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The Frejus's Safety Tunnel: the Italian side

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ABSTRACT

The Frejus road tunnel is a toll tunnel linking France with Italy. It is located between the town of Modane in France and Bardonecchia in Italy and runs parallel to the Frejus railway tunnel. It constitutes one of the main Alpine crossings between France and Italy. In the early 2000's, following serious accidents that occurred in the Mont Blanc (1999) and Frejus (2005) tunnels, the construction of the Safety Tunnel parallel to the existing Frejus Tunnel has become a necessity in order to upgrade the infrastructure in line with legal obligations. The project involves the construction of a safety tunnel and passageways connected to the existing road tunnel along which new emergency shelters can be built; the safety tunnel will be used as a second carriageway, allowing separation of driving flows and thus significantly increasing the safety level. The paper provides a general project overview, a detailed description of the solutions adopted in the design stage and the description of the data derived during the construction process.

Key Words: TBM and Conventional Excavation Method, safety tunnel, passageways, pull through.

2. INTRODUCTION

The Frejus Motorway Tunnel connects Bardonecchia (Piedmont) with Modane (Savoie), and represents an important link between Italy and France, along the Turin-Lyon axis.

Construction of the 13 km long single tube tunnel started in 1974, and it came into service on 12 July 1980, as a bi-directional traffic motorway. It runs parallel to the Frejus railway tunnel and it constitutes one of the main Alpine crossings between France and Italy allowing, nowadays, the passage of about 5000 vehicles per day.

In the early 2000's, following serious accidents that occurred in the Mont Blanc (1999) and Frejus (2005) tunnels, an EU Directive, 54/2004/EC, was published regarding the minimum safety requirements for tunnels and Legislative Decree 2006/264 was issued to include the new prescriptions in the Italian Codes. The directive seeks to ensure that all tunnels longer than 500 metres, and forming part of the trans-European road network, comply with the new harmonised safety requirements covering organisational, structural, technical and operational aspects. The construction of the Safety Tunnel parallel to the existing Frejus Tunnel has therefore become a necessity in order to upgrade the infrastructure in line with the new legal obligations. The project involves the construction of a safety tunnel, at a distance of 50 m from the existing motorway tunnel, with a connection ensured by 34 pedestrian shelters and 9 vehicles cross-passages. The work will also include the construction of 8 technical stations and two ventilation plants. At present, the excavation of the safety tunnel has been completed, as well as the main shelters and technical stations; final arrangements and equipments are being performed. Once the works will be completed, the safety tunnel will be used as a second carriageway, allowing separation of driving flows and thus significantly increasing the safety level of the main tunnel.

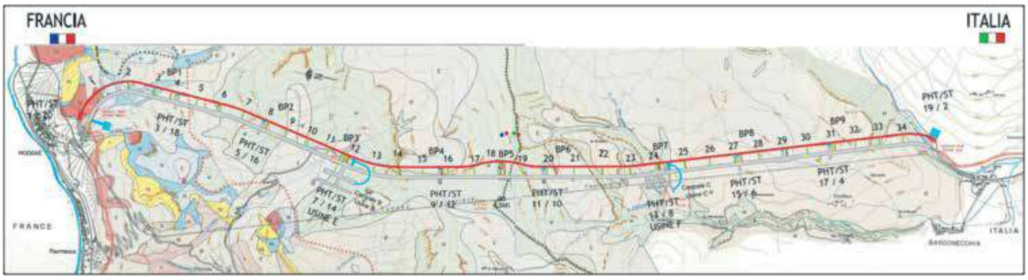

Figure 1. Schematic layout plan with route of the motorway tunnel and safety tunnel (in red)

With reference to the Italian section, the excavation is 6353 m long, 6287 m of which in mechanized excavation, using a TBM, and 66 m in conventional method. The Italian side includes the excavation of 16 pedestrian shelters, 5 vehicles cross-passages and 4 technical stations.

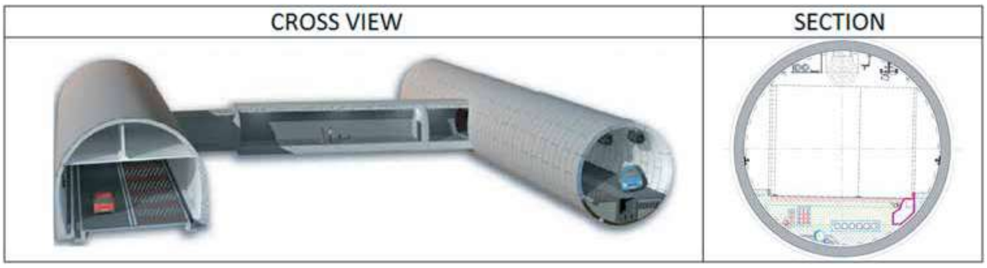

Figure 2. Cross view of the Frejus tunnels and section of the safety tunnel

3. GEOLOGICAL-GEOTECHNICAL OVERVIEW

The Frejus safety tunnel is located in the upper Susa Valley and it crosses three main stratigraphic units. The first stratigraphic unit interests a short section of the tunnel starting from the Italian portal. It is a quaternary deposit composed by different units such as man-made deposits, debris cover of slope, alluvial deposits, weathered and remodelled moraine deposits and glacial deposits. The second stratigraphic unit is the pre-quaternary substratum, made up of carbonate calc-schist, locally phyllites and marbles, graphitic calc-schist. The last stratigraphic unit is the unit of the "Lago Nero", which is the main unit encountered during the excavation and it is characterizes by the presence of calc-schist.

