Presentation of the successful crossing by the "Federica" TBM of a geological accident in Saint-Martin-la-Porte construction site

F. Gamba
Alpina S.p.A./Egis

E. Hugot, P. Gilli & C. Salot
TELT s.a.s.

G. Giacomin
Ghella S.p.A.

ABSTRACT: The 57.5 km long Mont Cenis Base Tunnel will link up Saint-Jean-de-Maurienne in France to the Susa plain in Italy. In 2015 additional exploratory work was launched from the Saint-Martin-la-Porte decline access tunnel. This included TBM excavation of a 9 km stretch of the southern tube of the Base Tunnel linking the existing access tunnels of Saint-Martin-la-Porte and La Praz. The purpose of this work was in part to check assumptions related to the geology and to acquire the experience required to excavate the Base Tunnel by means of a TBM through the Briançonnais Houiller zone. After excavating close to 300 metres, the TBM encountered a significant geological accident which disrupted progress and required adaptation work to be carried out. The geological context is presented along with the characteristics of the TBM. The major stages which enabled the geological accident to be successfully overcome will then be detailed along with the significant milestones involved in crossing the fault and the means used to strengthen supporting structures and terrains. The technical changes made to the cutting wheel which enabled boring to be resumed will also be detailed. The additional geological exploratory work by surveys and measurements of the deformations observed are presented.

1 PRESENTATION OF THE CROSS-BORDER SECTION

1.1 *The Mont Cenis Base Tunnel*

The planned Lyon-Turin link has a common French-Italian section between Saint-Jean-de-Maurienne and Susa-Bussoleno, which is the first functional phase of the entire project. This cross-border section includes the 57.5 km Mont Cenis Base Tunnel comprising two one-track tubes and also involves the excavation of three decline access tunnels, one adit and two air ventilation shafts (fig.1).

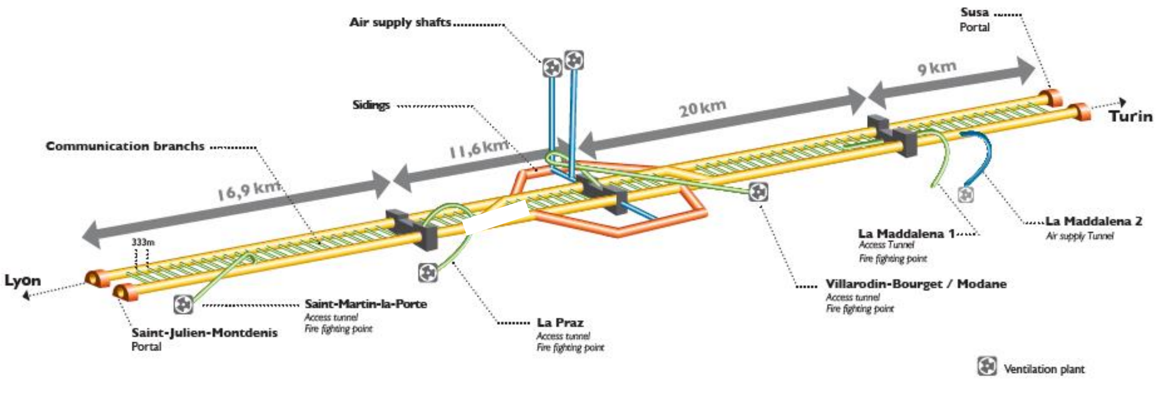

Figure 1. The Base Tunnel

Studies carried out during access tunnel work helped improving knowledge of the terrain, but these access tunnels will also be used to excavate the Base Tunnel on several fronts and once the tunnel has been commissioned they will be used for ventilation, maintenance and emergency service access, if needed.

The findings from access tunnel excavation work showed the specific and complex nature of a particular geological formation encountered when boring the Saint-Martin-la-Porte access tunnel. Initial work at the Saint-Martin-La-Porte site in Savoy took place between 2003 and 2010 with the construction of a 2,380-metre-long decline access tunnel. Boring work related to this access tunnel encountered quite exceptional difficulties when crossing the so-called "Productive" Houiller terrain. These difficulties come in the form of very high amplitude convergence phenomena in a sector in which the thickness of the overburden terrain was moderate, less than 300 metres (fig.2).

Figure 2. Convergence problems encountered in the Saint-Martin-la-Porte access tunnel.

In 2015, a second additional exploratory phase was therefore launched. As project owner, TELT entrusted the project management to Egis/Alpina and the works to a consortium of six public works companies - three French and three Italian: Spie Batignolles TPCI (agent for the consortium), Eiffage Génie Civil, Ghella SpA, CMC di Ravenna, Cogeis SpA and Sotrabas.

