Long-term simulations of thermal and hydraulic characteristics in a mountain massif: the Mont-Blanc case study, French and Italian Alps

J.C. MARÉCHAL, P. PERROCHET AND L. TACHER

Abstract

The use of hydrothermal simulation models to improve the prediction of water inflows in underground works during drilling is tested in the Mont-Blanc tunnel, French and Italian Alps. The negative thermal anomaly that was observed during the drilling of this tunnel in 1960 is reproduced by long-term, transient hydrothermal simulations. Sensitivity analysis shows the great inertia of thermal phenomena at the massif scale. At the time of tunnel drilling, the massif had not reached thermal equilibrium. Therefore, a set of simulation scenarios beginning at the end of the last glacial period was designed to explain the anomaly encountered in the tunnel in 1960. The continuous cooling of Alpine massifs due to infiltration of waters from the surface has occured for 12,000 years and is expected to continue for about 100,000 years. Comparisons of water discharge rates simulated in the tunnel with those observed indicate that this hydrothermal method is a useful tool for predicting water inflows in underground works.

Keywords *:* crystalline rocks, numerical modeling, France, Italy, thermal conditions

J.C. MARÉCHAL (✉)

Current:

Laboratory of Engineering Geology (LGIH), B19, University of Liège, Sart Tilman, 4000 Liège, Belgium.

Tel: + 32 4 366 20 34

Fax: + 32 4 366 28 17

e-mail: jc.marechal@ulg.ac.be

Former:

Laboratory of Geology, Swiss Federal Institute of Technology, 1015 Lausanne, Switzerland.

P. PERROCHET, L. TACHER

Laboratory of Geology, Swiss Federal Institute of Technology, 1015 Lausanne, Switzerland.

Tel: + 41 21 693 23 55

Fax: + 4 21 693 63 30

Introduction

Infiltration of water from glaciers into mountain massifs has a cooling effect on rock temperatures. This effect has been illustrated in many cases where large water inflows in tunnels are associated to negative thermal anomalies. The Trient gallery in the Mont-Blanc massif (Jamier 1975) and the Simplon tunnel in Penninic Alps (Bianchetti et al. 1993) are two examples of this phenomenon in the alpine context. Water-temperature measurements during drilling constitute a useful tool to predict circulating cold water in rock and to predict in some cases water inflows in tunnels. Negative temperature anomalies encountered during tunnel drilling indicate the presence of potentially high groundwater circulation ahead in the drilling direction. During drilling of the Mont-Blanc road tunnel, geologists observed the beginning of a negative thermal anomaly at 2.6 km from the Italian portal (Gudefin 1967). This anomaly was later explained by a large amount of cold water in the rock and was proved by encountering large water inflows in the tunnel, about 1 km farther ahead.

This problem is quantitatively best approached with numerical models that allow regionalisation of the hydrothermal characteristics around a specific site. Simulation of temperatures observed along the drilled section of a tunnel when a thermal anomaly is detected can help predict water inflows in forthcoming sections, by calibration of the hydrothermal parameters. This paper presents such an approach in the real case of the Mont-Blanc massif for which series of temperature and discharge data are available in the Mont-Blanc road tunnel.

The Mont-Blanc Case

During the 1960s, a road tunnel was drilled across the Mont-Blanc crystalline massif; locations are shown in *Figure 1*. This high-elevation massif is largely covered by glaciers (Vallée Blanche, Glacier du Géant) and mainly consists of crystalline schist and granite (von Raumer 1987).

From the French portal, 3500 m of crystalline schist, 6800 m of granitic rocks, and 1300 m of limestone were intersected by the tunnel as shown in *Figure 2*. A strongly tectonised zone consists of a fault zone 600 m wide and containing cataclastic rocks. The zone is almost vertical and parallels the massif alignment. Large water inflows were observed in this strongly tectonised zone in the granite at about 8000 m from the French portal (Baggio and Malaroda 1962). The tunnel was drilled from both Italian and French portals. Along the drilled section in the Italian part, after a normal increase of water-temperatures due to the increase of rock-cover thickness, the large water inflows were encountered after the observation of a gradual decrease in temperatures. Coming from the Italian portal and going north, the temperatures declined from 23°C at a distance of 9 km to 12°C at a distance of 8 km from the French portal (*Figure 2b*). At that point, the large water inflows were encountered. The initial discharge was 1084 L/s (*Figure 2a*) and declined to 450 L/s after four months (Baggio and Malaroda 1962). The present (1998) discharge rate is about 220 L/s (Maréchal 1998).

