Contribution of twenty years of exploratory work in the complex carboniferous formation of the Montcenis Base Tunnel

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ABSTRACT:

This paper discusses the work undertaken to explore the most geologically complex section of the 57.5 km Lyon-Turin cross-border base tunnel between Susa, Italy and Saint-Jean-de-Maurienne, France.This section, on the French side, has been subject to exploratory work in the Houiller briançonnais fields, between Saint-Martin-La-Porte and La Praz for nearly 20 years.After the realization of two access tunnels which had convergences up to 2 meters, this work, in the axis of the south tube of the base tunnel, was divided into 2 parts: 1.5 km realized using the traditional method to explore and cross the most converging terrain corresponding to the Front du Houiller and 9 km using a TBM for the other Houiller parts.The unknown and extremely difficult geological and geomechanical conditions in these carboniferous formations, under 300 to 1,200 m of covering, have made this work a real technical and human challenge that required a special and adaptive design with the testing and validation of constructive solutions before the launch of the construction of the base tunnel in this sector. This exploratory work has also made it possible to optimise the design and consolidation of economic forecasts and planning for this section.

1 INTRODUCTION

The European railway project for the Lyon-Turin cross-border section, for which studies began some twenty years ago, is located between Saint-Jean-de Maurienne, in France, and Susa, in Italy, on a mainly underground route with a 57.5-km-long twin-tube Base Tunnel, under the responsibility of the Franco-Italian public promoter TELT.

Figure 1 shows the Base Tunnel and its points of access: the Italian and French entrances and the four intermediate accesses, including the Saint-Martin-la-Porte and La Praz access adits, on either side of the SMP4 works (South tube), in the Briançonnais coal area, which is crossed for a distance of a dozen kilometres. The Avrieux shafts are also visible near the Modane safety site and the communication branches between tubes.

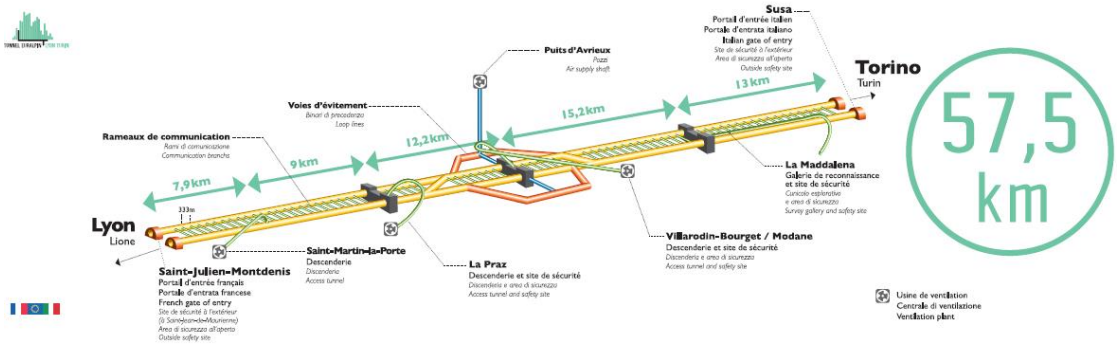

Figure 1. Base tunnel of the Lyon-Turin cross-border section

2 GEOLOGICAL CONTEXT OF THE BASE TUNNEL

The Base Tunnel route passes through an extremely complex geological context, both in terms of lithological variety and structural, geomechanical and hydrogeological aspects. The route lies between the outer Alps to the west and the inner Alps to the east, separated by the Pennine Front, and is marked by other major discontinuities and thrusts.

The formations that will be crossed from west to east by the Base Tunnel are described in Figure 2: from the western entrance of Saint-Julien-Mont-Denis, a sector that will be cut through the loose deposits of the Saint-Julien alluvial fan, the two tubes of the Base Tunnel will then be cut in the flysch lithotypes of the Zone ultradauphinoise (External Alps). Once the Pennine Front has been crossed, the route will intersect the Zone subriançonnaise, the Zone houillère, the Zone briançonnaise (Vanoise), the Zone piémontaise, the Zone briançonnaise (Ambin) and the Zone piémontaise (calcshistes).