The goals in pursuing exploratory work in this sector are numerous:

- verify assumptions related to the geology,
- specify the geotechnical data concerning the Productive Houiller at the level of the Base Tunnel,
- acquire the experience required to excavate the Base Tunnel using a TBM,
- determine the characteristics and adaptations required for the TBMs,
- adapt the excavation section, geometry and mechanical characteristics of the lining segments;
- analyse the behaviour of the terrain crossed and the force to be supported at the Houiller face and other areas,
- consolidate the working methodology based on the conditions encountered,
- explore any karst areas and underground water movements in the vicinity of the Base Tunnel,
- test different sealing and/or terrain consolidation products in the delicate areas.

1.2 *The Saint-Martin-la-Porte 4 site (SMP4)*

SMP4 exploratory construction site can be divided into four parts (fig. 3).

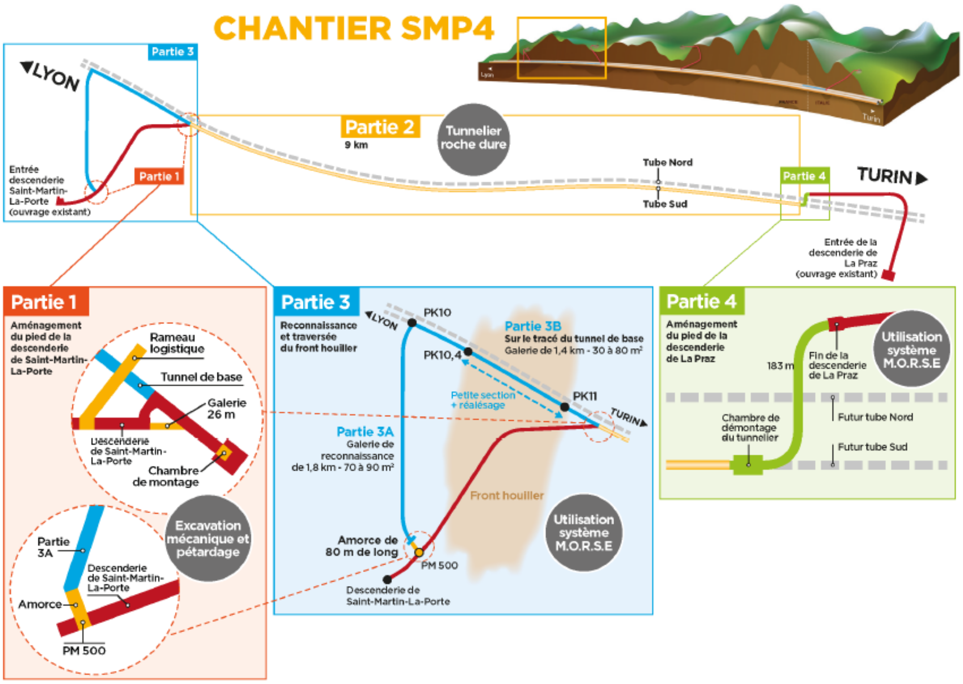

Figure 3. Presentation of the SMP4 site

The main work is focused on parts 3b and 2. Part 3b concerns the excavation of a 1.4 km adit using the so-called "conventional" methods. Part 2 consists in using a TBM to bore a 9 km exploratory adit along the axis and to the diameter of the future South tube of the Base Tunnel. The TBM, baptised "Federica", was given the task of excavating this adit and was designed to cope with the special geological constraints in this area. Built in France, in the NFM Technologies du Creusot plant (Saône-et-Loire), it has a 11.25 metre diameter cutterhead and 70 disc cutters, with a power output of 5 megawatts.

2 GEOLOGICAL CONTEXT OF THE SMP4 SITE

Exploratory work on this site aims at improving geological, hydrogeological, geomechanical and geotechnical knowledge of the sector. Figure 4 shows the projected geological context of SMP4 structures.

