnel (b)



(c) (d)

Figure 2 – Geological profiles of the Monteleone Tunnel (c) and the Fuciello Tunnel (d)

The problems encountered in driving the underground tunnels were closely related to the poor geotechnical characteristics of the materials tunnelled and also to the shallow overburdens. As shown in the charts (Fig. 3), most of the tunnels were driven through the Red Flysch formation, while the overburdens were mainly between 5 m. and 20 m., which is to say they were comparable to the diameter of the tunnel.



(a) (b)

Figure 3-distributon of the overburdens (a) and of the facies (b) in the sections of the underground tunnel

The partially saturated conditions typical of these materials ($Sr_{,average}$=68%) and the tendency, even in the clear absence of water flow, to absorb water from the atmosphere, caused a rapid change in the strength characteristics of the ground, with an instantaneous loss of consistency and the onset of swelling. Laboratory tests showed the presence, in the clayey sediment, of overall percentages of smectite and illite varying between 50% and 55%.

(a) (b)

Figure 4 – Sources of excavation in the Flysch Rosso unit (a) and the Flysch di San Giorgio unit (b)

2 A BRIEF HISTORY OF THE EXCAVATIONS: THE CONTEXT OF ROCKSOIL'S INTERVENTION

Excavation of the Cerzone and Fuciello underground tunnels commenced between July and November of 2008.

The design for the long and short term stabilization of the excavation, drawn up by the Contractor, involved sections of different types, which differed according to the overburden conditions.

Excavation of the Cerzone Tunnel, which began on 16th June, had to be conducted under overburdens of less than 15 m. for the first 150 m. and therefore with overburdens of less than one tunnel diameter.

The design specified 60 fibre glass structural elements (L=18.0 m. overlap = 5.50 m.) in the advance core and 36 metal forepoles around the profile of the excavation (L= 15.0 m. overlap 2.0 m.) under low overburden conditions.

The preliminary lining consisted of steel ribs with an HEB 180 profile, placed at intervals of one metre and covered by a layer of shotcrete (25 cm.) reinforced with steel mesh.

Substantial deformation of the excavation was encountered in the first few metres of tunnel advance with vertical subsidence of around 50 cm. and average diametrical convergence of 30 cm., which only stabilised after the tunnel invert was cast.

In order to limit these deformation phenomena, that were closely related to both the poor geotechnical characteristics of the ground passed through and the existing shallow overburden, the Contractor put into practice the following remedies:

- the length of tunnel advance steps was reduced which therefore increased the overlap of the ground improvement structural elements in the face;
- the techniques employed for implementing ground improvement were refined;
- the tunnel invert was cast closer to the face and the first lengths of tunnel advance were completed by casting the lining in the crown.

Despite the measures taken, sudden increases in deformation occurred at the face during the fourth step of tunnel advance. This brought down ground in the roof which the forepoles were unable to contain and finally a crater opened up at the surface.

Figure 5 – Cerzone Tunnel: collapse at north portals of 26-09-2008

A very similar situation occurred during the second length of tunnel advance in the Fuciello Tunnel although under relatively better geomechanical conditions.

Figure 6 Fuciello Tunnel: collapse at the north portals of 11-11-2008

At this point, with excavation suspended in the Cerzone Tunnel, the Contractor instructed Rocksoil to design tunnel section types adequate for the low overburden conditions and at the same time to revise the design of the section types for sections of tunnel with overburdens of greater than 20 m.
It was immediately clear from observation of the tunnel and analysis of the monitoring data that the tunnel section type employed was inadequate for tunnel advance under low overburden conditions. The forepoles were not able to limit deformation of the cavity ahead of and down from the core face (preconvergence and convergence) by determining the migration of lithostatic stresses on to the sides of the tunnel (an arch effect).

3 REVISION OF THE GEOTECHNICAL MODEL (THE SURVEY PHASE)

The revision of the design specifications for ground improvement and reinforcement involved a critical re-examination of the basic data (geological and geotechnical model), appropriately supplemented with a new survey campaign designed above all to define the deformability parameters of the rock mass. The survey found basically uniform physical characteristics and strength parameters, with a clear and progressive improvement in the characteristics of the lithotypes with depth.
The samples which were taken from the fine component of the flysch formations, which determines the response of these materials to excavation, found a prevalent presence of a silty component, with average percentages of greater than 60%, followed by clays and sands. From a granulometric viewpoint the material was defined as "clayey-arenaceous silt". The laboratory tests generally found a regular texture for the fine fraction (silt and clay) which was constant with depth. (Fig. 7).

