Geological and hydrogeological investigation for the new Lyons railway, middle Susa Valley, Italian Western Alps.

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SUMMARY. This paper describes the "state of the art" of geological modelling concerning the project of the transalpine Turin –Lyon rail link. The attention is focused on the italian side of the project, where two large diameter twin-tube tunnels are planned The methodology applied in geological surveys and the first results are presented.

1. INTRODUCTION

The new Turin-Lyons rail link is a well known and widely discussed project, whose realisation should start in the next years. Several geological studies have been produced, aiming to define the 3D geometry of geological structures and the physical-mechanical properties of the rock mass to be excavated. This paper presents the preliminary results of geological studies concerning the Italian side of the project in the sector between Bussoleno and the State boundary in the middle Susa Valley. In this sector (Fig. 1), the project involves the excavation of the 8 km long Italian segment of the 52 km Maurienne-Ambin Base Tunnel (from the State boundary to the West Venaus portal) and of the 12 km long Bussoleno Tunnel (from the East Venaus portal to the Chianocco portal) The two tunnels will be connected by means of a viaduct in the Venaus area. The construction of a pilot tunnel starting from Susa-Venaus along the Base Tunnel is also forecast. The studies on this sector have been co-ordinated and supported by Alpetunnel GEIE. SEA Consulting s.r.l., carried out the geological mapping and conceptual modelling, under the supervision of the Dept. of Earth Sciences of the University of Turin (Cadoppi et al., 1997; Delle Piane et al., 1996; Delle Piane et al., 1997.

2. METHODOLOGY

In these years the Italian partners of Alpetunnel GEIE gave a great emphasis to a correct description of geometric and mechanical features of the rock mass to be excavated.

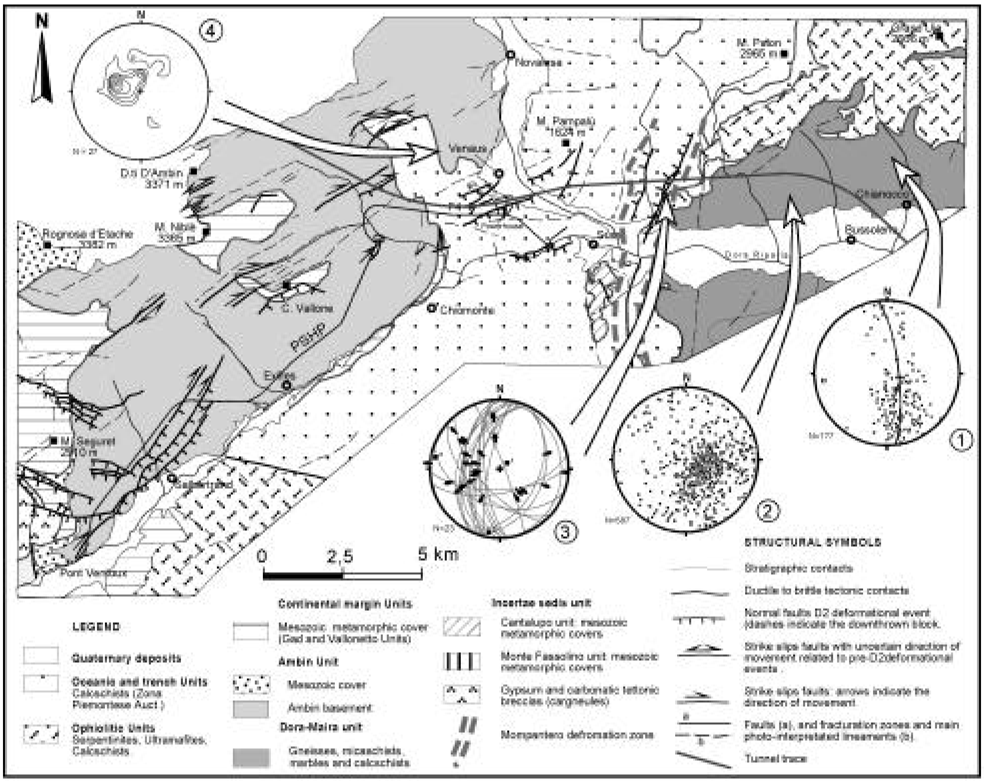

Figure. 1: Geological sketch map of the studied area. Also includes the lower hemisphere stereograms of some significant structural features and the dead reckoning plot of the Pont Ventoux – Susa Hydropower Plant.

