Groundwater in the Perthus Tunnel: feedback after excavation

Acque sotterranee nel Tunnel del Perthus: feedback dopo lo scavo

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Riassunto

Questo lavoro presenta le esperienze maturate durante la realizzazione della galleria ferroviaria ad alta velocità del Perthus, lunga 8,4 km, in materia di gestione delle acque in galleria, analisi degli impatti sulle acque superficiali e sotterranee, monitoraggio dei piezometri, iniezioni del terreno e controllo della qualità delle acque. Lo scavo ha interessato granodioriti, scisti, dioriti, gneiss, scisti neri e depositi fluviali grossolani (ciottoli e blocchi) presso il portale nord. Sono state attraversate anche alcune importanti strutture tettoniche, con flusso di acque sotterranee. Viene infine presentato uno studio geotermico sulle sorgenti idrotermali di Le Boulou, che non sono state impattate.

Abstract

This work presents the experiences gained during the construction of the Perthus high-speed railway tunnel (8.4 km long), as regards water inflow management, analysis of the impact on surface-waters and groundwater, monitoring of piezometers and water quality control, soil injections. The excavation met granodiorites, schists, diorites, gneisses, black schists and coarse river deposits (pebbles and blocks) near the north portal. Some important tectonic structures, and associated groundwater flow, were also crossed. Finally, a geothermal study on the hydrothermal springs Le Boulou, which were not impacted, is presented.

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The Railway Perthus tunnel project

The Perthus Tunnel is part of the high speed railway between France and Spain, located in the eastern sector of the Pyrenees, between Perpignan and Figueres. The underground works consisted of two main parallel tubes of 8,4 km length, 10 m diameter within a distance of about 30 m. Security galleries connect the two tubes every 200 m. An exploratory tunnel of about 450 m long has been excavated with traditional drill and blast method through an important ductile-brittle fault zone, approximately half way of the main tunnel. Two soil treatment tunnels of 6 m diameter and about 80 m and 170 m length respectively were realised from the end of the exploratory tunnel, parallel to the main tunnel axis.

The underground excavation work has been done with two double shield Tunnel Boring Machines (TBM) from Spain to France. The first TBM, called Tramuntana, started the 28/06/2005 and finished the 23/11/2007. The second called Mistral started the 30/09/2005 and finished the 1/10/2007 (Venturini et al. 2010).

Geological context

The geological context of the area has been elaborated before the start of excavations, based on boreholes with permeability tests and geological and stratigraphical field surveys. The geological model achieved, has been revised and updated during the excavation, according to the geological evidences received from the boring fronts. The hydrogeological model has been based on the geological data above mentioned, in addition to the piezometric measurements of the water points existing along the tunnel area and the chemical and isotopic water analysis. The studies of all above data have permitted to evaluate the reliability of the geological and hydrogeological reference model. This evaluation of reliability has determined the actions to be taken necessary for the tunnel design and realisation and to prevent the impacts on underground and surface water resources.