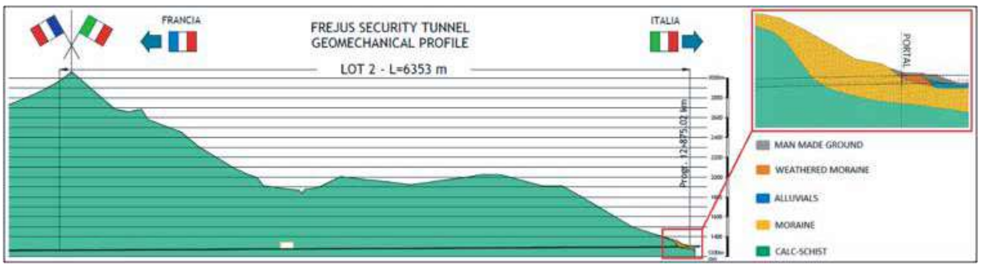

Figure 3. Geological profile of the Frejus security tunnel

The calc-schist formation presents schistosity planes parallel to the tunnel axis with a dip of about °45. It presents different facies: the phyllitic facies, characterized by an important mica and graphite content affecting the schistosity, which in turn influences the mechanical behaviour of the calc-schist (important decrease of the friction angle along the schistosity planes), generating a weakness zone; the carbonate facies, more compact and massive with lighter schistosity. An anisotropic in situ stress was measured, with horizontal stress being higher than the vertical one, with 1.2-1.4 ratio. The principle water inflows are encountered into fractured rocks and close to fault zones, which are generally characterized by seepages and limited water inflow [1]. The geotechnical parameters of the materials crossed by the excavation are shown in the following table.

Table 1. Geotechnical parameters

Lithology	γ	C_{peak}-C_{res}	ϕ_{peak}-ϕ_{res}	E_{peak}-E_{res}	ν
	[kN/m3]	[Mpa]	[°]	[Gpa]	[-]
Calc-schist	27	5 - 1	40 - 35	20 - 15	0.2
Fractured calc-schist	27	1 - 0.5	35 - 30	7 - 5	0.2
Deep Moraine	20	0.2 - 0.1	35	2 - 0.5	0.35
Moraine deposits	20	0.05 - 0.025	35	0.2	0.35
Weathered Moraine	21	0	35	0.02	0.35

4. EXISTING ROAD TUNNEL EXCAVATION EXPERIENCE

The design of the Safety Tunnel was carried out taking into account the experience gained during the excavation of the existing tunnel [2]. The excavation was realized in full section along the entire length of the tunnel and, apart from some specific areas, showed stable face-behaviour and did not require the installation of special measures. The support was mainly made up of rockbolts, between 3 m and 5 m long. A considerable amount of rockbolts was used and, on the Italian side, values of 150 m of drillings per linear metre of tunnel were reached and exceeded. Sections with steel ribs were limited and equal to about 600 m on the Italian side, including the portal, a circumstance that indicates the massive nature of the rock encountered. Average advance rates were in the order of 7.5 m per working day and the major convergences were recorded between the chainage 500+4 and 800+5 of the tunnel (Italy side) and are equal to about 25-15 cm. The higher values were recorded in the direction normal to the schistosity. Convergence rate measurements showed a maximum of 10 mm/day at a distance from the face of 3 diameters, then reduced to 1-2 mm/day at the final lining installation (after 80-100 days from the excavation). The following figure shows the excavation data of the existing tunnel along the safety tunnel geomechanical profile.

