The successful crossing of an extended fault zone in carboniferous squeezing rocks: a practical case from TELT's SMP4 construction site

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ABSTRACT: The Saint Martin La Porte « SMP4 construction site » is the last exploratory gallery of the 57,5 km long TELT project. In 2017 the excavation works of Part 3b commenced using the conventional method. Part 3b is a 1,5 km long section of the south tube that crossed the Houiller Front, a Carboniferous formation characterised by squeezing ground behaviour with high overburden. This Paper describes the successful crossing of the largest fault zone encountered at Ch 10+600 during the excavation of the exploratory tunnel. This fault has an extension of about 80 m with high squeezing rocks composed mainly of fault gouge, coal and tectonized shale. This geological accident demonstrated the successful application of the most recent innovations in yield-control support systems applied to conventional tunnelling as a result of more than 15 years of research work on "squeezing rock" at the Saint Martin La Porte site.

1 OVERVIEW OF THE LYON-TURIN PROJECT

1.1 *The Lyon-Turin project*

The railway project Lyon-Turin has a cross-border section with two railway stations in St. Jean de Maurienne and Susa and a twin-tube tunnel, 57.5 km long, called "Mont Cenis Base Tunnel". The international section comprises two one-track tubes and also includes the excavation of three decline access tunnels (France), one adit (Italy) and 4 ventilation shafts (Fig. 1)

In 2015, a second additional exploratory phase was launched. The project owner, TELT, entrusted the project and construction management to Egis / Alpina S.p.A. and the works to a consortium of six contractors – three French and three Italian: Spie Batignolles TPCI (the consortium lead), Eiffage Génie Civil, Sotrabas, Ghella SpA, CMC and Cogeis SpA. During 2022 this last exploratory gallery, located in Saint Martin La Porte, on the French side, was completed. The Saint-Martin-la-Porte 4 construction site (SMP4) is the last phase of twenty-years of studies carried out through access tunnel works which helped improve knowledge of one of the most complex alpine structures: the contact between the Sub-Briançonnais Zone and the Houiller Briançonnais Zone.

The goals in pursuing the exploratory works in this sector are numerous:

- verify assumptions related to the geology;
- specify the geotechnical data concerning the Houiller Carboniferous formation at the level of the Base Tunnel;
- analyse the behaviour of the terrain crossed and the forces to be supported at the Houiller face and other areas;
- consolidate the working methodology based on the ground conditions encountered;
- test different sealing and/or terrain consolidation products in the complex areas.

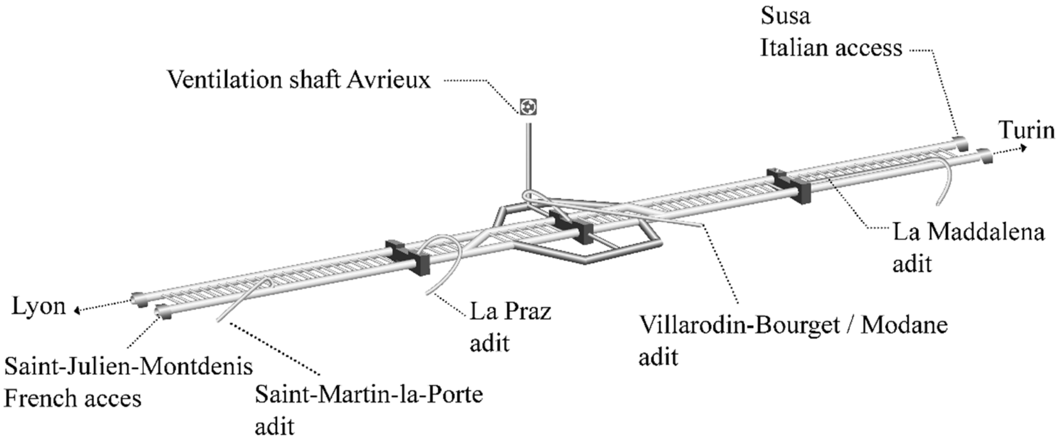


Figure 1. Tunnel Euralpin Lyon-Turin project.

1.2 *The SMP4 site Part 3b*

The SMP4 exploratory construction site can be divided into four parts. The main work is focused on parts 2 and 3b. Part 2 consisted in using a single-shield TBM to bore a 9 km exploratory tunnel along the axis and at the diameter of the future South tube of the Base Tunnel. Part 3b concerned the excavation of a 1.4 km tunnel using the so-called “conventional” method [Gamba (2019)]. The excavation of part 3b started in 2016 at Ch. 10+150. In October 2019 a second front was launched to achieve the break-through of the 1,4 km in 2022. In this paper we discuss the field data collected during face mapping; the approach for the excavation and support method suitable in these rock conditions; the final monitoring results and the application of the results on the future project phase for the tunnel excavation contract.

