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# A TBM Assembly Cavern in the French Alps

*This paper is concerned with the cross border section of the Lyon-Turin Line, i.e. the 57.5 km long Mont Cenis Base Tunnel between Saint Jean de Maurienne in France and Susa valley in Italy. Works at Saint Martin La Porte started in 2015 including the 9 km TBM excavation along the south tube of the base tunnel between the access adits of Saint Martin La Porte and La Praz. In order to assemble the TBM, a large underground cavern has been excavated at the end of the Saint Martin La Porte access adit. The size of this cavern, with a length of approximately 45 m, a span of 23 m and a height of 26 m, the geological and geomechanical conditions in the Carboniferous Formation at a depth of about 600 m made this work a real challenge. The excavation and support methods adopted are described, together with the rock mass conditions and the observed ground behaviour. The monitoring data obtained during excavation are briefly presented, including the works schedule and construction sequence.*

**Keywords:** Lyon-Turin Line, Mont Cenis Base Tunnel, Underground works, TBM assembly cavern, Sequential excavation

## 1 Introduction

The new Lyon - Turin Line is divided into three main sections, a national railway section at each end, French or Italian, and the central transnational section, which represents the most innovative section of the new line with its twin tunnels, each 57.5 km long.

150 years after the opening of the Fréjus tunnel, this central section is to replace the present mountain line with a lowland line represented by the Mont Cenis Base Tunnel. This section also includes three access adits (completed between 2003 and 2010), an exploratory tunnel, and two ventilation shafts [1].

## 2 Saint Martin La Porte Experience

During the excavation of the access adits of the base tunnel the complexity of the geological and geomechanical conditions encountered was well evidenced, this being in particular the case of the Saint Martin La Porte access adit. The first phase of this work was the construction of the

2,280 m long adit between 2003 and 2010.

Excavation took place through the Carboniferous Formation, the so-called “Briançonnaise Coal Field”. Large convergences were experienced under an overburden of nearly 300 m. Characteristic features of the ground observed at the face during excavation were the highly heterogeneous, disrupted and fractured conditions of the rock mass which exhibited very severe squeezing problems [2], [3].

In order to better control the conditions encountered, an innovative yielding support system was implemented with a near circular cross section, with an average equivalent radius of about 6 m, an average height of 11.7 m, and an average maximum horizontal span of 12.5 m. This support system, initially tested along a tunnel length which needed be remined (from chainage 1325 m to 1384 m), was systematically adopted after chainage 1440 m [4].

This innovative system comprises the following main stages:

• Stage 0: face pre-reinforcement, including a ring of grouted fiberglass dowels around the tunnel, designed to reinforce the rock mass ahead and around its perimeter over a 2 to 3 m thickness.

• Stage 1: mechanical excavation in steps of one-meter length, with installation of a support system consisting of dowels (length 8 m) along the perimeter, yielding steel ribs with sliding joints (TH type), and a 10 cm thick shotcrete layer. The tunnel is opened in the upper cross section to allow for a maximum convergence of 600 mm.

• Stage 2: the tunnel is opened to the full circular section at a distance of 25-30 m from the face, with application of a 20 cm shotcrete lining, yielding steel ribs with sliding joints (TH type) with 9 longitudinal slots (one in the invert) fitted with Highly Deformable Concrete elements. The tunnel is allowed to deform in a controlled manner and to develop a maximum convergence less than 400 mm.

• Stage 3: installation of a concrete lining at a distance of 80-100 m from the face.

## 3 Saint Martin La Porte SMP4 Works

In 2015, a second phase of investigations was started with the experience gained during the excavation of the Saint Martin La Porte access adit, in order to:

- Check and improve the available geological and geomechanical models.
- Gain insights into conventional versus mechanized (TBM) excavation of the Base Tunnel.
- Understand the response in difficult conditions, in particular in the Carboniferous Formation.
- Identify potential karst zones and underwater flow around the Base Tunnel.
- Test different products for waterproofing/improvement of the ground in problematic zones.

