Performance monitoring and analysis of a yield-control support system in squeezing rock

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ABSTRACT: Recent innovations in yield-control support systems allow to increase the rate of advance when tunneling in difficult conditions is associated with severely squeezing rock. Such systems which imply the insertion in the lining of highly deformable concrete elements are being adopted successfully in tunneling projects using conventional excavation methods. The Saint Martin access adit excavated in a Carboniferous Formation along the Base Tunnel of the Lyon-Turin rail line is presented as a case study. Numerical analyses are discussed to compare the results of computed and measured performance of a typical monitored section and to find out possible optimizations of the support system adopted.

1 INTRODUCTION

Tunnel construction in squeezing rock is very demanding due to the difficulty in making reliable predictions at the design stage. Squeezing conditions may vary over short distances due to rock heterogeneity and fluctuations in rock mass properties. Indeed, the selection of the most appropriate excavation-construction method to be adopted is highly problematic and uncertain. In deep tunnels, whenever squeezing conditions are anticipated, conventional tunneling appears to be yet the method most often used.

Conventional tunneling in squeezing rock generally takes place with a slow rate of advance. However, if the work at the face is well planned and appropriate stabilization measures are implemented, excavation can proceed at an acceptable rate of advance. A clear need to develop appropriate technological systems that help increase such a rate of advance is to be recognized (Cantieni & Anagnostou, 2009). It is the purpose of this paper to describe a recent innovative technological development and to present a case study to illustrate such a development.

2 THE SAINT MARTIN LA PORTE ADIT

The Saint Martin La Porte access adit is a vital part of the early works for the Lyon-Turin Base Tunnel, which is at the centre of the axes linking the North and South, and East and West Europe and is to be excavated between the portals in Italy and France.

The tunnel is being excavated in a Carboniferous Formation, “Zone Houillère Briançonnaise-Unité des Encombres“ which is composed of black schists (45 to 55%), sandstones (40 to 50%), coal (5%), clay-like shales and cataclastic rocks. A characteristic feature is the anisotropic, highly heterogeneous, disrupted and fractured conditions of the rock mass which exhibits a very severe squeezing behavior (Hoek, 2001; Barla, 2002).

Excavation takes place in essentially dry conditions. In order to assess the rock mass quality during excavation, detailed mapping of the geological and geomechanical conditions at the face was undertaken systematically (Figure 1).

Several support systems have been used in the Carboniferous Formation up to chainage 1400 m including either “stiff” or “soft” steel ribs (with sliding joints), rock dowels and mesh reinforced shotcrete.

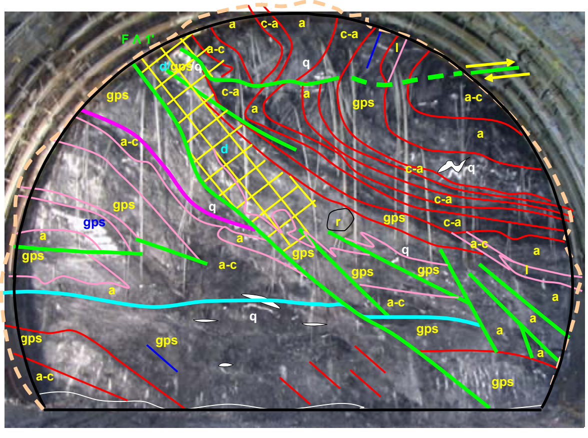

Figure 1. Geological and geomechanical conditions at the face at chainage 1443m (gps-sandstones, a-clay shales, c-coal, etc.).

A horseshoe shape profile was adopted with full face excavation and fiber-glass dowels reinforcement of the face. However, the stiff support experienced significant overstressing due to the severely squeezing conditions encountered and the soft support underwent very large deformations with convergences up to 2 m with the need of extensive reshaping of tunnel excavation.

The design concept finally chosen to cope with the severely squeezing conditions encountered was based on allowing the support to yield in a controlled manner, while using full-face excavation with reinforcement by fiber-glass dowels of the tunnel "core". In order to improve the working conditions and to control deformations, a novel "yield-control" support system (DSM in the following) was adopted with a near circular cross section as shown in Figure 2.

A detailed description of the construction stages can be found elsewhere (Barla et al., 2007; Barla, 2009). The main innovation of the DSM section is the adoption of a full circular section in stage 2 at a distance of 20-30 m from the face (Figure 2), with application of a 20 cm reinforced shotcrete lining, yielding steel ribs with sliding joints (TH type), with longitudinal slots (one at the invert) fitted with Highly Deformable Concrete elements (HiDCon). The mechanical behavior of these elements is ductile, nearly elastic perfectly plastic, and characterized by a constant limit stress of 8.5 MPa up to a maximum strain of about 50%. This allows the support system to undertake high deformations in a controlled manner, while applying a constant radial stress to the ground surrounding the excavation.