The area under examination is located within the massif of the Albères, one of those constituting the Hercynian basement of the eastern sector of the Pyrenees chain (Fig.1). The Pyrenees are made of rocks belonging to the Pre-Mesozoic series, with a Hercynian metamorphism, in the Upper Paleozoic, hence involved in the Alpine deformative phases. The stratigraphic sequence of the Palaeozoic basement of the Albères consists of sandstones and pelites with subtle intercalates of limestones and volcanic rocks. In particular, along the alignment of the excavation works, which are the object of the present study, the following lithostratigraphic units can be distinguished from south northwards: (i) granodiorites (beginning at the southern portal for about 30% of the alignment); (ii) schists and granodiorites (about 30% of the alignment); (iii) schists and diorites (about 20% of the alignment); (iv) gneiss (about 10% of the alignment); (v) black schists (about 10% of the alignment as far as the northern portal). At the end, in the sector of the northern portal, the base tunnel crosses the Roussillon Mio-Pliocenic basin made up in part of rather coarse (pebbles and boulders) fluvial deposits.
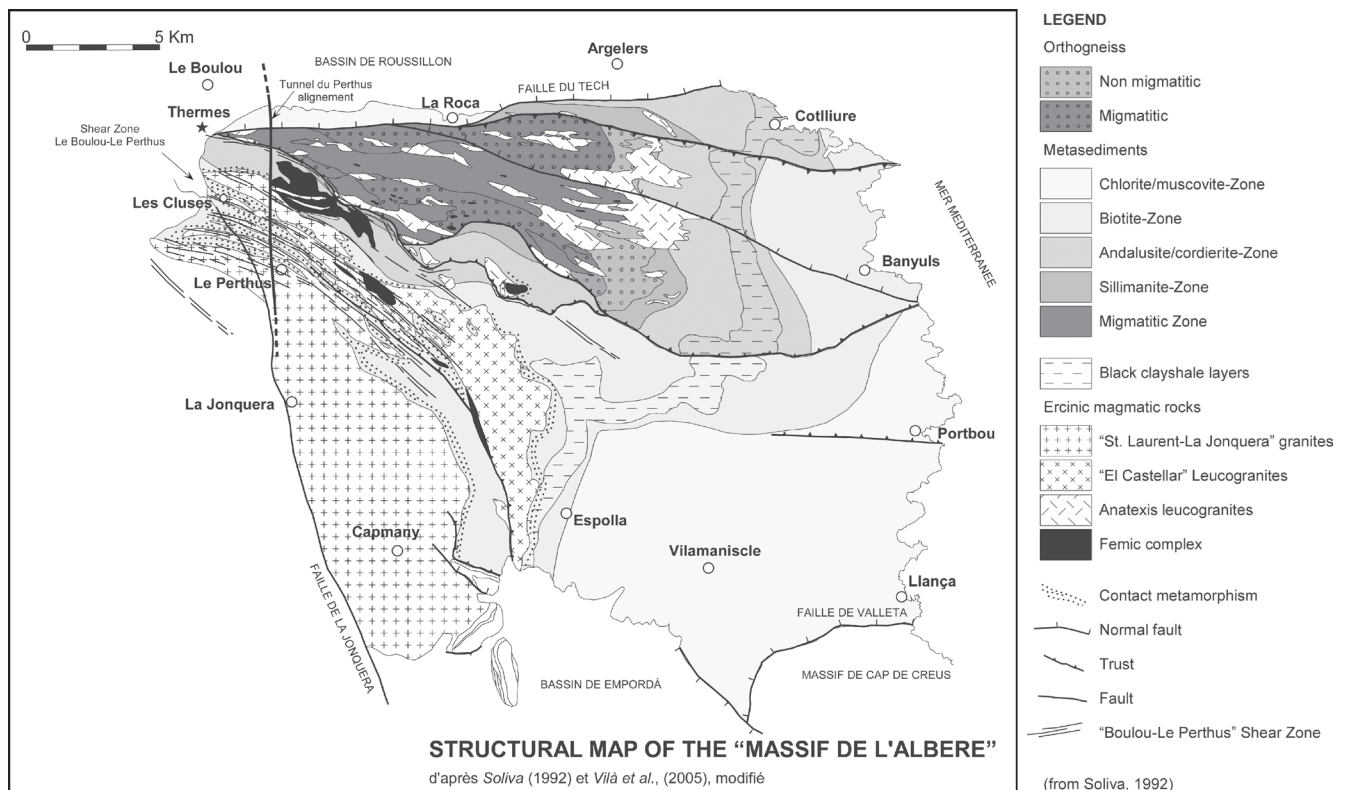

Fig. 1 - Geological framework of the area under examination.

Fig. 1 - Inquadramento geologico dell'area esaminata.

In various ways, and at a regional level, the alignments of the underground excavations intersect several important tectonic structures whose role in the organisation of groundwater flows is vital. The Le Boulou-Le Perthus fault zone is intercepted by the tunnel in the southern sector. This fault zone is about 5 km thick and it's characterised by the development of an intense foliation of N100°E to N120°E direction with vergence to the north. The granitoids, which are subject to ductile deformation, acquire a gneissic texture which increases in intensity the more it draws nearer to the main mylonitic horizons. The Montesquieu fault zone is made up of two distinct zones each of about 15 metres in thickness with a direction ranging from E-W to ENE-WSW. Both have a complex geometry and are composed of different anastomosed cataclastic planes characterised by the presence of cataclastic breccias and a clayey gouge. The shear planes incorporate lithons of schist from one to tens of meters in size, often altered due to circulation of hydrothermal fluids along the damage zones. The Le Boulou fault zone represents an important regional structure from both a hydrogeological and a geomechanical point of view: the former because of the presence of hydrothermal springs aligned along the deformation zones; the latter due to the poor quality of the soils. It has an average E-W direction and the main structure inclines 50-70° towards the north. It is a deformation zone of complex geometry characterised by tectonic planes ranging from one to tens of meters in size for an overall thickness of about 50 m. The central zone is made of clayey material (fault gouge), while the damage zones are characterised by schists and cataclastic gneiss. The processes of argillification are connected to a reduction of feldspar due to mechanical friction along the fault planes and, most probably, to the hydrothermal circulation along the damage zones associated with the main fault line; the presence of hydrothermal flows is likewise evidenced by the observation of recent deposits made up of gravels and sands cemented by a carbonatic matrix with associated carbonatic cement breccias which shows alteration and hydrothermal cementation (slice of microcrystalline silica).