The methodology chosen by the Italian team is mainly based on field surveys and geological mapping (scale 1:5.000 and 1:10.000) which have been used not only as a tool to give a visual representation of distribution of the different rock type, but also as an analytical instrument which, coupled with modern techniques of structural geology and stratigraphy, allows to deduce from surface outcrops the geometric and statistical rules which dominate in the rock mass. Structural and stratigraphic analysis allowed to define a 3D conceptual model by which the rock volume interested by tunnel excavation is subdivided in different structural and litostratigraphic domains, i.e. in domains with homogeneous lithological composition and distribution of fault, joint and fold systems (Forlati & Piana, 1998); these domains often correspond to "geotechnical units". Critical sectors where information from the surface is too poor and need a more deepened study are also highlighted by geological modelling. This allows to optimise the number and the localisation of expensive geognostic tests by directing them to the previously found critical rock volumes. This allows a considerable optimization of the geognostic surveys campaigns.

Lithological and geotechnical data obtained from different deep (500-700m) and shallow (50-200m) vertical boreholes and from geophysic investigations have been used for a subsequent refining of the geological conceptual model. Furthermore, in the frame of the study campaign, SEA Consulting, in collaboration with Pont Ventoux s.c.r.l. developed a study concerning the evaluation of TBM and D&B performances along the first 8Km of the Base Tunnel (Venturini et al., 2000). This study, still in progress, mainly based on TBM and D&B performances recorded during the ongoing construction of the Pont Ventoux – Susa Hydropower Plant of AEM Torino S.p.A. (PSHP in the following) which is located in the same sector of the Base Tunnel (Fig. 1).
Once obtained a clear picture of the geological framework the attention has been placed on the hydrogeological aspects. A conceptual hydrogeological model has been elaborated basing on mechanical and physical sources and drillholes monitoring and sampling started since 1997.

3. GEOLOGICAL ASPECTS

The tunnels will cross three main lithostratigraphic metamorphic units of the Alpine chain, composed of crystalline rocks (Fig. 1). These units are: 1) the Dora Maira Massif, composed of gneiss and micaschists overlaid by a cover of marbles and calcschists; 2) the Zona Piemontese mainly composed of calcschists and serpentinites; 3) the Ambin Massif composed of micaschists and gneisses.
The elaborated conceptual geological model is briefly summarised in the longitudinal sketch section of Fig. 2. With reference to this section five structural domains, can be distinguished.

3.1. Structural domains

Structural domain nr. 1 (Km 21+000 – 12+000) is composed of rocks of the Dora-Maira Massif which have been deformed mainly by folding in ductile regime. Marbles, calcschists and micaschists are the main rock types, therefore a great heterogeneity in lithological and mechanical properties of the rock mass is expected. Brittle phenomena causing loosing of cohesion (faults) are scarce and mainly concentrated along discrete surfaces. A major fault is represented by a low-angle N-dipping discontinuity which is characterised by a zone up to 50-70m thick of poorly cohesive dissolved carbonatic rocks (Fig. 2).
Four folding phases are superposed in this domain. Two of these (D1 and D2) produced a new schistosity (S1 and S2) i.e., in general, two primary surfaces of anisotropy inside the rock. Both these surfaces are locally folded by late deformative phases (D3 and D4). The lithological limits are parallel to S1. F2 foldings are locally non cylindrical, i.e. their axes vary from main E-W direction to N-S direction, giving way to complex 3D structures. Only in sectors where F2 is cylindrical (axes constantly striking E-W) the geometry of lithological limits (S1) is relatively simple and can be extrapolated at depth (Fig. 1, plot 1), whereas this is not possible in areas with non-cylindrical folding (Fig. 1 plot 2).
A further complication in geometrical reconstructions is that the first two phases are transpositives, i.e. originary stratigraphic levels are tightly folded and pinched out along the fold limbs, causing a complete change of the original setting. This has two important consequences on tunnel excavation:

1. Gneisses, calcschists and marbles, are now interbedded on a decametric to hectometric scale, therefore the rock mass is strongly heterogeneous;
2. The geometry of the folded rocks is often not extrapolable at great depth from the surface because of transpositive and non cylindrical folding phenomena.