Another small temperature anomaly occurs at 4000-5000 m from the French portal (*Figure 2b*); small water inflows (total of 95 L/s) are also encountered in this section of the tunnel (*Figure 2a)*.

Model Description

Calculations were performed with the groundwater finite-element simulator FEFLOW (Diersch 1996). The conservation equations are solved to simulate three-dimensional flow of groundwater and associated thermal transport by advection-dispersion-conduction.

The mass-conservation equation for the fluid phase is

$$\frac{\partial(\phi\,\rho)}{\partial t} + \nabla\cdot\rho\,\mathbf{q} = 0 \qquad (1)$$

involving medium porosity ϕ (-), fluid density ρ (kg/m^3) and flux vector $\mathbf{q}$ (m/s). The latter obeys Darcy's law

$$\mathbf{q} = -\frac{\mathbf{k}}{\mu}(\nabla p + \rho \mathbf{g}) \tag{2}$$

with medium permeability tensor $\mathbf{k}$ (m^2), fluid dynamic viscosity μ (kg/m/s), pore pressure p (N/m^2) and gravity acceleration vector $\mathbf{g} = g\nabla z$ (m/s^2). In the context of coupled flow and heat transport processes, both fluid density and viscosity vary with temperature T according to appropriate constitutive laws $\rho = \rho(T)$ and $\mu = \mu(T)$.

Equations (1) and (2) can be further developed to yield a governing flow equation in terms of pore pressure. However, in order to allow for the use of conventional hydrogeological parameters, such as hydraulic conductivity and specific storage, an equivalent hydraulic head formulation is adopted. Introducing the arbitrary temperature T_o , at which $\rho_o = \rho(T_o)$ and $\mu_o = \mu(T_o)$, Darcy's law in equation (2) can be rewritten as

$$\mathbf{q} = -\frac{\mathbf{k}\ \rho_o g}{\mu_o}\frac{\mu_o}{\mu}(\nabla\frac{p}{\rho_o g} + \frac{\rho}{\rho_o}\nabla z) = -\mathbf{K}_o\frac{\mu_o}{\mu}(\nabla H_o + \frac{(\rho - \rho_o)}{\rho_o}\nabla z) \tag{3}$$

where $\mathbf{K}_o = \mathbf{k}\rho_o g/\mu_o$ (m/s) is the hydraulic conductivity tensor at $T = T_o$, and $H_o = p/\rho_o g + z$ (m) is a fictitious hydraulic head also referenced to T_o.

Similar manipulations can be performed in order to introduce H_o and the specific storage (compressibility) of the medium S_o (1/m) in the mass conservation equation (1). This yields finally

$$S_o\frac{\partial H_o}{\partial t} + \nabla\cdot\mathbf{q} = -\frac{1}{\rho}\frac{\partial\rho}{\partial T}(\phi\frac{\partial T}{\partial t} + \mathbf{q}\cdot\nabla T) \tag{4}$$

where S_o includes compressibility effects of both fluid and skeleton.

Due to the generally great hydraulic gradients in mountainous regions, heat transport is assumed in this model to be dominated by forced advection and dispersion (no natural convection). This allows for applying the Boussinesq approximation, which consists in setting to zero the right-hand side term in equation 4. It implies that, except in the buoyancy term of (3), the density of water does not depend on the temperature. Due to the fact that significatively high water temperatures (about 70°C) are only reached in very deep zones beneath the tunnel and where water circulation is minor, viscosity dependency on temperature can also be neglected, which greatly simplifies the calculations and makes it possible to multiply the number of simulation scenarios in this rather large domain.