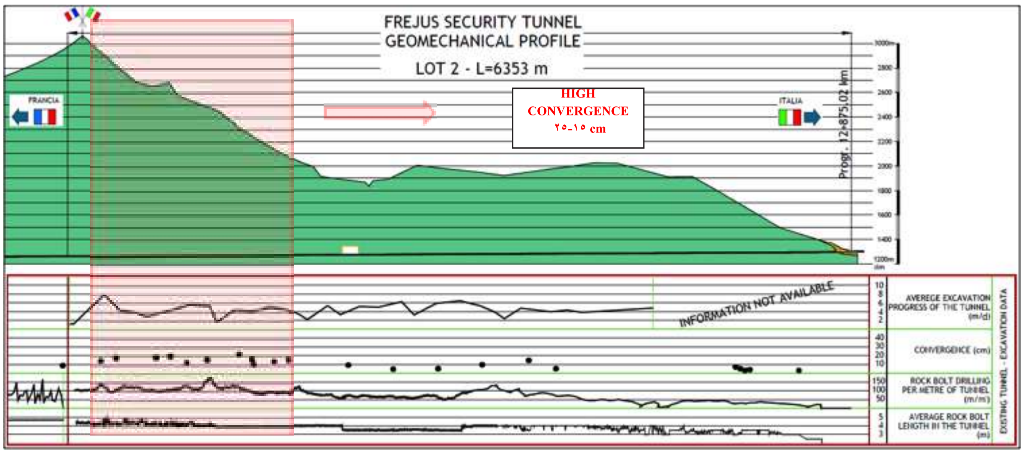

Figure 4. Existing tunnel – Excavation data

5. OVERVIEW OF THE PROJECT

5.1. Mechanized excavation

The main section of the tunnel was excavated by TBM, starting from the end of the French lot, at CH 656.45+6, to the Italian portal, at the CH 852.3+12, for a total length of 6287 m. Excavation encountered high overburden, up to 1800 m, and the calc-schist formation. A specific TBM design was adopted to excavate through these high deformable rocks, by using a single-shield TBM equipped by high breakaway thrust. In order to control the risk of jamming for the TBM and to reduce the ground pressure on the final lining, the TBM's design considers a shield conicity, a very important annular void with the possibility to increase the boring diameter and the capacity of bolting and drilling, so to manage high values of convergences. The TBM excavation diameter is 9,46 m, with the possibility of an over-excavation of 10 cm on the radius, reaching a maximum digging diameter of 9,66 m. The shield is 11,2 m long and it is made up of three sectors with a decreasing radius, in order to determine a conical shape that can guarantee a gap sufficient to absorb the development, over time, of the convergences of the excavation profile. The overall gap between the excavation profile and the tail of the shield is therefore 75 mm, which can be increased up to 175 mm using over-excavation cutting edges. The shield provides openings that allow, by means of hydraulic pistons positioned in the three shield sectors, to verify the "closure" of the excavation profile towards the extrados of the shield, in order to check the rock pressure on the TBM. The construction phases of the tunnel with TBM (see Figure 5) are as follows:

1. Excavation with diameter 9,66-9,46 m;
2. Positioning of the segment linings at the end of the shield, with injection of cementitious mortar at the base of the ring for an angle of °120;
3. Blockage with Pea-Gravel at the sidewalls when the °3-°2 ring has been positioned (monogranular gravel 6-3 mm diameter, clean, round shaped gravel);
4. At a distance of about 200 m from the face, placing of mortar in crown and, if necessary, injection with cement mixture (with ratio W/C < 1.0) of the pea-gravel previously placed;
5. Execution of drainage holes, 100 mm diameter, every 35 m.

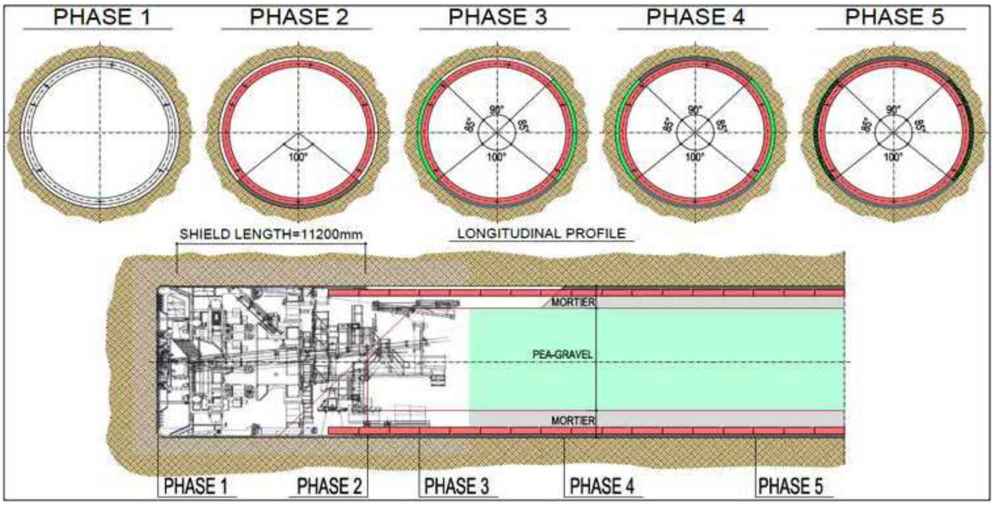

Figure 5. Construction phases

The concrete ring's diameter is 9.00 m at the extrados, and 8.20 m at the intrados (40 cm thickness). Six segments and one key compose each ring. The concrete class is C45/55 and 3 types of steel reinforcement have been defined. The geological condition of the rock mass, the overburden and the experience gained from the excavation of the existing tunnel governed the application of these 3 different reinforced segmental linings. In detail: the minimum reinforcement, 13 + 13 ϕ 12, was always adopted in the calc-schist formation; in presence of fractured calc-schist, especially under high overburden, the maximum reinforcement, 13+13 ϕ18, was adopted, while the medium reinforcement, composed of 13+13 ϕ14, was used under medium overburden, ranging between 750 m and 1350 m. Several numerical analyses, referred to the most critical cases, have been carried out using Itasca FLAC software to evaluate the tunnel lining static response.

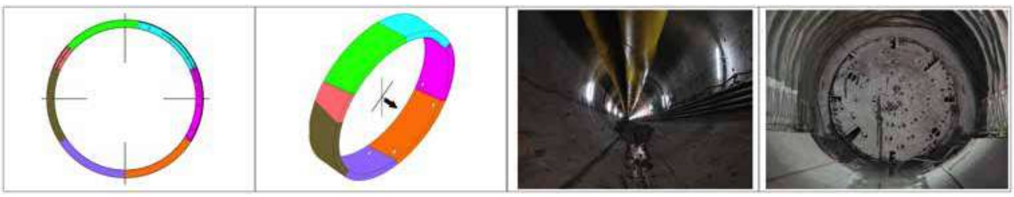

Figure 6. Concrete ring

5.2. Conventional excavation

At the Italian side Conventional excavation has been used for cross-passages between the existing tunnel and the safety tunnel and for the excavation of the safety tunnel sections close to the portal under low overburden in the moraines deposit.

