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Verification of rock temperature prediction along the Gotthard base tunnel - A prospect for coming tunnel projects

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ABSTRACT: The a-priori knowledge of in-situ rock temperatures is of paramount importance in deep tunnels, e.g. for the design of ventilation and cooling during construction and operation. New 3D numerical model simulation was applied for rock temperature prognosis, with increasing degree of complexity (e.g. thermal and hydraulic ground properties, topography, deep groundwater circulation, transient coupled heat/fluid transfer, uplift and erosion). During tunnel excavation, temperature and rock thermal properties were regularly measured. The completion of the Gotthard base tunnel reveals a unique opportunity of verification. Prediction and finding remained in good agreement; generally well within ± 15 %. The lessons learned in predictive modeling and in its evaluation can be decisive for future tunnel projects. For prediction, similarly sophisticated modeling tools should be used. A reliable input data base must be supplied by well-organized cooperation of earth science specialists. The geothermal surface and boundary conditions like surface temperatures, basal heat flow and uplift/erosion patterns must be determined beforehand. Rock temperature measurements along the planned trace below the highest cover, measured in special boreholes, are crucially important in order to enable proper model calibration. By considering these prerequisites, reliable rock temperature predictions will be possible even in complicated terrain.

1 Introduction

The knowledge of rock temperature is essential for the planning and construction of deep tunnels. In particular, the design of the ventilation and cooling system for tunnel construction and operation is based on this information. Improper prediction and unexpected temperatures during tunneling can cause serious problems, e.g. work interruption due to unacceptably high air temperatures (leading to additional cooling needs) as seen in past and current tunnel projects (e.g. Simplon base tunnel, 1905, Switzerland with rock temperatures >56 °C; Olmos irrigation tunnel, 2011, Peru, with rock temperatures >54 °C, Karcham-Wangtoo hydropower tunnel, 2009, India with rock temperatures >80 °C).

The Gotthard Base Tunnel (GBT) with its two tubes (total length 57 km, maximum rock cover 2.5 km) is a highly remarkable construction. Its planning was a great engineering challenge and its realization is a correspondingly remarkable achievement. AlpTransit Gotthard Ltd is the constructor of the Gotthard axis of the New Rail Link through the Alps with base tunnels through the Gotthard and Ceneri. A reliable rock temperature prediction of the GBT was indispensable for project planning.

The GBT passes through a number of crystalline rock zones (Figure 1). The final breakthrough was accomplished on 15 October 2010. During excavation, many new geologic and hydrogeologic findings, rock temperature measurements and sampling have been made as well as thermal conductivity determinations. A thorough study has been commissioned by AlpTransit Gotthard Ltd and subsequently performed to evaluate the new findings and especially to verify the rock temperature prediction by comparing the prognosis with the measurement results. In the following, the comparison and its results are presented and interpreted.

2 Rock temperature prediction

The elaboration of a reliable rock temperature prediction is, within the complex topographic, geologic/tectonic and hydrogeologic Alpine setting of the GBT realm, a highly demanding task. No ready-to-use methodology existed for the elaboration at the beginning of the prediction endeavor. The requirements for an adequate consideration and treatment of the complex conditions and processes have been mastered by a special 3-dimensional finite-element code that couples thermal and hydraulic processes to include conductive and advective heat transfer as well as the effect of geodynamic developments on the temperature field like uplift/erosion (Rybach and Kohl 1998). Special attention was given to the discretization of the model domain (Figure 2), with the use of an automatic mesh generator. Details can be found in Busslinger et al. (1998) and in Busslinger and Rybach (1999a).

A reliable data base for the input parameters -extension, special position, thermal and hydraulic properties of the geologic units; surface temperature history; basal heat flow; uplift/erosion rate- had to be carefully assembled. Details about the input parameters and boundary conditions, the special software, the modeling and its calibration, and the results are given in Rybach et al. (2006). The resulting predictive rock temperature profile along the GBT trace, along with the calculated uncertainty band, is given in Figure 3.

