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The Mont Cenis Base Tunnel

The New Lyon-Turin Line (NLTL) is an essential component of the "Mediterranean Corridor", one of the nine TEN-T networks Corridors, the future "European metropolitan railway" that will promote the movement of people and goods using an ecological mode of transport, the train. The goal is to reduce road transport, which increases pollution and greenhouse gas emissions. The core element of the new line is the 57.5 km Mont Cenis Base Tunnel. The reference geological model is based on the data obtained during the excavation of the inclined access adits at Saint-Martin-La-Porte, La Praz and Modane, including the La Madallena exploratory tunnel. With the planned investigations completed, all the collected data will allow a technical and economical optimization of the construction phase and operation & maintenance of the line. The impact on water resources is minimized by using a full-round waterproofing system up to a hydrostatic pressure of 10 bar. Expected residual water flows at the portals are exploited for both drinking water and heating purposes. With 12% of the tunnels already excavated, there are currently 800 people working on the NLTL. This unique project, with its extraordinary history and innovative features, has been proposed as the subject of an international case study.

Keywords: base tunnel, geological and hydrogeological conditions, geomechanical conditions, minimal impact, innovation

1. Introduction

This paper gives a general description of the "Mont Cenis Base Tunnel" with an overview of the geological, hydrogeological, and geomechanical problems as known and investigated so far. In doing so, the present status of the works and future expected developments are also highlighted.

The New Lyon-Turin Line (NLTL in French) shown in Figure 1 is a mixed freight and passenger railway infrastructure, designed according to European standards, from Settimo Torinese in Italy (interconnection with the Turin - Milan railway line) to Lyon in France and, at regional level, it joins Piedmont and Susa Valley in Italy to the Maurienne Valley in France.

The infrastructure extends for 270 km with 70% (about 189 km) in France and 30% (about 81 km) in Italy. The base tunnel with a length of 57.5 km is 77% in France and 23% in Italy. The entire project affects 112 municipalities between Turin and Lyon. The figures of such a project focus on the relevant territories that represent a human and natural heritage to be preserved. The project is of unquestionable supranational importance as a crucial section of the Mediterranean Corridor, the main East-West transport corridor of the "Core Network Europe", serving 18% of the population and

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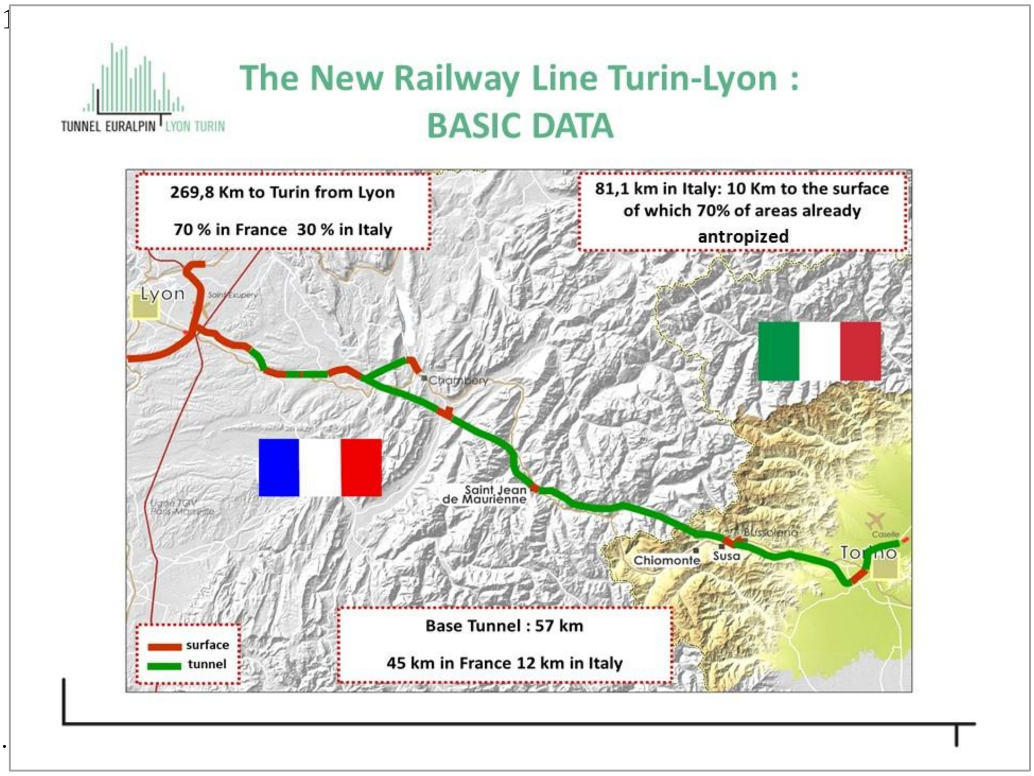

Fig. 1. The route of the New Lyon-Turin Line

TELT is the public promoter of the "cross-border section" shown in Figure 2, which is

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[1] European Commission. Core Network Mediterranean Corridor Study - Final report, December 2014

the first functional phase of the NLTL. This section is a priority as it allows for the crossing of the Alpine barrier substantially modifying the characteristics of the route, from being a mountain route to a flat rail route. Indeed, the main work of the cross-border section is the Mont Cenis Base Tunnel (a 57.5 km tunnel, with a slope of less than 0.12%).

The tunnel consists of two parallel tubes connected by three bypasses per kilometer and is equipped with four inclined access adits, railway service areas and ventilation shafts. The entire system of tunnels extends for over 160 km, with an overburden greater than 2,000 m in some sections. 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 their respective existing rail lines. The work is ranked among the most important and complex infrastructures currently under construction in the world.