3 PERFORMANCE MONITORING

High convergences developed between chainage 1200 to 1550 m, with the DSM section applied systematically following chainage 1400m. The special monitoring section at chainage 1443 m is taken as representative. Figure 4 shows the displacement distribution given by the multi-position borehole extensometer along direction 4 (right side) versus time and the mobilized zone around the tunnel where the radial strain is greater than 1%, a strain limit taken as the onset of squeezing behavior. It is of interest to observe that the zone around the tunnel with strains greater than this value is non symmetrically distributed, ranging in extent from 10-11 m maximum (right) to 1-2 m minimum (left).

It is clear that, where a more significant extent of the mobilized zone around the tunnel occurs in stage 1 (Figure 4), the support system in stage 2 undergoes greater deformations. The non symmetric response of the tunnel is mostly due to the anisotropic features of the rock mass, the presence of "strong"

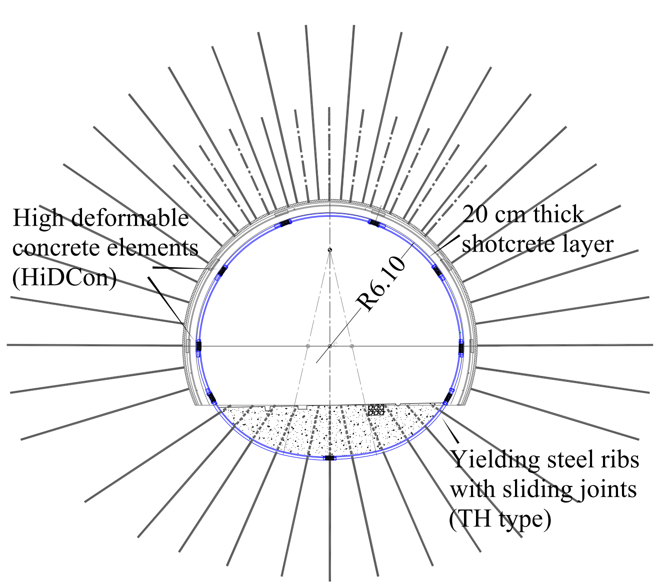

Figure 2. Detail of the yield-control support system (DSM Section) in stage 2.

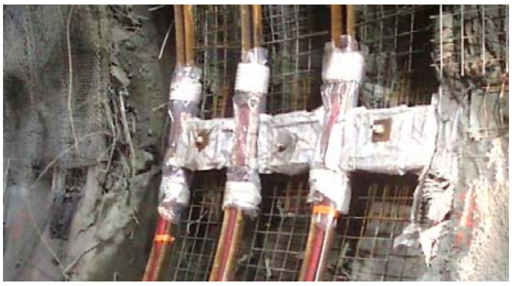

Figure 3. Highly Deformable Concrete (HiDCon) elements during installation between the TH steel ribs and before shotcrete placement.

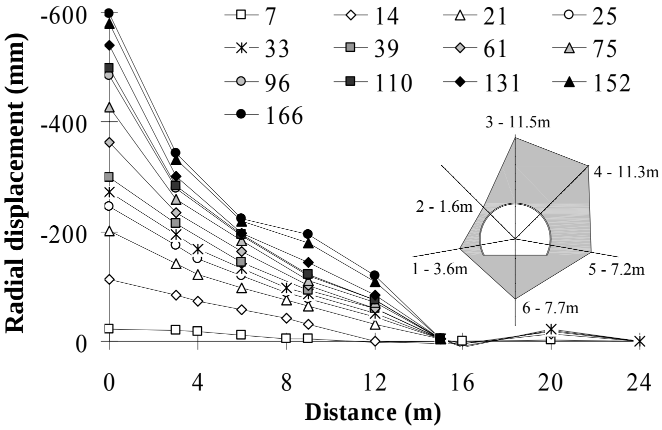

Figure 4. Displacement distribution along multi-position borehole extensometer 4 with sketch of the zone around the tunnel where the radial strain is greater than 1%.

(sandstones and schists) and "weak" (coal and clay-like shales) layers which dip from the left to the right of the tunnel cross section (Figure 1), and the local variations of the shotcrete lining thickness, strongly related to the rock mass non homogeneity.

