Water Resources Management in Tunneling: insights in the decision-making process to improve tunnels environmental sustainability

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Abstract An integrated decision-making process for water-resources management in tunneling has been developed by the authors during the design and construction phases of several large tunnel projects in Italy, France, Spain and Austria. All those projects concerns deep tunnels under construction or under design in mountain regions and therefore this integrated decision-making process is particularly suggested for complex, fissured and heterogeneous geological settings. Today there is an increased need for coordinating all hydrogeological activities in tunneling planning, in order to improve environmental sustainability. The proposed decision-making process include six main steps: (1) definition of the reference geological model, (2) quantification of geological forecasting reliability (3) prediction water-inflow rates into the tunnel (4) hazard analysis of hydrogeological impacts outside the tunnel, (5) study of tunnel groundwater-inflow valorization and re-utilization and (6) design of solutions to preserve or compensate any possible water lost. The application of this approach should help hydrogeologists and decision makers to improve the water resources management in tunnelling.

Keywords: Environmental sustainability, water-resources management, tunneling, Europe

1. Introduction

The need for new rail and road communication routes in Europe bring to design and construct long and complex underground infrastructures (i.e. railway base tunnels and road tunnels) in complex geological contexts such as the Alpine region.

During the last ten years considerable improvements have been achieved in the management of hydrogeological impacts on springs and wells related to underground works. This is due to the increased attention to environmental aspects related to water resources.

At present, the management of environmental impacts on groundwater circulation related to deep tunneling is an essential part of tunnels design. Nevertheless, today there is an increased need for coordinating all hydrogeological activities that are normally involved in tunneling planning.

During the planning stages designers' activities normally focuses on the way the groundwater influences the tunneling techniques and tunnel design. The assessment of environmental impacts in tunnel design has been introduced only in recent times. This is the consequence of some European Community Directives (00/60/CE, 91/271/CE and 98/83/CE), whose adaptation gradually increased in all nations of the Alpine region (Italy: D.L. 152/99, L. 36/94; France: Loi sur l'Eau 92-3/92; Switzerland: LEaux 24/01/91; and Austria: BGBI 215/59 and BGBI 74/97). These laws rightly and clearly impose the protection of groundwater.

Today those laws are applied but, as every tunnel has a very specific context, it is difficult to extrapolate the results achieved on a new situations. There is a lack of consolidated methodologies for evaluating tunneling impacts on underground water-resources in a complete and integrated manner. This paper describes a decision-making process aimed to help the water resources management in tunneling. This process should also improve the *environmental sustainability* of tunnels. The usage of water discharge drained into the tunnels and the exploitation of energy coming from those waters and from water and rocks heat transforms what was normally considered as a lost into a gain.

This paper tries to make a synthesis of experiences coming from the most important ongoing tunnel projects in Europe, such us the Turin-Lyon railway connection (53 km base tunnel between Italy and France in the western Alps), the underground Milan–Genoa railway (22 km long tunnel in Apennines and Alps, Italy) and the Brenner Basis railway Tunnel (54 km between Austria and Italy). The effectiveness of the approach was tested during the tunneling phases related to the Pont Ventoux Hydroelectric power plant (northern Alps in Italy), the Modane exploration tunnel of the Lyon–Turin railway connection (France) and the Perthus railway tunnel (8 km long between Spain and France).

This decision-making process links several topics aiming at the risk assessment analysis, to valorize the water resources and to compensate the impacts. Those topics are: (1) definition of the hydrogeological reference model (based on the geological data); this includes the geometric and hydrodynamic parameters characterization that allows to find the most critical areas and to give a qualitative and probabilistic forecast for the expected hydrogeologic conditions during tunneling and operation phases (Venturini et al., 2001); (2) quantification of the uncertainty in terms of geological forecasting reliability (e.g. Perello et al., 2005); (3) prediction of tunnel discharge rates with analytical solutions for steady-state final values (e.g. the analytical approaches of Goodman et al. 1965, Chisyaki 1984, El Tani 2003) or transient inflows (Perrochet 2005, Perrochet and Dematteis 2007); (4) prediction of springs and wells drawdown hazard around the tunnel (Dematteis et al. 2001); (5) valorization of groundwater-inflow, such as the groundwater-catchment into the tunnel and the energy recuperation from groundwater-inflow (Rybach & Pfister 1994, Unterberger et al. 2005) and (6) solutions that are to be adopted in order to compensate the impacts in the drained area outside the tunnel, such as the design of new groundwater-catchments.