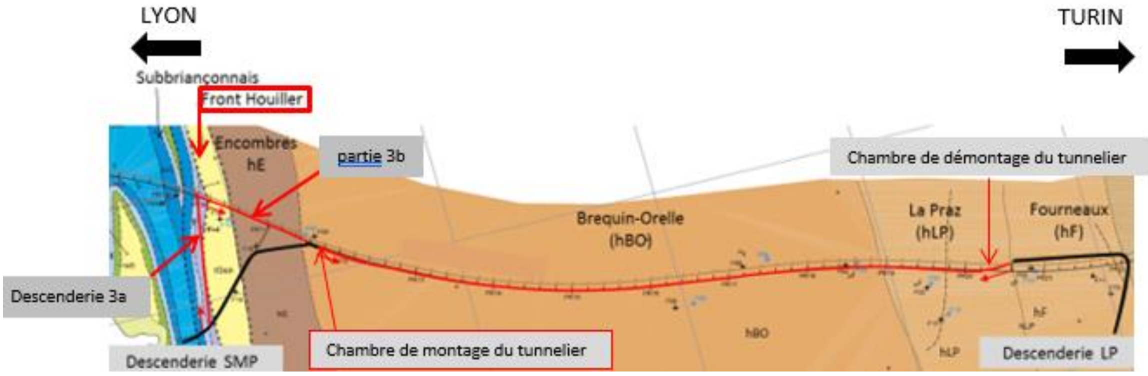

Figure 4. Geological context

The Saint-Martin-la-Porte access tunnel sector is characterised by the Briançonnais Houiller zone overlapping the sub-briançonnais zone by means of the Houiller Face, a tectonic accident made up of hectometric anhydrite layers at the tunnel level.

The excavation of part 3b, using conventional methods, crosses the last carbonated formations of the sub-brianconnaise unit (mostly limestone, calcareous shale and dolomites) then the anhydrites of the Houiller Face before entering the so-called Productive Houiller unit (Encombres hE Unit). The latter is characterised by a predominance of schists and carbonaceous facies (60%) as well as sandstone facies (25%) and a significant proportion of tectonised crushed levels (15%). These formations usually appear without continuity and in a highly disrupted structure giving rise to major convergence phenomena requiring specific systems to control deformations and stabilise the structure as well as protect the resources implemented.

As regards TBM excavation, the lithostratigraphic sequence to be crossed is well known and comprises metasandstone, more or less sandstone-type black schists with carbonaceous levels in the Brequin-Orelle unit. However, the sector is characterised by a large topographic overburden (between 700 and 1200 m) hence the difficulty in extrapolating from the surface geological and structural observations. On the basis of the terrain studies and on analysing the boreholes, a progressive increase in the sandstone-type fraction was discovered within the Briançonnais Houiller zone going from west to east, i.e. from the Brequin-Orelle unit to the La Praz unit. A similar progressive reduction in the carbonaceous levels in terms of quantity and thickness was also detected.

3 CROSSING THE GEOLOGICAL ACCIDENT

3.1 *The context*

The TBM excavation went normally for the first 300 m, crossing rocks with good geomechanical characteristics comprising schist-bearing sandstone masses with some rare levels of black schists.
From PK 12+085 (ring 193) the excavation came upon alternating destructured, even crushed, rocks comprising black schists and carbonaceous schists. This degradation in geomechanical conditions is associated to a sudden change in stratification, observed in the tunnel face surveys: on a large scale, the layers are subhorizontal before PK 12+085, approximately, and become subvertical in correspondence with the geological accident.

Initially excavation work continued up to ring 200 with several difficulties:

- significant over-excavations from PK 12+099 (ring posed 196/ring excavated 202);
- frequent stoppages of the conveyor belt due to excess material, difficulties in driving the belt, spillage of materials, blocking of hoppers;
- an increase in friction and the torque up to the blockage of the cutting wheel while in rotation;
- the presence of water and slurry.

Face surveys were carried out on the lower part of the TBM's cutting wheel: the face can be partially observed through the peripheral openings used to evacuate the spoil. The predominant lithologies observed before PK 12+085 comprise sandstones and, to a lesser extent, black schists, black carbonaceous schists and coal (fig. 5).

Figure 5. Materials encountered

Beyond PK 12+085, the formations turn up (orientation of the dip vector N 225/235, dip varying between 70 and 80. During face surveys, sudden changes of direction and dips were observed as well as developments of subsidence at the vault with water seepage, spontaneous collapses and the rupture of the face with collapses over the entire face.

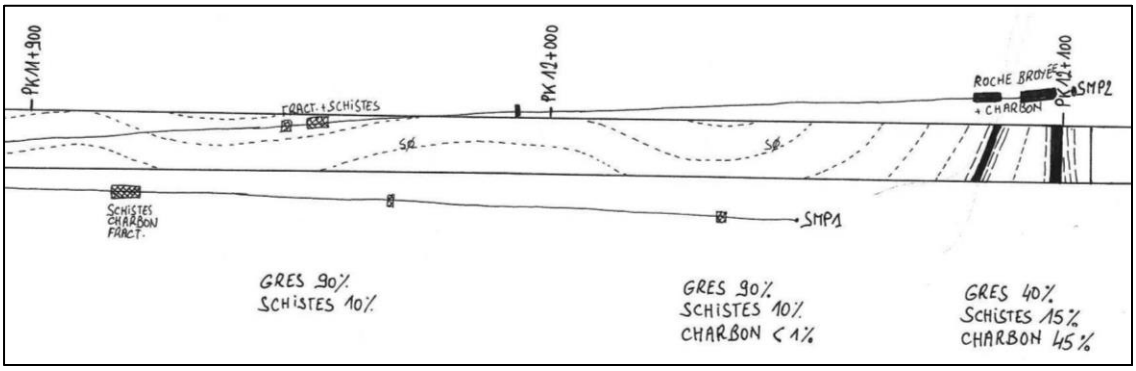

Figure 6. Attitude of the stratification (long profile)