The main works (SMP4 Works), which were initiated at the same time, can be subdivided into four parts as shown in Figure 1:

- Part 1: conventional excavation starting from the end of the existing access adit and construction of the TBM Assembly Cavern.
- Part 2: TBM excavation of the Base Tunnel South Tube (9 km long) between Saint Martin La Porte and La Praz.
- Part 3: conventional excavation of an exploratory tunnel 1.4 km long, which is expected to cross the previously encountered Carboniferous Formation (see Chapter 2 above) between the end of a second access adit just completed (length 1.8 km) and the existing first access adit.

- Part 4: conventional excavation at the end of the La Praz access adit of a new cavern for dismantling the TBM.

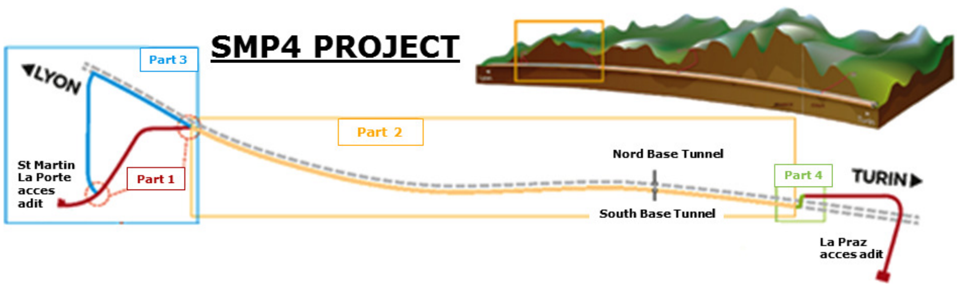



Fig. 1. SMP4 works. The completed Saint Martin La Porte and La Praz access adits are shown in red.

It is worth to mention that NFM Technologies du Creusot (Saône-et-Loire) has built the single shield TBM (see Fig. 2l) used to excavate the South Base Tunnel. With a head of 11.26 m diameter and 75 cutting disks, the nominal torque is 9 MNm (that can increase up to 35 MNm in case of necessity). The total power installed is 5 MW. This TBM is capable of extending the diameter up to 11.36 m. The rotational speed is 5 rpm and the total thrust applicable is equal to 180 MN.

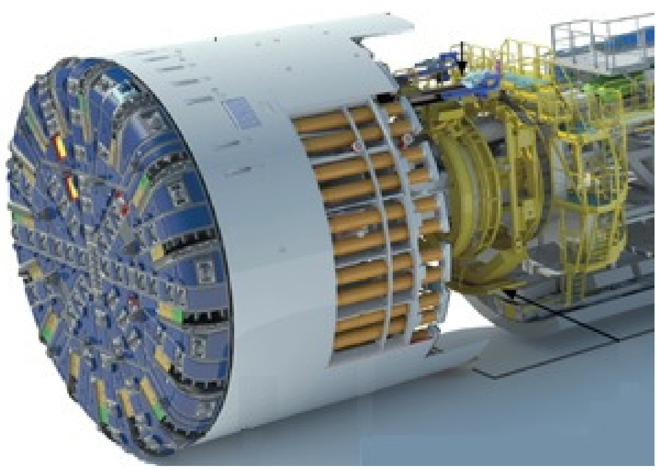


Fig. 2. TBM « Federica » used for excavation of the South BaseTunnel (9 km long) between Saint Martin La Porte and La Praz.

# 4 Underground Assembly Cavern

## 4.1 Layout and Geometry

The Assembly Cavern was excavated for the assembly of the TBM. The opening is 22.2 m in height (8.5 m at the crown, 11.3 m for the benches and 2.4 m for the invert), 24 m in span and 45 m in length. This 450 m² cross section allowed to set up two 10 MN gantry cranes to assemble first the cutting head, then the shield (11 m long), the TBM engine and finally its seven trailers (Figure 2).

The geometry of the cavern shown in Figure 3 was defined in terms of the space linked to the overall size of the TBM, the equipment and machines required for the assembly operations, for lifting and shifting. In particular, the initially planned cross-section was modified after the gantry crane was selected, allowing the height of the assembly cavern to be reduced of nearly 1 m.