5.2.1. Portal section

The last part of the safety tunnel extending from the progressive CH 918.45+12 (Italian side tunnel portal) to CH 852.3+12, for a longitudinal length of 66.15 m was excavated with a conventional method passing through a Moraine deposit.

Figure 7. Italian side portal

The excavation was carried out with full section excavation, using the A.De.Co method [3]. The section was divided into 7 excavation parts. The first three parts, with a length of 10 m each, considering the low covering, have been constructed using the variable section B2V, placing steel tubes around the cavity, for an angle of 120°, and fibreglass elements at the face. The following two parts were excavated by the cylindrical section B2, using only fibreglass elements at the face. The sixth excavation part, due to the improvement of the geomechanical conditions at the tunnel face, has been excavated by adopting cylindrical section B0, which just provides the placing of the prelining, with steel ribs and shotcrete. The last excavation part, in correspondence of the connecting section between the TBM excavation face and the conventional excavation face, was constructed by adopting a widening B0 section in order to facilitate the encounter between the two faces.

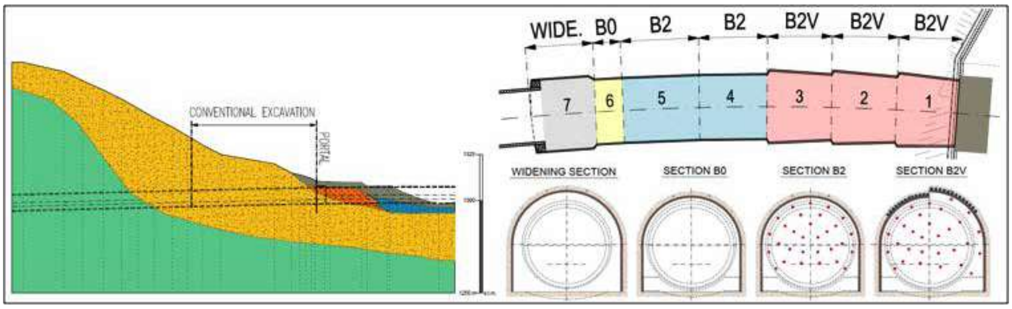

Figure 8. Excavation in conventional method

5.2.2. Pedestrian shelters

The existing tunnel and the security tunnel are connected in the Italian side by 16 pedestrian shelters arranged along the tunnel length every 400-300 m. Their construction is divided into three main sections: segment A at the intersection between the shelters and the safety tunnel (10 m long), segment B (with varying length depending on the distance between the two main tunnels) that is the main section of the shelters and segment C (10 m long) at the intersection between the shelters and the existing tunnel.

The project provided for a full section excavation with preliminary support consisting of rock bolts and shotcrete, the numbers and the thickness depending on the rock-mass geomechanical conditions. Steel ribs were used in correspondence of the intersections between shelters and the safety tunnels or existing road tunnel, to stiffen the connection node. The following figure shows the planimetry and the carpentries of the sections adopted.

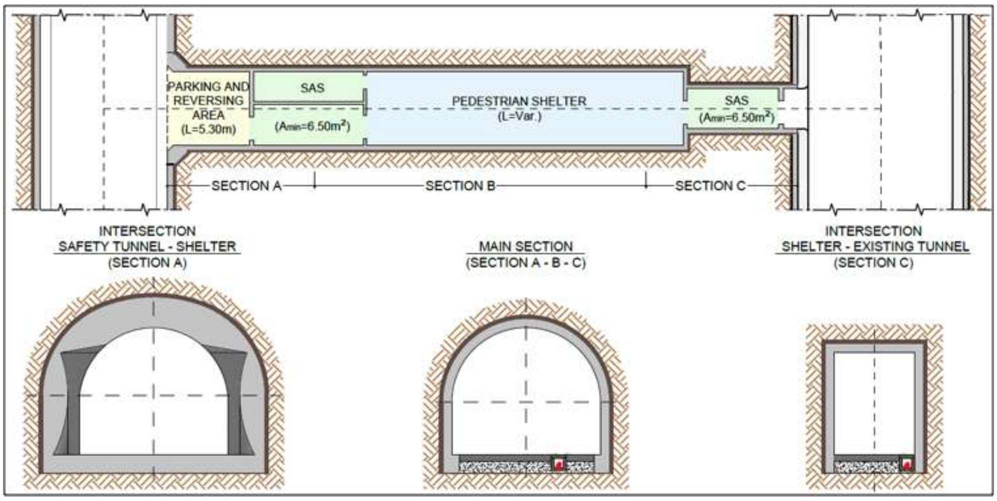

Figure 9. Pedestrian shelters – Planimetry and section

5.2.3. Cross-passages

On the Italian side of the safety tunnel, in addition to the shelters, there are also 5 cross -passages that allow the passage of emergency vehicles between the two main tunnels in case of need. As for shelters, their construction is divided into three main sections: segment A at the intersection between the by-pass and the safety tunnel (10 m long), segment B (with varying length depending on the distance between the two main tunnels) that is the main section of the by-pass and segment C (10 m long) at the intersection between the by-pass and the existing tunnel. Sections A and C have a wider geometry in order to allow an easy entrance and exit from the cross-passages for the emergency vehicles. For the cross - passages the project provided for a full section excavation with preliminary support consisting mainly of steel ribs and shotcrete, dimensioned considering the rock-mass conditions. At the safety tunnel/cross-passage intersection, rock bolts have been used too, due to the complex geometry of this zone that does not allow the laying of steel ribs. The following figure shows the planimetry and carpentry of the sections adopted.