Hydrogeological context

Geological formations have been divided into hydrogeological complexes characterised by different classes of permeability. The hydrogeological characterisation, the average permeability of the formations and the state of fracturing, have been based on the data obtained from 100 slug tests done in boreholes distributed along the tunnel alignment. In the present study, the classes of permeability have been defined according to the AFTES (Association Française des Travaux En Souterrain 1993) norms. The soils tested show in most cases a low to very low permeability due to scarce, if not inexistent, primary porosity. On the other hand, they sometimes present medium permeability determined by secondary porosity. The groundwater flows develop in accordance with the extent of fracturing and interconnection of the shear systems. Six different hydrogeological complexes have been identified.

Complex 1 – Quaternary deposits: consists of alluvial and alluvial-colluvial deposits. They form aquifers of limited lateral extension, which occupy the bottom of the valley of the main rivers with which they are in hydraulic equilibrium. They are not intersected by the excavation works and have been assigned a rate of medium to high permeability.

Complex 2 – Detritic deposits: is a very thin layer on hill slopes. Direct measurements were not carried out on these soils. Their hydrodynamic characterisation has therefore been estimated and they have been attributed a medium rate of permeability.

Complex 3 – Metapelites, gneiss and schists: the permeability levels measured in the slug tests are generally in the vicinity of 10^{-7} m/s which is a low to medium permeability. Along the zones of intense fracturing, the tests showed a characteristic anisotropy of the field of permeability, with the horizontal component being greater than the vertical one and groundwater flows being markedly compartmentalised. This result is coherent with the detailed geological study, which describes the presence of sub-vertical to sub-horizontal fault planes with fault gouge along the deformation planes. The latter constitute hydraulic barriers to the groundwater flows which, rather, proceed along the damage zones.

Complex 4 – Diorites, basic rocks and massive granodiorites: characterized by a low rate of permeability, which, on the basis of their brittle behaviour (as a response to the deformations), becomes medium-high in correspondence to the zones of intense fracturing. The values of permeability measured in the slug tests vary from 8×10^{-8} m/s for normal fracturing conditions to 6×10^{-6} m/s for intense fracturing zones and well-developed degree of interconnection between the fractures.

Complex 5 – The Le Boulou fault line: to this complex belong the soils, which constitute the damage zone of the Le Boulou fault line with a medium-high degree of permeability (K=3×10^{-6} ÷ 2×10^{-5} m/s). This fault differs from the core zone made of substantially impermeable (K=4×10^{-8} ÷ 2×10^{-7} m/s) clayey material (fault gouge). Along this structure are localised a number of thermo-mineral water points which are an economical resource for the area. For this reason, particular attention was paid to assess the risk of interference of this fault zone with the tunnel.

Complex 6 – Granodiorites of oriented texture and mylonites: the re-crystallisation and the formation of sericitic-argillaceous minerals along the schistous planes and the tectonic deformation determine a lowering of permeability. The values measured in the slug test range from 5×10^{-9} to 4×10^{-7} m/s and the degree of permeability is therefore low. Horizons of fracturing can be recognised, characterised by a medium degree of permeability (K = 10^{-7} ÷ 10^{-5} m/s) but with a low degree of interconnection.

Three hydrogeochemical types were identified:

a. Na-HCO$_3$ waters with high ionic salinity (80 - 180 meq/l) and high PCO$_2$ (close to 1 bar);
b. Ca-HCO$_3$ waters with medium-low ionic salinity (20 - 50 meq/l) and high PCO$_2$ (0.3 – 1 bar) which reveals their particular aggressiveness;

c. Ca-HCO$_3$ waters with low total ionic salinity (<20 meq/l) and low PCO$_2$ (in general 0.001 – 0.05 bar) which constitute most of the waters sampled in the sector of study.

In Figure 2 are shown the triangular diagrams of the main ionic species, which highlight how sodium is the dominant cation in the thermo-mineral water, while calcium is more present in the other water.