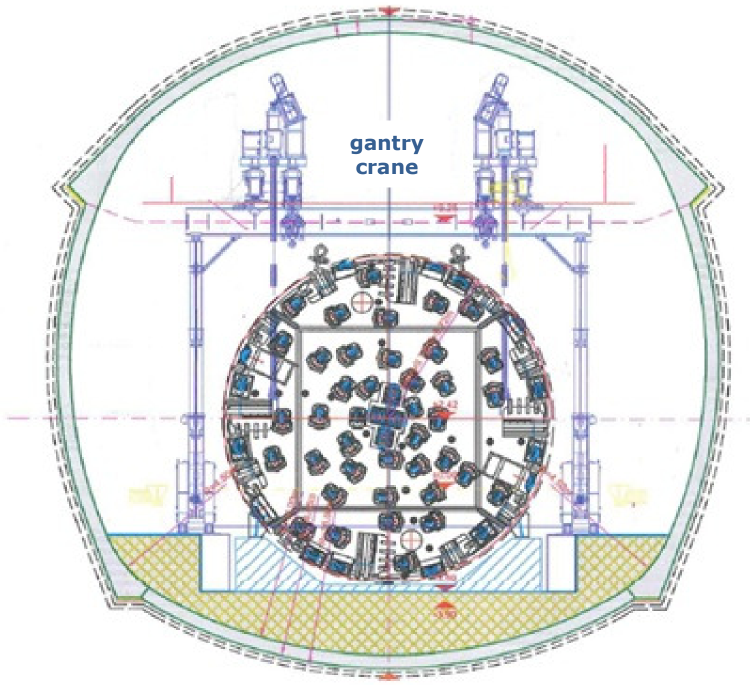



Fig. 3. The assembly cavern with a view of the gantry crane and the TBM head.

The data on the geological, hydrogeological and geomechanical conditions, which became available following the excavation of the two access adits and the additional investigative studies performed (Part 3 in Figure 1), allowed one to make the best choice possible for locating the Assembly Cavern as shown in Figure 4.

The following main factors were considered for the optimization of the cavern location: (a) The understanding of the geological conditions, in order to avoid any hazards associated with the presence of the “Briançonnaise Coalfield”. (b) Not to interact with any fault zone, which could result in the development of instability conditions. (c) The need to build an access ramp to the crown with a slope compatible with both the limits of the equipment and safety requirements.

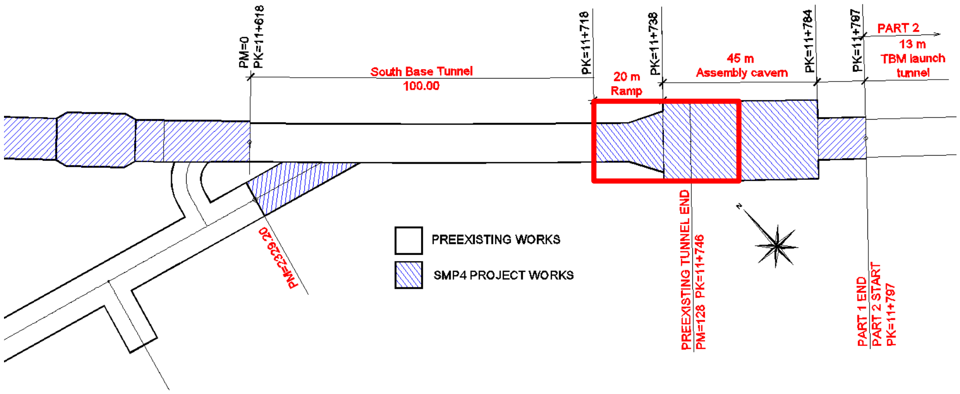



Fig. 4. Plan view of the Assembly Cavern. The red box shows the locations finally chosen.

## 4.2 Design Database

In 2010, excavation of the first 128 meters of the South Base Tunnel (Figure 1) was initiated. The rock mass encountered was sandstone; either a massive, greyish sandstone, or a fine, micaceous sandstone in bands, centimetric or decametric in thickness, frequently fractured. Quartz and calcite were also present.