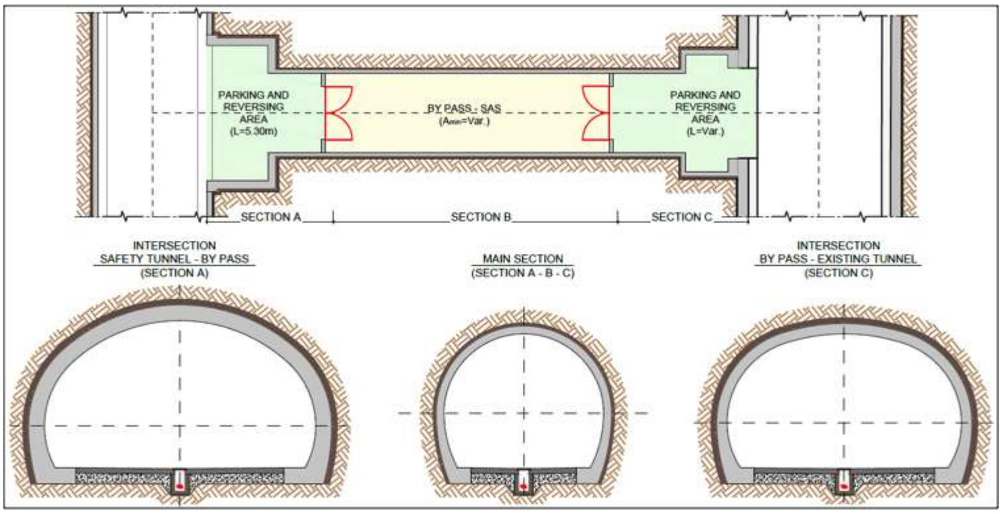

Figure 10. By-pass – Planimetry and section

5.2.4. Technical stations

Four technical stations are planned for the Italian section of the Frejus safety tunnel. As for shelters and cross-passages, their construction is divided into three main sections: segment A, segment B and segment C. The difference from other links is that section C is linked to the existing PHT, the technical rooms of the existing tunnel. The project provided for a full section excavation with preliminary support consisting mainly of steel ribs and shotcrete, considering the enlarged sections compared with shelter and cross-passage's sections, except in the intersection of safety tunnel/technical stations, where rock bolts have been used due to the complex geometry of the zone. The following figure shows the planimetry and carpentry of the sections adopted

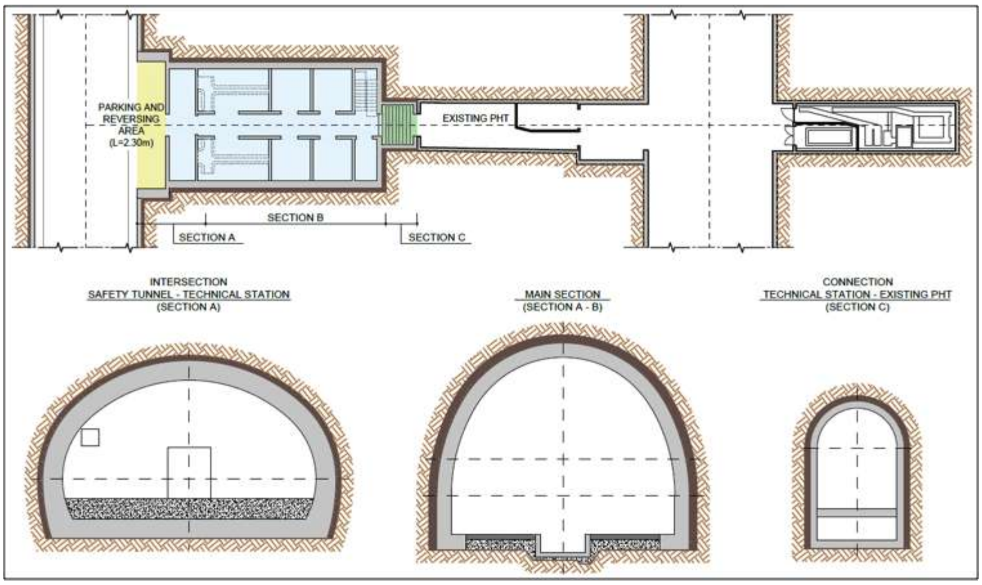

Figure 11. By-pass – Planimetry and section

Finally, starting from one of the technical station (named 8-13), it is also planned a ventilation plant that overpasses the existing tunnel and intersects an existing ventilation chimney, as reported in the following figure.

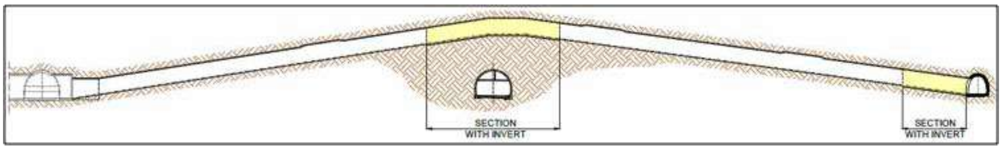

Figure 12. Ventilation plants

6. CONSTRUCTION STAGE

The results of the excavations are shown below, both for mechanized excavation and for conventional excavation. Some design choices, developed during the construction stage according to the stress-strain response of the rock mass, are also reported.