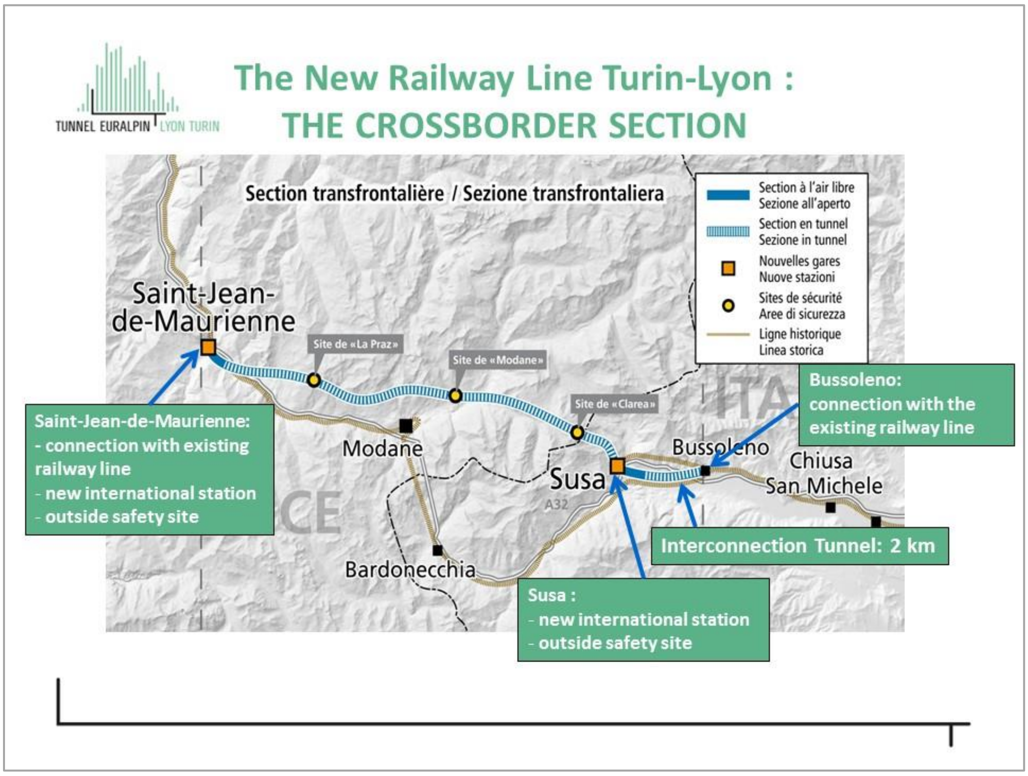

Fig. 2. The Cross-Border section

2. Description of the section and main geological, hydrogeological and geomechanical conditions

2.1 Tunnel characteristics

The tunnel is designed for a nominal speed (route speed) of 250 km/h and an operating speed of 220 km/h. The maximum longitudinal slope is 12.5 ‰, which is reduced in the station areas to a maximum of 2 ‰, with the length of passing or relief tracks of at least 750 m. The axial load is 25 tons/axle, the electric drive system is about 2x25 kV. The signaling and control system is the ERTMS/ETCS (European Rail Traffic Management System / European Train Control System) Level 2 system, coupled with a GSM-R radio communication system. The line provides for the transit of the Alpine rolling motorway shuttles (*AFA - Autoroute ferroviaire alpine*) and the "Modalohr" railroad cars.

The two single-track tunnels (Fig. 3) have a variable distance between 30 and 80 m, a usable internal diameter of 8.70 m, and a diameter of 8.40 m. Every 333 m, a connection branch, with a usable opening of 4.30 m width and 2.93 m height connects the evacuation sidewalks of the two rail tubes. Some of these branches, usually one every three, are fitted internally with technical rooms for the operation of the technological systems. Passenger shelter space amounts to 120 m^2. The tunnel will be excavated, depending on the expected geomechanical conditions, by using either conventional or mechanized methods with a TBM (Tunnel Boring Machine).

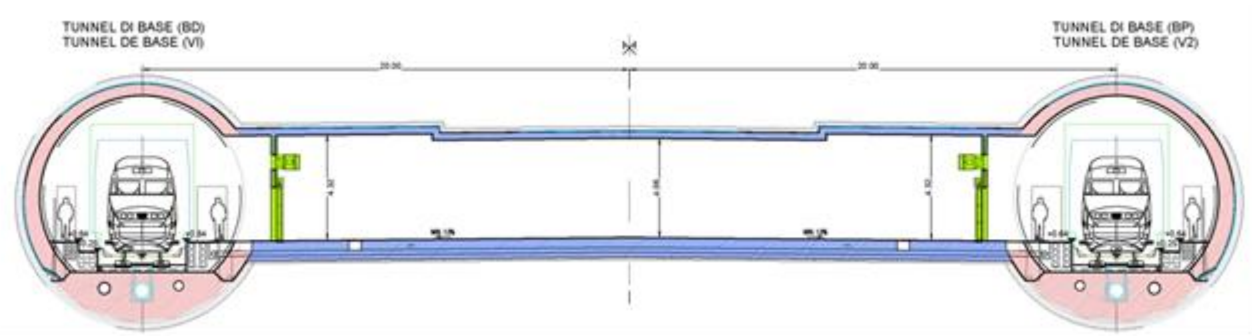

Fig. 3. Typical cross section of the two tunnels

The base tunnel has three underground safety sites, directly connected to the road level by the access adits of La Praz, Villarodin-Bourget / Modane and La Maddalena. These sites are to be halt points for any train in difficulty. Indeed, in these areas, a third tunnel is to be excavated between the two main ones and it can be used as a room to shelter passengers in the event of a train evacuation. With a length of about 400 m (length of a passenger train), this room is connected to the railway tunnels with branch inlet at a distance of 50 m.

In addition, along a 750 m length, which is also the length of a freight train, the railway tunnels are equipped with emergency firefighting installations. More specifically, the system provides a thermo-sensitive cable, a fire mitigation system with water vaporization, and a smoke extraction system. Outdoor security areas are also planned at both ends of the cross-border section in Saint Jean de Maurienne and Susa.

2.2 A summary of the geological, hydrogeological and geomechanical conditions

The base tunnel will encounter different ground conditions along its alignment including loose granular soils (alluvial deposits, glacial deposits), complex rock mass formations (arenaceous shale, coal-rich shale), evolutionary ground (anhydrites), high strength (mica schist and gneiss) or abrasive rock masses (quartzite).