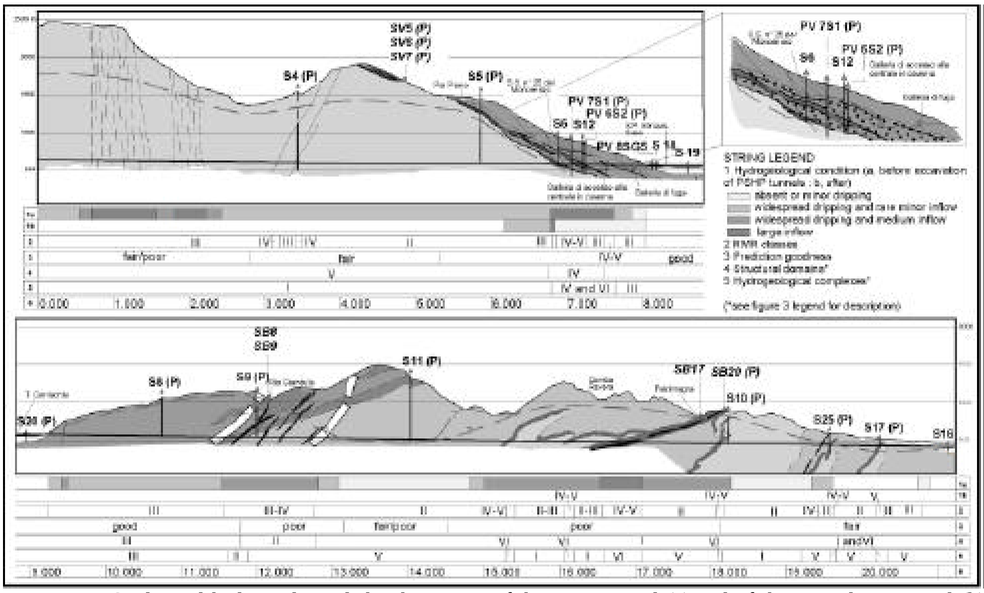

Figure. 2: Geological-hydrogeological sketch sections of the Base Tunnel (a) and of the Bussoleno Tunnel (b) with a detail of Susa- Venaus sector (c).

The execution of boreholes can only partially reduce the uncertainty, unless a great number of deep boreholes is carried out.

The contacts between marbles and micaschists could cause problems related to the excavation, since the interface marbles/micaschists is often affected by water-related dissolution, as the latter can behave as base levels for karstic water circulation. Therefore at the interface between these two rock types poorly cohesive breccias can be found.

According to the previous considerations geological model predictions are poorly reliable from Km 13+000 up to Km 18+200, whereas in other sectors the model has been confirmed by drillholes.

Structural domain nr. 2 (Km 12+800 – 11+800) borders toward the west the domain nr.1. It is represented by a brittle deformation zone dipping about 50-60° toward the west. This zone is characterised by the presence of anastomising discrete faults with metric to decametric tectonic breccia and gouge belts, which separate less deformed decametric rock lenses (lithons). The brittle deformation zone cut through marbles, calcschists and serpentinites-metabasites. Within this zone the tunnels will cross sectors of poorly cohesive rock mass, despite the favourable angle (almost perpendicular to tunnel direction; Fig. 1, plot 3) and the excavation condition will be difficult.

Structural domain nr. 3 (Km 11+800 – 7+500) is relatively homogeneous, being composed of calcschists and micaceous gneisses. Sporadic minor masses or lenses of serpentinites and metabasites could be intersected. Like domain nr.1, this domain has been deformed in a ductile regime too, by four folding phases but the D2 schistosity is here more pervasive and S1 has been completely paralleled to it due to the higher plasticity of the rocks; this fact, together with the lithological homogeneity causes minor problems of interpretation and extrapolation of critical lithological boundaries at depth, with respect to domain nr.1. No dissolution levels are present and faulting is not diffused. Therefore this sector doesn't show critical situations with reference to tunnelling.