6.1. Mechanized excavation

The section excavated by TBM has been constructed without particular problems, despite of the difficult geomechanical context. The advance has occurred with constant thrust values, on average around 25,000-20,000 KN, much less than the design maximum value equal to 80,000 KN.

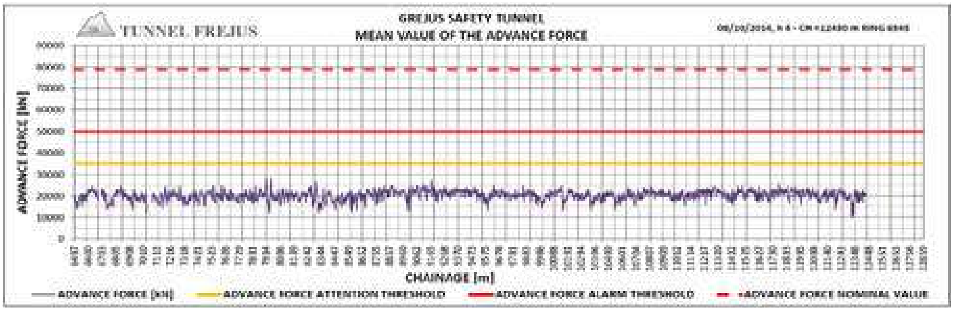

Figure 13. Advance force

The friction forces on the shield were always less than 10,000 kN, except for the section between chainage 7000 and 8400, where values were higher and punctually up to 20,000-18,000 kN. It can be observed that this increase in friction values is part of the project expectations, as it occurred in the same area where the maximum convergences were recorded during the excavation of the existing tunnel. In this section a radial overcutting of 10 cm was adopted.

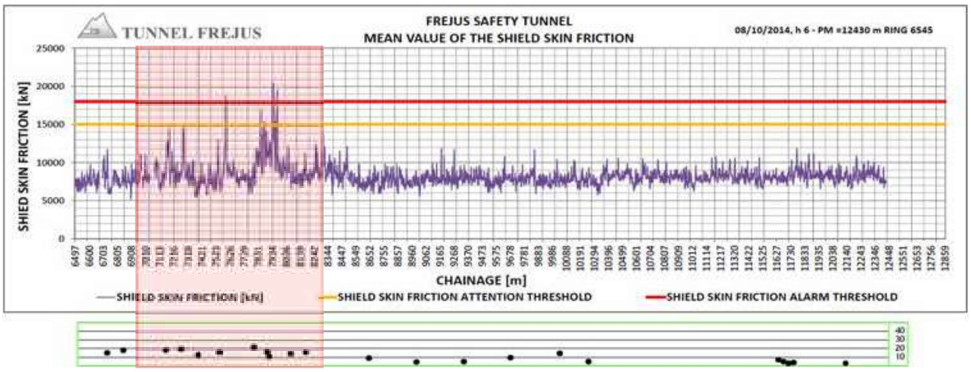

Figure 14. Shield skin friction

Excavation was carried out with an over-excavation of 10 cm for the medium and maximum coverings. Starting from the chainage 8400 approximately, the friction forces on the shield are contained in the range 9,000-7,000 kN, without highlighting critical situations with regard to the pressure on the TBM. The convergence values, determined by the telescopic pistons activated through the TBM shield, are also in the order of centimetre, without ever indicating a contact situation between the TBM and the surrounding rock-mass. The set of data collected, both in the design phase and during the execution of the works, has thus indicated the possibility of advancing, over the Progr. 000+11, without over-excavation. Finally, observing the data given by the strain gauges installed in the rings, it can be observed that the stress measured in the segmental lining is in agreement with the overburdens, showing higher values for higher geostatic conditions.

