Measurement of Massif temperatures through the Maddalena Exploration Tunnel

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The New Lyon-Turin Line (NLTL) is an essential component of the“Mediterranean Corridor”, one of the nine European Union TEN-T network corridors, the future “European metropolitan railway” that will promote the movement of people and goods by rail, an ecological mode of transport.

The cross-border Section extends from Susa-Bussoleno (Italy) toSaint-Jean-de-Maurienne (France) ; it is the first operational stage of the new Lyon-Turin rail link. It comprises the Mont-Cenis Base Tunnel (57,5 km of length), two open-air sections of approximately 2.8 and 4 km across the Susa and Saint-Jean-de-Maurienne plains, an interconnection tunnel extending to the entrance of the station of Bussoleno. The tunnel consists of two parallel tubes connected by three cross passages per kilometer and contains four inclined access adits, three safety areas and two ventilation shafts. The entire system of tunnels extends for over 160 km, with an overburden more than 2,000 m in the central section. The two international stations in Susa (Italy) and in Saint-Jean-de-Maurienne (France) are located at the tunnel portals, in addition to technical areas and interconnections to the existing railway lines. The Base Tunnel is ranked among the most important and complex infrastructure projects currently under construction in the world.

While the works on the Maddalena exploratory tunnel are completed with the excavation of metamorphic rock of the Ambin Massif reaching a total length of 7 km, further excavation works are underway on a 9 km exploratory tunnel on the French side. Three other access tunnels have already been completed on the French side for a total length of 9 km. Prevailing lithology features mica-schists and minute gneiss, water is present in small quantities and rock temperature rises as rock cover increases. Whereas this applies starting from progressive ch. 4 100, conversely, in the previous tract where cover decreases, i.e. between ch.3+405 and ch. 4-055, temperature measurements increase instead of decreasing. What occurs in this range? Water temperatures are in equilibrium with rock temperature before and after, but rock temperature rises in this range and water temperature decreases.

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1. The Mont Cenis Base Tunnel

The cross-border section, from west to east, comprises the Saint-Jean-de-Maurienne open-air section, the 57.5 km long Mont Cenis Base Tunnel through the Western Alps, the open-air crossing of the Susa plain and an Interconnection Tunnel extending to the entrance to the station of Bussoleno. The Maddalena exploratory tunnel along with the four exploratory tunnels already completed and the exploratory tunnel in progress in France, make up the preliminary activities for works on the main tunnel [1] [2].

The Maddalena exploratory tunnel covers the sector between the Chiomonte area and the mid-high Val Clarea, mainly on the valley's left slopes. The entrance to the exploratory tunnel is located in the municipality of Chiomonte (Turin, Italy), at 670 m. a.s.l. Works on the tunnel, completed in February 2017, involved excavations reaching a length of 7020 meters with a diameter of 6.30 m.

After a 3500 m section the tunnel aligns with the axis of the two tubes of the future Base Tunnel in a higher position (see Figure 1).

Figure 1 - Alignment (in red) of the Maddalena exploratory tunnel.

The pre-set goals of the excavation of this tunnel, all of which achieved, were briefly:
- to increase understanding of the Ambin Massif at depth and with high overburden above the tunnel (more than 2000 m);
- to complete a mechanised excavation test (with an open main beam TBM);
- to provide an intermediate connection point for construction and operation of the Mont Cenis Base Tunnel.

Geological, hydrogeological and geomechanical surveys, investigations and tests both on-site and in laboratory were conducted throughout the excavation, along with geophysical, stress and deformation monitoring.

In specific terms this involved systematic measurements of rock temperature and of the physical parameters of the waters, and sampling of the major sources of seepage.

1.1 Excavation method

The initial section of the Maddalena exploratory tunnel, from the entrance up to ch.0+198 was excavated using conventional hydraulic hammer tunnelling. The rest of the Tunnel was excavated by mechanized method, using a Robbins main beam TBM (see Figure 2) with grippers, with the following specifications:

- cutting head diameter 6.30 m.;
- 43 17” diameter cutters;
- seven 315 kW motors;
- maximum thrust capacity 13,600 kN;
- power at head 2,205 kW;
- overall weight (including 16 back-up carriages) 350 t.