The water of group (a) is connected to deep groundwater flows; the water of group (b) and group (c) are surface networks. The water of group (b) differ from those of group (c) on the basis of the greater CO$_2$ component originating in deep groundwater circuits and released most probably by water of type (a) during their climb to the surface.

Water point census and water monitoring

During 2004, 98 water points have been censed and 53 of them have been monitored. The monitoring started in October 2004 before beginning the excavations and is still active today (2010). The monitoring allows the control of drainage impact on the aquifers. This activity has been conceived and carried out according to the prescription of the *"Loi sur l'Eau"*, under the supervision of the French local authority.

This monitoring includes natural groundwater levels, spring discharges, groundwater and surface water chemical-physical parameters control (electrical conductivity, temperature, pH) and isotopic content control (Oxygen and Deuterium). The monitoring frequence was different for each water point (weekly, monthly, each two months and continuous) according to the underground boring progress and to the risk of drawdown and socio-economic importance of the water point. This activity has permitted to check the evolution of the physical-chemical features of the water and

to determine the water catchments of the water points and the possible interactions with ground water flow systems during excavations. Meeting with the local authorities, private companies (e.g. Thermes de Le Boulou) and private citizens have been organised when monitoring was ongoing, specifying measures undertaken, the reasons and the modality. This has created the right collaboration climate which has permitted to cope with critical situation with the needed speed and efficacy.

The water points to be monitored have been selected considering the following parameters: (i) distance from the underground excavation (the closer ones were preferred); (ii) the type water use (public or private catchments, in particular the drinking water points and the thermal springs were preferred); (iii) reference water point (at least one spring was chosen outside the area preview to be influenced by the tunnel in order to have a point of reference of the natural state of the ground water flow before and during the underground excavations).

Ground injection were done from the surface before the crossing of the Le Boulou fault zone, to improve the geotechnical parameters of the ground and to waterproof fractures and pores. Other kind of waterproofing treatments were also performed from the tunnel (e.g. in the *Mas Anglade* fault zone and in some scattered more intensely fractured zones). In all those cases the groundwater level was monitored with automatic and continuous probes installed in piezometers. In Figure 3 is shown the example of the water table drawdown during TBM excavation trough the Mas Anglade fault zone.

Isotopic monitoring at thermal springs

Isotopes of Oxygen 18 and Deuterium have been analysed in Jannette et Clementine thermal springs the 15/10/2004 before the beginning of the excavation. All the known thermal springs (Colette, Jannette, Clementine, Saint Martin and Le
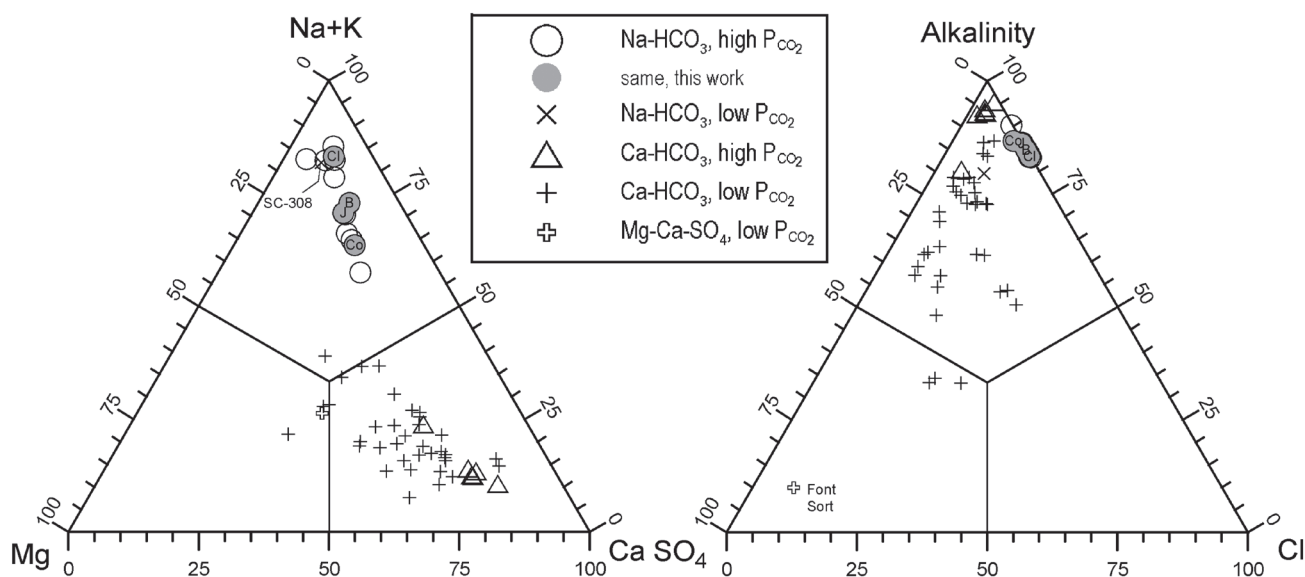

