Groundwater in the Perthus Tunnel: feedback after excavation

Antonio Dematteis, Riccardo Torri, Bertrand Chereau and Michel Ducrot

Abstract: This work introduces the experiences concerning water management, surface and groundwater impact observation wells, ground injections and water quality control of the 8,4 km long Perthus high speed railway tunnel. During excavation granodiorites, schists, diorites, gneiss, black schists and coarse fluvial deposits were encountered. Some important tectonic structures with associated groundwater flow have also been crossed. A study is then presented of the hydrothermal springs of *Le Boulou*, which have not been impacted.

Keywords: groundwater, excavation, monitoring, thermal springs, drawdown hazard

Antonio DEMATTEIS ✉
Riccardo TORRI
SEA Consulting srl
via Cernaia 27
10121 Torino - Italy
Fax:+390115119185

Bertrand CHEREAU, Michel DUCROT
Eiffage Travaux Publics, France

Antonio DEMATTEIS ✉
dematteis@seaconsult.eu

Riccardo Torri: torri@seaconsult.eu

Bertrand Chereau: bchereau@construction.eiffage.fr

Michel Ducrot: Michel.DUCROT@eiffage.com

Received: 07 october 2010 / Accepted: 18 november 2010
Published online: 17 june 2011

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.*

Il Tunnel del Perthus è una parte della linea ad alta velocità tra la Francia e la Spagna, situata nella zona esterna dei Pirenei, tra Perpignan e Figueres. I lavori nel sottosuolo sono consistiti in due gallerie principali parallele, di 10 m di diametro e 8,4 km di lunghezza, distanziate circa 30 m tra loro. Gallerie di sicurezza connettono le due gallerie principali ogni 200 m. Le due gallerie principali sono state scavate con metodo meccanizzato utilizzando due Tunnel Boring Machines doppio scudate (DS-TBM), procedendo dal lato spagnolo verso la Francia. La prima DS-TBM, chiamata Tramontana, ha iniziato lo scavo il 28/06/2005 e terminato il 23/11/2007. La seconda, chiamata Mistral, ha iniziato il 30/09/2005 e ha terminato il 01/10/2007. Inoltre, un tunnel esplorativo di circa 450 m di lunghezza è stato scavato approssimativamente a metà del tracciato del tunnel principale, con metodo tradizionale, per investigare una zona di taglio fragile-duttile dalla superficie alla quota del tunnel. Due gallerie di trattamento preventivo allo scavo delle DS-TBM, di 6 m di diametro, sono state realizzate a partire da questo tunnel esplorativo, con andamento parallelo all'asse del tunnel principale, per una lunghezza di 80 m da un lato e 170 m dall'altro.

The Perthus railway 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 in length, 10 m in diameter within a distance of about 30 m. Security galleries connect the two tubes every 200 m. An exploratory tunnel about 450 m long has been excavated with traditional drill and blast method through an important ductile-brittle fault zone, approximately half way into the main tunnel. Two soil treatment tunnels of 6 m diameter and about 80 m and 170 m in 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 on 28/06/2005 and finished on 23/11/2007. The second called Mistral started on 30/09/2005 and finished on 1/10/2007 (Venturini et al., 2010).

 DOI 10.4409/Am-026-11-0026

Geological context

The geological context of the area was 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 evidence received from the boring fronts. The hydrogeological model has been based on the geological data mentioned above, 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 an evaluation of the reliability of the geological and hydrogeological reference model. This evaluation of reliability has determined the actions 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 an 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.

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 fundamentall. 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 anastomotised 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 hydrogeological and geomechanical points 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.