Through the axial part of the Alpine chain, from West to East, the following different Geological Complexes are encountered: (1) Conoid at St. Julien Mt. Denis. (2) Ultra Dauphinois Area (Flysch du Cheval Noir). (3) Sub-Briançonnais Area (Massif de la Croix de Tete). (4) Sub-Briançonnais Houiller Area. (5) Internal Briançonnais Zone (Massif de la Vanoise). (6) Falda dei Gessi (*Chalk*) Zone. (7) Inner Briançonnais Area (Ambin Massif, Clarea and Ambin Complex). (8) Tectonic Ridge Area. (9) Quaternary deposits of the Cenischia valley. (10) Piedmontese Area (units of Puys-Venaus and Lower Susa Valley-Valli di Lanzo-Mt. Orsiera).

A reference geological and geomechanical model was developed to identify the most suitable methods to be adopted for excavation, the main geological risks, and the mitigation and management measures. Attention was devoted to geological critical conditions such as fault and severely fractured zones, high temperatures anomalies, presence of swelling or soluble minerals, etc. Critical geomechanical problems during excavation and construction were also investigated such as expected large convergences in squeezing rock conditions, subsidence, spalling and rock-bursting, and seismic action.

Hydrological investigations were carried out in order to assess the expected interference with aquifers such as water ingress into the tunnel and possible impacts on water resources, surface streams and rivers. Further considerations was given to the geomorphological conditions at the tunnels portals and the assessment of natural risks, i.e. slope dynamics, fluvial dynamics, and avalanche dynamics.

2.2 Specific issues - interfacing groundwater systems

Regarding the groundwater systems, the interface between the tunnel and the natural resources was investigated. Based on hydrogeological characterization studies, the different expected lithologies along the tunnel alignment were subdivided into hydrogeological complexes, each one characterized by homogeneous hydrological behavior, in other words by a single type of permeability (primary or secondary) maintained within a fairly narrow range of variation.

The degree of permeability was assigned to the rock masses as a function of fracture intensity in both standard fracturing conditions and in particular conditions. In other words, along the fault zones and the zones of intense fracturing, the construction method adopted was intended to be capable of avoiding water inflow into the tunnel.

Except for the first 350-400 m on the Susa side, the base tunnel is to be excavated with a slurry shield TBM, capable of creating a backpressure at the face greater than the groundwater hydrostatic pressure, in order to prevent water ingress into the tunnel. Immediately behind the TBM shield, gaskets are to be adopted with the segmental lining to make it waterproof around the entire perimeter of the tunnel, when the water pressure is lower than 10 bar. This is the case of the full first 6 km length of the base tunnel on the Italian side.

Where conventional excavation is adopted (e.g. inlet on the Susa side, connections between the tunnels, excavation of safety areas, some tunnel sections on the French side), continuous systematic sampling will precede this in order to detect, prior to excavation, the possible presence of water circulation. In this case, waterproofing injections are foreseen in order to minimize temporary interference. An all-round waterproofing membrane along the tunnel perimeter is to be installed as close as possible to the advancing tunnel face.

Possible exploitation scenarios of the geothermal potential were evaluated for the waters found in the tunnel along the non-waterproofed section. The water flow rates at the portals for both drinking water and water to be used as a thermal resource were assessed. The water temperatures on the Italian side are between 29 and 31° C and may reach 36 ° C. The waters on the French side are slightly “cooler”. It should be noted that in any event, if they are used, there will be little or no need for cooling, prior to re-entry into natural receptors.

The experience gained during the excavation of the three access adits on the French side as well as of the exploratory tunnel on the Italian side, provided measurements of the actual drained water, which resulted to be lower than expected. The experience gained during the investigations performed has been useful, on the one hand, for the realignment of the "Projet de Référence Final", and on the other end to detect the actual impact of the excavation on the water resources, which has so far proven to be low.

3. Work progress

A summary of the state of works is shown in Fig. 4. The cross-border section of the Lyon-Turin Base Tunnel is under construction. 12% of all the tunnels have been excavated and 20% is under contract. To investigate the rock mass conditions along the tunnel alignment, a total of 65 km of surveys were carried out, including 16 km of exploratory shafts or access adits, and 260 km of geophysical surveys.