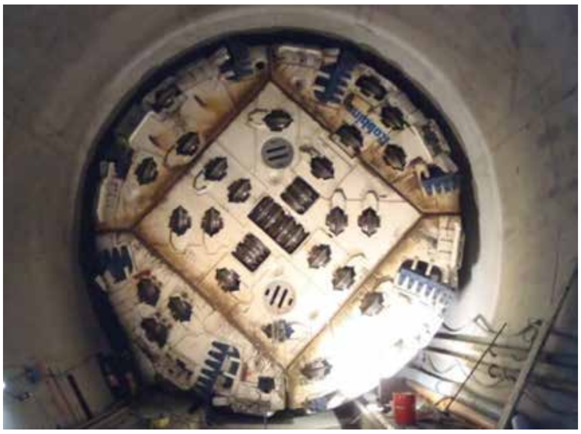

Figure 2 - Gea, the Maddalena exploratory tunnel TBM

Differently from the conventionally bored section, the final tunnel lining was not applied in the section excavated by TBM, and will be realised at a later date. The rock was therefore exposed and, where necessary, only temporary supports were installed. The structure and the general geomechanical, hydrogeological and geological conditions were reconstructed through systematic geological investigations made in advance on the Tunnel and the various observations and surveys conducted.

1.2 Geological summary

Most of the alignment of the Maddalena exploratory tunnel crosses the crystalline base of the Ambin Massif. More specifically, the lithotypes encountered are the aplitic gneiss of the Ambin Complex (AMC) and the grey mica schists and minute gneiss of the Clarea Complex (CL).

Only a limited portion near the entrance crosses quaternary deposits and the metasediments of Mesozoic cover [3].

In specific terms, the first 120 m of the conventionally excavated section passed through loose glacial (gi) and fluvio-glacial (fg) deposits. Then the excavation encountered a variety of lithotypes represented by carniole related to tectonic fault breccia (BCC), dolomitic marble, probably related to the GAD tectonic unit (DGA) and mica schist and calcareous schists, probably related to a Mesozoic cover of the Ambin (CMS) (Figure 3).

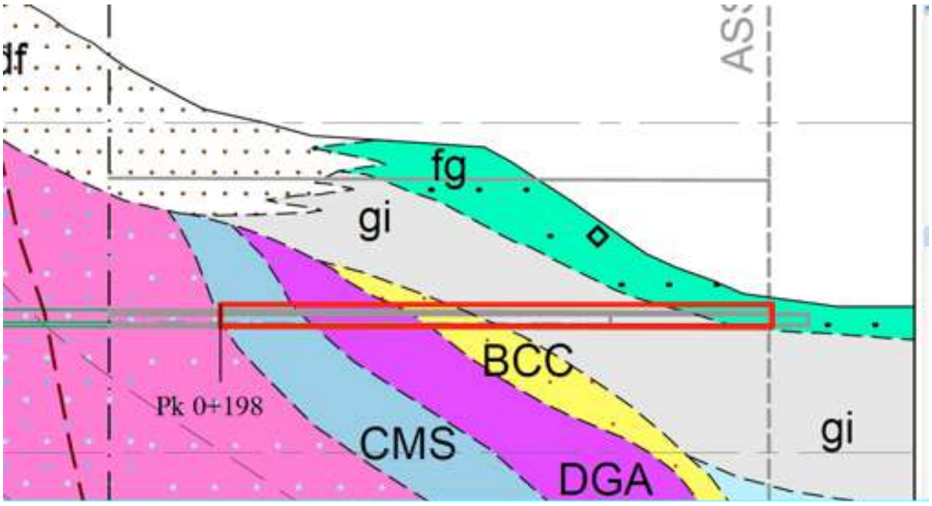

Figure 3 – Maddalena Tunnel geological profile as built (length excavated using conventional method in red).

The excavation of this sector was completed without encountering any particular geotechnical, geomechanical or hydrogeological problems.