These formations are increasingly deformed from west to east and are separated from each other by tectonised horizons and décollement horizons of varying thickness (gypsum, anhydrite and cargneule rocks).

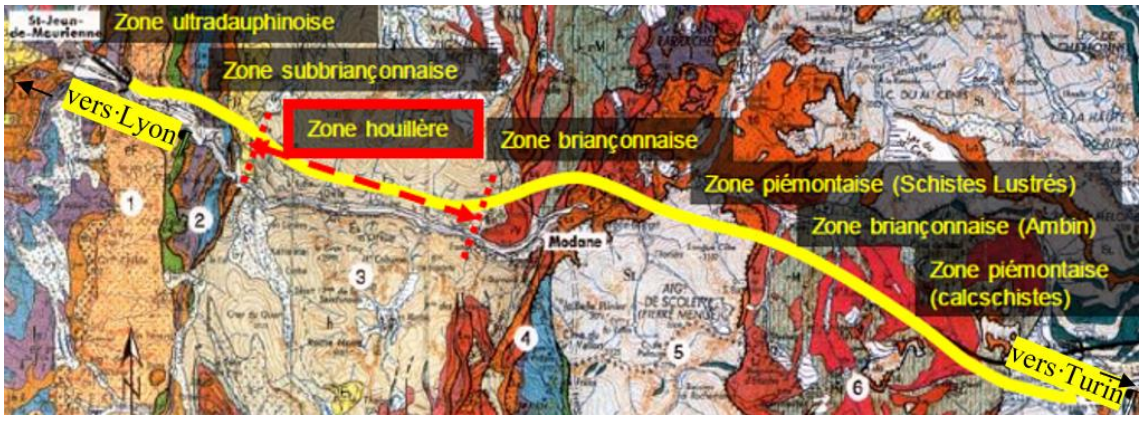

Figure 2. Location of the Zone Houillère on the Base Tunnel route (approximately 12 km long)

These very complex geological conditions, recognized with more than 40 deep boreholes from the surface, about 500 boreholes on advance and 17 km of access adits and gallery, did not affect the final layout of the main tunnel.

Since 2002, all the geological data of the project and the data relating to the structures have been entered into a geological/constructive portal.

3 GEOLOGICAL SURVEYS AND STUDIES

At the geological level (in the broadest sense), the exploratory and study phases were carried out in order to acquire sufficient input data to build the most complete geological model at the project scale. The objectives of these studies and surveys have evolved over time in order to reduce the risks associated with the geology during the works. The following is a summary of the evolution of the knowledge of the Zone Houillère Briançonnaise, one of the most complex zones of the project, as examined in the different phases of the studies.

- *Feasibility study: Between 1990 and 2001, the SNCF and FERROVIE DELLO STATO ITALIANE and then ALPETUNNEL carried out studies with Design Offices to demonstrate the feasibility of the project. Among the objectives was the establishment of a geological cross-section of the project and the characteristics of the geological formations. For the studies of the Zone Houillère Briançonnaise, the land is for the most part masked by superficial formations, which made it difficult to collect surface data. To complete this data and to know the characteristics of the rocky massif at the level of the future Base Tunnel, deep drillings (up to about 1000 m) were carried out in order to reach the height of the Base Tunnel, with generally difficult access in the mountains. The geological studies and exploratory carried out enabled the geological section of May 2000 to be drawn*

up, distinguishing between "productive" coal and "sterile" coal (depending on the presence or absence of coal seams in the schisto-sandstone massif, which were exploited locally on the surface until the 1950s) with a level of detail that was still not very high.