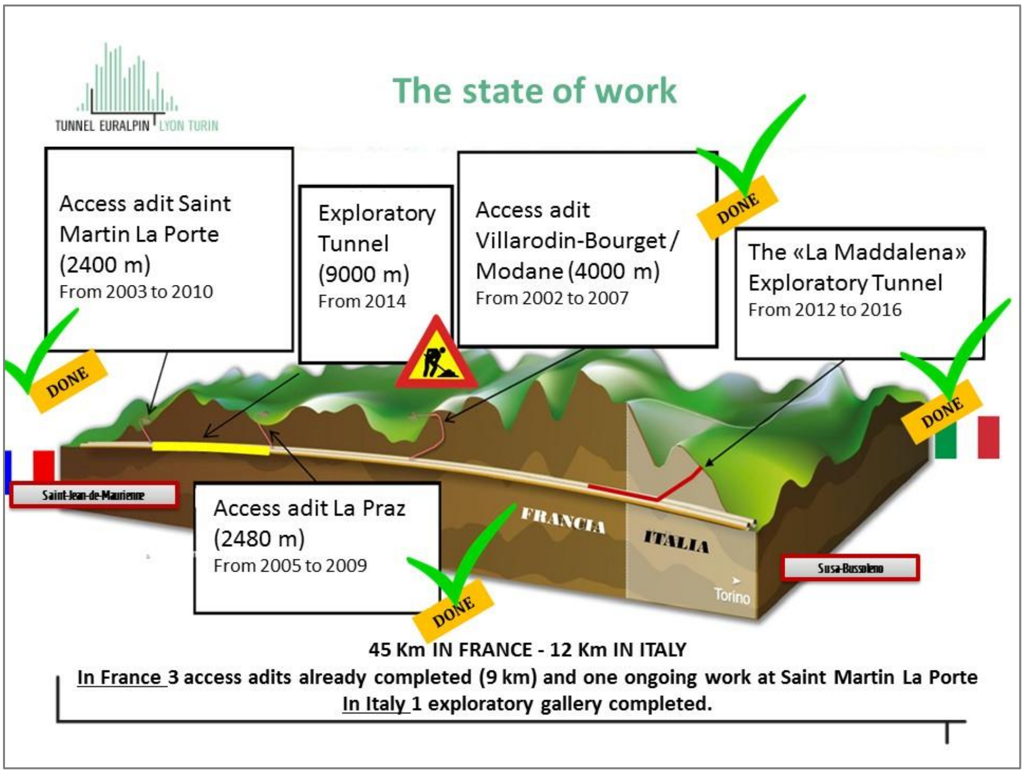

Fig. 4. Completed works and work in progress

The four access adits and the complementary works are listed below, from West to East:

- Saint-Martin-La-Porte access adit, in France, 2400 m length (completed).
- La Praz access adit, in France, 2480 m length (completed).
- Villarodin-Bourget / Modane access adit, in France, 4000 m length (completed).
- Ventilation shafts at Avrieux, in France, 500 m length (completed).
- La Maddalena Exploratory tunnel and ventilation gallery, in Italy, 7000 m length (completed).

3.1 La Maddalena exploratory tunnel

The entrance of the exploratory tunnel (Fig. 5) is located in La Maddalena, in the municipality of Chiomonte (Turin) at an altitude of 670 m above sea level. The tunnel is about 7 km long, with a diameter of 6.30 m and a variable slope along its length. The first 1,500 m are uphill; the lowest point is at 4,100 m chainage.

Starting from the 3,500 m chainage, the tunnel is located between the two tubes of the future base tunnel. Excavation works started in the late 2012 and the first 200 m were completed using conventional methods. The work then continued in the early 2013 with a Tunnel Boring Machine. During excavation geological, hydrological and geomechanical investigations were carried out, including borehole drilling, in situ and laboratory tests, geophysical investigations, stress and deformation monitoring with the main aim of investigating the Ambin Massif under a maximum cover greater than 2000 m of the Mont Cenis Base Tunnel.

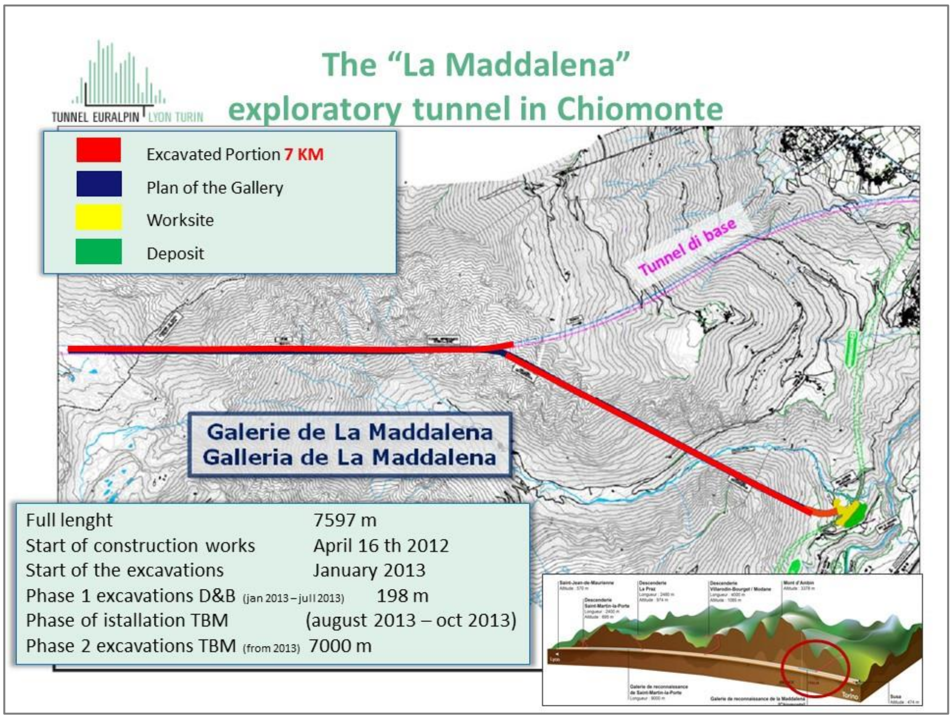

Fig. 5. The "La Maddalena" exploratory tunnel

At the end of February 2017, a total 7 km length of the exploratory tunnel was completed, thus achieving the following three main objectives:

- Investigation of the Ambin Massif.
- Use of mechanized excavation (the three tunnels on the French side were completed with conventional methods).
- Excavation under the highest overburden expected (greater than 2,000 m).

Indeed, the tunnel was used to update and improve the design documents of the Base Tunnel, thus increasing the degree of reliability of the available data. With the excavation completed, the tunnel will be used during the construction of the base tunnel and will be finished and furnished with all the necessary equipment for ventilation and safety functions of the tunnel itself when it will become operational in 2029.

The Chiomonte work site has a history that is in many ways unique and worth of mention. It was initially planned with the portal in Venaus, and the Promoter had to deal with tough opposition to the works, culminating in the 2005 clashes. The determination of both States to continue the work triggered a democratic process that led to setting up extraordinary entitities for discussion purposes: the Political Table of Palazzo Chigi (Italian Prime Minister's office) and the Technical Observatory.

After a complete redesign of the project and after moving the exploratory tunnel portal from Venaus to Chiomonte, the works started in a very difficult scenario. Hundreds of assaults on the site occurred between 2011 and 2016, wounded policemen, sabotage actions against the contractors engaged in the construction site, acts of violence against workers and their common areas, acts of sabotage against trains on the existing line. Subsequently, in some cases, this led to significant criminal convictions.