The structural domain nr. 4 (Km 7+500 – 6+800) is a deformation zone completely inside the Piemontese zone not far from the contact between the Piemontese Zone and the

Ambin Massif. This deformation belt mainly intersects marbles and calcschists; the mechanical properties of the rock mass are highly heterogeneous due to both brittle deformation and dissolution phenomena in carbonatic rocks. The deformation zone is an old, syn-metamorphic, ductile shear belt widely reactivated in late alpine horogenic stages by brittle tectonics. The most important discontinuities are low-angle shear zones dipping toward the SE (Fig. 1, plot 4). These shear zones, as in domain nr. 2, show an anatomised network of minor faults, usually related to metric or decametric belts of poorly cohesive carbonatic tectonic breccias, gouges and cataclasites, widely affected by dissolution related to water circulation. The behaviour of these rocks with respect to underground excavations is well known since the PSHP diversion tunnels has been partly excavated in this domain. Coupled surface and underground structural analysis allows to extrapolate the structures inside this sector with a good reliability.

The structural domain nr. 5 (Km 6+800 – Km 0+000) is represented by the Ambin Massif. On a lithological point of view this is the more homogeneous domain, since it is entirely composed of gneisses and micaschists. Despite the presence of at least three phases of superposed folding, structural features are well known and allow a precise reconstruction of the geometry of lithostratigraphic units. Extrapolation of surface observations at depth is less problematic, also because of the control which can be operated by comparison with PSHP tunnel crossing the same structural domain. Brittle deformation inside this domain is relatively scarce. Some NW-SE striking faults intersect the tunnel axis but the associated cataclastic zone is relatively small (few meters each). Important high angle NE-SW striking joint systems cross the tunnel axis near the French-Italian border. These systems are not problematic for geomechanic aspects, but they could represent high permeability channels inside the domain allowing considerable water inflow (see § 4).

3.2. Neotectonics

In order to obtain informations about recent fault kinematics activity SEA Consulting geologist also carried out a comparative structural analysis of faults observed in quaternary deposits and in the rock mass. Some faults have been detected in Pleistocenic to Holocenic deposits (1My-15.000y) which testify the presence of recent tectonic activity along the fault zone of domain 2 (Fig. 1, pot 3), and more generally along other minor faults of the studied region. This activity is also consistent with the presence of some small magnitude seismic epicentres near Susa. The recent crustal stress field which produced these earthquakes is extensional, with maximum compressive axis vertical and minimum compressive axis striking approximately E-W.

4. HYDROGEOLOGY

According to the results of the geological study, the area interested by the project can be subdivided in five hydrogeological complexes, with different hydrodynamics characteristics and chemical groundwater type. These complexes and their characteristics are reported in Fig. 3.

These complexes coincide with lithological units or groups of similar lithological units, within a single hydrogeological complex permeability values may vary with a narrow range, which has been mainly defined by means of Lugeon tests in drillholes and the evaluation of hydraulic connectivity between the discontinuities at the larger scale. According to Fig. 3 it is possible to realise how, on the other hand, the permeability and hydraulic connectivity within hydrogeological complexes at tunnel level show a wide range of variation.