The deformation (shortening) of the deformable elements installed in the primary shotcrete lining in the same cross section at chainage 1443 m were measured by using strain meters located across them as depicted in Figure 5. It is shown that smaller displacements occur in elements 4 and 5 (at the crown), whereas elements 6 and 7 (on the right sidewall) undergo the most significant deformations attaining a 25 % strain.

4 ANALYSIS

In order to simulate the response of the DSM yield-control support system in stage 2, by accounting for the presence of the HiDCon elements incorporated in the shotcrete lining and the interaction with the surrounding rock mass, a numerical model was set up by using the Finite Difference Method (FDM) and the FLAC code (Itasca Consulting Group, Inc., USA).

The 2D FDM grid was very finely discretised near the excavation perimeter and in the lining, where the typical size is 0.1m×0.1m. Since the target was the optimization of the support system in stage 2, the rock mass was modeled as a simple, isotropic, linear elastic material and considered as a confining medium for the support, not subject to any initial state of stress.

The lining and the HiDCon elements were modeled as elastic perfectly plastic Mohr-Coulomb materials. The mechanical properties adopted are summarized in Table 1. Loads were applied directly to the lining, according to a stress distribution which enabled one to reproduce the observed state of deformation of the composite lining. Therefore, loading of the support system is not the result of stress relief as usually done in numerical modeling when excavation is being simulated.

Interfaces were introduced between the support and the rock mass and between the deformable elements and the shotcrete lining, in order to prevent tensile stresses from developing in them.

With the intent to reproduce the observed asymmetric strain distribution in the lining and its deformed shape, the desired stress distribution as shown in Figure 6 was obtained. A comparison of the computed and measured displaced shape of the lining is shown in Figure 6, where illustrated is its initial geometry.

The comparison of computed and measured radial displacements on the tunnel periphery is satisfactory (Figure 6). However, there are significant differences in the displacements across the HiDCon elements when compared to the measured values. This is believed to be due to the local change of thickness in the shotcrete lining in proximity of these elements, because of the over-excavation which took place on the tunnel periphery. This obviously could not be considered in the model.

The computed thrust and bending moment in the lining are depicted in Figure 7. The bending moment distribution appears to be significantly influenced by

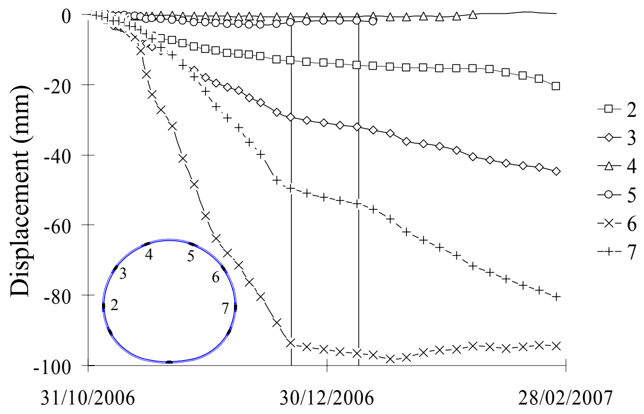

Figure 5. Special monitoring section at chainage 1443 m. Displacements in the elements versus time.

Table 1. Material parameters used in the analyses.

Setting	Rock mass	Shotcrete	HiDCon elements
Young Modulus E (MPa)	400	20000	4000
Poisson's ratio ν (-)	0.3	0.2	0.2
UCS (MPa)	0	32.0	8.5
Tensile strength σ_t (MPa)	0	3.2	0.85
Cohesion c (MPa)	0	9.2	2.45
Friction angle ϕ (°)	0	30	30

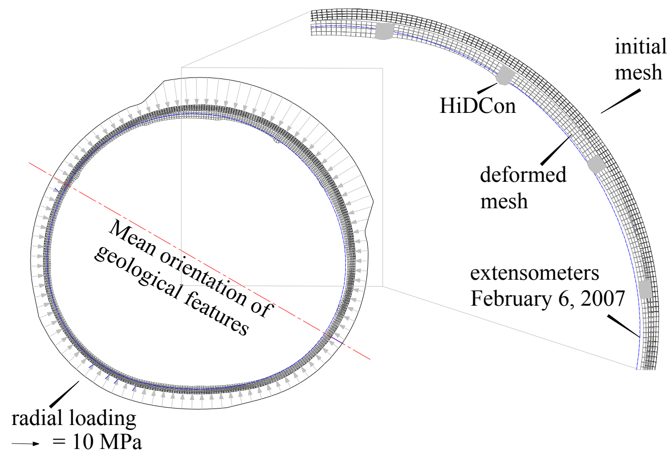

Figure 6. Load distribution and computed displaced shape for cross section at chainage 1443 m (reference monitored section).