2. Hydrogeological Reference Model

Fig. 1 shows the process adopted to define the Hydrogeological Reference Model (HRM). This process follows six important steps: the first and the second correspond to the geological studies, that produce the Geological Reference Model (GRM). These aspects are very important since they provide the geometrical framework of aquifers and aquicludes. No detailde discussion is provided here for geological studies since diffused information about it can be found in specialistic paper (e.g. Perello et al. 2005). The next four steps, carried out in the framework of the hydrogeological study, are devoted to the HRM development. HRM is an impacts forecasting tool and represents the base for all following steps (e.g. risk analysis, water-loss compensation research, valorization of groundwater inflows, etc.).

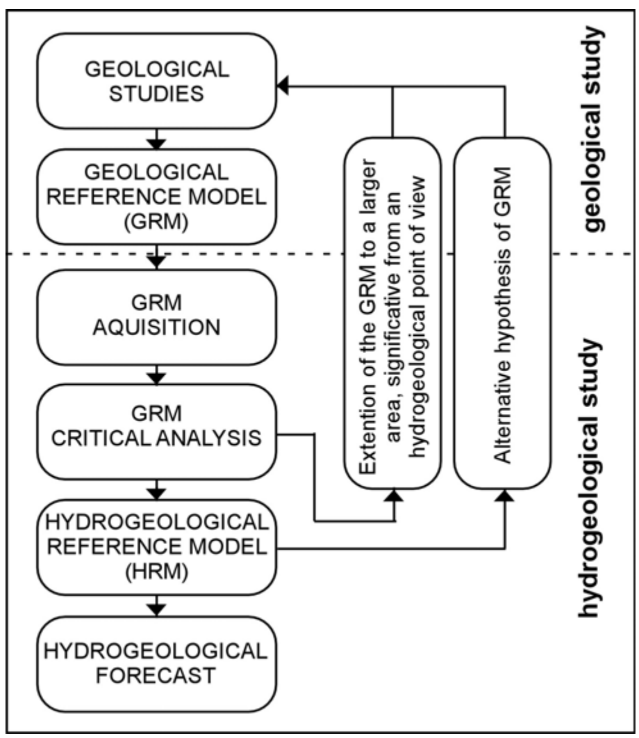

Fig. 1. Flow chart of geological and hydrogeological studies applied to deep tunnels.

Steps three to six are mainly devoted to the integration of GRM with the hydraulic parameters of aquifers, in order to predict water-inflow and water-pressure along and around the tunnel line. Those predictions are necessary because they strongly affect the costs of tunnel excavation and of tunnel maintenance.

Hydraulic parameters that mainly affect the hydrogeological conditions in the tunnel are the aquifer recharge-rate, the permeability and the hydraulic head. The transmissivity and storage coefficient (measured in boreholes, wells and springs) are also important for numerical simulations of groundwater flow systems.

The *aquifer recharge-rate* is the most important parameter influencing the groundwater-inflow into the tunnel. This is particularly true for high permeability sectors intercepted by tunnels in mountains regions, where the permeability distribution is heterogeneous and the scale of the drawdown area is very large (often in the order of some square kilometers).

The aquifer recharge-rate expresses the volume of infiltrated water in the catchments area above the tunnel level. The maximum discharge of water inflow into the tunnel will be less or equal to the aquifer recharge-rate.

The evaluation of this parameter is difficult; mainly for two reasons: the frequent lack of data required for this calculation (geological surveys and flow-systems geometry reconstruction on a very large scale – for many kilometers around the tunnel alignment) and possible errors in catchments area estimation (often estimated, as direct measurements are typically long and expensive procedures).

The hydrodynamic characterization of all the geological formations allows the classification of rocks into homogeneous hydrogeological complexes, which are characterized mainly by their degree of permeability, lying in a narrow range.