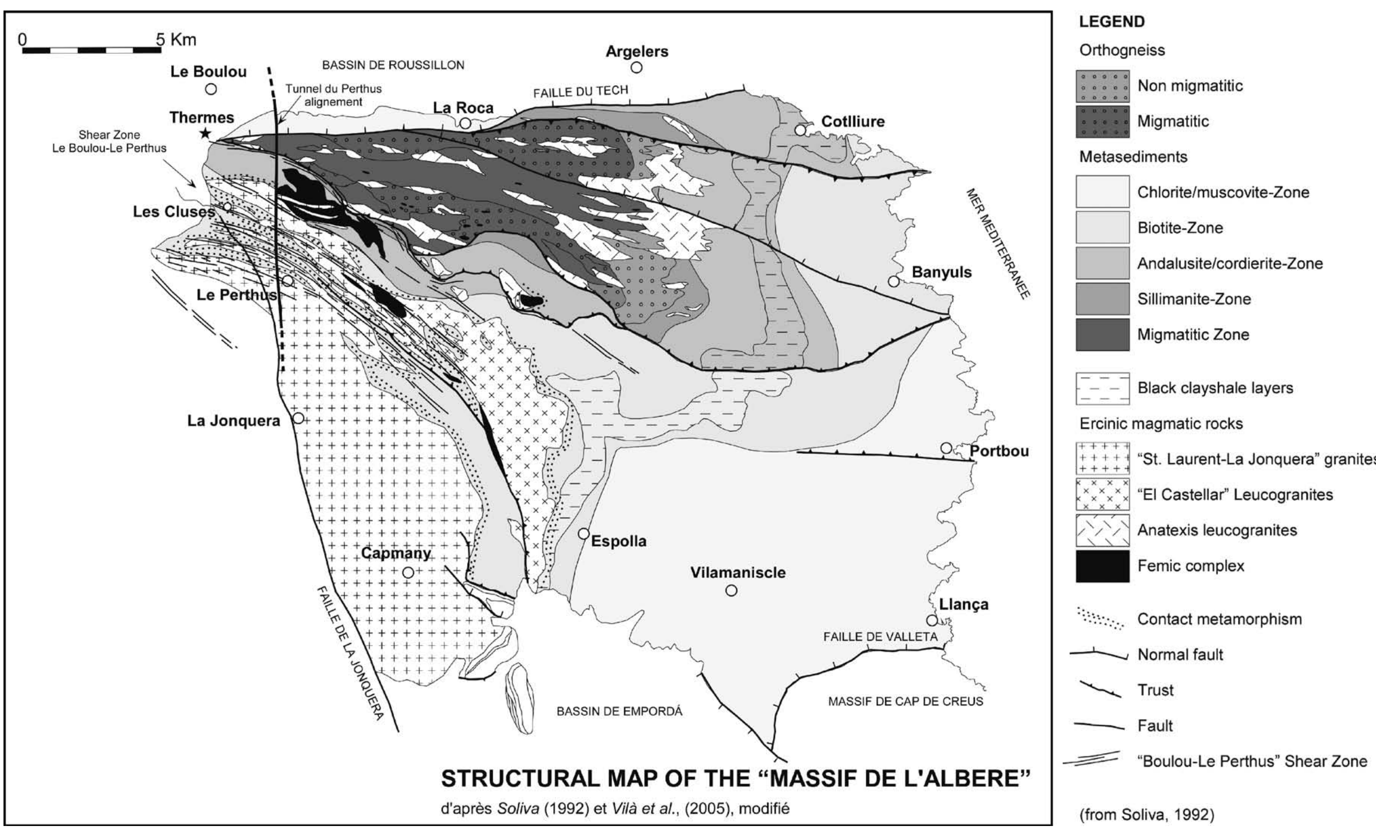

Fig. 1: *Geological framework of the area under examination. North is up*

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 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 intersected by the excavation works at the portals and they have been characterized with a 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 $8x10^{-8}$ m/s for normal fracturing conditions to $6x10^{-6}$ 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 ($K=3x10^{-6} \div 2x10^{-5}$ m/s). This fault differs from the core zone made of substantially impermeable ($K=4x10^{-8} \div 2x10^{-7}$ 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 $5x10^{-9}$ to $4x10^{-7}$ m/s and the degree of permeability is therefore low. Horizons of fracturing can be recognised, characterised by a medium degree of permeability ($K = 10^{-7} \div 10^{-5}$ 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 taken a census and 53 of them have been monitored. The monitoring started in October 2004 before beginning the excavations and continues 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, bimonthly 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 the checking of the evolution of the physical-chemical features of the water and the determination of the water catchments of the water points and the possible interactions with groundwater 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 facilitated the management of critical situation with the necessary speed and efficacy.