This geological framework is coherent with the data available from continuous core drillings performed before tunnel boring work began and the destructive soil investigations performed during excavation as the boring progressed.

One of this survey, called SMP2 in the previous figure, stopped due to the borehole instability at PK 12+100 in carboniferous layers associated to a sub-vertical foliation, different from the previous zones (quite sub-horizontal). Anyhow, those important elements available in advance from the borehole didn’t allow to deeply understand the geological context around the tunnel such as thickness, orientation and inclination of those layers and the geometry of a probably open fold. In particular, the fault zone met during the TBM excavation wasn’t identified by this survey: this fact, associated to carboniferous layers and sub-vertical foliation, led to the encountered difficulties, further worsened by the unexpected presence of water at significant pressure in the carboniferous layers.

In face surveys, the rock was classified according to the RMR and GSI classifications. The values attributed to the rock are shown in the table below. We can note the rapid change in the quality of the cluster as a result of lithological and structural variations (table 1).

Table 1. RMR and GSI changes

PM	12002	12017	12034	12045	12064	12086	12092	12098	12101	12103
RING	137	147	158	166	178	193	197	201	203	204
RMR	65	62	59	41	51	24	36	23	27	27
GSI	65-70	60-65	55-65	55-60	50-60	35-40	30-40	20-30	25-35	30-35

Tests to close openings on the cutting wheel were carried out with an expanding polyurethane foam in order to reduce the volume of incoming materials (12 of the 16 arms were closed).

After several attempts to resume boring to excavate ring n. 200, millimetric advances were recorded associated to off-limit parameters (torque, friction and extraction rate), the appearance of numerous cracks on the lining segments and a non-negligible oval shaping of the rings. All these conditions, associated to significant withdrawals (some 6,600 tonnes excavated compared to the 2,000 tonnes in theory), meant that the boring was stopped to consolidate the terrain and technically improve the TBM before resuming.

The main stages in crossing the fault are shown in diagram form in figure 7 then described in the successive chapters.