The *permeability degree* given to each hydrogeological complex refers to the average permeability measured by the complex and changes in a space defined by a minimum and a maximum permeability value.

In an alpine context, the flow is usually concentrated along permeable mainlines such as fault zones, single fracture, karst and chemical dissolution horizons, etc. The permeability degree of these structures can be considered as the biggest component of the permeability tensor with a direction parallel to the principal discontinuity system. The intersection between those high permeability discontinuities and the tunnel alignment can cause punctual and important water inflows into the tunnel itself.

The *hydraulic head* evaluation is also important during the design phase because of its influence on the hydrostatic head on the tunnel. This parameter affects the water discharge into the tunnel and its variations in time; together with permeability, allows to forecast the water inflows trend in unsteady-state flow. The hydraulic head in undisturbed conditions and its evolution during a complete climatic cycle is observed in piezometers, boreholes and rivers. In mountain regions, its distribution is strongly controlled by the topographic surface. The drainage in underground works in areas characterized by elevated hydraulic head may lead in the massif a large scale drawdown.

3. Hydrogeological forecasting reliability

The knowledge of the hydrogeological model reliability is one of the most important aspects for risk assessment in tunneling. Underestimation of uncertainty is probably the main reason for economical and construction problems. Unfortunately these models implies variable uncertainty, mainly due to the uncertainty attached to GRM caused by the complex behavior of natural environment.

An example of quantification of the geological model reliability is given by Perello et al. (2005). Starting from the GRM, a computational procedure has been established by the above authors, which allows to define the reliability-index as a value ranging from 0 to 10. The significance of this value in terms of possible variations of the forecasts has been deduced examining different case histories. There are three types of parameters influencing the reliability of geological forecasts:

- Investigation Parameters, i.e. parameters which define the quality of the geological and hydrogeological investigation methods used in order to explore the rock volume to be excavated;
- Interpreter Skill, i.e. the capacity of the geologist(s) which creates the model to interpret the data;
- System Parameters, i.e. parameters which define the geological complexity of the rock volume and therefore the system to be investigated;

By analysing the interactions between these parameters it is possible to understand the process leading to the construction of a geological model. This consequently permit to reach a quantification of the reliability.

4. Prediction of groundwater-inflow

According to direct observations the expected water discharge into the tunnel can be successfully calculated by comparing the results of two different methods, which respectively follow an analytical and an empirical approach. Numerical 2D or 3D modeling provides good results in terms of ground water inflow and drawdown prediction only when a reliable hydrogeological reference model is available (well known boundary conditions and geometric assessment, borehole tests available); in these cases, local complex situations can be numerically simulated in order to verify hypothesis and to improve the HRM.

The empirical method is based on the comparison with other tunnels, excavated in similar hydrogeological conditions, and on the basis of available hydrogeological information (in situ tests and chemical and physical measures, etc.).

The analytic approach is based on the application of Dupuit's formula, with corrections related to the geometry of aquifer layers, the intake area and the permeability reduction connected to hydraulic head variations and effective stress around deep tunnels.

Both methodologies are based on the HRM. The HRM describes the hydrodynamic characterization of all aquifer formations and the recharging conditions. It defines the boundary limits (permeable and not), the permeability tensor direction and the hydraulic connectivity between the aquifer formations and the potential drainage of each part of the tunnel. HRM provides the following results for the tunnel alignment:

- specific discharge of each homogeneous sector. The specific discharge is the drained flow (expressed in terms of length unit) by a particular hydrogeological complex in standard conditions of porosity or fracturation;
- location and discharge-rate for punctual inflows into the tunnel.

According to these detailed evaluations, the total drained discharge rate can be calculated for parts or the entire tunnel alignment.

Concerning the water inflows, the location of the most critical sectors allows local sealing treatments planning. These are essential for keeping water inflows close to tolerated values, preserving the water resources and avoiding dangerous situations during construction.

Fig. 2 shows an example of the increasing discharge graphs in steady state at the three portals of an important base tunnel in the Alps.