- *Preliminary Reference Project: after the Summary Preliminary Project of 2002-2003 (APS), an engineering group was commissioned to carry out the Preliminary Reference Project (APR) on behalf of Lyon Turin Ferroviaire between 2004 and 2007, based on the available input data, new boreholes and, for the Zone Houillère Briançonnaise, the first results of the excavation of the Saint-Martin-La-Porte and La Praz boreholes, which are described in detail in chapter 4. The objectives of this APR at the geological level were to specify the litho-stratigraphic and structural conditions for the construction of the rock massifs through which the base tunnel would pass. This APR made it possible to draw up graphic geological documents, including a provisional geological section that was more precise than in the Feasibility study. The Zone Houillère Briançonnaise was subdivided into 4 lithological units (Encombres, Bréquin-Orelle, La Praz and Fourneaux).*

- *Reference Project: In 2013, the Reference Project was produced by an engineering consortium for Lyon Turin ferroviaire, with an update of the APR based on additional geological and structural surveys, new core drilling and excavation data from the La Praz and Saint-Martin-La-Porte access adits, and 3 horizontal drillings at the bottom of the Saint-Martin-La-Porte and La Praz access adits. The degree of knowledge of the geological, geomechanical and hydrogeological conditions has thus been improved and resulted in the synthetic geological cross-section forecast for the 2014 PR (Figure 3).*

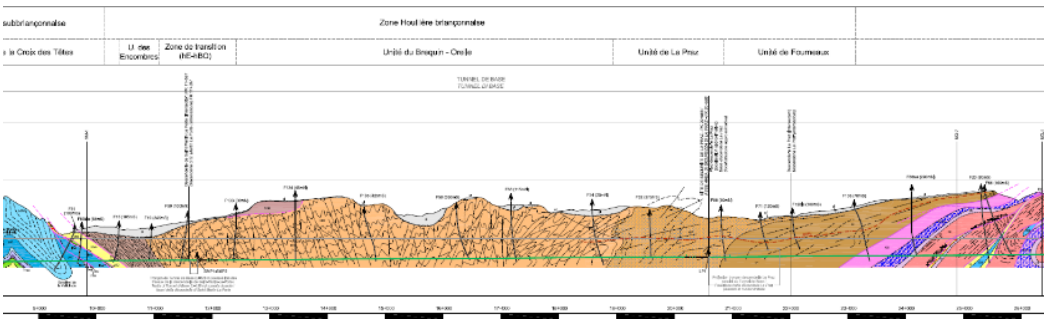

Figure 3. Geological profile of the Zone Houillère Briançonnaise at the stage of the Reference Project

- Final Reference Project: The Final Reference Project was updated from the Reference Project on the basis of data from the new Saint-Martin-La-Porte 4 access adit (Part 3a) and from a borehole at the foot of the La Praz access adit (Part 4). The main developments concerned the improvement of geological and structural knowledge in targeted areas such as the Zone Houillère Briançonnaise, with changes in the geometry and strength of the layers between the APR and the PRF. The geometry of the formation boundaries has evolved as a result of taking into account and interpreting the new data from the digging of the access adits.

- Project Phase: this last phase of studies, before the DCE phase for the works, was carried out by a group of project managers between 2018 and 2021, on behalf of Tunnel Euralpin Lyon Turin. These studies took into account all the data and in particular those of the SMP4 construction site (parts 2 and 3b in part, presented in Chapter 5) which was still active at the time. As for each study phase, all the components (geological, geomechanical and hydrogeological) were studied by the project managers in order to establish the calculation hypotheses for the civil engineering studies and to reduce the geological risks as much as possible.

4 ACCESS ADITS

Underground exploratory work has also enabled the Zone Houillère Briançonnaise to be recognised via:

-The first access adit at Saint-Martin-La-Porte (SMP1 and SMP2), to the west of the Zone Houillère Briançonnaise,

-The La Praz access adit, east of the Zone Houillère Briançonnaise,

- The SMP4 exploratory work (Parts 1, 2, 3a, 3b and 4).