This sandstone is regularly interspersed with blackish shale-siliceous bands, which may contain coal. Moreover, the rock mass is often folded, with several multi-decimetric layers. Also encountered were zones with clearly visible faulting. In all cases, the rock mass conditions were estimated from fair to good and overall satisfactory for the large size cavern to be excavated.

The data collected thanks to drilling, tunnel excavation and detailed borehole logging, as well as feedback from experience, allowed one to anticipate with confidence the expected rock mass conditions and finally confirm the chosen location of the Assembly Cavern as shown with the red box in Figure 4.

For the purpose of rock mass characterization two different facies, i.e. Sandstone and Shaly Sandstone were defined by using the Rock Mass Rating (RMR) system, thus deriving the Geological Strength Index (GSI), in order to be able to assess the rock mass deformability and strength parameters as summarized in Table 1.

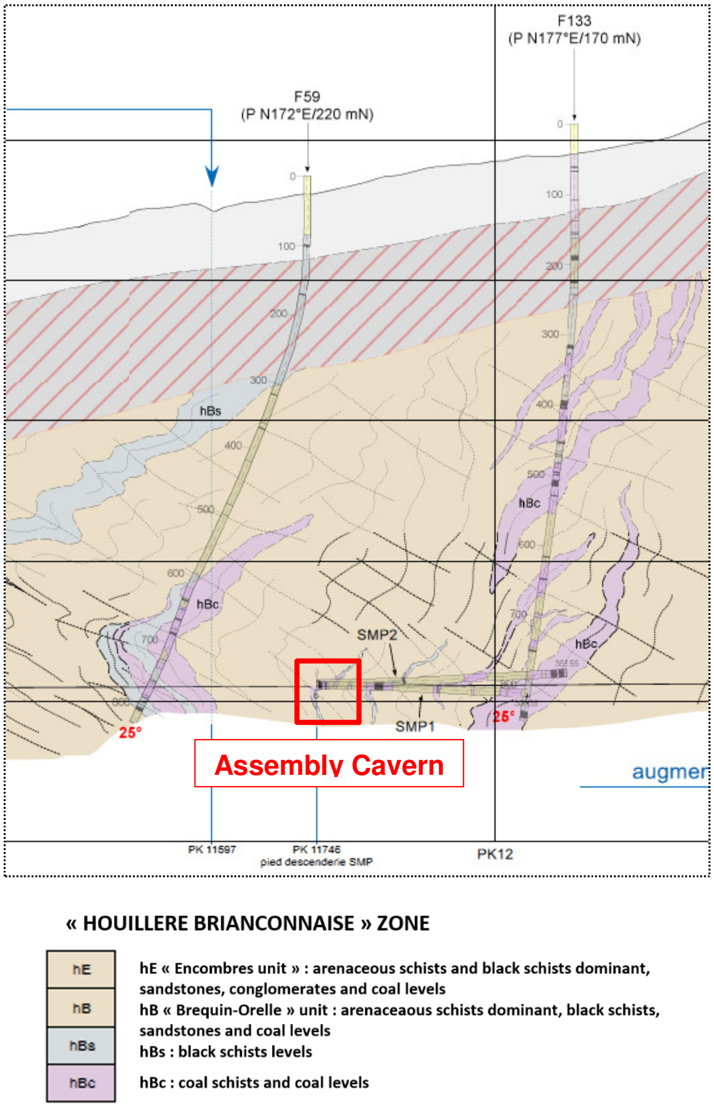



Fig. 5. The geological and rock mass conditions in the near vicinity of the Assembly Cavern

| **Parameters** | **Sandstone** | **Shaly Sandstone** |
|---|---|---|
| Intact Rock Strength ($\sigma_{ci}$) | 60 MPa | 40-60 MPa |
| RMR | 60-65 | 50-55 |
| GSI | 55-60 | 45-50 |
| Rock Mass Deformation Modulus (Ed) | 17 GPa | 11 GPa |
| Rock Mass Cohesive Strength ($c_m$) | 3-4 MPa | 2.5-3 MPa |
| Rock Mass Friction Angle ($\varphi_m$) | 40-45° | 35-40° |
| Rock Mass Strength ($\sigma_{cm}$) | 14-15 MPa | 11-13 MPa |