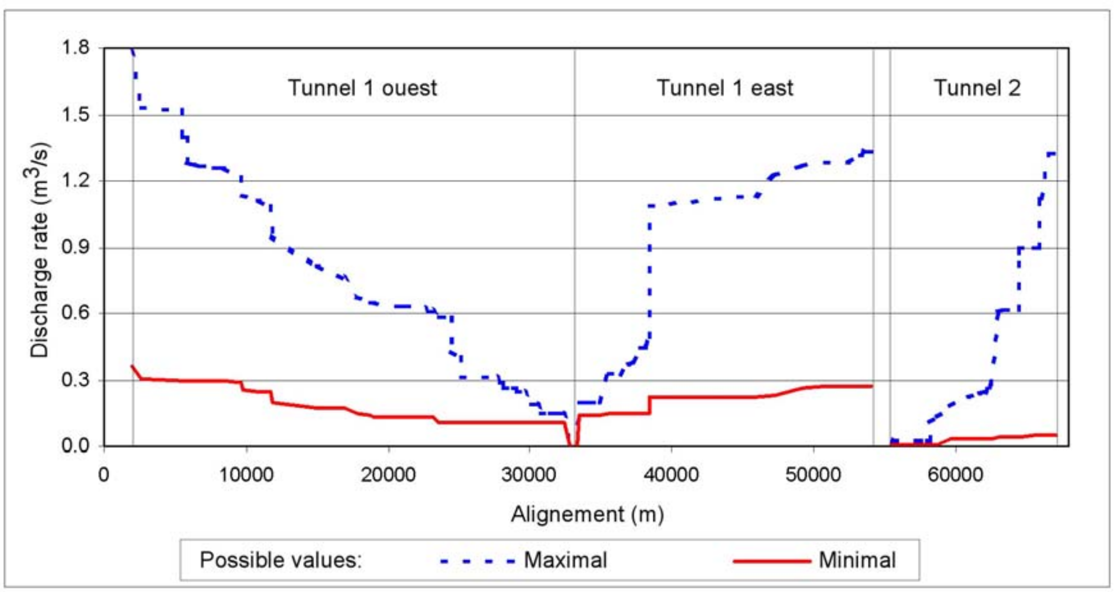

Fig. 2. Prediction of discharge-rates at the tunnel entrances of a 65 km long railway line in the Alps.

5. Drawdown hazard index outside the tunnel

Previous steps allow now to develop the environmental risk analysis, which is one of the main goal of the entire process here described. The aim of this analysis is to attribute a perturbation probability to each known spring and wells (“water-points” hereafter).

The construction of an underground tunnel in mountain regions may have significant impacts on the regional hydrogeological system. Water drainage through a tunnel is likely to cause a drawdown of the hydrostatic level and a decrease of water-point discharge. This phenomenon can persist after the tunnel construction if the final alignment is not completely water-proof (condition which is almost never attained). The drawdown impact can be in terms of both groundwater quantity and quality, and the effects can affect on the surface: vegetation modifications, slope instability, chemistry changes of thermal waters, and hydrogeological basin lowering level.

An example of methodology for evaluating tunneling impacts on groundwater-flow is described by Dematteis et al. (2001). This method is a probabilistic analysis called Drawdown Hazard Index (DHI) based on the systems approach, already applied on rock engineering by Hudson (1992). Fundamental variables for the aquifer-tunnel system are considered on a binary level through cause-and-effect relationships. The approach of the fully-coupled-model (Jiao 1995) was applied in this study to quantify the impact of a variable change on the drawdown hazard index.

The system aquifer-tunnel is described by means of 8 variables together with their interaction. This method was tested on a real case-study, where data on water-points discharge were recorded before and after the tunnel construction. In order to calculate DHI, a numeric value for all variables describing the hydrogeological condition of each water-point is given.

The following variables define the expected conditions in the tunnel, for those sectors near to springs:

- average permeability of the hydrogeological formation;
- frequency of fractures;
- overburden thickness;
- plastic-zone width around the tunnel.

These variables refer to the spring:

- distance from the tunnel;
- intersection with fault or karst;
- type of spring (superficial, deep, mixed defined on geological, hydrogeological and geochemical data);
- topographic effect (function of the morphological shape of the basin slope).