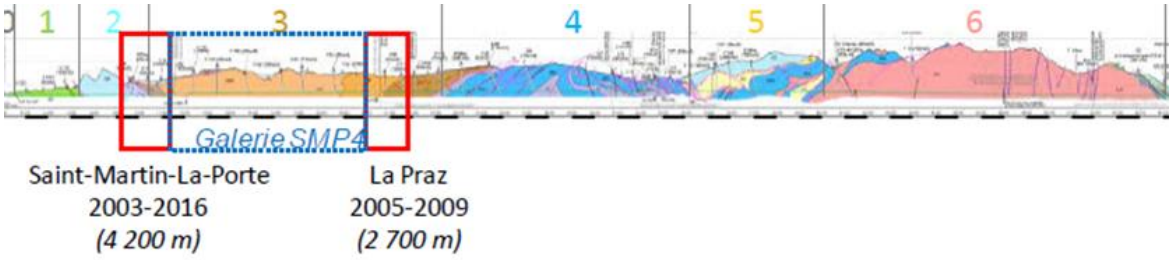

Figure 4. Position of the SMP, La Praz access adits and of the SMP4 exploratory work.

- *SMP1 (2003-2007)*

From the Saussaz platform at Saint-Martin-La-Porte, the SMP1 contract initially envisaged the construction of a 2040-metre-long access adit and two exploratory tunnels at the foot of the access adit, each about 1500 metres long, running in the opposite direction, east-west, along the route of the future tunnel (Figure 5).

The main objectives of this work were the geological exploration of the Zone Houillère Briançonnaise (Encombres Unit) and its contact with the Sub-briançonnais formations (Coal-bearing Front), the full-scale examination of the mechanical behaviour under heavy cover of the terrain crossed and the testing of different lining methods, in the short, medium and long term. More specifically, for the east tunnel, the aim was to define the productive coal/sterile coal boundary and to assess the possibility of using tunnel boring machines (TBMs) for the base tunnel in the sterile coal-bearing strata. For the west tunnel, the aim was to identify the characteristics of the productive coal-bearing strata and establish the position of the coal-bearing face in actual fact.

During excavation of the shaft (from PM 800 onwards), the work encountered strongly thrusting ground with metric convergences in the coal seam (Figure 6) and the planned rigid support, which was not adapted to the constraints encountered and led to strong convergences, was replaced by a phased system with a flexible support, bolting and compressible blocks. This system made it possible to support these strong convergences. A blocking ring was put in place for the linear section that experienced the strongest convergences. The combination of these special conditions led to an overrun in time and budget, which required a modification of the Contract and its termination.

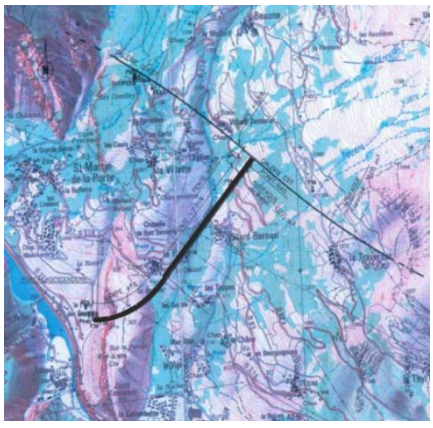

Figure 5. Plan view of the SMP1 project

Figure 6. Metric Convergences

- *SMP2 (2007-2010)*

Following the SMP1 works, a second contract, SMP2, which iteratively took into account the previously encountered excavation conditions with the application of an adapted multiphase support system, was undertaken with objectives broadly identical to SMP1. A modification to the initial route was made to avoid the converging terrain for the continuation of the work on the access adit and thus make it possible for the base tunnel level to be reached more quickly and safely in order to continue the exploratory work in the tunnel at the base tunnel level. This modified route corresponds to the line circled in red in figure 8.