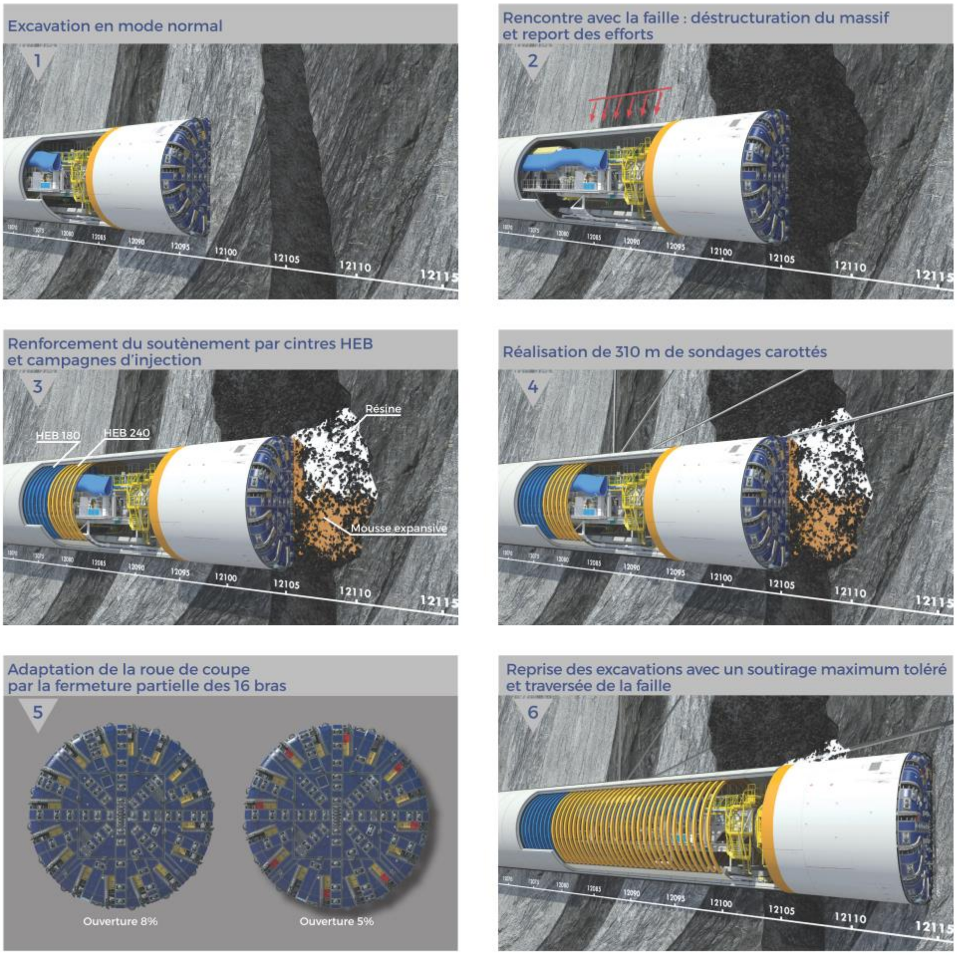

Figure 7. Geological accident: the main stages in crossing the fault

3.2 *Strengthening the support*

Several phenomena were observed on the support (mismatching between rings, millimetric cracks, concrete fragments from the lining segments, deformations and oval-shaping of lining segments) at the rear of the TBM up to PK 12+075, i.e. 30 m before the cutting wheel stopped in the fault at PK 12+ 105 (fig. 8). The large volumes withdrawn actually caused a broad destructuring of the zone and the force was carried over to the lining segments to the rear of the TBM, in the terrain already excavated.

Figure 8. Phenomena observed on the support

The support installed up to ring 197 (concrete segments C45/55, ~100kg/m3 of steel) had to be reinforced by installing HEB 180 or 240 ring beams, then more resistant rings (concrete C80/95 with 160 to 190 kg/m3 of steel) were used (fig. 9).

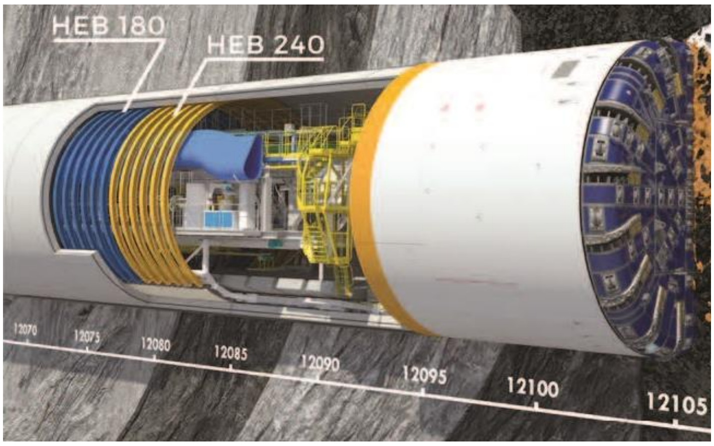

Figure 9. Strengthening the support by laying ring beams

This work required the implementation of systems designed with the TBM and available on the site as well as adaptations to the TBM to enable anticipated installation behind the shield tail of invert segments to support the ring beams.

Indeed, Federica is designed to power the lining segment erector via a conveyor table located behind the tail: the installation of invert segments is planned between 25 and 30 m from the face and a ring beam erector is available between 35 and 40 m from the face. Following the deformations and cracks, the support required rapid reinforcements behind the tail: for this reason the segment feeder was dismounted and the invert segments were installed back to the rear of the tail using a specific hoist. The lining segment erector was modified and adapted to install ring beams just behind the shield tail.

These operations were accompanied by radial bolting of the vault rings with reinforcement and drainage self-drilling bolts 3 to 4 m long as well as a control of the ring grouting with re-grouting if required.

3.3 *Non-destructive soil investigation campaign*

Simultaneously with the work to reinforce the support and reinforce the face, non-destructive soil investigations were performed to understand the nature and geometry of the geological accident. One of the TBM's two core drilling rigs used for destructive soil investigations was adapted to enable non-destructive soil investigations to be performed at the front of the TBM, from the reentrants planned at the level of the shield, in order to explore the extension and nature of the geological accident.

An additional rig installed on a gateway at the rear of the shield enabled areolar surveys to define more precisely the geometry of the fault and check the possible presence of empty spaces (fig. 10).


Figure 10. Non-destructive soil investigation workshop and example of core materials extracted

Overall, 310 m of non-destructive soil investigations were performed in one month enabling the geological context of the accident area to be defined with a good degree of reliability: a plurimetric passage of carbonaceous and graphitous black schists and coal, folded and upright in this area, cut into by a major sub-vertical accident (around 75°) and therefore subparallel to the cutting wheel (fig. 11).