The conservation equation for advective-dispersive-diffusive transport of thermal energy is

$$(\phi\,(\rho c)_l + (1-\phi)\,(\rho c)_s)\frac{\partial T}{\partial t} + (\rho c)_l\,\mathbf{q}\cdot\nabla T = \nabla\cdot(\phi\,\mathbf{\Lambda}_l + (1-\phi)\,\lambda_s\mathbf{I})\,\nabla T \qquad (5)$$

where $(\rho c)_l$ and $(\rho c)_s$ are volumetric heat capacity (J/m^3/K) of liquid and solid phases, respectively. In the above equation, λ_s $\mathbf{I}$ (J/m/s/K) is the thermal conduction tensor of the solid (assumed isotropic) and $\mathbf{\Lambda}_l$ (J/m/s/K) the hydrodynamic thermal dispersion tensor of the fluid, defined by

$$\mathbf{\Lambda}_l = (\rho c)_l\,(\,(\alpha_L - \alpha_T)\frac{\mathbf{v}\otimes\mathbf{v}}{\|\mathbf{v}\|} + \alpha_T\,\|\mathbf{v}\|\,\mathbf{I}\,) + \lambda_l\,\mathbf{I} \qquad (6)$$

with longitudinal and transverse thermal dispersivities α_L and α_T (m), thermal conduction of fluid λ_l , pore velocity $\mathbf{v} = \mathbf{q}/\phi$, and the identity matrix $\mathbf{I}$.

Equations (3), (5), and (6) are simultaneously solved for specific initial distributions of the unknown fields [$H_O(x, y, z, 0)$, $T(x, y, z, 0)$] and their respective boundary conditions.

Geometry

The aim of the model is to reproduce the principal thermal anomaly at the tectonised zone, 8000 m from the French portal; the small anomaly at 4000-5000 m is neglected at this stage. The model domain has a parallelipipedic form with an orientation NE-SW; the finite-element mesh is shown in *Figure 3*. The base of the model is located at an altitude of 0 m, and the upper limit is defined by the local topography (the altitude of the Mont-Blanc summit is 4807 m). The tunnel is in the middle of the domain, oriented NW-SE perpendicular to the massif axis, at an elevation of 1300 m. The domain lateral boundaries are (1) in the northwest, the valley of the Arve, in the region of Chamonix, France; and (2) in the southeast, the valley of Doire, in the region of Courmayeur, Italy. Northeastern and southwestern limits correspond to high elevation crests, namely the Aiguille-Verte and Aiguille de Bionnassay massifs, respectively. These limits were selected because they are far from the tunnel and can be treated as classical no-flow boundaries.

Boundary Conditions

The four vertical boundaries of the model are assumed to be hydraulically and thermally impermeable, with a vertical thermal gradient. At the bottom of the model a geothermal flux is specified and a no-flow boundary condition is applied. Because information such as distributed infiltration rates and free-surface elevations are poorly known or not known in this mountainous region, hydraulic heads corresponding to the topography are imposed everywhere at the surface; water is at atmospheric pressure. Given the large parts of the domain covered by snow or ice, this approach seems more realistic than imposing a uniform infiltration rate.

Thermally, the surface of the model is set to the temperature of 0°C under the glacial covering and to the average air temperature elsewhere, according to an altitude gradient. Sensitivity simulations (Maréchal 1998) show that these surface temperatures have virtually no influence on the thermal fields around the future tunnel location. Tunnel boundary conditions are atmospheric pressure and no thermal flux.

Transient Mode

First simulations show that steady-state hydrothermal simulations are not able to reproduce the principal thermal anomaly observed during the tunnel drilling (Maréchal 1998). Indeed, enforcing rock hydraulic conductivities that are calibrated with discharge rates observed along the strongly tectonised zone systematically produces simulated temperatures around 0°C in this zone, whereas observed temperatures are around 12°C. Large time scale, transient simulations are required to account for the great thermal inertia of mountain massifs. Moreover, numerous sensitivity simulations suggest that the massif was not at thermal equilibrium at the time of the drilling in 1960 (Maréchal 1998). In order to implement a practical transient simulation scheme, a three-step approach was designed to enable the introduction of significant changes in boundary conditions. The three periods that are simulated are 1) the last glacial period (1,200,000 to 10,000 yr BC); 2) post-glacial period until tunnel drilling (1960); and 3) the tunnel period (1960-97). The Little Glaciation during the last century is neglected because only a slight progression of glaciers occured during that time. The three models are diagrammed on *Figure 4,* and model parameters are shown in *Figure 5*.