 DOI 10.4409/Am-026-11-0026

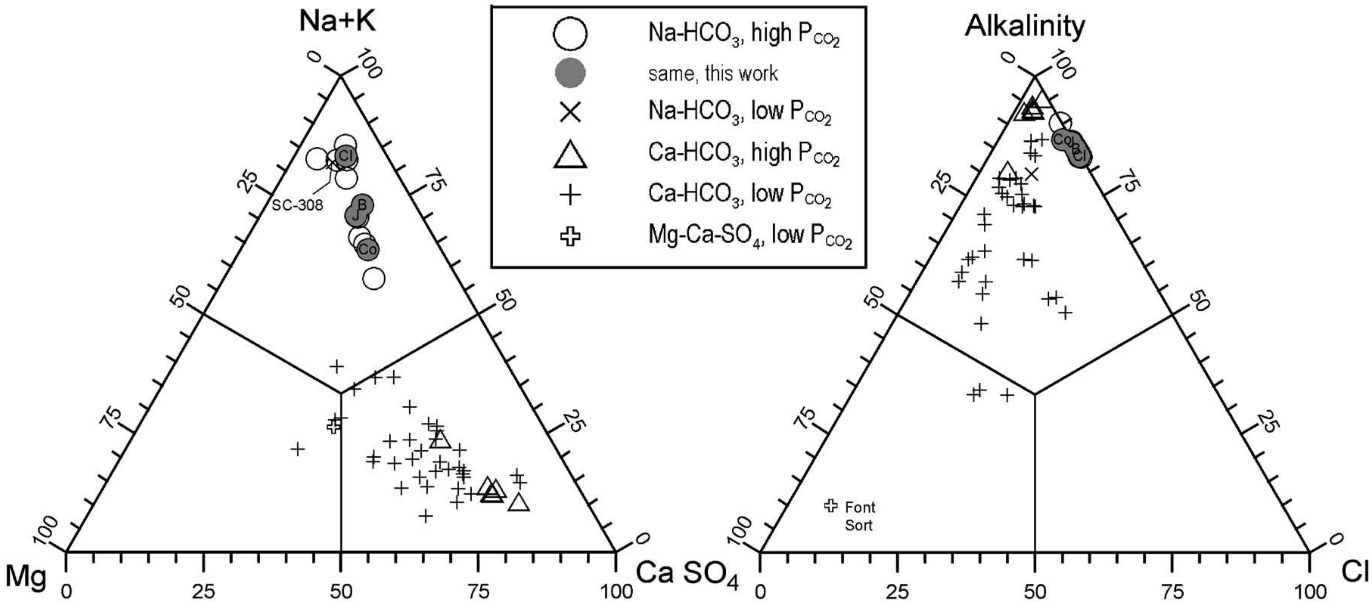

Fig. 2: *Triangular diagrams of the main ionic species. The circular symbols indicate the water points recharged by deep groundwater flows*

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 preview area to be influenced by the tunnel in order to have a point of reference of the natural state of the groundwater flow before and during the underground excavations).

Ground injections 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 kinds of waterproofing treatments were also performed from the tunnel (e.g. in the *Mas Anglade* fault zone and in some scattered more intensely fracturated 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 through the *Mas Anglade* fault zone.