Since 2012, the Chiomonte site is a "strategic site of national interest" and site workers are flanked by police forces. Despite these objective difficulties, the site has nevertheless proved to be an opportunity for the territory with almost 200 people having found employment: 42% of them from Susa Valley and 14% from the rest of Piedmont (44% from Italy or abroad). Of the 460 companies involved, 211 (43,23 %) are from the Province of Turin and 67 (13.06%) from the Susa Valley.

"External" (as impact receptors perceive them) and internal environmental monitoring are among the most significant activities, and are meant to control both the work in progress and environmental quality for the workers. Under the control of ARPA (Regional Agency for Environmental Protection) more than 135 parameters were monitored, with a real-time update system. Furthermore, evaluation activity was launched with a panel of experts from the Department of Science of Public Health and Pediatrics of the University of Turin, to assess the site's impact on public health (VIS *in Italian*). It has produced excellent results for the current construction site that will also be used for the final works.

Construction work at the Chiomonte site is also a center of attraction for technicians and civil engineers, geologists, students and citizens willing to see the works, and the Tunnel Boring Machine, close up: from 2014 to the present day more than two thousand people visited the site. Recently, in October 2016, Tunnel Art Work was also inaugurated (Figure 6): Italian and French street-artists turned the tunnel into an art gallery at chainage 2,800 m, in the very heart of the mountain. The story of the La Maddalena work site is just beginning. This is the location where the main excavation work on the Italian side will start.

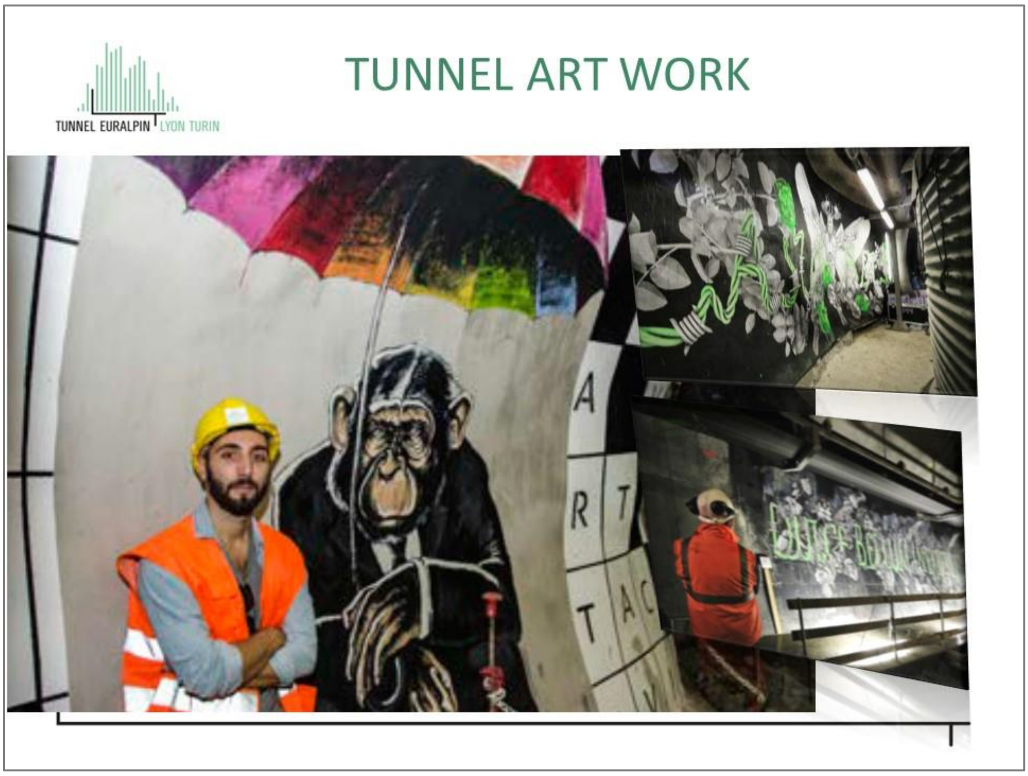

Fig. 6. Some of the artwork created in the Maddalena exploratory tunnel

3.2 Investigation works at the Saint-Martin-La-Porte SMP4 site

The excavation of the Saint-Martin-la-Porte access adit, between 2006 and 2010, resulted to be particularly difficult through the Carboniferous Formation, “Zone Houillère Briançonnaise-Unité des Encombres“, where very large time dependent convergences were experienced, up to nearly 2 m in a number of tunnel sections.

In order to gain in the understanding of the tunnel response, detailed investigations were carried out including specialized laboratory tests, detailed performance monitoring during excavation, modelling studies, etc. This resulted in the adoption of a novel design concept with the systematic use of full-face excavation and reinforcement coupled with a yield-control support system by using a near circular cross section.

From the early 2015 to the present (see Figure 7 for an overall view of the Saint-Martin-la-Porte site), a new inclined access adit (Part 3a) and a part of the South-Tube of the Base Tunnel through the so-called productive coalfield (Part 3b) was excavated by conventional methods in order to reach the future base tunnel alignment. Also, one assembly room (Part 1) and dismantling room (Part 4) were completed to allow for assembling the Tunnel Boring Machine (“Federica”) which has recently started excavation along the base tunnel alignment and is to reach after a total length of 9 km the La Praz site (Part 2).