Charts are given below to show what has been said above more clearly. They show changes in the physical and strength characteristics of the materials with depth, based on the results of the laboratory tests performed.

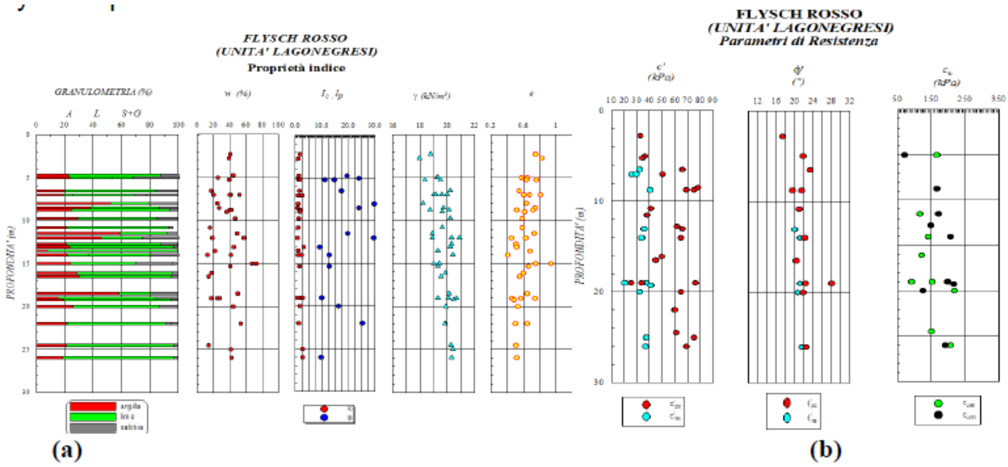


Figure 7-Phyical parameters (a) and strength parameters (b): variability with depth

As concerns the strength parameters, it can be seen that the drained cohesion (peak and residual) varies appreciably with depth, which affects the basic homogeneity of the physical characteristics of the material (water content, index of consistency, etc.) and confirms the actual variability of the material as a function of depth. The angle of friction on the other hand is different, since it is an intrinsic parameter of the material and depends exclusively on the granulometry and/or mineralogy of the particles. In fact the values are less scattered than those for cohesion (Fig. 9).

The parameters for the deformability of the rock mass were determined using down-hole seismic tests. The elastic modulus E was then obtained from the Vs values for velocity, using the classic formula in the scientific literature, while the dynamic modulus was appropriately reduced on the basis of the results obtained from borehole tests (pressuremeter) (Fig. 10). A comparison is given below of the deformability moduli, which vary with the relative overburdens. It shows the changeover from the final design specifications (PE - Fortorina Scarl) and the modified design specifications (PV - Rocksoli SpA).

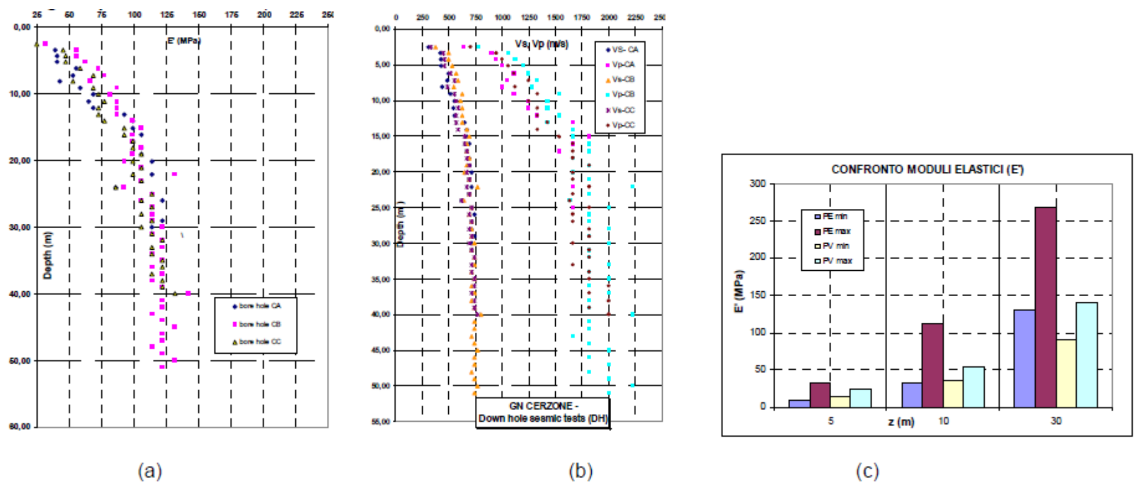


Figure 8 Results of the downhole seismic tests (a) and (b); comparison of the elastic moduli (c)