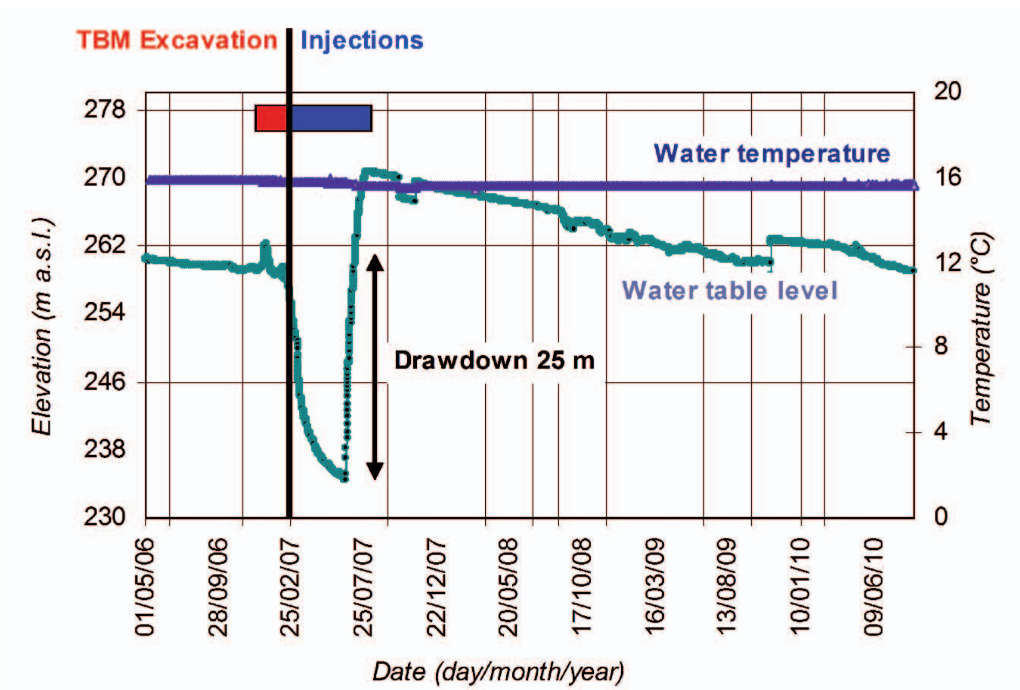

Fig. 3: *Monitoring of groundwater level and temperature during the TBM excavation through the Mas Anglade fault zone. The rectangles show the excavation (red) and injection (blu) periods.*

Isotopic monitoring at thermal springs

Isotopes of Oxygen 18 and Deuterium had been analysed in *Jannette* and *Clementine* thermal springs on 15/10/2004 before the beginning of the excavation. All the known thermal springs (*Colette, Jannette, Clementine, Saint Martin* and *Le Boulou*) have been monitored monthly between February to August 2007 when the tunnels excavation 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 was measured before and after the underground works. This continuity of isotopic conditions of the thermal springs, compared with other hydro-geochemical and discharge monitoring evidence, led to the conclusion that there was no interference between the underground works and the thermal aquifer.

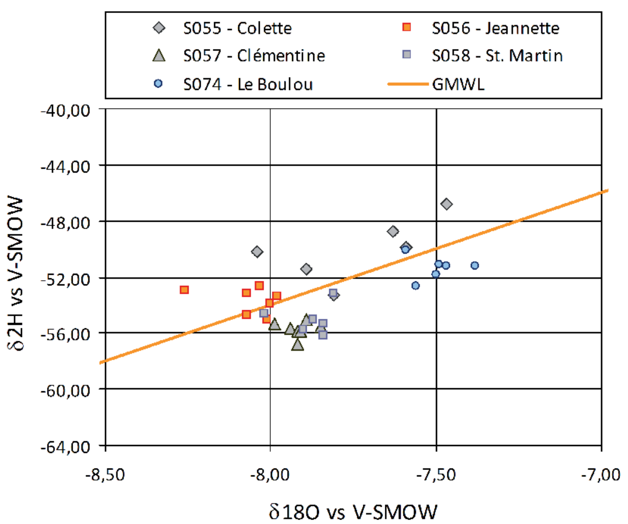

Fig. 4: *Isotopic composition (^{18}O e D) of the Le Boulou thermal springs. The red line shows the World Meteoric Line (WML). All springs have been sampled monthly from February to August 2007.*

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 the checking of and, when needed, the correction of the pH (between 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 sream was done up hill and down hill of the water treatment plant output (see Fig.6).