This methodology allows the evaluation of the aquifer-tunnel system that defines the drawdown, to get the DHI value for each known water-point. It leads to the achievement of two major goals: (1) detection of vulnerable tunnel sectors (e.g. low overburden, permeable fault zones, karst zones); (2) identification of areas not at risk, where compensation water supply sources could be found.

6. Valorization of the water inflow

The valorization of groundwater drained into a tunnel is a function of the quality and the quantity of these waters. These latter are in turn related to the geological, environmental and technical context in which the tunnel is drilled.

Also, legal and administrative constraints are part of the assessment and have to be taken into account in a valorization project.

Five types of valorizations can be considered: drinking-water, industrial use, agricultural use, geothermal use or hydroelectric use.

The three main elements of a valorization-project are: classification of the tunnel groundwater inflows (quality, quantity and localization of the water seepage along the tunnel), feasibility study (identification of all possible usages) and water-catchment design. The parameters to be defined are the following:

- water-inflow discharge;
- localization of water inflow and description of the water seepage (punctual in cases of faults, diffused in cases of porous aquifer, etc.);
- physical, chemical and biological water features;
- legal and administrative requirements (i.e. water protection for drinking purposes);

- technical requirements (i.e. materials that have to be used and that have to be adapted for specific uses, constraints for allowing the access and the inspection of the groundwater vents);
- excavation techniques and type of lining required.

Based on these parameters the method allows the feasibility evaluation of the valorization project:

- quantity of available water;
- type of valorization;
- identification of potential users;
- economical aspect (investment and feedback): water and energy value in the specific site of exploitation, infrastructure cost, maintenance cost, investments cost and valorization (investments versus gain).

The design of the best valorization solutions allows the definition of all technical and economical aspects of the project.

Fig. 3 shows an example of water catchment inside an existing tunnel. This solution was developed for drinking-water catchment in an alpine area in France, inside a road-tunnel under construction. The vent is a 40 m long tunnel (with a section of 2,5 x 2,3 m) driven perpendicularly to the main road tunnel, with drainage boreholes to maximize the water inflow.

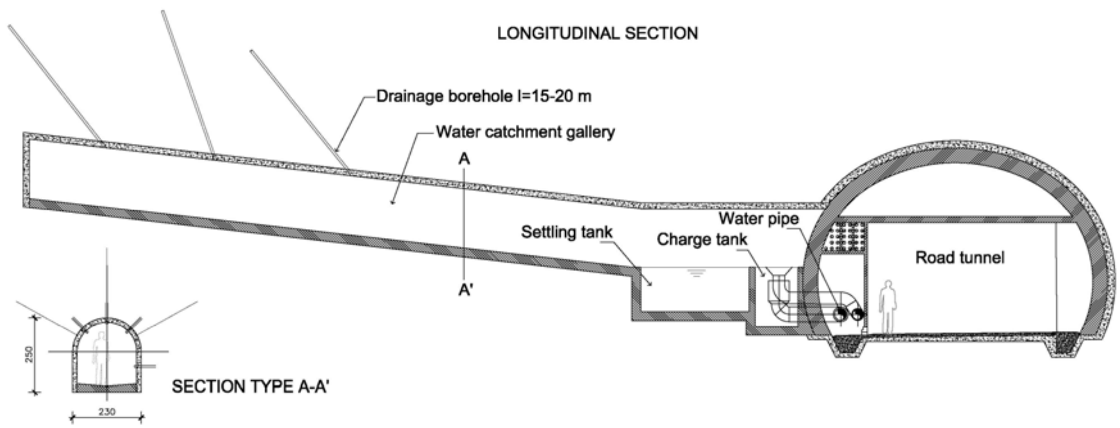

Fig. 3. Example of a water catchment gallery departing from an existing road tunnel.

7. Compensation of the water loss

It is most likely, as mentioned above, that a tunnel excavated in mountain regions will drain groundwater. This drainage is often the cause of drawdown of springs and wells exploited for water-supply. When the drainage can not be avoided, it is necessary to make a special study to find a compensation for these damages. Compensations usually require new water-supply sources located in areas not affected by the water-table drawdown due to tunneling operations.