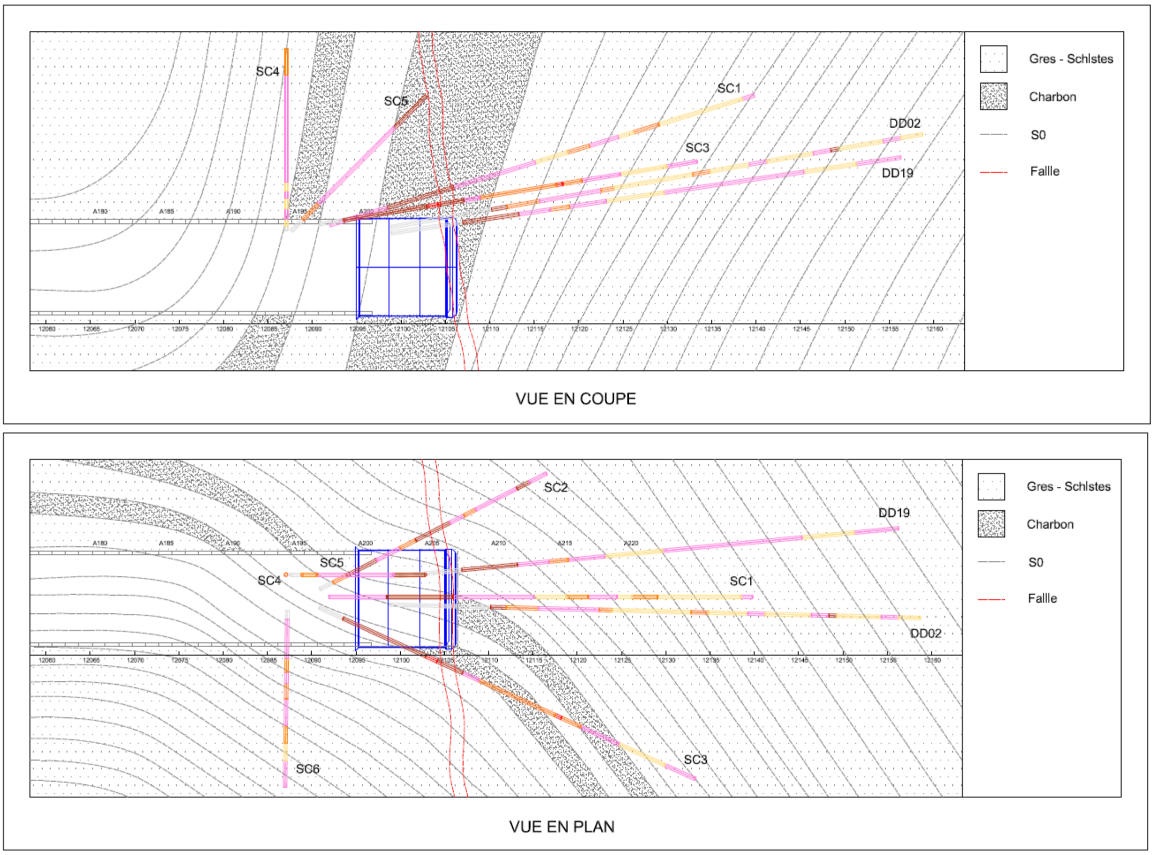

Figure 11. Summary of non-destructive soil investigations performed and assumption related to the geological context

The characteristics of the fault show a fragile type of displacement, with the formation of gouge and clay breaches at the core of the accident. The thickness of this accident is limited: the plastic carbonaceous levels concentrated most of the deformation and limited the extension of damaged zones. Despite the volume of over-excavations recorded, the non-destructive soil investigations did not identify empty zones above the TBM, since collapses most likely filled the withdrawal areas.

3.4 *Grouting*

Given the presence of empty spaces around the cutting wheel and the nature of the materials extracted, several grouting operations were performed in the following order:

- expanding polyurethane foam grouting just in front of the cutting wheel to fill in empty spaces and seal the cutting wheel;
- grouting using a dual-component cement-based resin that is very fluid and with low viscosity for the part in front of the zone filled with the foam in order to penetrate the materials and consolidate them;
- grouting with pressurised water reactive resin through the vault reentrants in order to finalise the treatment in front of the cutting wheel.

These grouting operations were performed from reentrants crossing the upper part of the shield that were used for surveys and through self-drilling fibreglass bolts performed to match the disc cutters. They helped improve the characteristics of the terrain to be bored and limit, in association with the closing of the cutting wheel, withdrawals when resuming boring. This objective was in fact essential in order to control the extraction flow rate, conveyor management and therefore the regularity of the boring.