2 GEOLOGICAL CONTEXT

Part 3b of the Mont Cenis Base Tunnel crosses the contact between the Houiller Front and the Houiller Briançonnais zone, a Carboniferous formation, with an overburden of about 700 m. Excavation took place in dry conditions. As described by Rettinghieri (2008) this zone is characterised by the presence of black schists, meta-sandstones, sometimes highly tectonized, intercalated by coal levels. The main schistosity is oriented from NE to SW with a variable dip between 30° to 70°.

The complexity of this heterogenous formation demanded continuous advance probing that was undertaken with horizontal core or percussion drilling from the tunnel axis. The holes were overlapped for safety reason, with an overlap of about 20 m. During this phase an extended fault zone was identified at the end of borehole extensometer n. 15. Approaching Ch. 10+610, a campaign of boreholes was launched, and in July 2020 the fault zones were identified with an influence area of about 40 m minimum. Other boreholes permitted to define the orientation of the fault dip to E with 40° to 60°. The final geological synthesis is illustrated in figure 2.

The Houiller Briançonnais zone presents a highly heterogeneous, disrupted and fractured condition of the rock mass, which exhibits very severe squeezing problems and asymmetric deformation of the tunnel face. At the level of the South Tube in Part 3b, the behaviour of the massif with the directions of major constraint is different compared to the SMP1-2 adit. There was important extrusion of the face which resulted in the systematic installation of 30 m extrusometers with an 8 m overlap to identify a potential face collapse.

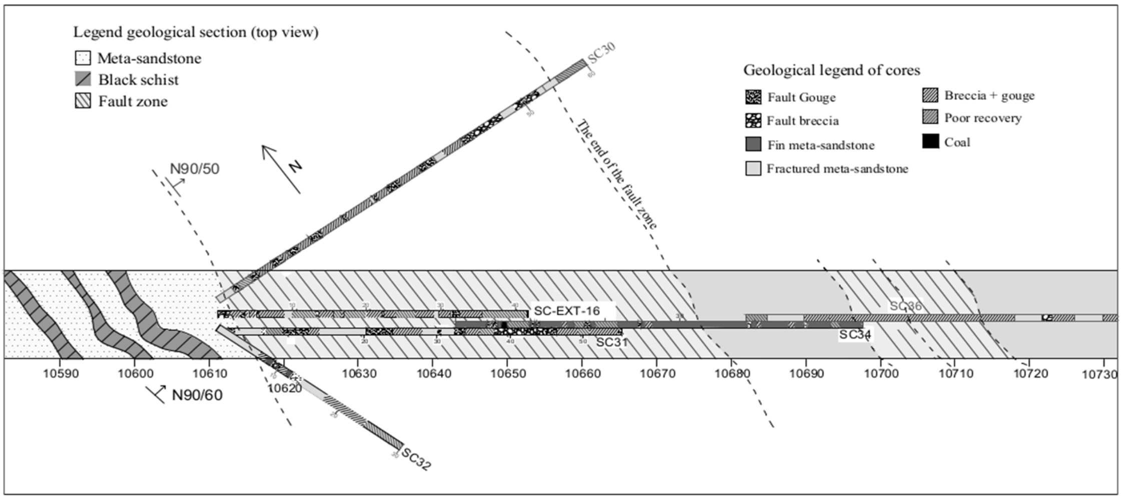


Figure 2. Geological interpretative top view with boreholes simplified interpretation and fault limits.

3 CROSSING THE GEOLOGICAL ACCIDENT IN FULL FACE

The long experience of excavation of the *Houiller Productif* in SMP1/2 and SMP4, in particular after the fault at Ch. 10+300, led to the development of an “abacus of support tools” based on the observational method and validated by a FE-3d back-analysis. As described in Triclot (2007), the encountered highly fractured Carboniferous rock mass with squeezing behaviour imposed the implementation of different ground support systems.