As expected, the section excavated with TBM, between ch. 0+198 and 7+020, passed through the domed structure of the Ambin Massif, the rock forming the Ambin Complex over the outer section, and those forming the Clarea Complex over the central section (Figure 4).

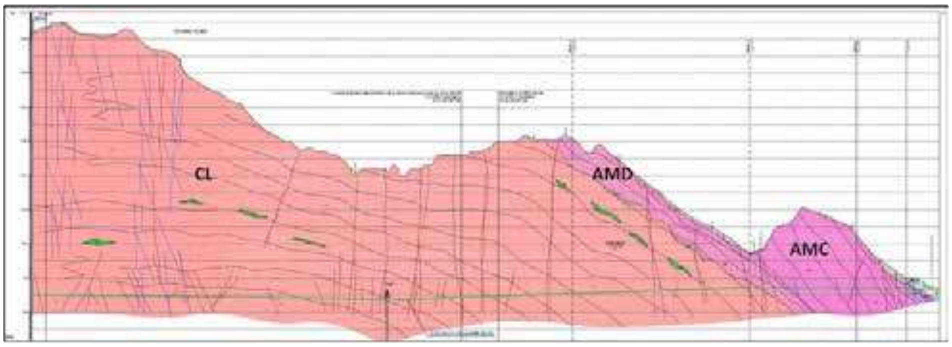

Figure 4 – Maddalena Tunnel geological profile as built (length excavated using TBM in green).

More specifically, the lithotypes encountered included aplitic gneiss of the Ambin Complex (AMC) (from ch. 0+198 to 1+148), then a transition zone (AMD) of albitic gneiss becoming grey mica schists and the minute gneiss of the Clarea Complex (CL) from ch. 1+350 up to the end of the tunnel at ch. 7+020.

Within the aplitic gneiss (AMC) of the Ambin Complex, in the band in contact with the overburden between ch.0+198 and 0+265, high concentrations of arsenic were encountered. The nature of this concentration is probably related to hydrothermal phenomena along the contact zone between the cover and the aplitic gneiss. The excavation material, less than 3000 cu. M., was deposited in specific dumps and treated as waste.

The contact between the transition Complex and the Ambin Complex is of a flexible tectonic nature, whereas the passage between the Ambin Complex and the Clarea Complex is characterised by intense fracturing.

On the structural aspects

In structural terms the excavation revealed substantial homogeneity. Within the Ambin Complex the schistosity has a steeper inclination while in the Clarea Complex it tends to incline at nearly horizontal angles. In terms of discontinuities (joints and fractures) an average of 5 - 6 families with a certain frequency, typically arranged NE-SW and NW-SE and in some cases N-S. The most pervasive families are nearly always set on pre-existing schistosity.

As in the case of joints, the fault systems also generally seem to be set on the pre-existing schistosity, especially in the Ambin Complex where they are oriented with an average orientation of 120/45.

In general, all the faults crossed are minor faults, with a maximum thickness of a decimeter (except for the tectonic structure of around a meter at ch. 1+150 at the contact between AMC and AMD). Generally, these structures seem to develop mostly with the presence of cataclasite and only marginally of clay.

On the geomechanical aspects

In geomechanical terms the tunnel section excavated by TBM encountered a rock mass varying between fair and good in quality. The quality of the rock actually encountered was certainly better than predicted (Figure 5) [4].