Table 1. Rock mass parameters initial assessment

The in situ state of stress was estimated by using the data collected during excavation of the Saint Martin La Porte acces adit with hydraulic fracturing and overcoring tests. On this basis a stress ratio $K_0$ (minimum principal stress $\sigma_h$ to maximum principal stress $\sigma_v$ ratio) in the range 0.5-0.8 was estimated in relation to the axis of the Base Tunnel.

For the purpose of design analyses, the rock mass parameters were defined as shown in Tables 2 and 3, where reference is made to the “Sandstone” rock mass of Table 1, this being the rock mass type prevailing in the Assembly Cavern area. Different sets of design parameters (“expected” and “conservative” estimates) were defined for Short-term (Table 2) and Long-term conditions respectively (Table 3).

| **Design Conditions** | **Deformation Modulus (GPa)** | **Poisson's Ratio (-)** | **Cohesive Strength (MPa)** | **Friction Angle (°)** | **Stress Ratio (-)** |
|---|---|---|---|---|---|
| Expected | 10 | 0.30 | 4 | 35 | 0.8 |
| Conservative | 7 | 0.35 | 3 | 25 | 0.8 |

Table 2. Rock mass parameters for design analyses (Short-term conditions)

| **Design Conditions** | **Deformation Modulus (GPa)** | **Poisson's Ratio (-)** | **Cohesive Strength (MPa)** | **Friction Angle (°)** | **Stress Ratio (-)** |
|---|---|---|---|---|---|
| Conservative | 5 | 0.35 | 2.5 | 20 | 0.8 |

Table 3. Rock mass parameters for design analyses (Long-term conditions)

Different methods have been adopted for design purposes as follows:

- Convergence-confinement method in order to compute for the different sets of parameters the ground reaction curve and the extent of the plastic zone around the cavern.
- Analysis of structurally controlled instability of the cavern in order to identify potential instability modes and define the support measures in terms of rock bolt patterns, length, and primary lining.
- Stress analyses with the Finite Element Method (FEM) in order to compute the rock mass response in elastic plastic conditions (Mohr-Coulomb model) during staged excavation in intrinsic conditions (no support present) and with the primary and permanent support measures installed as planned.
- Assessment of face stability during excavation by analytical and empirical approaches.

For the purpose of two-dimensional FEM modelling in plane strain conditions, the convergence-confinement method was used in order to define the proportion of unloading $\lambda$ to model the excavation and reinforcement measures installation of the cavern.

Starting with simulation of the top heading excavation and accounting for a progressive increase of the value of $\lambda$ up to installation of the final lining 15-20 m from the tunnel face, the benching down process with excavation and application of the reinforcement and lining measures as planned was also closely simulated.

FEM modelling was carried out with the CESAR software package. Figure 6 shows as an example a detail of the FEM model used on the left and the resulting displacements around the cavern on the right at the end of the excavation and support installation process.