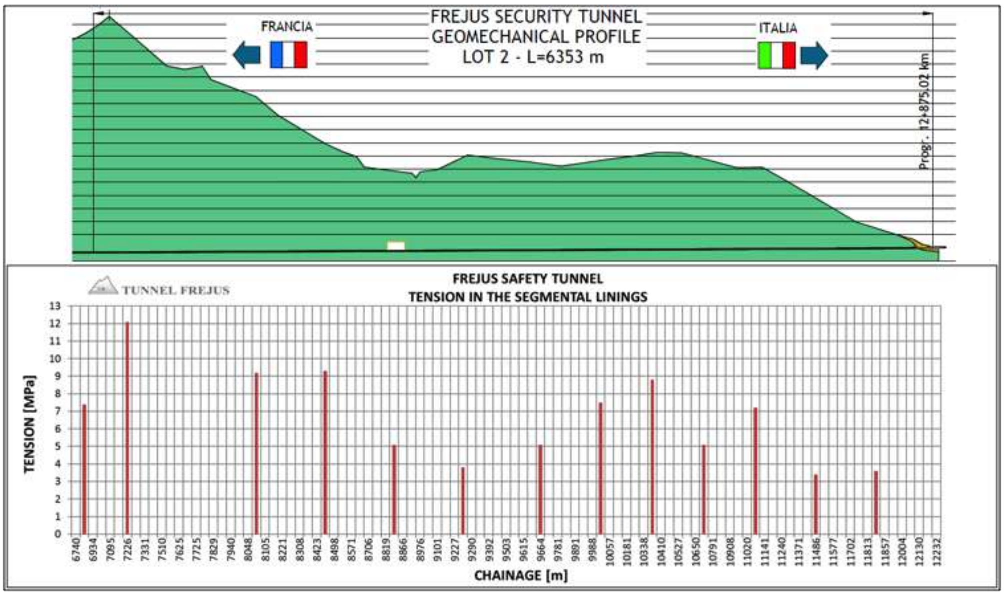

Figure 15. Tension in the segmental linings

An important aspect of the design during the excavation phases was the distance between the existing tunnel's axis and the safety tunne's axis. During excavation on the French side, it was found that in the areas where the maximum convergences were expected, the mechanized excavation had induced cracks on the existing tunnel, thus showing a phenomenon of interference between the two tunnels. In order to minimise this interference, specific numerical analyses have been carried out to determine the distance between the two tunnels that reduces the risk of damage to the existing tunnel. While the average distance between the two tunnels is 50 m, these studies led to an increase of the distance to 95 m under the highest overburden as shown in the following figure.

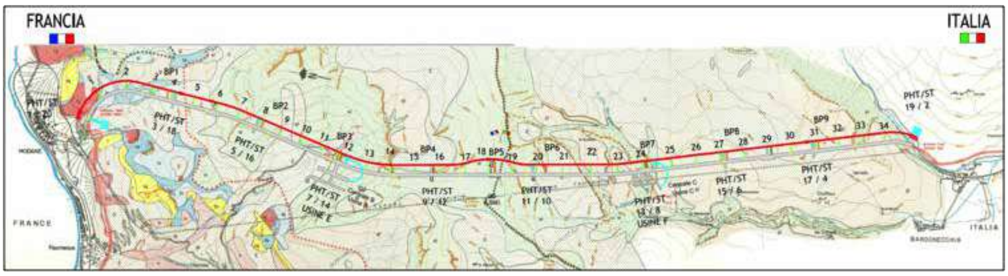

Figure 16. Zone of interference between tunnels

6.2. Conventional excavation

The conventional excavation involved the section of the safety tunnel at the portal and the cross-passages between the main tunnels. The excavation of the terminal section of the safety tunnel was carried out in the morainic deposits according to design forecasts, without any particular problems (diametric convergences less than 15-10 cm). With regards to the cross-passages, the excavation was instead entirely carried out in the formation of calc-schist. The design predictions indicated for the rock mass a value of GSI averaged between 50 and 60. The excavation was always carried out in context in line with the design predictions, except for shelters 22 and 23 and cross-passage 6, in correspondence of the section where the maximum shield friction force was recorded during the excavation by TBM. The excavation of shelters 22 and 23 immediately showed an accentuated deformation behaviour characterized by the difficulty of maintaining the excavation profile during advancement. The rock mass was worse than planned, with GSI minimum of 35-30 at shelter 23 and with an average value between 40 and 50 for both shelters. During the excavation advance on the preliminary lining, composed by 3 m long rock bolts and shotcrete, cracks developed, while, only for shelter 23, in the area of the intersection between the safety tunnel and the shelter there were spalling phenomena due to the strong compressions generated on the walls of the intersection.

Figure 18. Cracks on the preliminary lining of the shelters and segmental linings

In order to overcome these problems additional preliminary supports were designed. In order to give a greater confinement to the cavity, starting from numerical back analyses on convergences that have made it possible to identify the loosened portion of the rock mass around the cavity, 6 m long rock bolts have been installed while at the intersection between shelter 23 and the Frejus safety tunnel, rock bolts of 8 m were installed. Spalling on the segmental linings has also been completely restored. The figure below shows all this supplementary support.

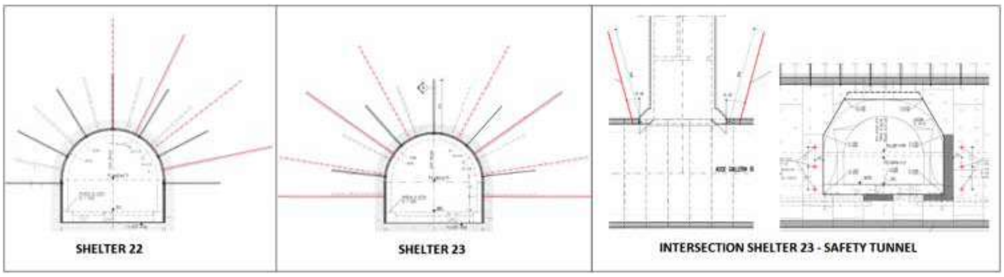

Figure 19. Shelters 23-22 supplementary preliminary support (red)

A worse condition of the rock was found also in correspondence of cross-passage 6 where high convergences developed. The preliminary support was composed by steel ribs followed, after the completion of the excavation, by the final lining on the crown. In order to overcome this problem in the zone subject to this behaviour, the invert was designed as a supplementary support. This allowed to control the closure of the cavity and continue the excavation without problems.