Fig. 4 illustrates the phases of a groundwater compensation-project for tunnel excavation:

- forecast of drying-up risks of the springs due to tunnel excavation;
- computation of the quantity (minimal and average discharge) and analysis of the quality (chemical characteristic) of groundwater losses;
- definition of water-resources usage (drinking water, irrigation, etc.);
- scheduling of meetings with owners or water-resources managers (e.g. public or private companies);
- proposal of alternative solutions, displayed on topographic map;
- technical and financial studies documented by a detailed report illustrating all the elements for the realization of the project. In this phase all possible solutions have to be evaluated and compared in order to choose the most suitable one.

Different solutions can be adopted and each one is characterized by a specific realization time. Generally speaking, three main solutions categories can be proposed:

- *urgent* solutions (short term): water-treatment aimed to improve water-quality on a local scale, (typically a stream or a spring), by a mobile treatment-unit (time usually required: <24 hours);

- *transitory* solutions (medium term): this type of actions can start with a delay of some months and can be adopted during the whole tunnel-construction period;
- *permanent* solutions (long term): aimed to solve all the problems due to water-losses in a satisfactory and durable manner; they can represent the evolution of a transitory solution, by mean of actions taken just before a transitory solution is no longer operative.

Urgent and transitory solutions have a short realization-time and are characterized by generally low costs. Further minimal modifications (that will be discussed later on) of these solutions can result in permanent solutions.

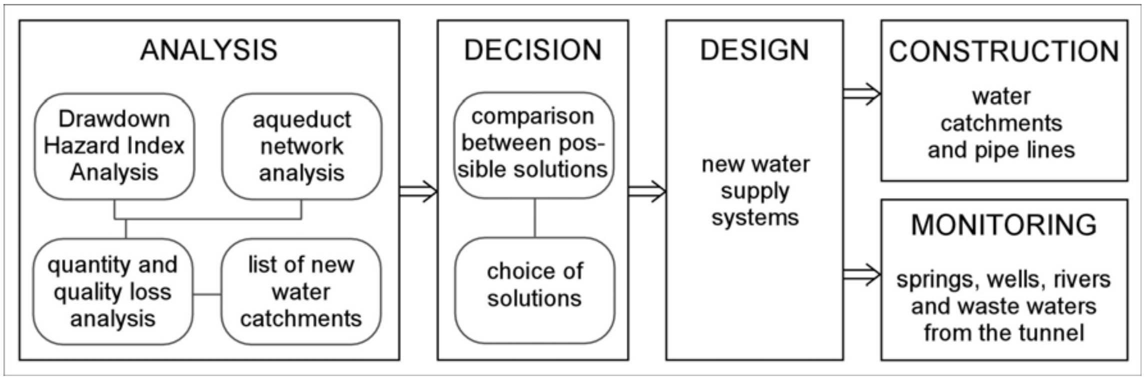

Fig. 4. Flow chart of water-supply compensation study to be performed in case of groundwater drawdown after tunnel excavation.

8. Concluding remarks

The decision making process presented in this paper is a sequence of study and analysis methods aiming at the achievement of a correct management of the groundwater component in tunnel projects; it wont to introduce the concept of *environmental sustainability* of the tunnels. This process should be used during planning and excavation phases of tunnels. It has been elaborated according to the last ten years experience in planning and construction of main passengers and goods transportation lines in Europe. Great attention is given not only to the study of the so-called *impacts* of tunnelling - negative aspects consequent to the excavation of the tunnels - but also the *opportunities* that can be researched and obtained exploiting the waters drained from the tunnel and the heat that is very often associated with.

The hydrogeological methods proposed in this paper want to be an example of the type of methods to be implemented in order to have a good water resources management in tunneling. The importance lies more in the complete sequence of hydrogeological methods to be followed rather than the choice of each specific method (e.g. quantification of hydrogeological forecast reliability, drawdown hazard index for springs and wells). Whatever will be the specific method used, each method will have to be validated, and the full sequence must lead to a repeatable result – applying the same methods on the same context will have to give the same results. Following the complete sequence should help finding the most appropriate and durable solutions. This will represent the decision making tool to be used by hydrogeologists when dealing with the local authorities charged of the projects' governance.

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