The support system adopted to excavate Part 3b, known as the “light method” from Barla (2015), was chosen to maintain the desired clearance and to avoid the need for re-profiling. The support is installed in three phases, A, B and C with an ever-increasing rigidity. The main characteristics are the use of a support that yields to the ground constraints (convergences), provided by type TH steel sets with sliding connections, radial steel bolts as full-face support in phase A. In phase B at a minimum distance from the face, normally 25 to 30 m from the face, the support is adapted to the behaviour of the rock mass by excavating the invert and installing variable number of HiDCon elements (High Deformable Concrete) in between the TH steel ribs and aligned with their sliding joints, all of this being reinforced with a fibered shotcrete layer (fig. 3), carefully applied to ensure that the sliding joints are not compromised. Systematic reinforcement of the rock mass behind the face was achieved by means of 12 m-long grouted fiber-glass elements with an overlap of 6 m.

Finally, when the radial convergence rate has stabilised, phase C, corresponding to a circular concrete ring, is implemented.

Sometimes in presence of clayey ground a rigid “heavy method” was used that consisted in preventing ground deformation by installing heavy support systems such as HEB steel ribs and shotcrete. However, as we will see this system has a very limited use.

The process to overcome the fault zone can be divided into 4 different stages.

1. Reduction of the excavation section from 120 m^2 to 70 m^2 (reduced section: RS) or to 32 m^2 (small section: SS) in very defavourable ground with different types of steel ribs.
2. Reprofile to the final section (GS) of 120 m^2.
3. Excavate the invert 25-30 m from the face with a second reprofile.
4. Concreting of a final blocking ring, 400 mm thick, at least 6 months after the initial excavation to allow the majority of the convergence to occur.

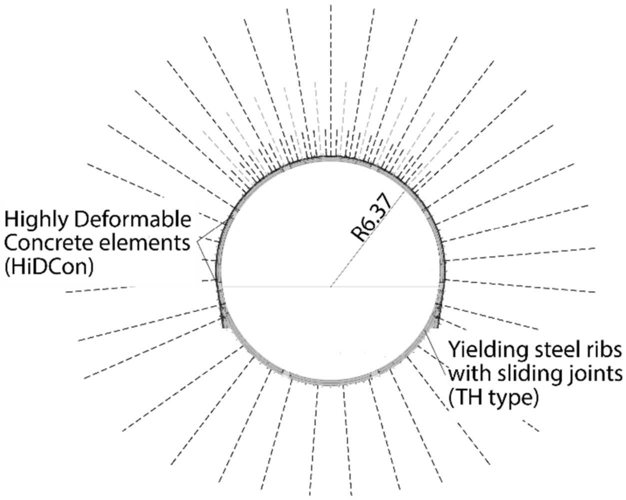


Figure 3. Typical profile applied in the case history. Different radial lines correspond to different AFR38 rock bolts installed (radial, at 45° and forepoling).

3.1 *Stage 1 – Change of section to reduced section and small section*

The behaviour of the massif during the reconnaissance phase showed a relevant radial deformation and extrusion of the face in the order of a centimeter which forced us, in agreement with the support tools developed by the contractor's design office (BIEP), to reduce the excavation radius to the so-called reduced section over a length of 6 m initially, and then to the so-called small section to reduce all the geological risk of instability and the possibility to better control the deformation of the face thanks to the yielding support. In these particular geological conditions the mechanical excavation was carried out in segments of one meter length.

3.1.1 *Stage 1 – Reduced section*

The RS section type was a classical "heavy support" section excavated mechanically in horizontal steps of one meter due to the presence of significant fault gouges. This section was excavated between 21 August 2020 and 1 September 2020. The support is composed of HEB240 steel ribs (R: 4.7 m) with radial (length 8 m) and forepoling (length 8 m) rock bolts and with a 40 cm thick layer of shotcrete (Fig.4). This type of support was used between Ch.10+611 and Ch. 10+617. No inverted is installed.

The geological conditions encountered, associated to the face extrusion, imposed a reduction of section with an adaptation of the plant used during the excavation cycle.

3.1.2 *Stage 2 – Small section*

The Small section (SS) was excavated between Ch. 10+617 to Ch. 10+681 from the 18 September to 21 December 2020. The mechanical excavation in the SS was carried out in segments of one meter length with an ITC 120N tunnel heading and loading machine.
The support system consisted of systematic radial and 45° rock bolts (length 6 m), TH36 steel sets with sliding joints (R: 3.15 m), forepoling rock bolts (length 4 m), installation of the invert at a distance adapted to the behaviour of the phase A support and the installation of HiDCon deformable elements (Fig. 5).

During this phase, at a distance of 10 m from the face, radial convergences of 300 mm was observed with the formation of cracks, and occasional expulsion of HDC elements.

At Ch. 10+681 a borehole confirmed the end of the fault zone, observed also with a better RMS and GSI in the full-face mapping.