The same approach was applied in the Polmengo gallery in the alpine Pennic gneisses (Busslinger and Rybach 1997). The authors have also used a transient simulation beginning in 10,000 yr BC to reconstruct the thermal anomaly due to a highly water-conductive Triassic metasedimentary zone intersecting the gallery.

Model 1 : the glacial period (1,200,000 yr BC to 10,000 yr BC)

Because of the long time span of the glacial period, this model is run in steady-state conditions. During this period, air temperature was lower than now (interglacial periods are neglected). Thus, cold-base-glaciers were probably present down to elevations of about 3000 m (12,000 years ago), whereas the present lower limit is about 4000 m. It is assumed that during the glacial period the infiltration at the surface of the massif occured mostly at an altitude inferior than 3000 m and was very small. Consequently, this first model is only thermal, with a heat flux of 85 mW/m^2 specified at the bottom and average air temperatures at the surface colder than now. This model allows the calculation of the initial thermal field of model 2. Because of the absence of cool water circulation and despite the lower external temperatures, the interior of the massif is globally warmer (at steady state) than now, as shown by the results.

Model 2 : the post-glacial period (10,000 yr BC to 1960 A.D.)

This period begins at the end of the last glacial period and continues to the drilling of the tunnel in 1960. Because of the increase in altitude of the limit of the cold-base glaciers that occured during climate warming, the massif starts to be affected by the infiltration of melt waters and, thus, gets globally colder. Considering the long duration of this period, the hydraulic part of the model is simulated at steady-state with the surface at atmospheric pressure, and the thermal part is transient with constant boundary conditions. The strongly tectonised zone is also taken into account in the model by the introduction of high hydraulic conductivities, as shown in *Figure 5.* The model results show the need to consider a transient thermal regime in order to calculate the initial thermal field for model 3 and to obtain a good reproduction of the observed anomaly.

Model 3 : the tunnel period (1960 to 1997)

This period is the shortest one. The model takes all the parameters of model 2 as the initial input of the thermal and hydraulic fields, but with the tunnel implemented; atmospheric pressure is specified along the tunnel axis and hydraulic and thermal conditions are transiently simulated up to 1997. The results show the relatively rapid decline of discharge rates in the tunnel as observed in reality (quasi hydraulic steady-state reached after a period of about six months). On the other hand, the great inertia of simulated thermal profiles during this short period indicates that the massif is far from its thermal steady-state.

Simulation Results

Hydrothermal material properties are summarized in *Figure 5* and *Table 1*. These values are valid for the three models, and were estimated by conducting sensitivity analyses and calibration based on temperature data in the tunnel (Maréchal 1998).

Model 1: The Glacial Period

The only process considered here is heat conduction.

Sensitivity to thermal parameters

For the three lithologies existing in the Mont-Blanc Massif, rock thermal conductivities given in litterature are presented in *Table 2*. To simplify the notation in the following text, the thermal conductivity of solid is indicated by λ.

Figure 6a shows that results are very sensitive to rock thermal conductivity λ in the range 2.5-4 W/m/K. Simulated temperatures along the future tunnel axis decrease when thermal conductivity increases. In effect, for a given bottom geothermal flux, the geothermal gradient in a massif with low thermal conductivity is greater than in a massif with high conductivity. The greatest difference (20 °C) between sensitivity runs is observed in the middle of the massif, where the rock cover is the greatest.

The Mont-Blanc crystalline schist unit contains very anisotropic rocks. Laboratory thermal tests performed on rocks of this type indicate a high anisotropy of thermal conductivity (Goy et al. 1996). Thermal conductivity parallel to schistosity is, in some cases, twice as much as thermal conductivity perpendicular to schistosity. In the Mont-Blanc massif, the schistosity is nearly vertical, and therefore the upper value of 4 W/m/K is incorporated in the model. No laboratory data are available for the Mont-Blanc granite, and so the average value of 3.5 W/m/K is assumed. For comparison, a value of 3.9 W/m/K has been measured on the Aar granite (Switzerland), located in the same structural context (Rybach and Pfister 1994).

Simulated temperatures increase logically with the specified geothermal flux (*Figure 6b*). Values were tested from 70 to 100 mW/m^2. For a flux equal to 100 mW/m^2, a maximum of 61°C is observed in the middle of the future tunnel axis. For a flux reduced to 70 mW/m^2, temperatures are reduced in the same proportion to 43°C.