Feedback on groundwater impact analysis

An impact analysis on springs and wells concerning the drawdown hazard prediction was performed before 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 excavation. 71% of water points do not present any risk, their DHIndex 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).

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* and *Le Boulou*). For all water points the observed impact is coherent with what forecasted before excavation, showed in Table 1

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

CLASS	*PROBABILITY*	*N_i of point*	
1	NEGLIGIBLE	67	71%
2	LOW	14	15%
3	MEDIUM	5	5%
4	HIGH	8	9%
		94	100%

Feedback on groundwater inflow into tunnel

During tunnel design, therefore before the excavations started, water inflow in the tunnel was studied and forecasted. using the analytical approach of Muskat-Goodman:

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

Where **α** is the reduction coefficient (considered equal to 0,1) to pass from short term (transient and instantaneous water inflow) to long term (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 the radius of the tunnel. In this step, it was consider 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 at about 0.007 $m^3/s/100$ m.

These predictions showed a total long term discharge (steady state) from the tunnel of 0,059 m^3/s. This discharge represents the

DOI 10.4409/Am-026-11-0026

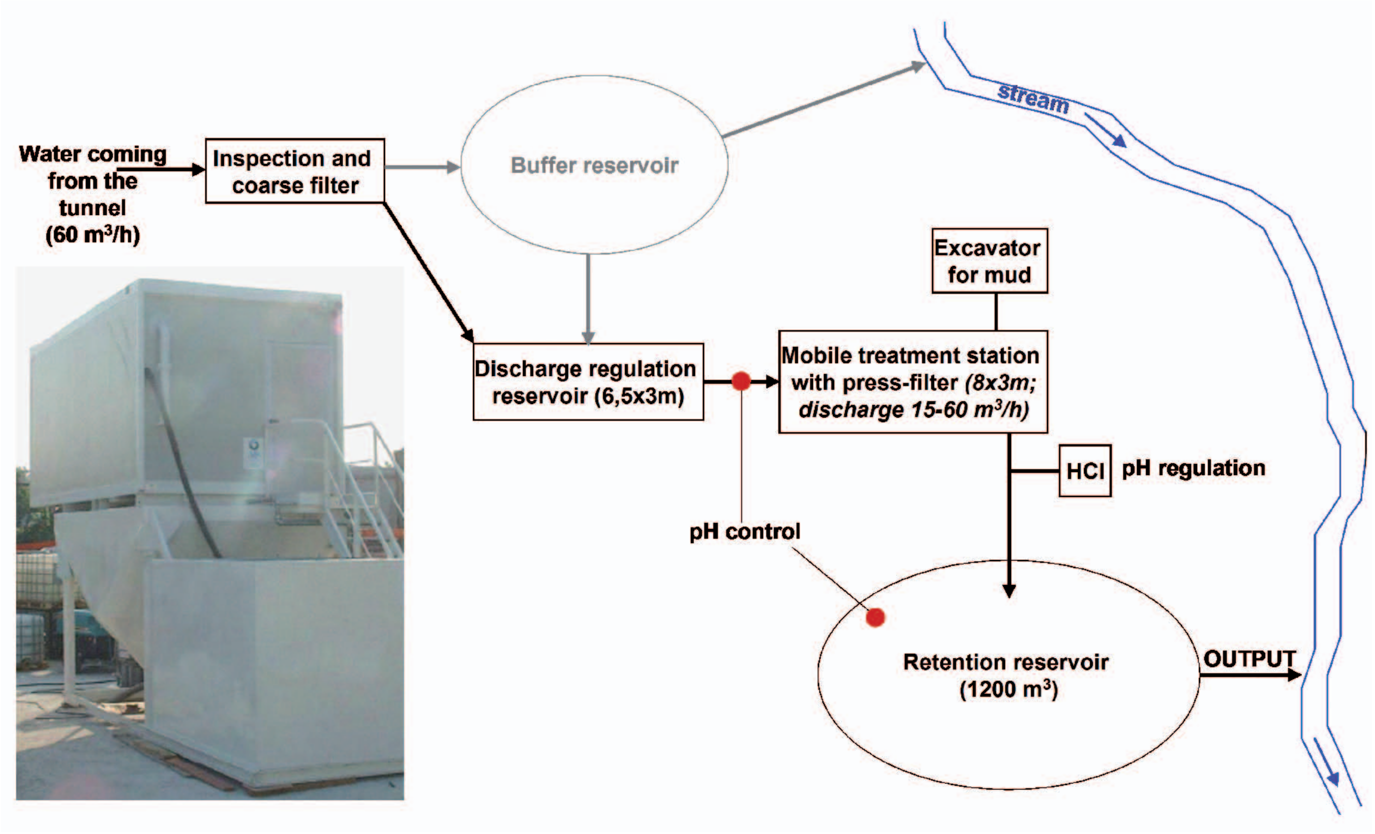

Fig. 5: *Water treatment plant installed on the work site to separate suspended mineral particles after flocculation and sedimentation.*

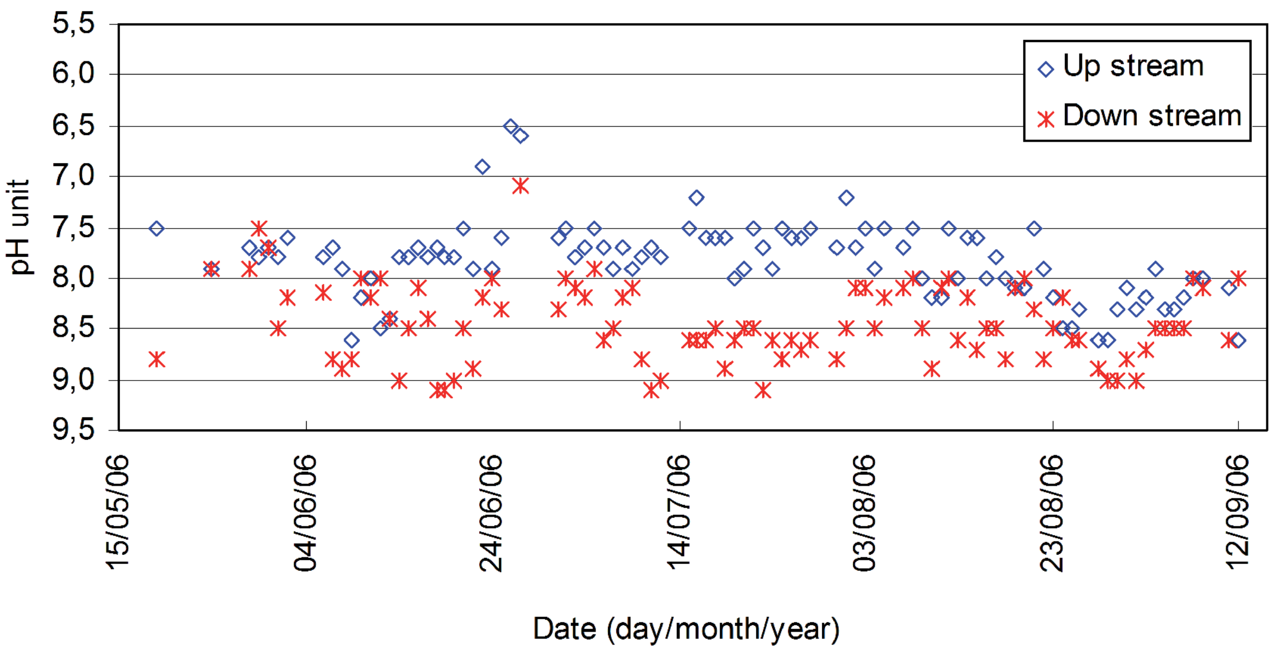

Fig. 6: *Monitoring of pH values into the stream close to the water treatment plant*