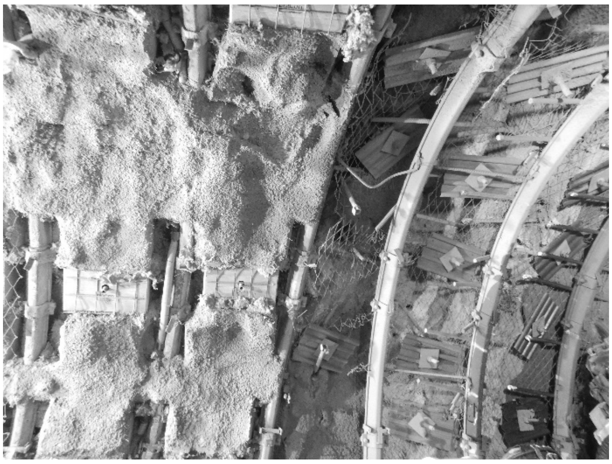


Figure 4. View of the reduced section with HEB240 excavated in horizontally stepped face.

Figure 5. View of transition between phase A and phase B in the small section.

3.2 *Reprofiling to final section*

The phase of reprofling to the final section (GS), started on 21 January 2021, took six months and was carried out in segments of one meter in length with the same phasing as the small section. The support system consisted of the systematic application of a 5 cm shotcrete layer, radial and 45° AF38 rock bolts (length 8 m), TH36 steel sets with sliding joints (R: 6.37 m) and forepoling rock bolts (length 8 m) (Fig 6.)

Figure 6. Phase of full-face excavation during the reprofiling of the SS. This photograph shows the phase A flexible support system.

3.3 *Invert and phase B*

In the final section the invert is installed at a distance of 25-30 from the face. Due to the significant radial convergence encountered in this fault zone that caused plastic behaviour of the TH ribs, a systematic replacement of steel ribs was required before the excavation of the invert and the application of a 25 to 30 cm shotcrete layer with 8 longitudinal slots fitted with HiDCon elements.

3.4 *Final concrete lining*

The last phase, phase C, consisted in the installation of a formed concrete ring when the rate of convergence had reduced sufficiently. This phase took place after the breakthrough of Part 3b in April 2022 with the use of two formworks, one for the invert and another for the crown (fig. 7).

According to the contract requirements, the final radius of the concrete ring was designed to 5.30 m with a minimum concrete thickness of 400 mm. In the 1.4 km of part 3b 8 concrete rings of different lengths were installed. According to the results of convergence monitoring in the fault zone at Ch. 10+610, a concrete ring was constructed from Ch. 10+580 to 10+710. Due to the total diametrical convergences that exceeded 900 and even 1200 mm, a phase of partial reprofiling was carried out in the invert before the implementation of the concrete blocking ring. The blocking ring is equipped with instrumented sections (strain gauges) and optical sights to monitor the evolution of the tunnel and obtain information to model the tunnel final lining in 200 years.

Figure 7. Concreting of the blocking ring in the fault zone.

4 DEFORMATION MEASUREMENTS AND GEOTECHICAL MEASUREMENTS

Several phenomena and deformations were observed on the support right from the first surveys. For these reasons a reinforced convergence monitoring system was installed with a section every 3 to 5 m. Specific monitoring was carried out to see how these deformations evolved and to estimate the strain levels by installing in each type of section:

- Inverted borehole extensometers during full face excavation,
- optical prism sections,
- multipoint borehole extensometers,
- Strain gauges on the shotcrete, pressure cells between compressible blocs and shotcrete line and wire extensometers installed on the yielding blocs.

In the blocking rings, constructed between May and August 2022, the monitoring system is composed of:

- optical prisms sections every 10 m,
- strain gauges on the concrete lining.