The geothermal flux in this region is estimated to be 80-90 mW/m^2 (Medici and Rybach 1995). For these two values, the difference in simulated temperatures in the middle of the massif is equal to 6°C. In the model, the mean value 85 mW/m^2 is assumed.

Results

The steady-state thermal field simulated with the above values provides the initial conditions for model 2. The resulting temperature profile along the future tunnel axis is given in *Figure 6c*.

This temperature profile indicates a maximum of 40°C near the middle of the massif under a rock cover of about 2000 m. The geothermal gradient at that location is about 0.020 K/m. This relatively low value illustrates the effect of high topographic elevations on the thermal field.

Model 2: The Post-Glacial Period

In this model, groundwater circulation is considered and, therefore, values of various hydrogeological input parameters are needed.

Hydraulic-conductivity field

The structural history of the Mont-Blanc massif has led to a physical anisotropy of the rocks. The orientation of anisotropy is similar in the different units. In crystalline schist, granite and limestone, respectively, the schistosity, the fractures, and the stratification are parallel to the massif axis and nearly vertical. Consequently, these water-conductive structures generate preferential flows characterized by the following principal hydraulic conductivities :

- K_1: horizontally, parallel to the massif axis;
- K_2: horizontally, perpendicular to the massif axis;
- K_3, vertically.

An anisotropy ratio of 100 for the three lithologies gives the best calibration results (Maréchal 1998). In the following, the variables K_1 and K_3 are referred to as the " hydraulic conductivity K ", and $K_2 = K/100$ is always implicitly enforced.

Rock hydro-dynamical parameters defined by calibration tests on observed temperatures are given in *Figure 5*. Each structural unit is assumed to be a homogeneous medium. In the granite outside the tectonised zone and in the crystalline schist, $K = 10^{-8}$ m/s. In the limestone, $K = 3 \times 10^{-8}$ m/s. The tectonised zone intersected by the tunnel is divided into two parts according to field observations in the tunnel (*Figures 5* and *7*). The first part, about 500 m long, is assigned a hydraulic conductivity value of 10^{-7} m/s. The second part is characterized by a thickness of a few tens of metres and by a hydraulic conductivity 5×10^{-7} m/s. This part produces the largest water inflows in the tunnel (70% of the total discharge). In the direction of Italy, next to the tectonised zone, a very dry section, 300 m long, is considered and is assigned a hydraulic conductivity of 10^{-9} m/s.

Sensitivity to hydrogeological parameters

Sensitivity to unknown parameters such as the anisotropy ratio in the massif and the hydraulic parameters of the tectonised zone is addressed below. Results are shown in *Figures 8a*, *8b* and *8c*.

The anisotropy ratio considered in this massif is 100, which corresponds to zones of fracturing, schistosity, and stratification in the massif (Bertini et al. 1985; Gudefin 1967; Baggio and Malaroda 1962). Results of sensitivity simulations indicate the appropriataness of such a ratio. With no anisotropy or with anisotropy only in limestone, the massif is too cold (*Figure 8a*), making it impossible to match the observed data. In this case, regional oversized flow systems develop throughout the model from the summit in the middle of the massif toward the low-elevation boundaries. A ratio of 100, parallel to the massif orientation, results in smaller groundwater flows, generally directed from the top toward the glacial transverse valleys (Vallée Blanche, Glacier du Miage), and results in a much better match of the hydrothermal data.

Variations of hydraulic conductivity of the longer part of the tectonised zone induce large differences in simulated temperatures in this zone (*Figure 8b*). Increases in hydraulic conductivity induce an increased cooling effect of the zone [*Figure 8b*, cases (c) and (d)]. Larger quantities of cold water penetrating the tectonised zone from the top of the massif yield low temperatures in the zone's immediate vicinity. Case (a), for which $K = 10^{-8}$ m/s, considers a tectonised zone in which 600 m of highly fractured materials are neglected. In this case, the simulated thermal anomaly approximates the one observed (case b). Hence, this anomaly is mainly the consequence of intense circulation in the shorter section (tens of metres), where the two largest discharge rates were detected in the tunnel. The section that is 600 m long contributes only to the longitudinal extension of the anomaly.