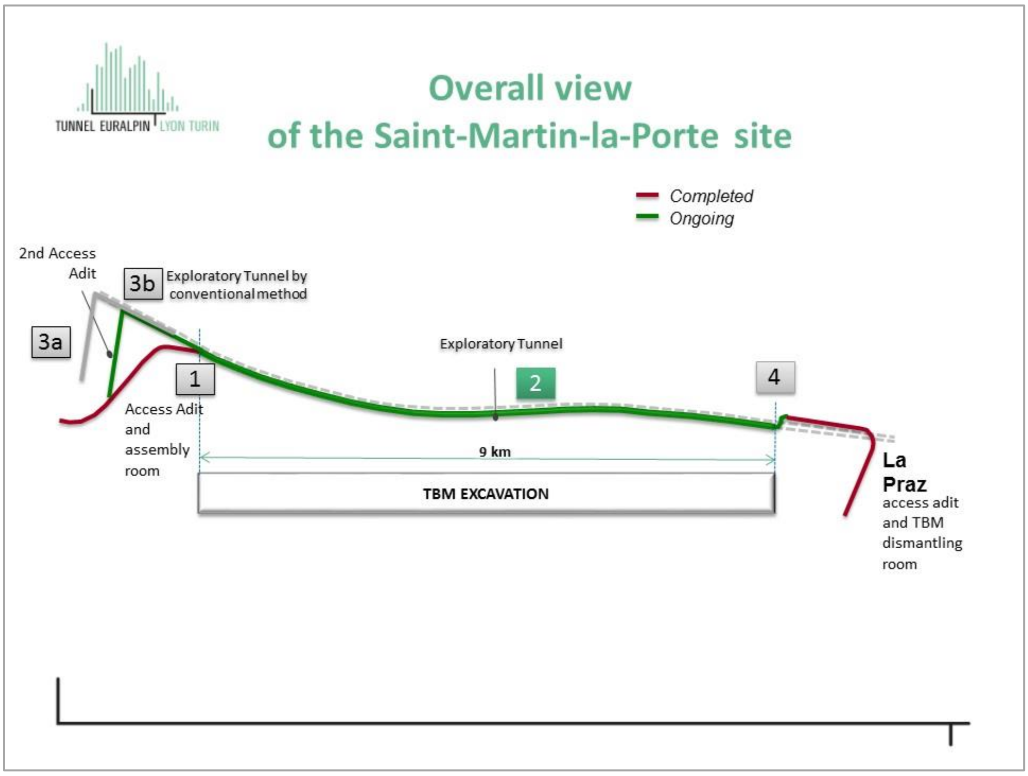

Fig. 7. Saint-Martin-La-Porte site

In Saint-Martin-La-Porte SMP4 site, just as in Chiomonte, investigative studies are continuing, by also paying the greatest attention to the environment and monitoring of the surface and groundwater environment (according to the French prescriptive protocol "Loi sur l'eau"). As far as noise and vibrations, and airborne dust levels, all values recorded so far appear to be within the norms.

Protective measures were also taken for the flora and fauna, including the identification and the subsequent avoidance of areas of ecological importance, the adaptation of the planning of the works to avoid consequences for the fauna in sensitive periods (e.g. hibernation), the reporting and the deviation of the route in areas with protected plant species.

In a former sawmill in Saint-Martin-La-Porte, the factory that produces pre-cast segments has been operational since 2016. Located just 3 km from the site, it can provide the segments required for the tunnel without affecting significantly on local road traffic and it employs about 70 workers. The total employment budget of the SMP4 construction site to date includes over 400 people, with local labor percentages very similar to those of Chiomonte.

3.3 Expected work progress from 2017 to 2019

In early 2017, the ratification process of the 2015 Agreement between France and Italy for the start-up of the final works was finalized. The main public tenders will be announced between 2017 and 2018. The implementation schedule complies with the agreements between the States and the INEA *(Innovation and Networks Executive Agency)* dated December 2015. The Grant Agreement (Figure 8) provides for a set of works for € 1.9 billion to be achieved by 2019, 40% of it being financed by the European Union (roughly 813 million Euro). This means that by 2019 the works needs to have achieved 22% progress on a certified total cost of 8.6 billion and on an operation start-up, time horizon set for 2029.

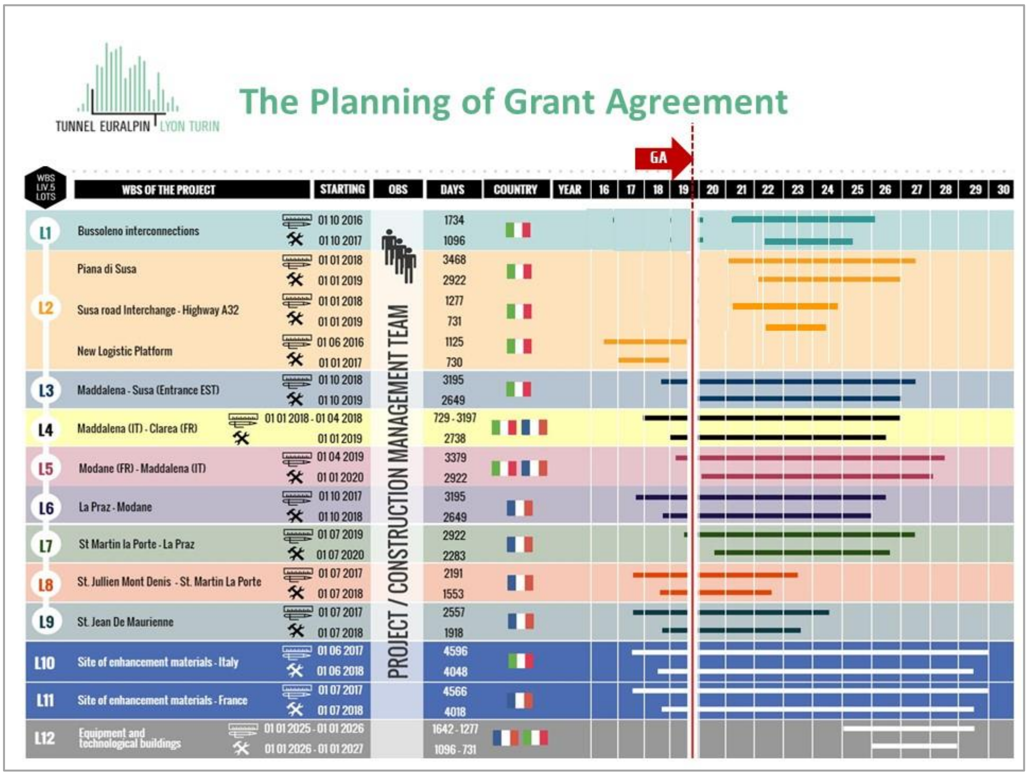

Fig. 8. Planning of NLTL according to the Grant Agreement

Some of the major engineering public tenders are already under way: the 110 M € call for the Construction Management of all the French underground lots was published in late 2016. It will be soon followed by a similar call for the Italian side. During the current year and the first months of 2018 the Promoter plans to initiate a set of works with a financial commitment of over half a billion Euro.