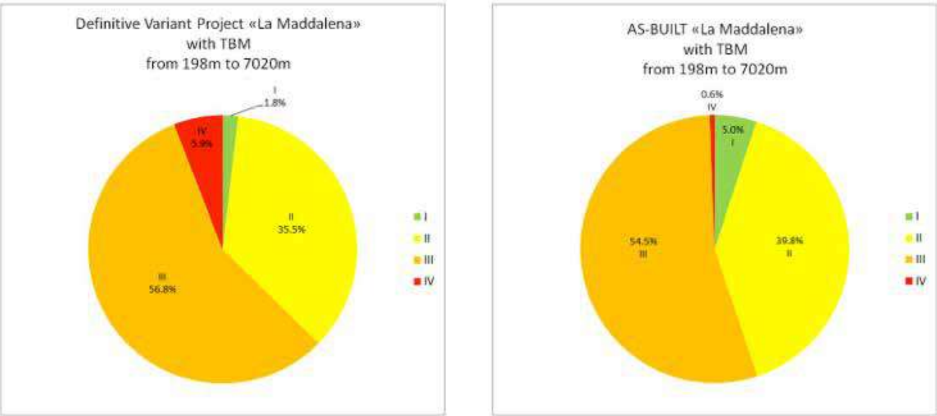

Figure 5 - Comparison between forecast rock quality and actual quality, RMR classes (Bieniawski, 1989).

Figure 6 gives details of the distribution of the Bieniawski RMR classes (1989) [5] along the various sections of the Tunnel. The higher RMR values are associated with the aplitic gneiss (AMC), characterised by a massive structure and high strength.

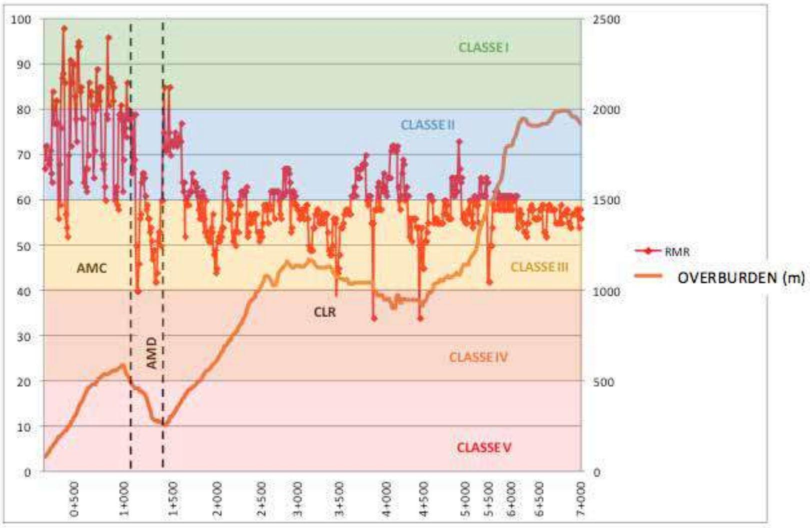

Figure 6 – Distribution of Bieniawski RMR classes (1989) along the section of tunnel excavated by TBM.

The minute gneiss and quartzitic mica schist (AMD), as well as the Clarea mica schists (CLR) shows a decrease in rock mass quality. The decrease in these two units is linked to the schistose and micaceous nature of the rock and a generally greater degree of fracturing of the rock with discontinuities often set along the foliation [6].

1.3 Hydrogeological summary

Hydrogeological parameters were recorded and monitored throughout excavation works on the Maddalena exploratory tunnel. The inflows drained from the massif crossed by the Maddalena Tunnel were monitored in two different ways:

a) daily measurement of total inflow rate at the portal (ingress to water treatment facility);

b) bi-monthly measurement of inflow rate along the tunnel; including measurement of temperature and conductivity, and chemical analysis of the some of the main inflows. Bi-monthly monitoring along specific sections increased understanding the stabilized flow-rates of the individual tunnel sectors and sections. Conductivity and temperature data are macro-indicators of the possible type of water and infiltration mechanism. Three types of chemical tests were conducted on the water samples taken along the tunnel:
   - full chemical analysis, major and minor anions and cations in accordance with italian Law 152/2006, ann. 5 Tab. 2);
   - analysis of potability for human consumption: in accordance with italian Law n. 31/2001;
   - isotopic analysis: O18 – deuterium.

The exploratory tunnel reached progressive ch. 7+020 on February 2017. In the end the total flow-rate recorded was 89 l/s. The intercepted inflows were mostly of a diffused, drip by drip nature, with localised increases and the rare occurrences of a few liters per second around the more fractured areas [7].

Figure 7 shows the progress of total flow-rate (at portal) during the course of works, the progress of which is indicated by the red line.