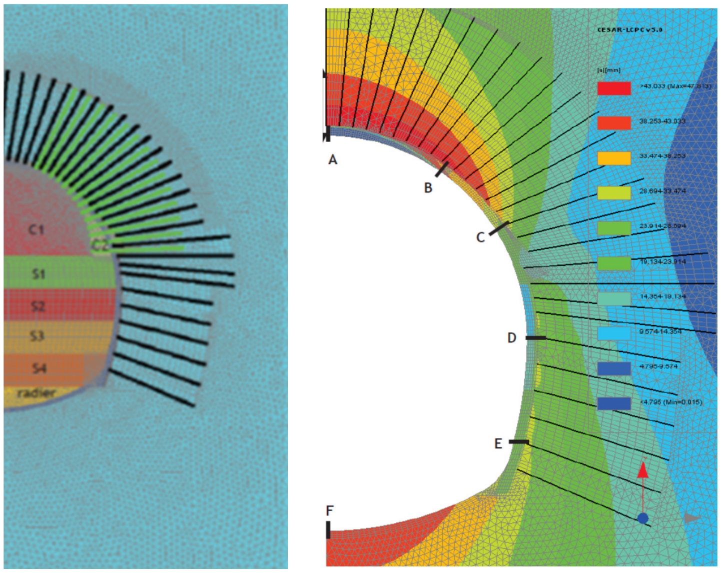



Fig. 6. FEM model showing the excavation support stages simulated (on the left). Displacement distribution at the end of the excavation and reinforcement simulation process (on the right).

The main results obtained from FEM modelling can be summarized as follows:

- With the top heading excavated and with the reinforcement system installed (central opening and widening stages) the extension of the plastic zone around the cavern results to be 2 m approximately.
- Following benching down and invert arch excavation with reinforcement system installation the extent of the plastic zone is approximately 3 m at the crown and nearly 1 m at the sidewalls.
- In the long-term conditions simulated, the plastic zone is 4 m thick at the roof and remains almost unchanged elsewhere; in all cases, its extent is within the efficiency range of the bolts.
- The maximum predicted displacements at the end of the crown excavation are 45 mm at the roof and 30 mm at the haunches. With benching down completed, these displacements become respectively 55 and 45 mm, while at the sidewalls a nearly 30 mm displacement is anticipated.
- The convergence along the bottom line of the top heading arch is a few millimeters in the short-term, reaching around 10-15 mm in the long-term.
- The bolt length as represented in the model appears to be satisfactory and in accordance with the stability analyses based on the discontinuity sets in the rock mass.
- The stresses in the support (steel arches and concrete) computed by assuming the most conservative parameters for the rock mass attain values close to the threshold values.
- With the less conservative parameters, in line with the expected values, however, the stresses obtained with the model remain below allowable values.

## 4.3 Excavation and Construction

As anticipated above, the top heading and benching down excavation method was used. First, excavation of a central heading took place followed by its lateral extension to the side headings to form the full top heading. Then benching down took place. Given the presence of a prevalent sandstone rock mass, as anticipated, the drilling and blasting method was adopted.

As illustrated in Figure 8, where different excavation and reinforcement stages during construction are shown, the excavation and construction work took place progressively from the top down by creating different bench levels and forming arched walls. The excavation was completed with an invert arch. The cavern is supported with rock bolting, heavy steel arches and shotcrete.

The excavation-support installation sequence for the top heading consisted of the following:

- excavation of a central heading with pre-support of the face with 12 m long fibre-glass dowels, on a 1.5 x 1.5 m grid, installed with 6 m overlapping;
- immediate installation of 10 cm thick fibre-reinforced shotcrete and 4 m long Swellex bolts on a 2.0 x 1.5 m grid;
- subsequent installation of 8 m long R38 self-drilling rock bolts, 38 mm in diameter, in a staggered pattern on a 2.0 x 1.0 m grid;
- excavation of the lateral extension to the side headings in 2 to 4 m sections and installation of fibre-reinforced shotcrete and R38 bolts;
- installation at a 10 - 20 m distance from the advancing face of steel arches (HEB 240) at 1 m spacing and steel shuttering filled with 45 cm thick concrete;
- anchoring the base of the arches to the rock mass with self-drilling R38 10 m long bolts.

With the top heading completed, benching down took place with 5 m long advances, with bench height varying between 2 m (first bench below the top heading) and 4 m (the remaining benches). For each bench the work proceeded by excavating first a central heading followed by slashing to the sides (left and right), until the full bench was excavated to the top of the following bench.

The support system of the sidewalls for each bench consisted of 15 cm thick fibre-reinforced shotcrete and radial bolting by using again self-drilling R38 bolts of various lengths (10 m first bench, 8 m elsewhere), with a variable grid varying between 1 bolt per 2 m$^2$ and 1 bolt per 3 m$^2$. Then, the steel arches (HEB 240) were installed systematically with 1.0 m spacing.