GEOTECHN-ICAL UNIT	Z	γ	c'_{peak}	ϕ'_{peak}	$c'_{residual}$	$\phi'_{residual}$	E'
AM / Ag-Ar (Flysch Rosso)	[m]	[kN/m3]	[kPa]	[°]	[kPa]	[°]	[MPa]
	0- 10	18,50 19,00	10-25	20-21	0-10	18-20	15-25
	10-25	18,50 19,0	25-60	20-23	10-30	20-21	25-60
	> 25	19,00 21,00	60-75	20-23	30-35	20-21	60-130

Figure 9 Geotechnical parameters associated with the Flysch Rosso formation

4 ANALYSIS OF DEFORMATION IN THE CERZONE TUNNEL (THE DIAGNOSIS PHASE)

An analysis of deformation observed in the Cerzone Tunnel furnished both an understanding of the failure mechanism which occurred at chainage 5+386, and the type of intervention needed to construct the tunnel without difficulties and with limited deformation.
The tunnel advance which commenced on 12/06/2008 was characterised by the following: modest face advance speeds, especially for the first two advances; tunnel inverts cast after too long a delay with respect to face advance; the total absence of crown linings being cast (see Fig. 10).

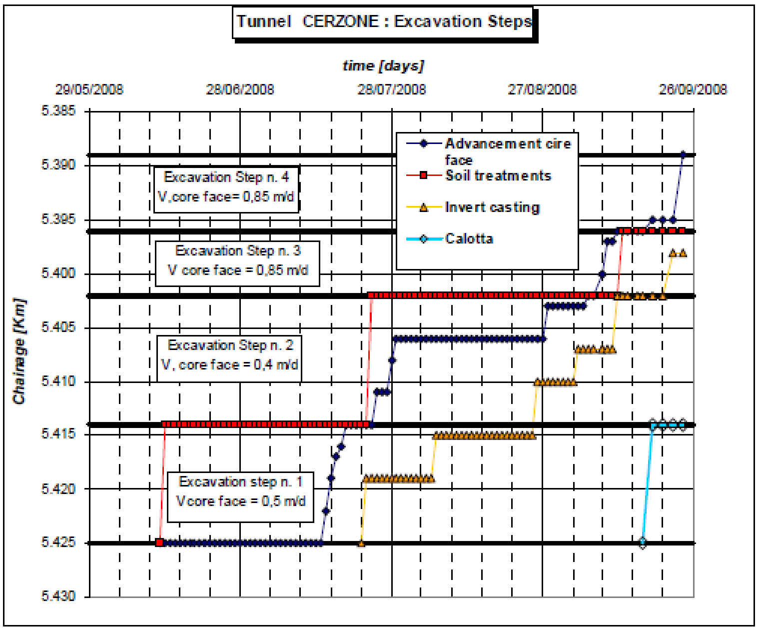


Figure 10 Operating stages for the Cerzone Tunnel from 12/06/2008 until 26/09/2008

An analysis of the monitoring data for the section at chainage 5+403 (third excavation field) shows two quite distinct deformation mechanisms. At the first stage, a fragile failure can be seen close to the face, with average diametric convergence of between 30 cm. and 40 cm., due to a sudden loss of strength, which is characteristic of the material during the decompression phase of the rock mass (Fig. 11 a). The commencement of excavation required in order to cast the tunnel invert caused a reduction in diametric convergence as the steel ribs thrust into the invert (see Fig. 11b). The speed of vertical settlement increased from 15 mm./d., during face advance to 120 mm./d. during excavation of the tunnel invert, to then stabilise when the invert was actually cast. The phenomena just described involved the formation of a band of material characterised by plastic behaviour which extended to surface level. The metal forepoles placed around the excavation had not therefore performed any effective preconfinement action.