For the construction phase management, TELT has set a schedule based on Work Breakdown Structure (WBS), which is developed by identifying of sub-objectives and activities that are occasionally defined at an extremely detailed level. The aim of the WBS is to identify and implement, down to the last hierarchical level, work packages *(deliverables)* which are clearly manageable and assigned to a single manager, so that they can be programmed, scheduled, supplied with a budget, monitored and evaluated.

This approach is particularly suited to the characteristics of the cross-border section, which is characterized by a dozen cost allocation keys between the Italian State, the French State and the EU. This will depend on the type of asset (for example, the two main ones are 25-25-50 for investigation, 35-25-40 for the final works). A division into 12 geographical lots is anticipated (following the pattern of possible excavation fronts starting from the completed access adits and reconciling technical and territorial requirements). The need, at all times, is to be able to track the current value of completed works with respect to budgeted and certified costs.

In line with this methodology, the twelve geographical lots (Figure 9) are in turn broken down into several contracts, divided between work contracts (with varying amounts from 150 M € to 1.500 M €), consisting in part of engineering contracts (about 3-5% of the main contract) and service contracts.

The Promoter, operating under the control of the States and the EU, sees promoting competition as the right strategy to obtain the best possible offers. This is why an European Road Show will begin in the spring of 2017 (primarily in France and Italy) to illustrate all the legal, technical and economic issues required to participate in the tenders. The itinerant and widely participatory format of the Road Show will ensure face-to-face interaction with international companies and will encourage local SMEs to create pools for tender participation.

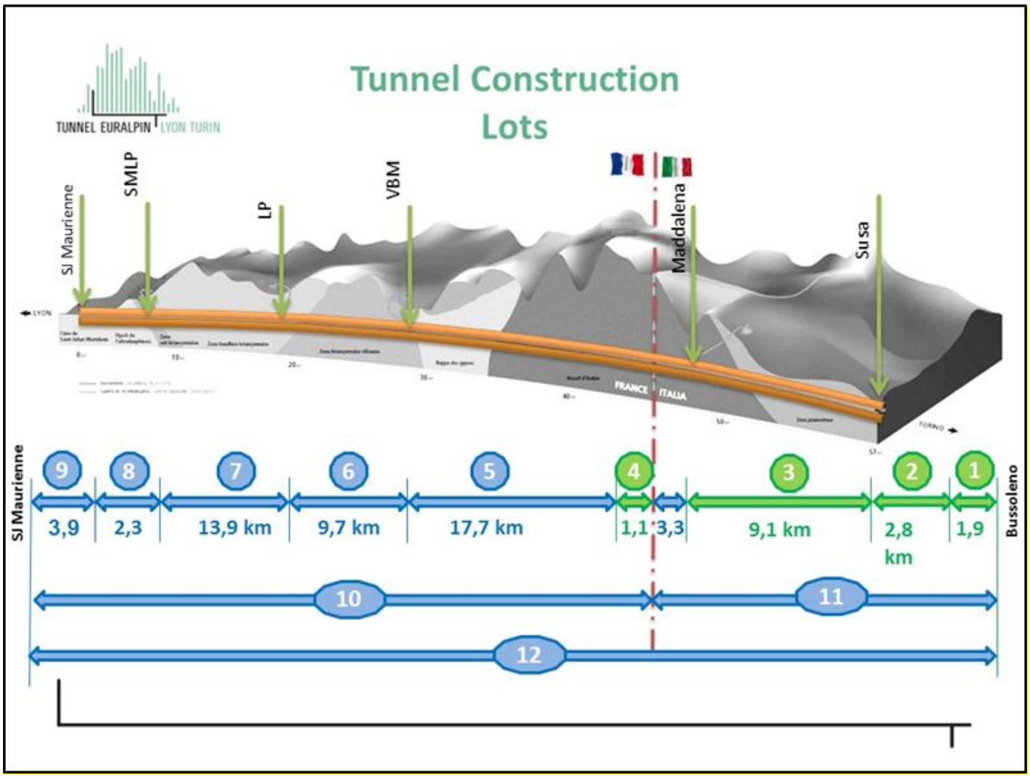

Fig. 9. The lots of the Mont Cenis Base Tunnel

3.4 The environment: a priority issue

The new priority corridors are the basis of the European Union development model that aims to achieve transport competitiveness and sustainability. The modal shift from road transport to the more environmentally friendly railway is mainly being obtained through last generation railway lines that are key to achieving the EU targets of revitalizing the economy and of reducing CO_2 emissions.

The NLTL is fully integrated into this framework and its cross-border section is a formidable lever to improve the environment, especially in a delicate environment such as the Alps. By transferring 55% of the volumes transported towards France to rail (today it is less than 9%), the Lyon-Turin Base Tunnel will achieve, once fully operational, an annual reduction of CO_2 emissions equal to the total production of carbon dioxide of a city of three hundred thousand inhabitants.

If the positive effects on the environment when the tunnel is in operation are quite obvious, the real challenge is to minimize impacts during the construction phase. The Promoter has set itself important goals for the coming years, and not only in environmental terms. In December 2015, TELT applied to join the Global Compact and was admitted as a Public Organization. This membership affects all implementation phases of the project. At the end of 2017 it will undergo a first test with the submission of the COE (Communication of Engagement), the biennial report in which a company must document all measures taken for the respect and the socialization of the United Nations objectives in terms of labor, environment and anti-corruption.