These successive exploratory works in the access adits (SMP1 and 2) have enabled a better understanding of the Productive Coal-bearing levels under heavy cover, in the short/medium/long term, with a division into 4 behavioural classes (A, B, C, D) according to the degree of tectonisation and the proportion of convergent schistose characteristics and more appropriate sandstone characteristics (Figure 5).

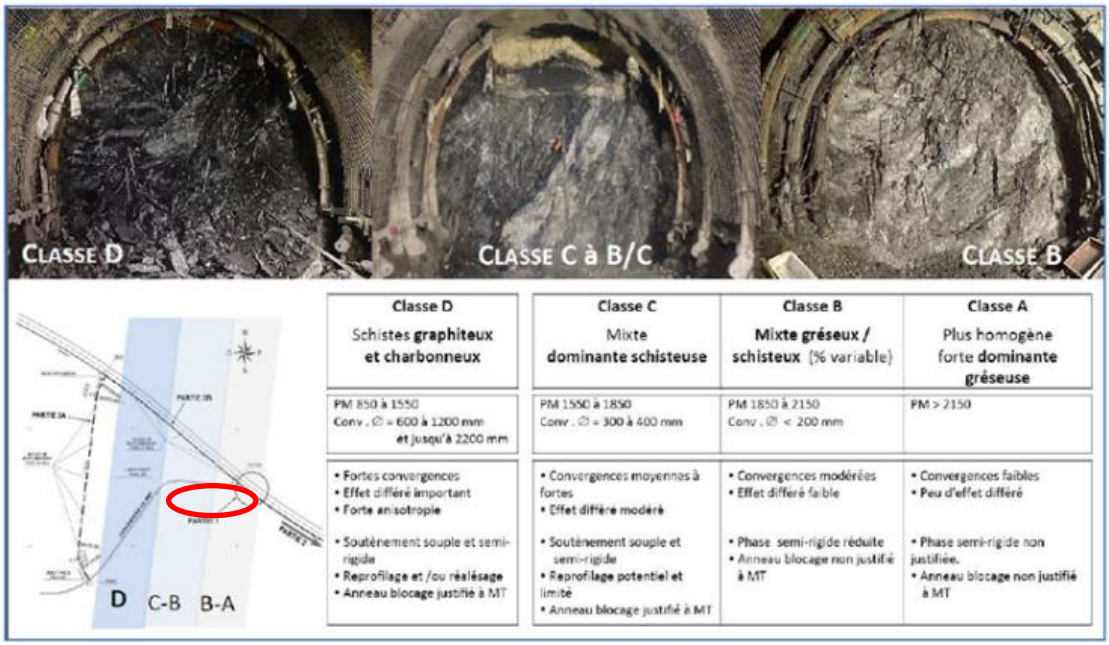

Figure 5. Application of the Observational Method to optimise the execution of the St-Martin-la-Porte 4 tunnels of the Lyon-Turin Project. 2018 (from the paper by E. Mathieu, P. Lochon, E Egal, A. Saitta, J. Triclot)

In particular, it was possible to define the class D coal-bearing stratum encountered between MP 850 and 1550 of SMP1 under a cover of 150 to 400 metres which corresponds to the productive coal or convergent coal (HC). It is characterised by strong lithological and structural heterogeneity, with crushed coal layers of decimetric to multi-metric thickness, zones of faults with clay gouge, crushed or simply very fractured shales, fractured, sheared and boudins sandstone banks. Its behaviour is reflected by:

- Major convergences. These are greater than 120 cm in diameter with maximum values of 200 cm.
- A very marked anisotropy of deformations. The value of the K0 ratio, measured during the work, is around 1.2.
- A relatively weak extrusion of the working face, of the order of centimetres.
- A significant delayed effect, marked by a lack of stabilisation of the deformations of the temporary support.