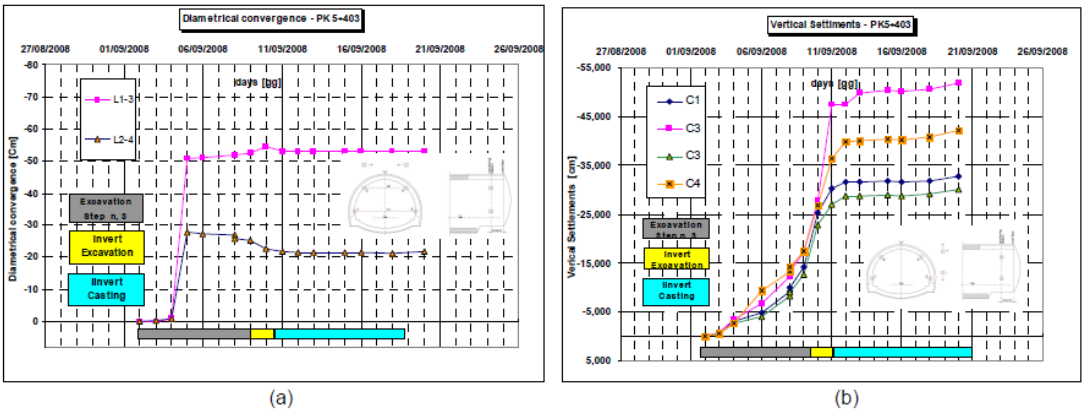
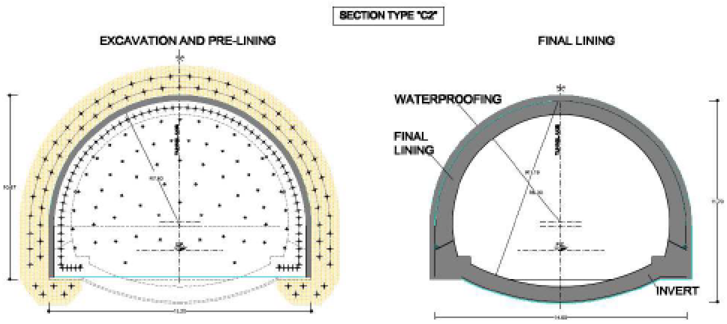


Figure 11-Convergence monitoring station at chainage 5+403: Diametric convergence (a) vertical settlement (b)

1 NEW TUNNEL SECTION TYPES PROPOSED BY ROCKSOIL (THE THERAPY PHASE)

An examination of what emerged from the study of diagnosis showed the need for the following:
a) improvement of the tunnel advance steps, by increasing the overlap of the ground improvement in the face;
b) improvement of ground improvement and reinforcement in advance around the cavity, by eliminating the forepoles, and using techniques to limit the creation of a plastic band around the cavity, and also to reduce preconvergence phenomena ahead of the face;
c) improvement of operating procedures to reduce the times between excavation and closing the preliminary lining by casting the tunnel invert to a minimum;
d) rationalisation of production to comply with contractually agreed schedules for the completion of the project.
A section type was selected for shallow overburdens (5 m. - 20 m.) based on the data acquired in the supplementary survey, on the downhole seismic tests and on interpretation of the monitoring data (diagnosis phase). It involved full face excavation, with a concave shaped face, after first employing ground improvement and reinforcement in the core ahead of the face.



ADVANCEMENT COREGROUND REINFORCEMENT	
N. 65 (±20%)	fiber glass structural elements 60/40 or cemented structural elements length= 18.00m overlap= 9.00m
CAVITY REINFORCEMENT	
N.59	steel valved pipes (injected 2v/m) or fiber glass structural elements length= 18.00m overlap= 9.00m
BASE REINFORCEMENT OF STEEL RIBS	
N. 5+5	steel valved pipes (injected 2v/m) or fiber glass structural elements length= 13.00/18.00m
STEEL RIBS	2 IPN 200 step=1.00m(±20%)
DRENAGE PIPES	N.4 length>=30.00m overlap >=10.00m
SHOTCRETE	pre-lining th= 0.25cm core face th= 0.15cm

FINAL LINING= thickness 0.80cm
INVERT= thickness 0.90cm
LEAN CONCRETE = thickness 0.10cm

Figure 12 – Section type C2: ground improvement and steel structural work

Around the excavation, however, ground improvement was employed instead of forepoles to create an adequate layer of “treated” ground (more rigid and stronger than the natural ground), which would facilitate the migration of lithostatic stresses to the sides of the tunnel so that they would be unloaded below the level of the excavation (an “arch effect”). The injections specified would find it hard to work by means of permeation, except in sections with sandy layers, and consequently the effect required was that of compressing the ground again in order to bring it to a state of stress. The characteristics of the new section type, termed C2, are summarised in figure 12.
For the central sections of the tunnel, however, where the overburdens are between 20 m. and 30 m., the ground improvement and reinforcement of the existing section types was improved, in order to simplify performance of the work (excavation of cylindrical, rather than truncated cone sections) and reduce, amongst other things, the possibility of potential reductions in the specified thickness of the final lining in the crown due to possible errors in positioning steel structures. The characteristics of the section type, termed B2, are summarised in figure 13.
The dimensions for the operations specified (ground improvement and linings) were calculated using numerical finite difference analysis (2D and 3D).