3.5 *Modifications to the cutting wheel*

After the first withdrawals leading to blockages and the cutting wheel being immobilised, it was necessary to reduce materials flowing into the excavation chamber. The disc cutter housings were therefore blocked with blocks of polystyrene and expanding polyurethane foam was injected into the booms. These operations were carried out on 1 boom in 3 but, upon restarting, they turned out to be insufficient because the foam was compressing rapidly on contact with the terrain at the level of the buckets, the material penetrated again and the torque force of the wheel exceeded the limits for the machine once more. So it was decided to reduce the opening of the cutting wheel from 8 to 4.5% in several stages:

- preparatory work (inspection, manual draining, cleaning, cutting out old scraper supports and steel plates);
- preparing new supports and steel plates for reducing the openings of the buckets;

- welding of the new elements (scraper supports, plates, brackets, grizzly bars) involving adding for each of the 16 booms 2 additional steel closing plates compared to the initial configuration.

3.6 *Monitoring deformations*

As anticipated in § 3.2 several phenomena and deformations were observed on the support right from the first surveys. For these reasons, simultaneously with the lining segment reinforcement work by installing ring beams, specific monitoring was carried out to see how these deformations evolved and to estimate the strain levels by installing:
- Saugnac gauges on the cracks;
- optical prisms on segments and ring beams;
- strain bars on ring beams and on the shield;
- strain bars sunk into the concrete and pressure cells at the extrados of the segments;
- flat cylinders in the segments;
- probes to measure pore pressure from incoming water.

These instruments were used to continually monitor how the degradations changed over time while the other operations were being performed then during the unblocking and excavation resumption phase. The deformations of the rings were also continually monitored by a so-called RCMS system, comprising biaxial inclinometers installed on each segment of the same ring, enabling the oval-shaping of the rings to be assessed (fig. 12).

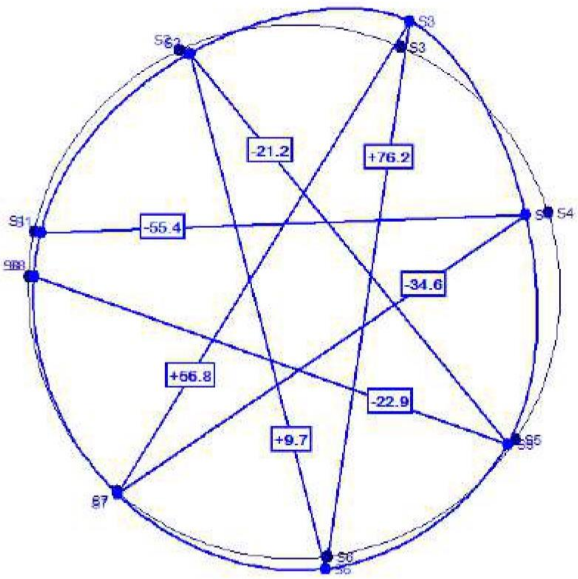

Figure 12. Chart of convergences and visualisation of the deformation (in mm)

The concrete lining segments underwent up to 100mm in cord variation, became oval shaped under the pressure of more significant horizontal strains associated to management of the vault ring grouting. Indeed, this grouting, initially planned between the tenth ring behind the tail, was brought up to the second last ring laid to reduce oval-shaping and improve the distribution of forces in the ring. The maximum strain measured through the bars sunk in the segment concrete was around 15 MPa of compression, confirmed by the flat cylinder tests. The maximum pressure levels measured at the extrados of the segments (in contact with the mass) are around 1000-1500 kPa. The maximum strain levels measured for the reinforcement ring beams placed on the intrados of the rings were around 20 MPa.

Simultaneously with the monitoring in the tunnel, inspections were carried out on the surface to monitor settling and piezometric levels, which did not record any notable variations in relation to the volumes withdrawn.

3.7 *Resuming boring*

The boring work resumed slowly with careful management of the volumes of materials withdrawn and TBM parameters through the accident area. Boring conditions went back to normal from ring 207 approximately (fig. 13).

For the accident area, which concerned some 15 rings, the excavated weight was some 20,000 tonnes more than in theory, including a part comprising drained water which was assessed as being 20% of the total.