As we can see from the graph, the flow-rates show a variation, over time, characterised by abrupt increases and decreases, which reach the final value of 89 l/s. During the excavation, the measured flow-rate varied according to three factors, which acted together in the various portions of the tunnel:

1) increase in infiltration due to the advancing excavation;
2) increase in infiltration due to charging by rainwater infiltrating the sectors with lower overburden (near the entrance);
3) decrease in flow-rate due to stabilisation or depletion of contributions 1) and 2) as above.

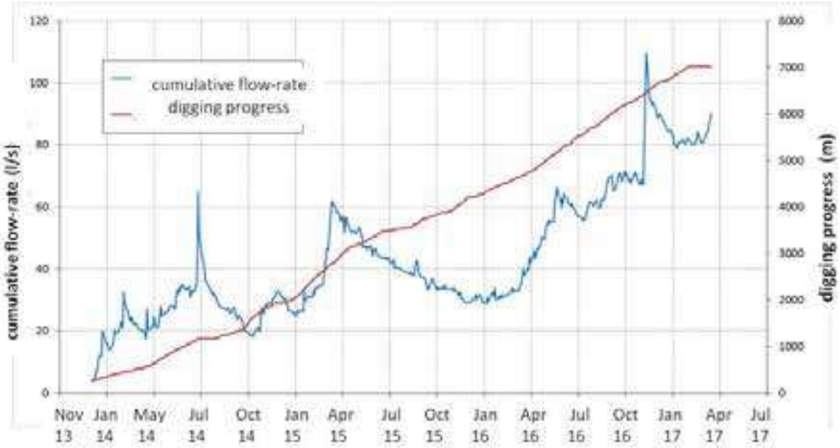

Figure 7 – Total recorded flow-rate at portal and progress of excavation

Data on the cumulative flow-rate, comprising the sum of the contributions monitored at two-monthly intervals in specific sections along the tunnel was of great use in understanding the hydrogeological behaviour of the various portions of tunnel.

2. Geothermal gradient monitoring

The geothermal gradient was monitored by measuring the temperature of the rock in bores (3 m long) made at the tunnel walls. Monitoring stations were established starting from chainage 0+435 every 50 m (mobile stations), up to ch. 7+000, with a permanent station every 500 m, for a total of 13 stations starting from chainage 535m.

In addition to temperature data of the rock mass, inflow water temperature data were also available from the bi-monthly recordings, as previously explained.
Putting the rock mass and inflow water temperature data on the same graph (Figure 8), we can see that:

- in general, the temperature of the rock and of the water share a similar increasing trend;
- the water temperature in the section where a positive rock temperature anomaly was encountered was, on the contrary, 4-5 °C lower, giving

rise to a negative water temperature anomaly;
- the water temperature encountered in tunnel can be considered in thermal balance with the rock one, apart from the section interested by the thermal anomaly.

The thermal anomaly of the water could be linked to a greater supply of fresh water coming directly from the surface (despite the high overburden) and not yet mixed with the deepest hot water.