Fig. 7. Cross section of the the Assembly Cavern with photographs illustrating the excavation and construction stages in sequence 1, 2, 3 and 4.

It is worth mentioning here that the excavation of the top heading was slowed down due to a cave-in of approximately 200 $m^3$, which occurred on the right sidewall of the Assembly Cavern as shown in Figure 8. The reduced spacing of the discontinuities in the rock mass associated with unfavourable orientations in this area caused sandstone blocks to become unstable and fall down. This meant stopping the excavation, replacing the reinforcement measures installed and refilling with shotcrete.

Fig. 8. Local instability at the right sidewall during excavation oft he top heading.

The time duration for completing the cavern was overall nearly 3 months for the top heading (up to backfilling the arches) and 2 months for benching down excavation and support placement up to completion of the work.

## 4.4 Civil Work and Equipment Installation

This phase covered the completion of the cavern with the installation of drainage pipes and pipes for the supply network, and in-situ concrete casting**.** To save time during this phase, the reinforcing frames were prepared in advance, transported into the tunnel, and set up using cranes.

With the concreting completed, the next step was to install the gantry crane. All the engineering work, including setting up the gantry crane, took around 1 month. With the above in mind, 7 months of work in total were required to complete the Assembly Cavern.

As illustrated in Figure 9, the cutting head and shield were assembled, followed by the back-up trailers. The TBM could then be shifted to the face in order to finalise the assembly of the thrust frame and begin excavation.

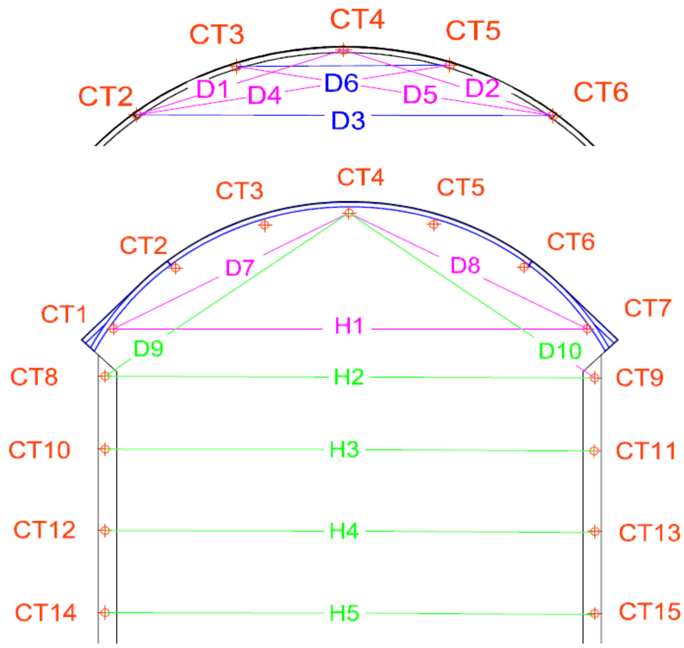
Fig. 9. The TBM head during assembling and lifting.