Another important unknown parameter is the depth of the tectonised zone. Although this zone is intersected by the tunnel, its vertical continuity downward is unknown. At the surface, the tectonised zone crops out near the Aiguille de Toule and the Pointe Helbronner, and tracer (uranin and eosin) experiments show relatively rapid circulation (about three months for 2000 m) between the land surface and the tunnel (Dubois 1993; Maréchal 1998). Four penetration scenarios were assessed between the model bottom elevation (z = 0 m) and the altitude of the tunnel (z = 1300 m), namely z = 0, 450, 900, and 1300 m. Simulations show that the cooling in and around the tectonised zone increases when the depth of penetration increases (*Figure 8c*). This effect is due to an increased volume of water circulating through the tectonised zone. However, this phenomenon is not very marked for the couple 0-450 m (difference of 0.5 °C). It induces a heating of 2°C when the altitude of the zone's bottom is increased from 0 to 900 m, and a heating of 5°C when the zones's bottom corresponds to the tunnel elevation (z = 1300 m). In the final simulation, full penetration of the tectonised zone is assumed (z = 0 m).

The width of the tectonised zone observed at the land surface is similar to that measured in the tunnel (600 m). The presence of glaciers at the massif surface makes it difficult to determine its lateral extension parallel to the massif. Sensitivity simulations (not shown) to this uncertain extension toward NE and SW indicate very little effect on the thermal profile.

Results

The time-evolution of simulated temperatures since the end of the glacial period (10,000 yr BC) to 1960 AD is presented in *Figure 9*. The thermal anomaly mainly develops through the tectonic zone during the first 5000 yr after the end of the glacial period, when a cooling of 20°C occurs. Between 5000 yr BC and 1960 AD, temperatures change only slightly (5 °C). Temperatures simulated for 1960 AD aproximate those measured during the drilling of the tunnel. Maximum differences are about 3°C in the vicinity of the tectonised zone. These results are considered to be satisfactory.

The calculation of the total budget of the model indicates that simulated infiltration is about 50 mm/yr. This value is considered to be reasonable in a mountain massif with large glacier cover where little infiltration occurs.

If the tunnel had not been drilled, the thermal anomaly would have continuously propagated downward for about the next 100,000 years, as shown in *Figure 10*. Indeed, the thermal results after this period closely approximate those at steady state. This result illustrates the great inertia of thermal phenomena at the scale of the mountain massifs.

Model 3 : The Tunnel Period

Conditions during the tunnel period are simulated under thermal and hydraulic transient conditions. Comparisons of simulated discharge rates with those observed in the tunnel are given in *Table 3* at one day and at steady state. Utilization of a value of storage coefficient S_0 $= 10^{-5}$ 1/m allows for a good match between simulated and observed discharge rates. The steady-state flow regime is reached after a few months.

The model overestimates flows, probably because of the assumption of a fully saturated domain. In reality, the presence of the tunnel induces a drawdown of the water table and therefore creates unsaturated flow conditions, which are not considered in the present model. *Figure 11* illustrates the flow conditions prior to (*Figure 11a*) and following (*Figure 11b*) tunnel implementation. Before the tunnel drilling (*Figure 11a*), two different flow systems exist. Flow paths are oriented from the peaks (Aiguille du Midi and Aiguille de Toule) toward low points (valleys of Arve and Doire). After the tunnel drilling (*Figure 11b*), flow paths are essentially directed toward the tunnel. The tectonised zone behaves as a vertical drain and conducts groundwater to the tunnel.

These results are satisfactory and indicate that the model is reasonably well calibrated, both thermally and hydraulically. Improvement of results would require mesh refinement around the tunnel and inclusion of variably saturated flow processes.

During about 500 yr after the tunnel drilling (1960-2460 AD), the time-evolution of simulated temperatures shows that the high-permeability tectonised zone reacts first, whereas the middle, less permeable part of the massif reacts later, as shown in *Figure 12*. Then, the middle of the massif cools more rapidly, whereas the temperatures in the tectonised zone (7-8°C) decrease more slowly. After ten thousand years (11,960 AD), the maximum temperature in the middle of the massif is 13°C, compared to a value of about 30°C today. At steady state, temperature stabilizes at 6°C in the middle of the massif and at 1°C in the tectonised zone.