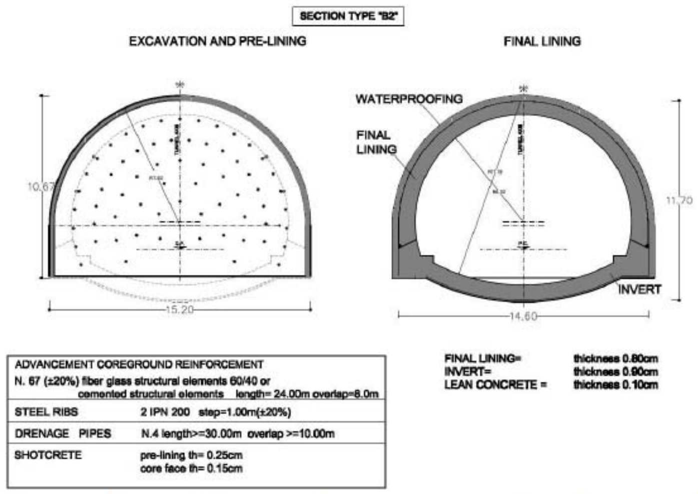


Figure 13 – Section type B2: ground improvement and steel structural work

2 THE MONITORING PHASE DURING CONSTRUCTION

Excavation of the Cerzone Tunnel resumed in January 2010 with the new section types selected by Rocksoil engineers and work on the Fuciello and Monteleone tunnels followed, when the administrative procedures for the approval of the new design of the section types was complete.
At the time of writing this paper, excavation of the Cerzone Tunnel was 60% complete, the Monteleone Tunnel was 45% complete and the Fuciello Tunnel had been finished (inclusive of the final linings). At present, work on the San Pietro tunnel has not commenced for administrative reasons.
A report on the Cerzone Tunnel is given below, because the deformation phenomena monitored is very representative of the problems encountered in the excavation of the other tunnels.
As already mentioned, the surface area of the cross section of the tunnel to be excavated was 145 sq. m. and the weight of the pairs of steel ribs, with IPN steel profiles, specified to support the excavations, varied between 1,500 kg and 1,900 kg, depending on the profiles employed. The volume of shotcrete placed around the walls of the cavity, including that used for buffers at the end of each tunnel advance was approximately 25 cu. m. per metre. Ground reinforcement in the face involved the placing on average of 1,400 m. of structural

fibre glass elements, while 1,000 m., was employed, where specified, around the cavity. Despite the very large quantity necessary for excavation, the operational stages were appropriately streamlined to generate production rates of 20.70 m./month for the C2 section types and 43.50 m/month for the B2 section types.

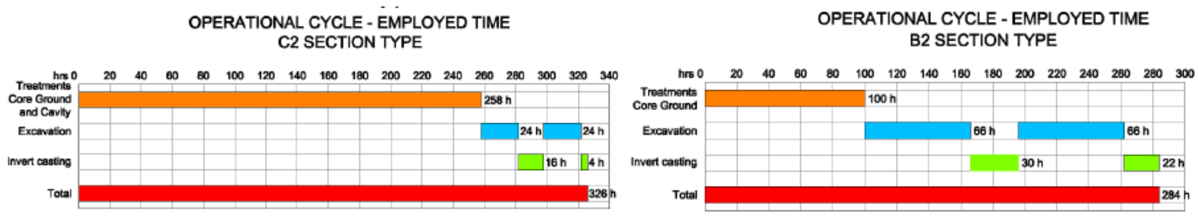


Figure 13 – Work cycle times by section type

Continuous interpretation of monitoring data acquired for each step of tunnel advance was used to fine tune the specifications for the section type in terms of:

a) the number of fibre glass structural elements in the face (from 65 to 75) and around the cavity (from 49 to 55);

b) the length of the steps with which the tunnel invert is cast (from 4.0 m.to 6.0 m.);

c) spacing of the steel ribs (from 0.80 m to 1.0 m);

d) distance from the face at which the lining in the crown is cast (from 12 m. to 15 m.).