Fig. 2 - . Triangular diagrams of the main ionic species. The circular symbols indicate the water points recharged by deep groundwater flows.

Fig. 2 - Diagrammi triangolari inerenti gli ioni principali. I simboli circolari indicano punti d'acqua ricaricati mediante flusso sotterraneo profondo.
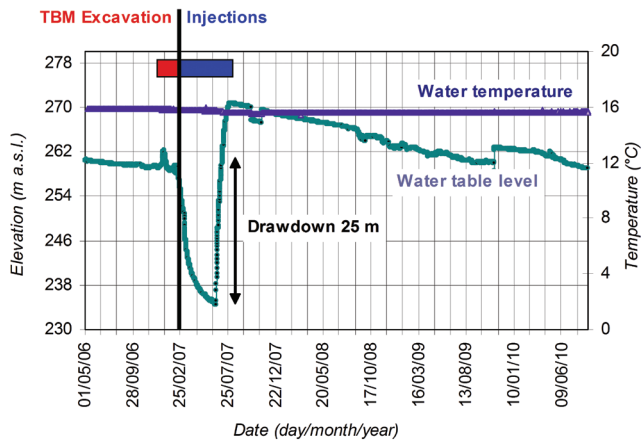
Fig. 3 - Monitoring of groundwater level and temperature during the TBM excavation trough the Mas Anglade fault zone. The rectangles show the excavation (red) and injection (blue) periods.

Fig. 3 - Monitoraggio di livello e temperature delle acque sotterranee durante la escavazione mediante TBM attraverso la zona di faglia di Mas Anglade. I rettangoli indicano i periodi di escavazione (rosso) e di iniezione (blu).

Boulou) have been monitored monthly between February to August 2007 when the tunnels excavation have been reached the section near the Le Boulou thermal site.

All samples showed values in line with the Global Meteoric Water Line (GMWL) which is the average isotopic composition of the rainwater on world scale (Fig. 4). During the monitoring there has been change on the isotopic concentration of springs coherent with a typical isotopic seasonal variation. A continuity of isotopic conditions of the thermal springs' have been measured before and after the underground works. This continuity of isotopic conditions of the thermal springs, compared with others hydro-geochemical and discharge monitoring evidences, allowed to conclude on
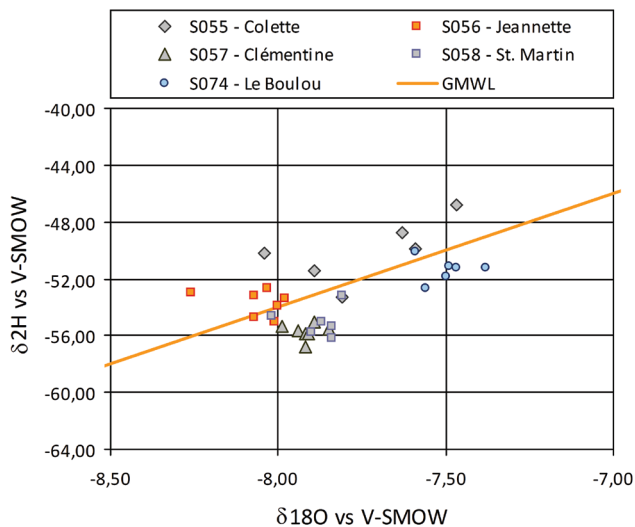

Fig. 4 - Isotopic composition (^{18}O and D) of the Le Boulou thermal springs. The red line shows the World Meteoric Line (WML). All springs have been sampled monthly from February to August 2007.

Fig. 4 - Composizione isotopica (^{18}O e D) delle sorgenti termali Le Boulou. La linea rossa indica la World Meteoric Line (WML). Tutte le sorgenti sono state campionate mensilmente da febbraio ad agosto 2007.

the absence of interference between the underground works and the thermal aquifer.