The support structure was defined on the basis of feedback from the SMP1 contract. It was broken down by excavation class, thus allowing the risks and responsibilities to be shared between the

company and the contracting authority. Among the support profiles implemented, class 6 is detailed here, which proved to be suitable for strong convergences and which included a methodology with three work zones more or less distant from the working face:

- zone A - the working face zone: from 0 to 40 m behind the working face
- zone B - the advance zone: 40-80 m behind the face
- zone C - zone behind the advance: more than 80 m behind the working face.

This work methodology made it possible:

- on the one hand, to "control" and accompany the deformations of the land around the excavation with the installation of supports – first flexible, then rigid and finally blocking – to let the terrain express itself and avoid distortions and deformations in the supports. Indeed, the earlier a rigid support is put in place, the greater the stresses applied by the terrain on the support.
- secondly, to define three workshops at different distances and thus obtain an increase in progress and better budgetary control.

Contrary to the previous SMP1 contract, the support provided for in the contract proved to be adapted to the digging conditions. Modifications and changes to the profiles were made during the course of the work in line with the changes in convergence observed. In order to optimise costs and deadlines, it was decided to lighten the supports during the execution of the project, as the convergences were noted to be gradually reducing.

This classification of the terrain adopted and the support methodology employed were used in the subsequent SMP4 works for the implementation of an observational method with an adaptation of the support according to the terrain as noted during drilling in progress.

- *La Praz*

Even though the exploratory objectives of this access adit also concerned the Zone Houillère, the unit considered was that of La Praz which, overall, presents better-quality terrains (shaly sandstones and metaconglomerates) than those previously described in the Encombres unit. This access adit enabled the boundary between the La Praz and Fourneaux units to be shifted to the west. It should also be noted that one of the major problems of the rock mass traversed was of a hydrogeological nature, linked to the potential presence of water and hydrothermal ascents at the foot of the access adit.

5 SMP4 EXPLORATORY WORK

As soon as excavation of the SMP1/2 access adit was completed, it was decided that further investigations should be carried out in the Zone Houillère along the base tunnel route, as the conditions there would certainly be different (different orientation, higher cover) and the feasibility of excavation with a tunnel boring machine (TBM) needed to be demonstrated. A programme of horizontal exploratory drilling along the tunnel axis was carried out to assess the quality of the ground to the east and thus confirm the feasibility of constructing a TBM assembly chamber near the foot of the access adit. With this confirmation, a supplementary contract for works called SMP4 could be launched for various underground works (Figure 6):

- improvements at the foot of the Saint-Martin-la-porte and La Praz access adits with the creation of an assembly and dismantling chamber for the tunnel boring machine corresponding to parts P1 and P4 respectively
- the start-up of a tunnel boring machine (TBM) to link these two access adits along the southern tube of the base tunnel project in the less convergent coal-bearing terrains (Brequin-Orelle unit then La Praz unit) representing a linear distance of approximately 9km corresponding to part P2 with the main objective of demonstrating the feasibility of the TBM project
- the excavation of a new access adit using the traditional method over a distance of approximately 1,800 metres from the existing access adit to reach the base tunnel in the Jurassic and Triassic terrains upstream of the coal-bearing terrains, corresponding to part P3a.