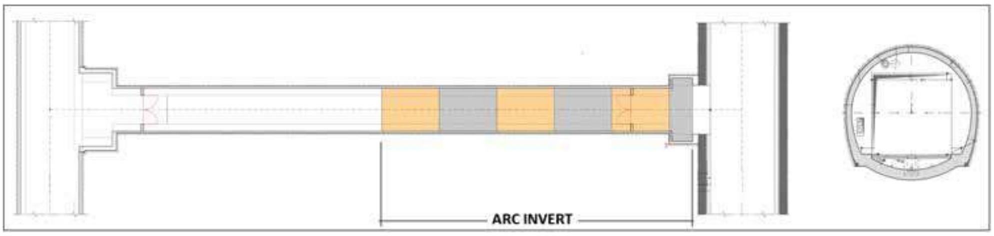

Figure 20. By-pass 6 supplementary support

Another important aspect of the design concerned the issue of the intersection between the two main tunnels and the cross passages. In detail for the intersection between the safety tunnel and cross passages, as a result of specific numerical analyses, temporary support systems for the segmental linings have been provided during the cutting phases of the linings. It consists of 8 m-long ϕ32 rock bolts in the closest area to the cut and 4.5 m-long ϕ24 rock bolts in the remaining areas. A reinforcement beam was also designed around the contour of the cutting through 3D analyses conducted with SAP2000 software distributed in Italy by CSI Computer and Structures able to take the loads of the rock mass in the long term.

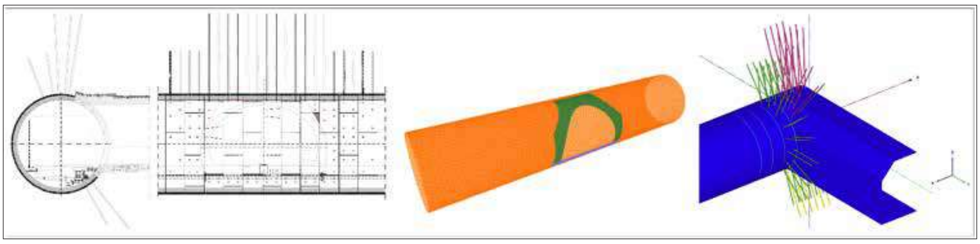

Figure 21. Example of intersection between Safety tunnel and cross passages

On the existing tunnel side, for the cross-passages having the larger geometry, the intersection was designed through 3D FEM analysis performed by the calculation software Itasca FLAC 3D. The study was conducted starting from all the data given by the monitoring system present on site and the measures of stresses in the existing tunnel lining. Thanks to a back-analysis process, it was possible to identify the most suitable construction phases for the intersection in order to minimize interference between cross-passage and existing tunnel lining. The construction phases provide firstly the installation of a steel reinforcement framework inside the existing tunnel, the completion of excavation, with the last part of the tunnel excavated in two phases: a first phase in reduced section and a second phase in widened section, followed by the construction of the intersection portal that takes the loads after the cutting and finally the cutting of the existing lining. The intersection between shelters and existing tunnel were instead designed with simpler model due to their small geometry.

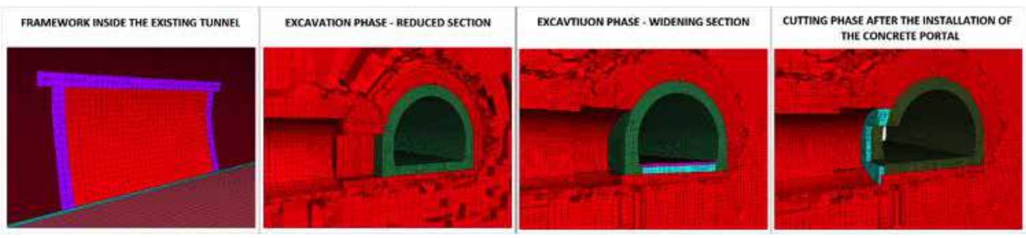

Figure 22. Analyses of the intersection between by-pass and existing tunnel

7. CONCLUSION

The construction of the Safety Tunnel parallel to the existing Frejus Tunnel has been designed to upgrade the infrastructure in line with the new legal safety obligations. The project involved the construction of a safety tunnel, at a mean distance of 50 m from the existing motorway tunnel's axis and the connection between them, in the Italian side, ensured by 16 pedestrian shelters and 5 vehicles cross-passages. The work also included the construction of 4 technical stations and one ventilation plant. At the moment, the excavation of the safety tunnel has been completed, as well as the main shelters and technical stations; the final arrangements and equipments are being performed. Once the works will be completed, the safety tunnel will be used as a second carriageway, allowing separation of driving flows and thus significantly increasing the safety level. The safety tunnel was successfully excavated. Starting from the experience gained from the excavation of the existing road tunnel and from the well-known geomechanical context, a project has been developed to overcome the possible problems encountered during excavations. The excavation of the safety tunnel was carried out through a single shield TBM and thanks to the presence of a complete monitoring system it was able to overcome particular problems that emerged during excavations. The design was in fact updated according to the data provided, according to A.De.Co Approach. The excavation of the cross-passages, technical stations and ventilation plant were carried out using a conventional method, by full-face excavation, updating the planned reinforcement according to the conditions present on site, especially where major ground movements were detached during excavation. The planned measures, increasing the number and length of rock-bolts or the steel ribs' interaxis, and providing the in situ cast of the invert, were able to allow completion of the excavation, overcoming the problems that emerged.

8. ACKNOWLEDGEMENTS

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