Dewatering the tunnel during construction

The evacuation of groundwater inflows and adduction of cold water to cool the TBM were managed with two separated pumping systems during excavation. Two pipelines (220 mm diameter) for the evacuation and two (same diameter) for the adduction where installed. Four pumps of 0,022 m^3/s were positioned at each excavation front (2 in use, 2 for backup). The maximum groundwater inflow recorded punctually into the tunnel during excavation was about 3-4 l/s. The total groundwater discharge from the two tubes after 1,5 years from the end of the excavation was around 0,003 m^3/s.

Water quality treatment plant at the portal during construction

A system of water quality treatment allowed to check and, when needed, to correct the pH (among 5,5 and 9,5), the hydrocarbons (< 2 mg/l) and the suspended matter (MES < 50 mg/l) of waters flowing out of the tunnels. The water treatment plant installed on the work site (see Fig. 5) had a 0,017 m^3/s capacity and was installed at the northern portal of the tunnel, in France. A systematic monitoring of water quality of the natural stream was done up hill and down hill of the water treatment plant output (see Fig. 6).
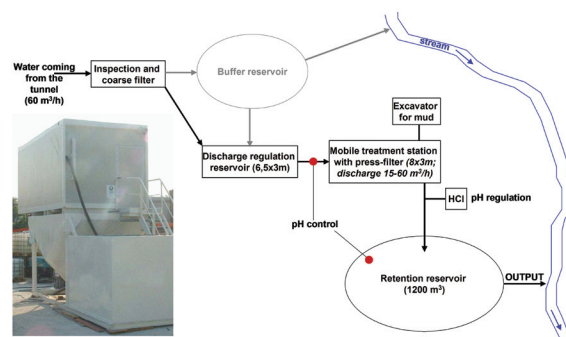

Fig. 5 - Water treatment plant installed on the work site to separate suspended mineral particles after flocculation and sedimentation.

Fig. 5 - Impianto di trattamento delle acque installato sul sito per la separazione dei materiali sospesi dopo flocculazione e sedimentazione.
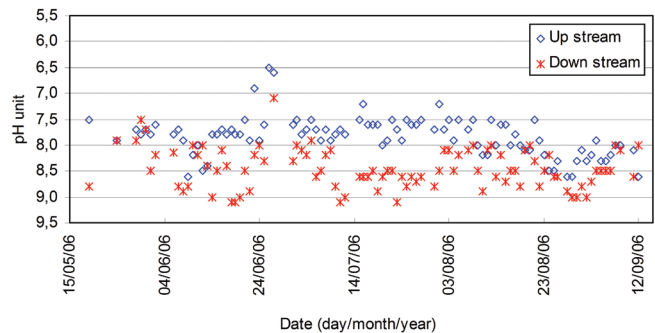

Fig. 6 - Monitoring of pH values into the stream close to the water treatment plant.

Fig. 6 - Monitoraggio dei valori di pH nell'acqua in prossimità dell'impianto di trattamento delle acque.

Feedback on groundwater impact analysis

An impact analysis on springs and wells concerning the drawdown hazard prediction was performed before the excavation using the analytical and statistical DHI method (Drawdown Hazard Index, Dematteis et al. 2001). Table 1 shows the number of water points assigned to the four classes of probability of drawdown according to the DHI scale before the excavation. 71% of water points do not present any risk, their DH Index being below 0,1. The remaining 29% show a low to high risk. Coherently with the hydrogeological reference model, where a marked compartmentalisation of the groundwater flows is described, the totality of water points with medium to high DHI degree are located near the alignment of the tunnel, at a maximum distance of 500 m and in correspondence with sectors where the tunnel intercepts the major fault zones with active groundwater flow systems ($K>10^{-6}$ m/s).

Tab. 1 - Classes of probability of drawdown attributed to water points before the excavation (from Torri et al. 2007).

Tab. 1 - Classi di probabilità di abbassamento attribuite a punti d'acqua prima dell'escavazione (da: Torri et al. 2007).

Class	Probability	N_i of point	Rate %
1	negligible	67	71%
2	low	14	15%
3	medium	5	5%
4	high	8	9%
		94	100%

During excavation and up to two years after the excavation no impact has been recorded on public potable waters. Until today also at the Boulou Thermal site no impact has been registered on known springs (Colette, Jeannette Clémentine, St Martin e Le Boulou. For all water points the observed impact is coherent with what forecasted before excavation, showed in Table 1.