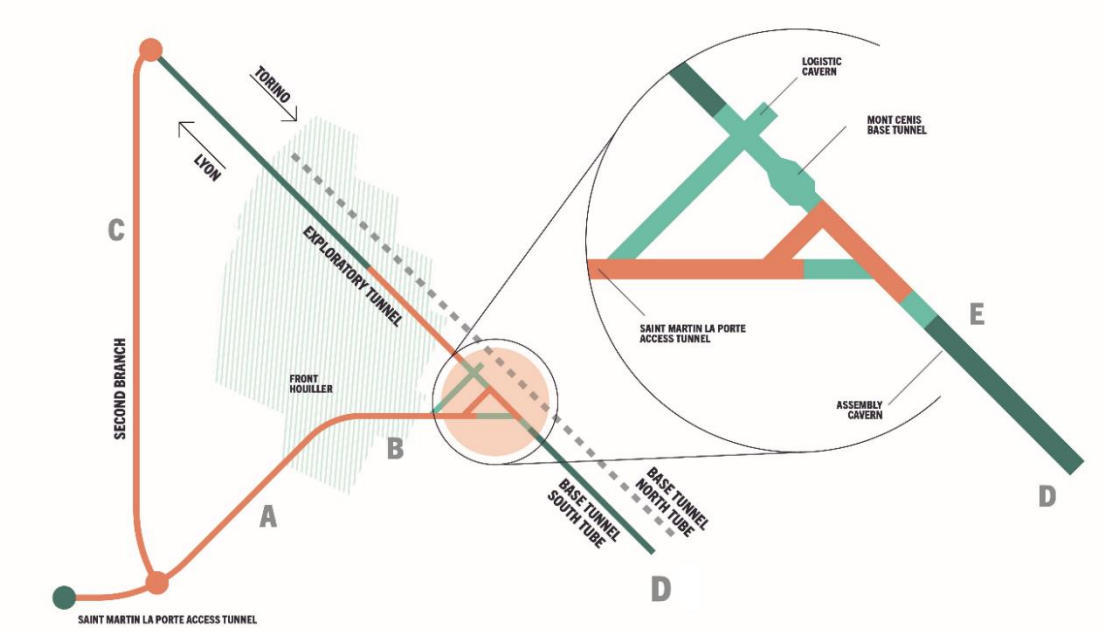

Figure 6. Schematic diagram of the exploratory work at Saint-Martin-la-Porte (Brino, 2022) with A-B: main branch of the Saint-Martin-la-Porte access road; C: secondary branch of the Saint-Martin-la-Porte access road; D: southern tube between Saint-Martin-la-Porte and La Praz excavated with the tunnel boring machine (TBM) from the base of the main branch; E: assembly cavern of the TBM that excavated the southern tube between Saint-Martin-la-Porte and La Praz.

In addition to the objectives already achieved by the previous contracts for the SMP access adit, the SMP4 contract was to verify various points along the axis of the base tunnel:

- geological exploration of the Jurassic carbonates (limestone and dolomite), Triassic rocks (gypsum and anhydrite), schistose rocks such as the Zone Houillère Briançonnaise (different characteristics of the coal-bearing strata) and the contacts between these different formations
- full-scale examination of the mechanical behaviour under heavy cover of the terrain crossed
- testing of different support methods (rigid-flexible)
- examination of the possibilities of reusing the excavated materials
- testing of different methods of exploration at the point of advance
- full-scale examination of the relatively large to very large convergences observed in the so-called productive features of the coal-bearing strata, as well as the possibly marked rheology of several features of the coal-bearing strata and the anhydrites of the coal-bearing strata front
- investigation of the possible presence of gas (methane) in the terrain crossed. Gas concentrations never exceeded detection limits.

In addition, this contract was intended to make it possible to:

- validate the reliability of the execution of the base tunnel using a tunnel boring machine
- acquire the necessary experience for excavating the base tunnel with a TBM
- determine the characteristics and adaptations to be made to the tunnel boring machines
- adapt the excavation section, the geometry and the mechanical characteristics of the segments
- check the hypotheses made concerning the geology
- analyse the behaviour of the terrain and the forces to be absorbed, including at the coal-belt face

- consolidate the construction methodology according to the conditions encountered with the adaptation of the excavation profiles of which an example is illustrated in figure 7 for the crossing of the fault zone around the PK 10,300
- identify possible karst zones and groundwater circulation in the vicinity of the future tunnel project
- establish the ground temperatures and their influence on the construction of the base tunnel.

The lessons learned and feedback are being processed for the recently completed SMP4 works.