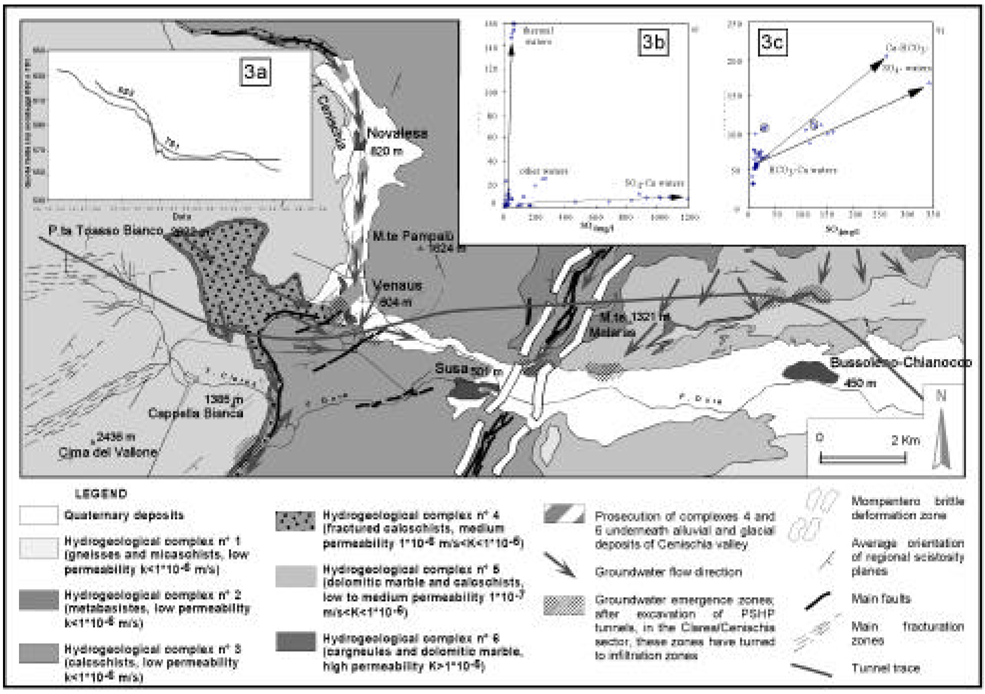

Figure. 3: Hydrogeological sketch map with representation of the geological complexes and main flow systems. Also shown is the depression of water head near the Venaus Portal due to the PSHP drainage (3a) and groundwater chemical facies (3b, 3c).

A conceptual model of ground water paths has been reconstructed on the base of hydrogeochemical and isotopic data obtained both from surface water springs and from groundwater sampling in boreholes and PSHP tunnels. Continuous monitoring of pH, conductivity, temperature and flow rate of springs and of temperature and piezometric levels in drillholes allowed to characterise the different flow systems by means of the variation of their physical parameters too. This results in the conceptual model briefly summarised in the following. With reference to Fig. 3, in structural domain nr.1 a main flow system is developed inside the complexes nr. 3 and 4, with maximum flow rates in high permeability complex nr. 4. Waters infiltrate in the higher parts of the mountain slope and migrate toward the bottom of the valley; the complex 1 acts as a barrier and concentrates the flow at its top, driving the flow mainly toward the East. Waters circulating in this system are identified by a Ca-HCO_3-SO_4 chemical facies, and are more evolved than the Ca-HCO_3 type waters circulating in quaternary deposits and in the upper 0-50m of the fractured crystalline substratum (Fig. 3c). Large water inflow at tunnel level are expected within this flow system.

In structural domain nr. 2 there is a second flow system (Fig. 3), though less constrainable by chemical and isotopic data. Probably all ground water of this system is discharged in the alluvial deposits of the Susa Valley bottom.

In structural domain nr. 3 no important deep flow systems are presents. Instead, main flow system is located in structural domain nr. 4 which is highly permeable. The base of this flow system is the poorly permeable Ambin Massif (hydrocomplex 1). Surface waters supply the flow system both from the right side and from the upper Cenischia Valley bottom. Today ground waters of this flow system are drained by the tunnels of the PSHP, at a lower altitude with respect to the Cenischia Valley bottom. This caused a depression of the hydraulic head (Fig. 3a). The waters of this system are $Ca\text{-}SO_4$ type (Fig. 3b). The drainage today operated by the tunnels of the hydropower plant grants that the Base Tunnel will intersect the permeable complex at an altitude higher than the hydraulic head and therefore no water inflow is expected. In the Ambin Massif no major water systems are expected; an exception is represented by the above mentioned joint zone near the Italian-French border. Furthermore the S4 deep drillhole intercepted a poorly productive pressurized thermal system (water at 37°C under a topographic cover of 650m) with chemically anomalous waters indicating long lasting water/rock chemical interaction. An hypothesis to explain this anomaly is that great quantities of waters deeply infiltrating in the Ambin Massif along major joint system acquire high temperatures and then ascend rapidly along minor circuits located in small fault zones causing local temperature anomalies (high geothermal gradients) in the rock mass. Further tests and drillhole campaign are necessary to confirm this hypothesis. This thermal anomaly could be of critical importance in terms of excavation operations.

5. DISCUSSION: CONSTRUCTIVE ASPECTS

5.1. Base Tunnel (Italian side)

The Italian side of the Base Tunnel is a sector where the geological factors influencing the tunnel construction are relatively well known.

The geomechanical conditions are quite fair, with classes II and III RMR prevailing (86% classes I-III vs. 14% classes IV-V). The experience derived form the excavation of the PSHP suggests that good TBM performances can be reached in this domain with the exception of brittle deformation zones (Fig. 4a).