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 estimated at 0,037 m^3/s, excluding the water drawn 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 the *Dupuit* equation:

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

Where ***K*** is the hydraulic conductivity of the aquifer, ***l*** is the length of the aquifer portion crossed by the tunnel; $\boldsymbol{d_z}$ 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 $\boldsymbol{r_0}$ the radius of the tunnel. The parameter d_z 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 $d_z < L$.

During excavations groundwater inflow has been systematically recorded, 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) 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 is anyway possible to separate the water drawn from the massif. In Figure 7 the total groundwater discharges into the tunnel recorded between June 2006 and November 2007 are shown. These measurements 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

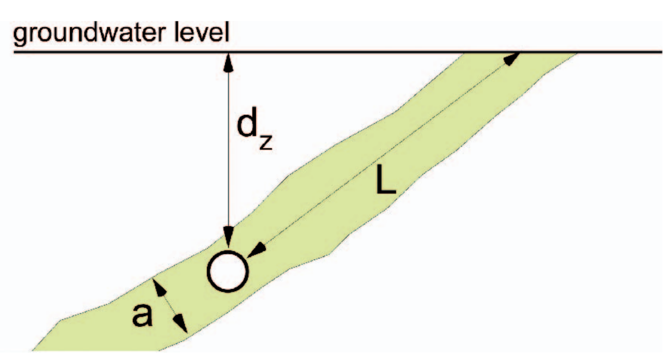

Fig. 7: *Conceptual diagram of a drainage tunnel in a inclined aquifer.*

of tunnel excavated between June 12/06/2006 and 4/01/2007, with practically continuous recorded measurements, the average specific discharge is approximately 0,00019 $m^3/s/100$ m. 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 discharges that occurred during excavation, since they diminished so rapidly that it wasn't possible to record them. The highest value in the chart does 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 previously.

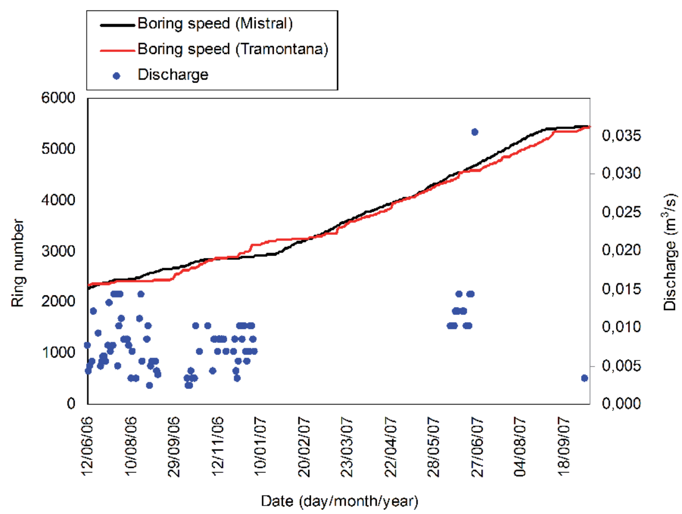

Fig. 8: *Monitoring of groundwater discharge into tunnels during excavation. Lines show the excavation speed and dots show the mesurements of total groundwater discharge into tunnel during excavation. Each ring is 1,5 m long*

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

Acknowledgment: Presented at Session "Hydrogeological impacts of tunnels", GEOITALIA 2009, Rimini, September 2009 (session's conveners: Alessandro Gargini, Valentina Vincenzi, Michele Sapigni).

DOI 10.4409/Am-026-11-0026

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