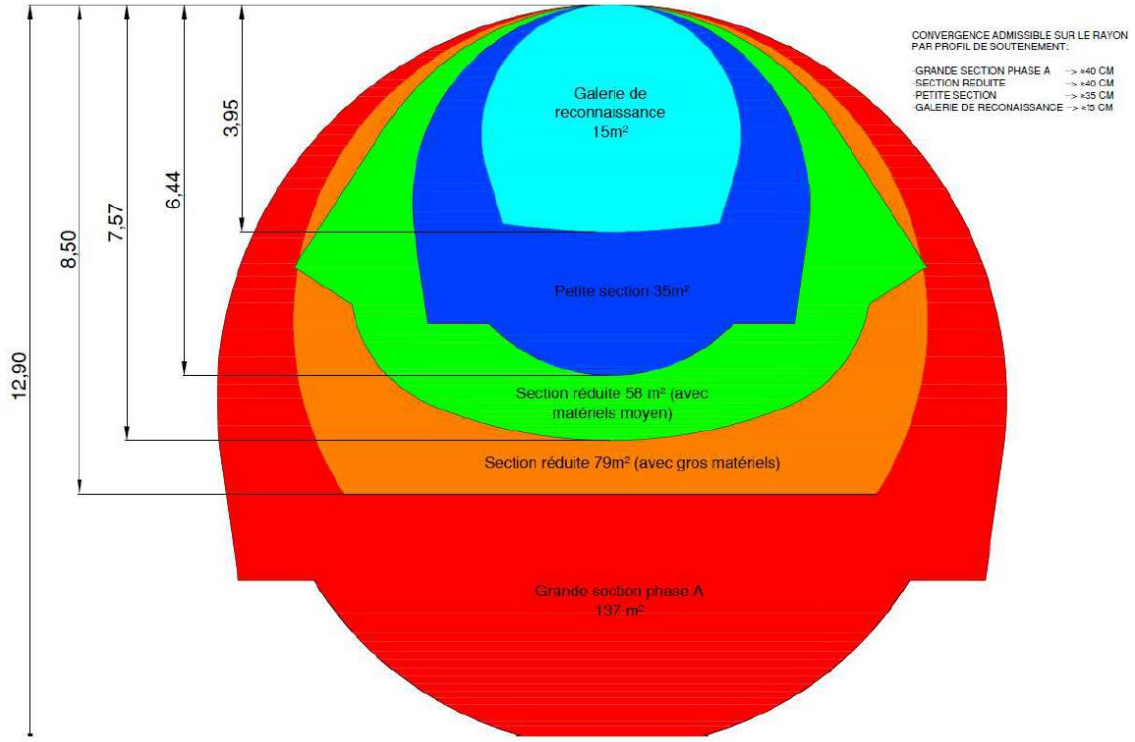

Figure 7. Geometry of the excavation profiles for the passage of the fault zone around the PK 10,300

6 CONCLUSIONS

Over the last twenty years, successive and complementary exploratory and study phases have made it possible to build and refine a detailed geological model, as described in the paper, for the construction phase of the Base Tunnel of the Lyon-Turin cross-border section, with the aim of limiting geological uncertainties as much as possible.

In particular, the main changes in the studies/works in relation to the Zone Houillère Briançonnaise were as follows:

- Clarification of the geological, geomechanical and hydrogeological hypotheses to be taken into account for the North Tube,
- Validation of an optimised methodology for excavation and support of the area near the coal-belt front in order to accompany the convergences in the construction process,
- Validation of the feasibility of tunnelling in the Zone Houillère Briançonnaise outside the zone close to the front for the second tube (North) in this zone.

These advances in terms of knowledge and know-how have contributed and will continue to contribute to the technical, budgetary and planning control of the project by optimising the work.

During the works, progress exploration will be carried out with the aim of anticipating geological uncertainties, prior to excavation. The geological model of the Base Tunnel in the Zone Houillère Briançonnaise will reach its final version after the excavation of the tunnel and the interpretation of all the data produced during the works.

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