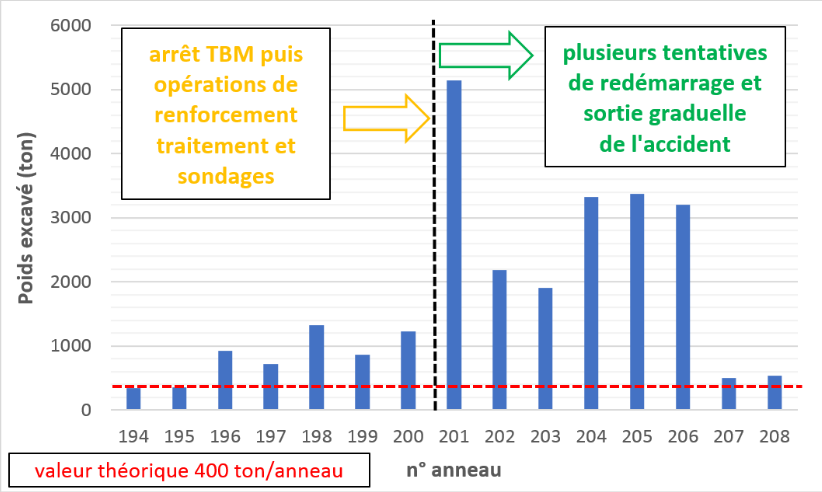

Figure 13. Chart of the excavated weight per ring in the accident area

4 CONCLUSIONS

The difficulties encountered by the TBM as it approached the 300 m mark required boring to be stopped for several months, a range of different operations to be performed and stages to be crossed before boring could be resumed. The successful crossing of this accident enable to reach several goals in the project, in particular the exploration and crossing of the Houiller with an 11.25 m diameter hard rock single shield TBM, the ability to cross fault zones and carbonaceous passages with over 700 m of overburden, the possibilities of adapting the machine and support reinforcement.

Above all, the lessons learned from this operation were applied when a new fault around PK 15+120 (approximately ring 2209) similar to the previous one was encountered, with the necessary operations and adaptations enabling this new accident to be crossed in less than one month.

5 ACKNOWLEDGMENTS

Authors would like to acknowledge the dedicated work of all the people involved in the design and construction process of the SMP4 works, in particular the contracting authority (LTF first and later TELT), the construction contractor (joint venture Spie Batignolles TPCI, Eiffage TP, Sotrabas, Ghella, CMC, Cogeis) and the work management companies (Egis Structures & Environnement and Alpina S.p.A.).

6 REFERENCES

Barla, G. 2009. Innovative tunnelling construction method to cope with squeezing at Saint Martin La Porte access adit (Lyon-Turin Base Tunnel). *In Vrkljan (ed.): Eurock 2009 – Rock Engineering in Difficult Ground Conditions – Soft Rocks and Karst, pp. 15–24.* CRC Press/Balkema.

Barla, G., Bonini, M. & Debernardi, D. 2010. Time dependent deformations in squeezing tunnels. *International Journal of Geoengineering Case Histories 2, No. 1, pp. 40–65. DOI: 10.4417/IJGCH-02-01-03.*

Brino, L., Monin, N., Fournier, C. & Bufalini, M. 2013. Nuova Linea Torino-Lione - Ritorni d'esperienza, Congresso Internazionale Società Italiana Gallerie, *Gallerie e spazio sotterraneo nello sviluppo dell'Europa, 17-19 ottobre 2013, pp. 595-604,* Pàtron Editore, Bologna.

Descoeudres, F., Giani, G.P. & Brino, L. 2015. Il tunnel di base del Moncenisio per la nuova linea ferroviaria Torino-Lione: aspetti geomeccanici e confronto con i grandi trafori svizzeri, *Gallerie e Grandi Opere Sotterranee, settembre 2015, n. 115, pp. 21-31,* Pàtron Editore.

Gamba, F., Brino, L., Triclot J., Hugot, E., Barla, G. & Martinotti G. 2017. A TBM assembly cavern in the French Alps, *Geomechanics and Tunnelling, Base Tunnels, Vol.10, n.3, giugno 2017, pp. 256-264,* Ernst & Sohn Berlino.

Monin, N., Brino, L. & Chabert, A. 2014. Le tunnel de base de la nouvelle liaison ferroviaire Lyon-Turin : retour d'expérience des ouvrages de reconnaissance, *Congrès International AFTES 2014, 13-15 ottobre 2014,* Lyon.

Rettighieri, M., Triclot, J., Mathieu E., Barla G. & Panet M. 2008. Difficultés liées aux fortes convergences rencontrées lors du creusement de la descenderie de Saint Martin La Porte. *Congrès International AFTES 2008.* Monaco.

Subrin, D., Vu, T.M., Sulem, J., Robert, A., Monin N. & Brino L. 2009. Geometrical treatment of convergence and levelling data for the description of the anisotropic behaviour of carboniferous coal schists met in the St-Martin-La-Porte access gallery, *AITES-ITA 2009 World Tunnel Congress, 23-28 maggio 2009.*Budapest.