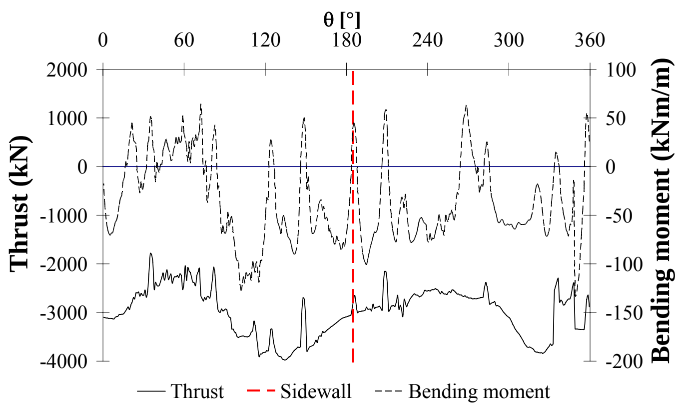

Figure 7. Bending moment and thrust distribution in the lining for the cross section at chainage 1443 m (θ increases clockwise from the left wall).

the presence of the HiDCon elements incorporated in the lining, while the thrust is always compressive. It is noted that the loads imposed on the support, which is able to reproduce the observed deflected shape during excavation in a satisfactory manner, induce a distribution of stress which is far from being uniform as one would expect if the same support was to behave as a flexible support.

To find out if any improvement could be obtained in the lining response, in order to avoid some of the deformable elements from being overstrained, other analyses were undertaken with the intent to model: 1) the presence of less slender elements in the lining, with aspect ratio equal to 1 (case 1); 2) the increase in the number of elements, having the same shape with aspect ratio equal to 2, as in the actual tunnel at chainage 1443 m, incorporated in the lining on the right side, in the same sector where the most severe strains were observed to occur (case 2).

It is apparent from the results reported in Table 2 that the displacement across each deformable element in case 1 is about one half of the displacement computed for the cross section at chainage 1443 m, with the strain level being however very similar. In case 2 the deformable elements 5 and 6 undergo a strain which is approximately twice that of the remaining elements, where the strain is approximately the same.

Also, given that the deformable elements in case 1 experience a lower shortening, the shotcrete lining is to share a larger strain and stress level than in the previous case (Figure 8). On the contrary, the increase in the number of deformable elements on the right side results in a significantly lower stress in the lining.

5 CONCLUSIONS

It is concluded that the increase in the number of deformable elements placed in the lining where this is expected to be more strained is a reasonable option with respect to the corresponding symmetric distribution.

Therefore, in order to cope with non symmetric loading conditions of the lining, as expected whenever the rock mass exhibits an anisotropic behavior, it is suggested to distribute the deformable elements where more severe straining is expected to occur.

In such a case, although the number of deformable elements in the lining remains the same, thus making it possible to cope with the same tunnel convergence, a better behavior is expected in the tunnel in placing the deformable elements where the maximum strains occur.

Table 2. Computed displacements and strains across the HidCon elements.

HiDCon	Chainage 1443 m		Case 1		Case 2	
	(mm)	(%)	(mm)	(%)	(mm)	(%)
2	22	6	13	7	40	10
3	75	19	34	17	39	10
4	57	15	30	15	51	13
5	68	18	36	19	109	27
6	84	22	40	22	93	23
7	41	11	21	11	45	11

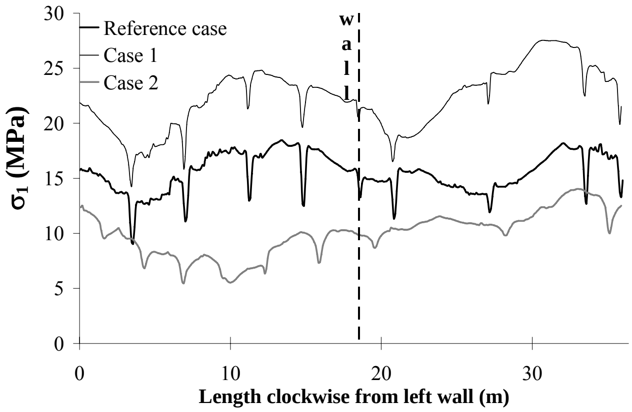

Figure 8. Computed maximum principal stress in the lining for the monitored section at chainage 1443 m and in cases 1 and 2.

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