Feedback on groundwater inflow into tunnel

During tunnel design, therefore before the excavations' start, water inflow in the tunnel have been studied and forecasted. using the analytical approach of Muskat-Goodman:

$$q = \alpha \, \frac{2\pi k H}{\ln\left(\dfrac{2H}{r}\right)}$$

Where α is the reduction coefficient (considered equal to 0,1) to pass from short time (transient and instantaneous water inflow) to long time (at steady state conditions) water inflow, as a result of depletion of the aquifer, the decrease of groundwater level and the reduction of permeability of the rock mass due to the closure of the fractures; k is the rock mass average permeability; H is the hydraulic head; r is the radius of the tunnel. In this step, it was considered

a homogeneous rock aquifer with an average permeability of 5.3×10^{-7} m/s and a hydraulic head of 80 m. The specific discharge rate was predicted of about 0.007 m^3/s/100m.

These predictions showed a total long term discharge (steady state) from the tunnel of 0,059 m^3/s. This discharge represents the sum of water coming from the bypass (0,028 m^3/s), from the exploratory tunnel (0,022 m^3/s) and from the whole length of the two tubes of the main tunnel (0,009 m^3/s). The steady state inflow of the main tunnel (including bypass) was estimate at 0,037 m^3/s, excluding the water drown by the exploratory tunnel.

In December 2006, when the excavations were at the beginning, but already started, the forecasted discharge on the stretches not yet excavated was updated, considering the observations on the tunnel already done. For the stretch included between the high point of the tunnel and the Northern entrance, for a length of 6500 m, a reduction of the total outflow was suggested. For this stretch the global outflow forecasted was 0,017 m^3/s, including the bypass discharge, but excluding the exploratory tunnel discharge. This update of the forecasted maximum transient discharge was carried out using a new equation, derived from Dupuit equation:

$$Q = \frac{4\pi K l d_z}{\ln\left(\dfrac{e^{\frac{4\pi L}{a}} + e^{\frac{-4\pi L}{a}} - 2}{e^{\frac{4\pi r_0}{a}} + e^{\frac{-4\pi r_0}{a}} - 2}\right)}$$

Where K is the hydraulic conductivity of the aquifer, l is the length of the aquifer portion crossed by the tunnel; d_z is the water head above the tunnel roof; L is the length of the water flow system upstream of the tunnel, a is the thickness of the aquifer and r_0 the radius of the tunnel. The parameter dz was introduced as the layers that lie along the axis of the tunnel are not always vertical. If the layer is vertical, then $d_z = L$, and if the layer is inclined $dz < L$.

During excavations have been systematically recorded groundwater inflow, punctually at the excavation faces and outside the portal, in the water evacuation pipelines. These data permit us today to describe the variation of water inflow during excavation (representative of the transient state)
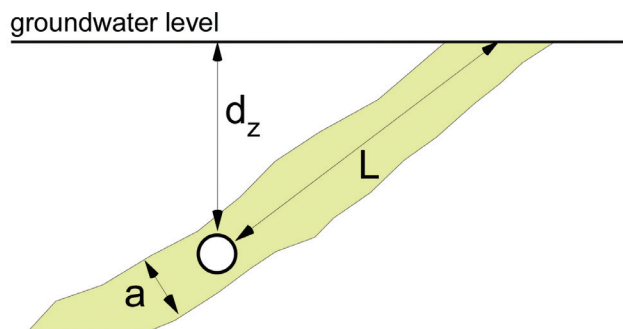

Fig. 7 - Conceptual diagram of a drainage tunnel in a inclined aquifer.

Fig. 7 - Diagramma concettuale di un tunnel drenante in un acquifero inclinato.

and three years after the excavation's end (representative of the steady state). During excavation, the outflow recorded included both waters drawn from the massif and used for the excavation works. It's anyway possible to separate the water drawn from the massif. On Figure 7 are shown the total groundwater discharge into tunnel recorded between June 2006 and November 2007. These measures have been compared with the boring speed of the two TBM. The average groundwater discharge into the tunnel during this period is 0,008-0,010 m^3/s. If we consider the 4830 m of tunnel excavated between June 12/06/2006 and 4/01/2007, with practically continuous recorded measures, the average specific discharge is approximately 0,00019 m^3/s/100m. It's worth mentioning that this average specific discharge was much higher in fault zones (e.g. Mas Anglade fault zone), where the water discharges have been two orders of magnitude higher. It should be also noted that the discharge in the fault zones shown in the chart of Figure 7 are probably less important than the maximum punctually really occurred during excavation, as they have so quickly reduced that it wasn't possible to record. The highest value in the chart do not show the peak, but a transitional discharge level between the peak and the stabilised outflow. The greater discharge (approximately 0,035 m^3/s) has been recorded where the tunnel crosses the fault of Creu de Signal, where the drainage has caused the drawdown of two small springs as mentioned in the previous chapters.