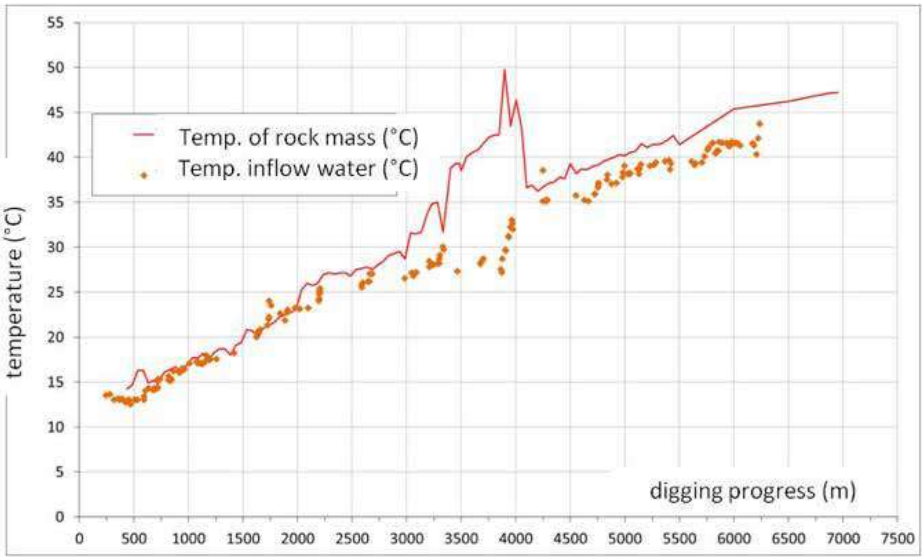

Figure 8 – Temperature of rock mass and inflow water along the tunnel (monitoring data December 2016)

From chainage 3+500 the conductivity values measured on the inflows encountered during works on the Maddalena exploratory tunnel showed a decreasing trend (Figure 9). Conductivity is an indicator of the ionic composition of the inflow water. Three distinct macro-sectors can be approximately distinguished from the ionic composition of the water:

- blue: portal - ch. 1+1100; conductivity constant and lower than 500 s/cm;
- orange: ch. 1+100 - 3+200; highly variable conductivity with peaks above 2000 s/cm;
- yellow: ch. 3+200 - 5+400; conductivity decreasing as works progress into the massif, toward values < 500 s/cm.

The geochemical data revealed a complex situation in the central portion of the tunnel, due to mixed conditions. Proceeding into the core of the Ambin Massif, the deep water circulation conditions revealed by the geochemical analysis, tend to become uniform.

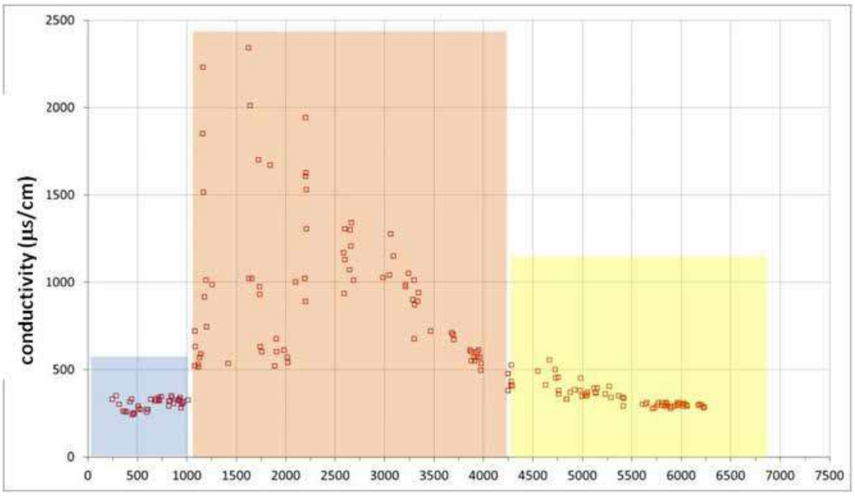

Figure 9 – Water conductivity values (bimonthly monitoring data). The different colours indicate the three macro-sectors

Analysis of the temperature data in relation to the overburden along the alignment of the tunnel (Figure 10) revealed:

- that the rock mass temperature increases at a regular rate and the temperature itself is not correlated, if not generally, with the variations in the overburden. In an overall view, the effect of overburden on the geothermal gradient is most influenced by the morphology in three dimensions;
- a positive thermal anomaly between ch. 3+400 and 4+050;
- with the exception of the section with the positive anomaly, the temperature in tunnel from chainage 4000, where the excavation of the section of the Maddalena exploratory tunnel becomes parallel to the two Base Tunnel tubes, confirmed the predictions, which expected values higher than 30°C with and maximums around 47°C , where rock mass temperature is correlated with more systematic variations in the overburden [8].

Figure 10 – Rock mass temperature according to overburden along the tunnel (data from mobile stations)

From chainage 2235, rock mass temperature began to rise above 30° with an increasing trend toward the completion of excavations at chainage 7+020, where temperatures reached 47°C, and air temperature likewise continued to increase. The following chapter describes the cooling system used in the tunnel.