Comparisons of these results with those obtained without the tunnel indicate that the tunnel results in a faster cooling rate by increasing downward flows, as shown in *Figure 13*. At steady-state, the temperature is about 1°C in the tectonised zone if the tunnel is present and about 5°C in the same zone without the tunnel. In the middle of the granitic massif, steady-state temperatures are about 14°C without the tunnel and about 5°C with the tunnel. After 50,000 years of simulation, the temperatures in the middle of the granite (in the case with tunnel) are equal to those calculated in the tectonised zone (in the case without tunnel).

Conclusions

The numerical simulation of the thermal profile observed during the drilling of the Mont-Blanc road tunnel fits well with observations, and simulated water-discharge values are similar to those measured in the tunnel.

The results show the strong inertia of thermal phenomena at the scale of a mountaineous massif. The cooling of the massif begins at the end of the last glacial period and continues for a period of about 100,000 years. This result can be extended to all of the alpine massifs, which are not at thermal equilibrium and are being affected by cooling circulations since the end of the last glacial period.

In the Mont-Blanc case study, the implementation of the road tunnel has increased the cooling rate by modifying groundwater circulation in the massif. In the tectonised zone, temperatures after 10,000 years of simulation with the tunnel are lower than after 100,000 years without the tunnel. Temperatures in the middle of the massif, however, are equal in both cases.

The models developed in this study yield satisfactory hydrothermal results around the tunnel, as indicated by the good match of simulated and observed temperatures and by a reasonable representation of water inflows. However, rather large uncertainties exist in the rest of the massif. This situation is due to the general lack of exploratory drillings in mountains and to the lack of knowledge of actual surface boundary conditions. A systematic study of uncertainties in the massif could be the subject of a future study. However, this work shows that the use of hydrothermal models to reproduce (by mean of step by step fitting) temperature profiles observed during the drilling of underground works can help to improve the prediction of groundwater inflows without knowing previously the hydraulic parameters.

Acknowledgment

The authors thank the EVIAN Mineral Water Foundation for supporting this work. The authors thank also Dr B. Olofsson and Dr A. Rivera for contributing to improve the present paper.

References

Baggio P and Malaroda R (1962) Il traforo del Monte Bianco; prime osservazioni geologiche sul tratto dalla progressiva 2500 alla progressiva 3700 (parte italiana). Accad Naz dei Lincei Sc fis mat e nat 33: 149-153

Bertini G, Marcucci M, Nevini R, Passerini P and Sguazzoni G (1985) Patterns of faulting in the Mont Blanc granite. Tectonophysics 111: 65-106

Bianchetti G, Zuber F, Vuataz FD and Rouiller JD (1993) Hydrogeologische und geotermische Untersuchungen im Simplontunnel. Matériaux pour la Géologie de la Suisse 88

Bowen R (1989) Geothermal Resources, 2nd edn., Elsevier, New York

Busslinger A and Rybach L (1997) Sondiersystem Piora-Mulde. Geothermische Untersuchungen. 3D-Modellierungen. Intern Report no. 2007, ETH Zürich

Diersch HJ (1996) Interactive, Graphics-Based Finite Element Simulation System FEFLOW for Modeling Groundwater Flow, Contaminant Mass and Heat Transport Processes, WASY Ltd, Berlin

Dubois JD (1993) Typologie des aquifères du cristallin: exemple des massifs des Aiguilles Rouges et du Mont-Blanc. PhD, EPF Lausanne, Switzerland

Goy L, Fabre D and Menard G (1996) Modelling of Rock Temperatures for Deep Alpine Tunnel Projects. Rock Mechanical Rock Engineering 29(1): 1-18

Gudefin H (1967) Observations sur les venues d'eau au cours du percement du tunnel sous le Mont-Blanc. Bulletin BRGM 4: 95-107

Jamier D (1975) Etude de la fissuration, de l'hydrogéologie et de la géochimie des eaux profondes des massifs de l'Arpille et du Mont-Blanc. PhD, University of Neuchâtel, Switzerland

Maréchal JC (1998) Les circulations d'eau dans les massifs cristallins alpins et leurs relations avec les ouvrages souterrains. PhD, EPF Lausanne, Switzerland

de Marsily G (1986) Quantitative Hydrogeology. Academic Press, New York.