Classes IV and V will be mainly concentrated within the shear belt cutting through the base of the Piedmont zone and the Ambin Massif (see § 3). This shear belt will be met within the first 1800 m from the Venaus portal; D&B technique should be preferred in this segment, due to extremely poor geomechanical conditions, as it can be deduced also from the experience of the PSHP (Fig. 4b).

No water inflow is expected in this zone, due to the drainage operated by the tunnels of PSHP. From that point onward the excavation with TBM seems to be the best solution from a geological point of view.

Water drainage could represent an important factor near the Italian-French border where the intersection with two main joint zones is expected. These are, at the moment, the less constrained geological feature of the Basal Tunnel. In order to better understand the role of these structures in terms of water flow (joint opening at depth) a future task could be the realisation of a deep drillhole and hydraulic tests in the Clarea Valley. These joint systems could control the temperature at tunnel level by influencing thermal water circulation; therefore a local high geothermal gradient through the Italian-French border can be expected (see § 4).

5.2. Bussoleno Tunnel

In Central section of the Bussoleno Tunnel the geological factors influencing tunnelling are poorly constrained due to the complex structural setting described above (see § 3), whereas near the portals the geological conditions are well defined. The geomechanical conditions are very favourable in the first part of the alignment, from the Susa-Venaus portal up to Km 11.800 (RMR classes varying between II and III). From there on a segment of about 1Km is

met where unfavourable geomechanical conditions are expected (RMR classes IV and V prevailing). The following section up to km 18.200 is characterised by the occurrence of poorly cohesive levels of partly dissolved carbonatic rocks whose exact location and length are not known, due to complex geometry of the contact between gneisses and carbonatic rocks (see § 3). Further investigations are required for an adequate planning of tunnel excavation in this section. A possible solution could be a deep oriented borehole located approximately at Km 15.000 and deviated to follow the tunnel trace up to Km 16.000-16.500. From Km 18.200 onward, geomechanical conditions are relatively well known even if the rock mass is heterogeneous. A section with excellent to fair RMR classes (I-III) in gneisses and micaschists is expected between Km 18.200 and 19.300 approximately, while the rest of the tunnel will cut through a rock mass made of carbonatic rocks with a wide range of geomechanical conditions.
Hydrogeological conditions are still poorly known in the central section of the Bussoleno tunnel.

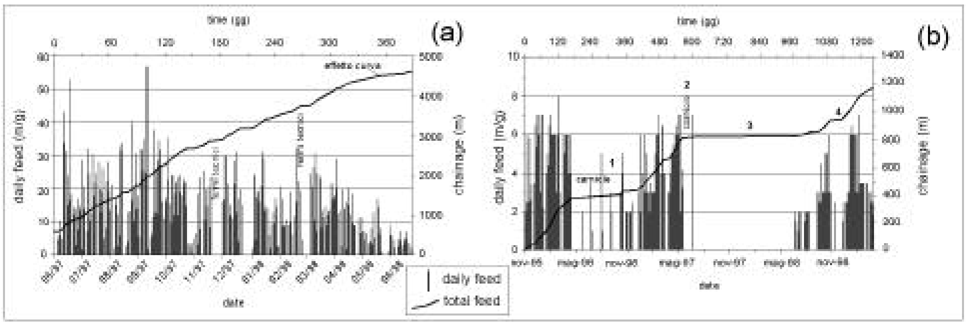

Figure. 4: Diagrams showing the excavation performances during the construction of the Pont Ventoux – Susa Hydropower Plant; graph (a) shows D&B performances in the structural domain 4 and the plateau n. 1 and 3 correspond to the intersection with the most important shear zones; graph (b) show open TBM performances in typical conditions of structural domain 5. Histograms represents the daily performances.

Keeping in mind the need of further investigations some preliminary considerations on excavation methods can be done. If the time factor is not considered as fundamental, the great heterogeneity of the rock mass in this tunnel would suggest that the excavation with D&B method should be the preferred one in order to avoid long periods of work stops which could be caused by TBM stops for difficult ground conditions. Anyway it must be considered that also with D&B methods time loss would be necessary in order to treat the ground with consolidation techniques.

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