3. Temperature abatement in tunnel

Tunnel ventilation was achieved using a simple injection system (air delivery), drawing fresh air from the outside and injecting it into the tunnel through a ventilation station installed at the portal on a dedicated steel structure, which pumped fresh air through a flexible duct to the excavation front (Figure 11).

Ventilation for the section of tunnel excavated by TBM, from chainage 0+198 to 7+020 required the use of a 2000 mm diameter flexible duct (each section of which 100 m long). The 2000 mm diameter flexible duct was connected to the TBM through a 1800 mm rigid steel duct.

The ventilation station with two coaxially mounted 2x160 kW motors was capable of delivering sufficient pressure to compensate losses due to leakage and friction. The fans were controlled by the inverters the station was equipped with.

Figure 11 - Fan

In sizing the ventilation system, particular consideration was given to special needs in the hypothetical event of encountering Radon gas.

The TBD was equipped with a dust extraction and abatement system in the back-up carriages, consisting of fans and filters. The air sucked in from the cutting head passed through the system and expelled behind the back-up after removal of all suspended dust.

Ventilation of the niches was achieved again through a simple injection system (air delivery), drawing air directly from the main tunnel ventilation duct and injecting it, into the niches, through branch ducts with adjustment shutters.

The system adopted was based on the need to achieve an acceptable ventilation air temperature at the TBM head for excavation works in the tunnel. It was decided to cool only part of the total ventilation air, and site experience demonstrated that cooling around 50% of the incoming air was sufficient to ensure acceptable conditions in the tunnel. Cooled air making up 50% of the total air (22 m3/s) was delivered into the tunnel by the fan. Further cooling was ensured by batteries of finned heat exchangers, which complied with working standards that consider the air flow rate over the surface of the battery and air speed across the battery in relation to available cooling surface. The system used cooled water rather than gas to cool the air, which made it extremely flexible and simple to install and operate. The system comprised two sections: one external, the other internal.

External Section – Tunnel air treatment upstream of fan. The external section comprised a battery of finned heat exchangers with filters connected to an external air condensing chiller unit. Complete with air temperature controls. The air condensing chiller unit is located near the battery, on a metal structure adjacent to the steel structure supporting the fan.

Internal Section – Tunnel air treatment in tunnel. The internal section comprised a battery of finned heat exchangers, in casings, installed at the start of the final section of ventilation duct near to the TBM head, installed in the upper part of the Deck. The internal battery was connected to an air condensing chiller unit installed on the Deck.

The sizing of the entire system was calculated on the basis of the following design data:

- Air flow rate at tunnel entry;
- Air temperature at tunnel entry (maximum value, at external ambient temperature);
- Relative humidity (maximum value);
- Thermal load to remove;
- Required air temperature at TBM head;
- Air delivery flow rate in tunnel

4. Conclusions

The excavation of the Maddalena exploratory tunnel provided a great deal of information on the characteristics of the Massif to be crossed by the Mont Cenis base tunnel, and consequently increased our knowledge of it. The direct data were used to assess the geological reference model and to adjust the design estimates of, for example, the temperature of the massif and the inflow infiltration in tunnel. With regard to the temperature in the Ambin Massif where the Mont Cenis Base Tunnel will pass through, the data collected during excavation of the Maddalena exploratory tunnel section parallel to the two Base Tunnel tubes (between chainages 51+500 and 48+500 , corresponding to the section between chainages 4+100 and 7+020 of the Maddalena tunnel) revealed temperatures increasing from 36.1°C to 47.2°C. These values confirmed the predictions, which expected values higher than 30°C with maximums around 47°C at chainage 48+000. The positive thermal anomaly recorded between chainages 3+400 and 4+050, which cannot be explained by the arrival of hot water from the Massif, given that only minor inflows were encountered over this sector with temperatures lower than the general trend, is still to be clarified. The use of a mathematical model to take in due account the three-dimensional morphology of the slope, with input data derived from the measurement along the 7 kilometers Maddalena exploratory Tunnel, could serve as a reference model for excavation of the main tunnel. At this point we can only await confirmation from the data produced by the excavations on the Base Tunnel.

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