4.1 *Results and analyses of monitoring*

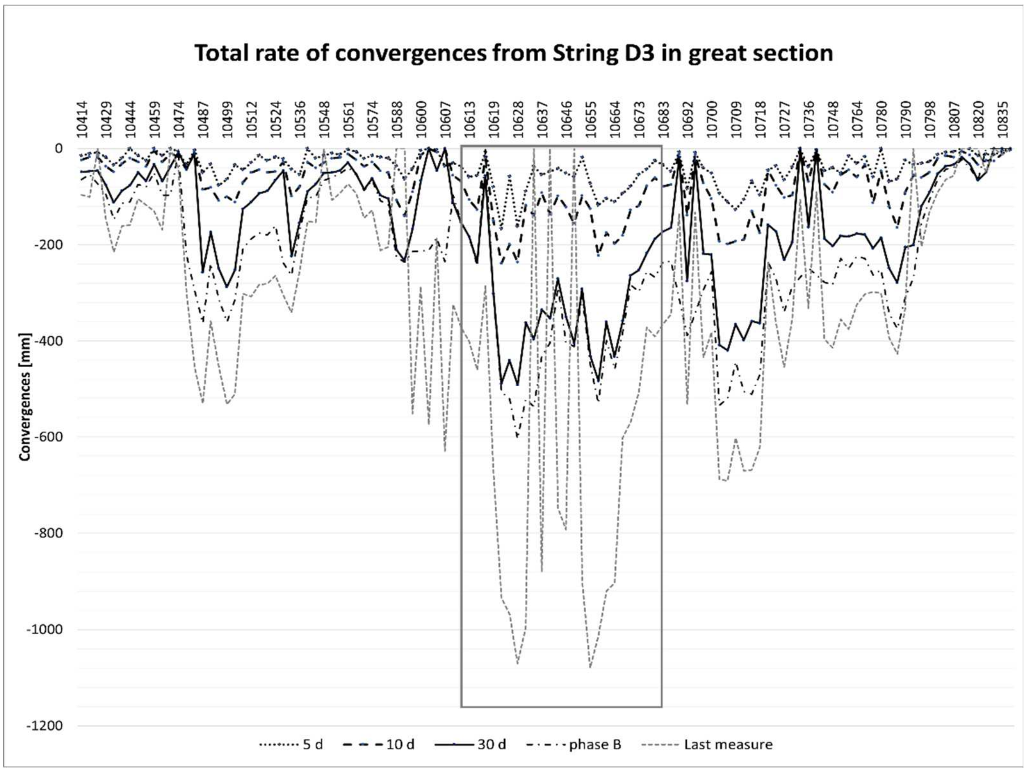
As described above, the fault zone from Ch. 10+610 is characterized by strong radial convergences in all the phases. In the RS the total rate of radial convergence is about 80 to 100 mm on

HEB steel ribs with evidence of plastic behaviour and continuous extrusion of the face of 120 to 240 mm. The area of influence of the excavated face was estimated to be 14 m.

In the SS the total rate of radial convergence was about 250 to 350 mm in the fault zone with face extrusion of 120 mm. The area of influence of the excavation was estimated to be between 9 and 11 m. The behaviour of the rock mass was asymmetric with a strong deformation of some HiDCon elements and cracking. The wire extensometer at Ch. 10+629 measured a displacement of 118 mm. The same deformation was observed in the GS where phase B absorbed the maximum deformation measured in Part 3b. At other times the development of vertical tension cracks and the expulsion of some retaining plates of AF38 bolts was observed.

Before the concreting of the blocking ring, in the final section, the total rate of radial convergence with the maximum deformation recorded on the D3 string is of 900 to 1200 mm. In table 1 the synthesis of convergence monitoring in GS is presented, different lines indicate the rate of deformation (mm) in different moments and distances from the face. The strain gauge on the shotcrete measured a maximum stress value up to 23 MPa in the crown and 33 MPa in the invert at Ch. 10+630. The evidence of cracks and expulsion of HDC is observed particularly between Ch 10+620 and Ch. 10+660. The wire extensometer at Ch. 10+678 measured a displacement of 225 mm.

All these data confirmed relevant squeezing rock behaviour with a tendency to stabilize over a long period of time. The concreting of the blocking ring started when the residual convergence speed had reduced to less than 0.5 to 1 mm per day.



Tab 1. The total rate of convergence cumulated in GS, the fault zone is indicated by the thick rectangle.

5 CONCLUSION

This paper presents a relevant example of how to cross a fault zone in critical conditions, by successfully applying a well-established method developed during more than 15 years of work with SMP1/2 and SMP4.

Once again, the application of the interactive observational design approach was essential for achieving excavation in this type of conditions. The geotechnical and monitoring data obtained

are fundamental for studying this complex zone and improving the method. In addition, the geological conditions encountered in the South Tube will be encountered during the excavation of the North Tube by the next contract, CO7. The key to the successful application of the 4-phased excavation approach is to find the optimal timings and distances from the face, including the concreting of the phase C blocking ring to guarantee the support system for the period defined by the contract.
After this extended fault zone, no further relevant geological accidents were encountered during the excavation of part 3b. But, if we consider the geological context and the total rate of diametric convergence that exceeded 1200 mm, it is only thanks to the lessons learned during the geological accident of Ch.10+300, described by Festa (2020), and the capacity to rapidly adapt the type of profile were we able to overcome this geological and technical challenge.

6 ACKNOWLEDGMENTS

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