## 4.5 Performance Monitoring during Excavation

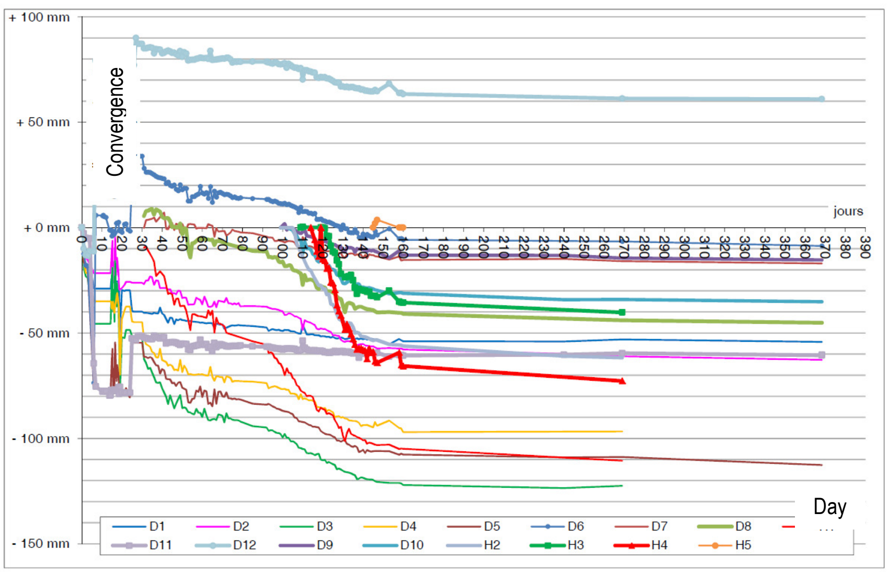
A monitoring system was installed in the cavern with the main purpose to observe the response during excavation and construction and to check if the predicted cavern performance was in line with the observed behavior. This system ws intended to monitor the displacements of the cavern contour and in the surrounding rock mass, and to infer the state of stress in the supporting structures during excavation and construction.

The monitoring system comprised targets for convergence measurement, installed on the excavation perimeter and in particular on the top heading arch. Strain meters and load cells were used to monitor the rock bolt loads as excavation proceeded. In addition, load cells monitored the load changes at the base of the top arch. Five point borehole extensometers, 12 and 24 m long, were installed to measure the ground displacements in the rock mass around the cavern.

During excavation, as shown in Figure 10, maximum convergences up to 40-50 mm occurred along the horizontal line $H_1$ at the base of the top heading. If the attention moves to the sidewalls convergences (lines $H_2$ to $H_5$ in Figure 10), values ranging from 70 and 100 mm are observed prior to concreting. Values up to 100-120 mm occur following excavation of the invert. It is noted that a maximum convergence up to 80 mm was monitored at the base of the arch in the cross section where the cave-in instability developed as previously described.




(a)




(b)

Fig. 10. Convergence monitoring system (a). Typical convergence history along selected lines, D1 to D9 and H1 to H5 (b)

It is of interest to compare the monitoring data and the observed performance pattern, during excavation and construction, with the results of the design analyses. It is noted that in general the most significant differences between the observed and computed stresses in the steel arches occur during the top heading excavation and reduce significantly during the benching down stages.

On the other end, the multipoint extensometers show that the zone around the cavern where deformations occur is in accordance with the computed extent of the plastic zone, i.e. 2-3 m at the crown and 1 m at the sidewalls, In fact, the maximum differential displacements up to 10-15 mm are observed between the points located in the vicinity of the cavern perimeter.

In all cases, it is worth noting that, as also shown by the convergence monitoring history (Figure 10), a stability conditon is obtained in a short time-interval, i.e. 10 to 15 days, from support installation.

## 5 Conclusions

Following a description of the main works forming the so called SMP4 Project, the attention of this article has been devoted to the excavation and construction of the Assembly Cavern. This large size opening was constructed at the end of the Saint Martin La Porte access adit in order to create a site where the TBM adopted for excavation of the Mon Cenis South Base Tunnel could be assembled.

It has been shown that the final location of the Assembly Cavern could be chosen with confidence, starting with the suite of geological, hydrogeological and geomechanical data collected during the first phase of the works carried out between 2003 and 201n. With the additional investigations performed, including the conventional excavation of a first length of the Base Tunnel, the sandstone  and shaly sandstone rock mass could be well characterised for design purposes.

A description of the geological and rock mass conditions has been given together with the excavation and support system finally adopted, with the first excavation of the top heading followed by benching down in stages. The design methods adopted have also been illustrated and the results obtained, in terms of the rock mass and rock support response during excavation and following construction, have also been reported.

Following the presentation of some of the representative performance monitoring data collected during excavation and construction of the Assembly Cavern, it has been shown that this rather challenging work could be completed successfully in order to allow for the TBM to start excavation of the South Tube of the Base Tunnels, which is now under execution.

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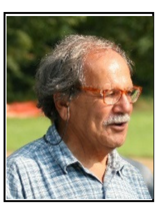

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