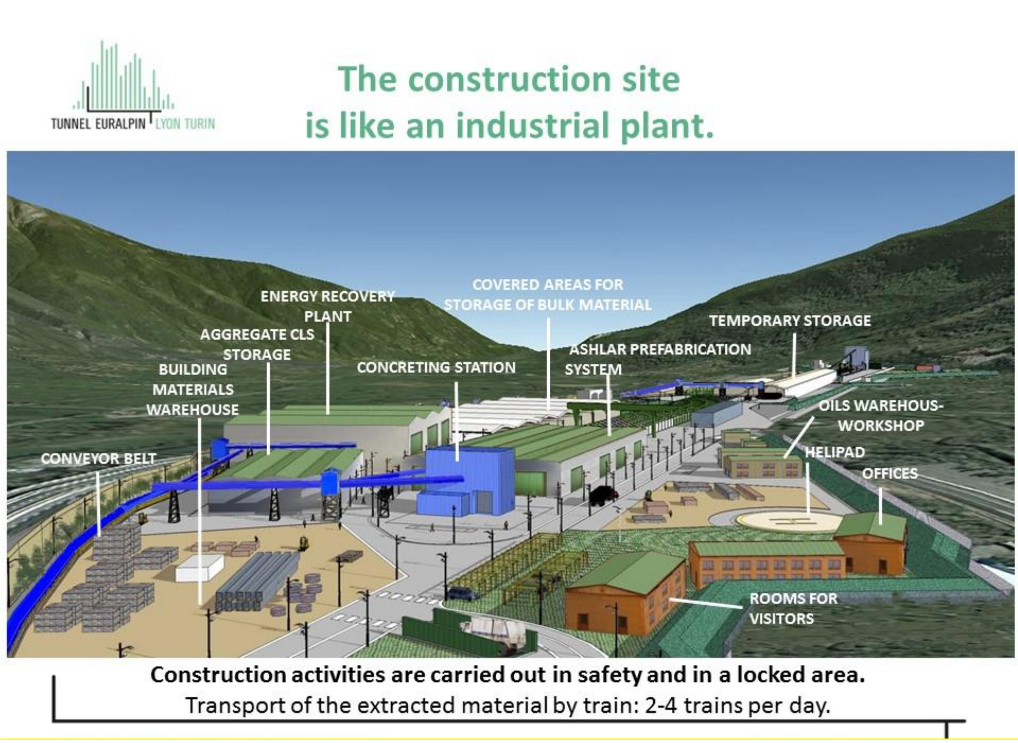

Fig. 10. The lots of the Mont Cenis Base Tunnel

Regarding the environment, as previously mentioned, the exploratory work sites have been very useful both in Italy and in France, to test a variety of mitigation actions, to set up monitoring plans and to establish virtuous mechanisms that develop efficient interfaces with supervisory bodies. The experience gained is thus converging into a series of guidelines for the implementation of the definitive works- These will become the TELT environmental policy. The key issues are the protection of natural assets and biodiversity, efficient use of resources, health and well-being of individuals, the enhancement of cultural heritage and the landscape, the pursuit of excellence.

3.4.1 The reuse of materials and the circular economy

Several important measures are already included in the final project and have been shared with the territory (particularly in Italy, where they have been debated within the Turin Lyon Observatory, chaired by the Government Commissioner). For instance, the layout of the industrial sites factors in the need to minimize any interaction between the works and the surrounding environment (natural and urban). In these sites, all the operations related to the base tunnel, such as excavation, transportation and storage, will take place in a closed and controlled environment. In the open air, covered and soundproofed conveyor belts will be used in most cases to link the industrial and the logistics sites.

The analysis of the quantity and quality of the material extracted from the excavated access adits, has shown it includes a considerable amount of high quality materials for reuse as construction materials: up to an estimated 65% to be reused within the works, 42% of which as fill material and 23% as aggregate for concrete. The remaining material produced, and not reused within the NLTL project, will be destined to permanent storage and used for the morphological re-modelling and re-naturalization of specific sites (e.g. old quarries).

3.4.2 Enhancement of the landscape, territory and culture

Although the cross-border section runs underground through a tunnel, the landscape is a key component of the NLTL project. The crucial nature of this concept, which was incorporated into the project from the preliminary design stage, leads the landscape to be defined as the key element of both the data used for the project's design's and of the overall outcome. This perspective is quite evident in the facilities serving the tunnel. Primarily the stations, but also the technical and security buildings and the ventilation centers that were all designed following high quality architectural criteria.

The Japanese Architect Kengo Kuma designed the Susa and the Saint-Jean-de-Maurienne International stations with the aim of creating new attractive venues to attract people at different times of the day, even when the station is closed, complementing conventional railway activities (both relating to NLTL and the Historical Line) with commercial activities (shops, bars and restaurants), cultural activities as well as sports, recreation and information facilities.

In Italy, the Maddalena ventilation center has been built in a traditionally winegrowing area, and its design reminds one of a wine cellar and, in line with this concept, the surrounding areas will be landscaped with vines planted in areas well-exposed to sunlight, and with apple trees in less sunny areas.

3.4.3 Integration through knowledge

Prior to full commissioning of the project, the sites themselves will be designed to be communication spots for visitors, with information stands, multimedia facilities and artists' contributions. The goal is to integrate the Lyon-Turin into its territory, so it engages with its surroundings and becomes a benefit feature for residents, from its earliest construction stages.

3.5 The key issue of Anti-corruption

Ever since 2012, an Anti-corruption Protocol has been implemented at the Italian site. It was signed by LTF (the Promoter that later became TELT), by the Prefecture and by the Unions. As of today, with the recently completed excavation of the La Maddalena exploratory Tunnel, the site has been subjected to 850 anti-mafia audits and 2 prohibitory disqualification audits. Results demonstrate the effectiveness of the control measure that are performed according to Italian law, but made even more stringent by a protocol that does not set threshold limits. The States have decided to extend this mechanism to the entire section for the definitive work, regardless of the nationality of the work sites.

The Lyon-Turin is thus the first case in Europe of anti-mafia legislation being applied transnationally. With the ratification of the 2015 Agreement, Regulations for cross-border section work contracts became law in both States. The provision applies to all companies that enter the supply chain, in whatsoever capacity, regardless of nationality. It also includes the accreditation of enterprises to a bi-national *White list* (12 months period of validity, renewable) as a pre-condition for participating in the works.

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