Medici F and Rybach L (1995) Geothermal map of Switzerland 1995 (Heat flow density). Matériaux pour la Géologie de la Suisse 30

von Raumer JF (1987) Les massifs du Mont-Blanc et des Aiguilles-Rouges: témoins de la formation de la croûte varisque dans les Alpes occidentales. Géologie Alpine 63: 7-24

Rybach L and Pfister M (1994) How to predict rock temperatures for deep Alpine tunnels. Journal of applied Geophysics 31: 261-270

Tables

Table 1 : Hydraulic and thermal characteristics of the model.

Parameters	*Symbol (unit)*	*Crystalline schist*	*Granite*	*Tectonised zone*	*Limestone*
Porosity	ϕ (-)	0.05	0.05	0.10	0.10
Hydraulic conductivity	K (m/s)	1×10^{-8}	1×10^{-8}	1×10^{-7} 5×10^{-7}	3×10^{-8}
Volumetric heat capacity	$(\rho c)_S$ ($J/m^3/K$)	2.2×10^6	2.1×10^6	2.1×10^6	3.5×10^6
Thermal conductivity	$\lambda = \lambda_S$ (W/m/K)	3.7	3.5	3.5	2.4
Thermal dispersivities	α_L (m) α_T (m)	5 0.5	5 0.5	5 0.5	5 0.5
Geothermal flux	(mW/m^2)	85	85	85	85

Table 2 : Thermal conductivities of lithologies existing in the massif *[W/m/K].*

Lithology	*Thermal conductivity* $\lambda = \lambda_S$	*Reference*	*Comments*
Crystalline schist	2.5 - 3.5 2.9 - 4.1	Goy and al. 1996 Rybach and Pfister 1994	Alpine Ambin Massif Gothard Massif and Penninic zone
Granite	2.5 - 3.8 3.9	de Marsily 1986 Rybach and Pfister 1994	Mean value Aar Massif
Not karstified limestone	1.7 - 3.3	Bowen 1989	Mean value

Table 3 : Comparison between simulated and observed discharge rates [L/s].

Zone	*Q obs* *t = 1 day*	*Q sim* *t = 1 day*	*Q obs* *t = 13 500 days*	*Q sim (Model 3)* *steady-state*
Tunnel (total length)	1566	2090	≈ 450	514
Tectonised zone	1084	1380	220	300
Tunnel (without tectonised zone)	482	710	≈ 230	214

Figures

Figure 1 : Location of the Mont-Blanc Massif, showing position of the road tunnel (modified after von Raumer 1987)

Figure 2 : Geological section along the Mont-Blanc tunnel, showing a) water inflows and b) water temperatures during the tunnel drilling (after Gudefin 1967)

Figure 3 : Finite-element mesh of the Mont-Blanc massif model, viewed from the south

Figure 4 : Diagrams of the three models, showing the time periods simulated

Figure 5 : Thermal and hydraulic characteristics of the geologic units

Figure 6 : Relation between simulated temperature and distance along the tunnel under steady-state conditions and without infiltration. a) Sensitivity to rock thermal conductivity. b) Sensitivity to geothermal flux. c) At the end of the last glacial period (10,000 yr BC)

Figure 7 : Distribution of hydraulic conductivity in and around the tectonised zone, showing degree of fracturing and water inflows

Figure 8 : Sensitivity of temperature distribution along the tunnel to various unknown hydrogeologic parameters. a) Anisotropy ratio. b) Hydraulic conductivity in the longer part of the tectonised zone. c) Depth of tectonised zone

Figure 9 : Relation between temperature and distance along the tunnel for various simulated times prior to tunnel construction and as observed during tunnel construction

Figure 10 : Relation between simulated temperature and distance along the tunnel for various times without tunnel after the time of tunnel construction (1960)

Figure 11 : Distribution of hydraulic head in the massif in a vertical section along the tunnel. a) before tunnel construction. b) after tunnel construction

Figure 12 : Relation between simulated temperature and distance along the tunnel for various times with tunnel since the time of tunnel construction (1960)

Figure 13 : Relation between simulated temperature and time, for middle of the granite and tectonised zone, with and without tunnel