An analysis of the data from the convergence measurement stations for shallow and deep overburdens showed that diametric convergence varied from between 2.5 cm. (chord L2) and 7.0 cm. (chord L1), with maximum gradients of deformation of 16 mm/d, until the tunnel invert was cast. The gradient recorded after the ring of the preliminary lining was closed with the casting of the tunnel invert was 7 mm./d. until the measurement stabilised completely.

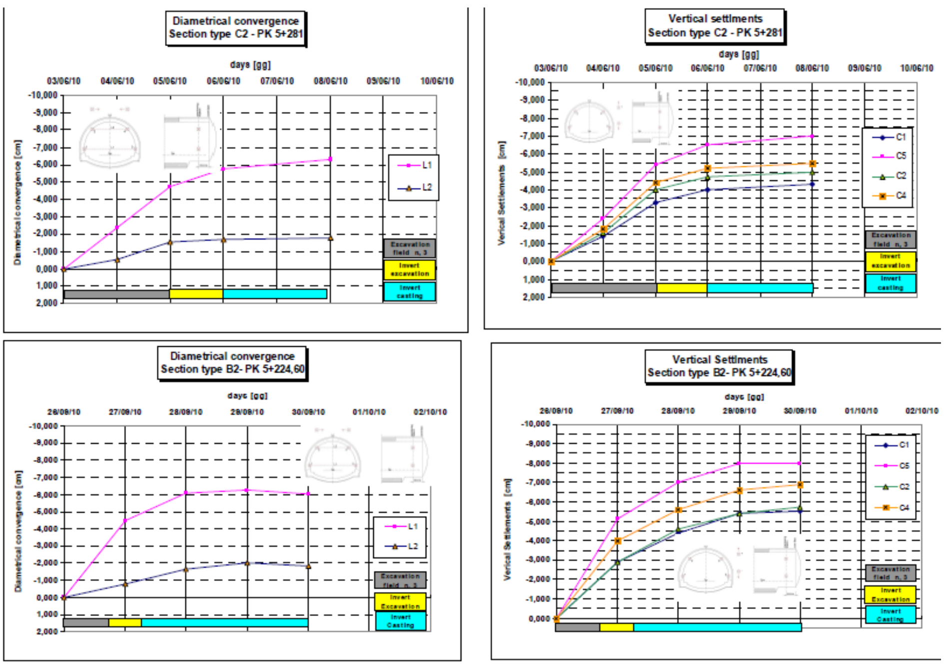


Fig 14 – Convergence measurement stations for section types C2 and B2

The conclusion drawn is that under deep overburdens, where the ground conditions were better, fibre glass structural elements in the face were employed to control plasticisation phenomena around the cavity, and this confirmed the design predictions. However, under shallow overburdens, where the ground conditions were poor, the formation of plastic flows was controlled by fibre glass elements in the face and grouted fibre glass elements around the cavity.

In both cases, characterised by different values for the overburdens and for the geotechnical conditions, it was possible to contain deformation within limits compatible with the statics of the excavation by using appropriate tunnel section types (B2 or C2).

3 CONCLUSIONS

Construction difficulties were encountered from the outset in the construction of the tunnels on the new Val Fortore State Road 212, which underlined the inadequacies of the design specifications for passing through the *Flysch Rosso* formation and especially through the shallow overburden sections.

Substantial deformation of the cavity (average diametric convergence of between 200 mm. and 300 mm.) occurred during excavation of the Cerzone Tunnel (September 2008). Despite measures taken by the Contractor to contain deformation, the face fell in and this brought work to a halt.

The new section types proposed by the authors, based on the ADECO-RS approach, and the on-site technical assistance provided by Rocksoil engineers enabled excavation to resume without difficulty and with limited deformation. The streamlining of the work cycles made it possible, amongst other things, to reach production peaks of between 20 m./month (C2 sections) and 40 m./month (B2 sections) of finished tunnel.

Finally, the experience gained in the Fortorina yard shows that:

- application of the ADECO-RS approach makes possible to excavate tunnels with excellent productions and in maximum safety conditions even in soils structurally complex under low overburden, where generally half-face tunnel advance by using the criteria suggested by NATM results in reduced and discontinuous productions and unsatisfactory levels of safety for the workers (Lunardi P., 1999), (Andre D. and others, 1999), (Martel J. and others, 1999);
- to adopt the full face advance after reinforcing the core-face does not guarantee by itself the result if you have not well understood the basics of the ADECO-RS approach, you have not well-designed the stabilizing interventions, or even you have replaced some stabilization tools recommended by ADECO-RS with others seemingly similar but certainly not as effective.

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