Lastly, for what concerns the long term drainage, at the end of excavations, the discharge reduced for a natural progressive sealing of the fractures in the plastic zone around the tunnel and also because of the final tunnel lining which have made its walls waterproof. The tunnel lining has been made with precast segments made of reinforced concrete, sealed with

waterproofing joints dimensioned to resist the idrostatic pressure. The average stabilised discharge measured two years after the end of works at the two tubes of the North entrance was approximately 0,003 m^3/s. This discharge refers to a length of approximately 6500 m between the high point of the tunnel and the Northern entrance. The forecasted discharge excavation of this section of the tunnel was 0,017 m^3/s.

The forecasted discharge was overestimated mainly because the degree of permeability of the rock mass under normal conditions of fracturing was overestimated. The biggest amount of water inflow was related to a few fault zones crossed during excavation.
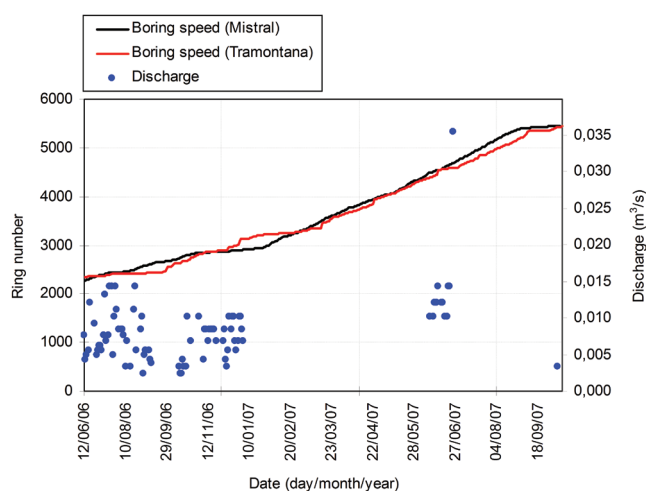
Fig. 8 - Monitoring of groundwater discharge into tunnels during excavation. Lines show the excavation speed and dots show the measurements of total groundwater discharge into tunnel during excavation. Each ring is 1,5 m long.

Fig. 8 - Monitoraggio dell'afflusso di acque sotterranee nel tunnel durante l'escavazione. Le linee indicano la velocità di escavazione e i punti indicano le misure degli afflussi totali di acque sotterranee nel tunnel durante l'escavazione. Ogni anello è lungo 1,5 m.

REFERENCES

AFTES (1993) Association Française des Travaux En Souterrain: Text of recommendations for a description of rock masses useful for examining the stability of underground works. Tunnel et Ouvrages Souterrains n°117, May-June 1993.

Dematteis A, Kalamaras G, Eusebio A (2001) "A systems approach for evaluating springs drawdown due to tunnelling", AITES-ITA 2001 World Tunnel Congress, Milano, Italy 10-13 June, II, 257-264.

Soliva J, Brunel M, Matte P (1992) La zone de décrochement ductile Le Boulou-Le Perthus dans la granodiorite de Saint-Laurent (Pyrénées Orientales) *"The ductile detachment zone Le Boulou-Le Perthus in the granodiorite of Saint-Laurent (Eastern Pyrenees)"*. C.R. Acad Sci. Paris, Série II, n. 312, 639-646.

Torri R, Dematteis A, Delle Piane L (2007) Drawdown hazard of springs and wells in tunneling: predictive model and Verification. Proc. XXXV IAH Congress, Groundwater and Ecosystems, Lisbon 17-21 Sept. 2007, 10 pp.

Venturini G, Spanò M, Scionti V, Ducrot M, Vincente P, Casado J (2010) France – Spain High-Speed Rail Link, Perthus Base Tunnel: Crossing Very Difficult Terrains with Two Double Shield 10m-Diameter TBMs. ITA-AITES World Tunnel Congress 14-20 May 2010, Vancouver, British Columbia, Canada.

Vilà M, Pin C, Enrique P, Liesa M (2005) Telescoping of three distinct magmatic suites in an orogenic setting: Generation of Hercynian igneous rocks of the Albera Massif (Eastern Pyrenees). Lithos 83 (2005), 97-127.