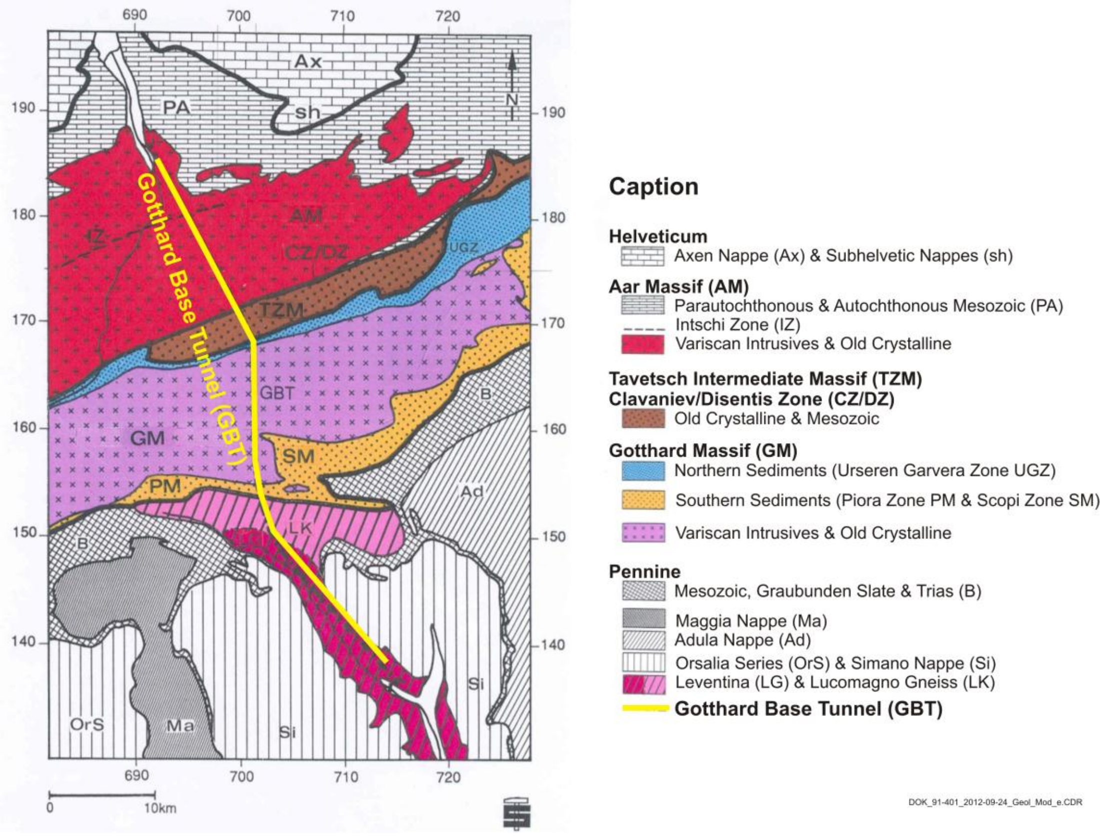

Figure 1. Trace of the Gotthard Base Tunnel, with the traversed geologic units

3 Tunnel temperature measurements

During tunnel construction, the effective rock temperatures have been regularly measured at the construction sections Erstfeld, Amsteg, Sedrun, Faido and Bodio by the project geologists, usually every 200 – 300 m along the GBT axis. The applied measurement procedure followed a detailed directive, developed within the framework of the Piora exploratory adit (Rybach et al. 2006). Hand-held, calibrated devices were used. For the temperature measurements, special boreholes have been drilled into the tunnel wall (5 to 10 m deep, slightly inclined). The drillholes were filled with water prior to measurement in order to guarantee the thermal coupling between temperature probe and rock. Measurements did not start before thermal equilibrium in the hole was established (after about 1 day). To improve the accuracy of the data as well as to eliminate unwanted effects (temperature change due to tunneling etc.), the measurements were repeated periodically. More details about the actual rock temperature measurements can be found in Rybach et al. (2006).

The temperatures of water inflows have also been measured; they show very similar values as the rock temperatures all along the GBT, indicating thermal equilibrium between rock and deep groundwater at tunnel depth. The results of rock temperature measurements are plotted on Figure 3.

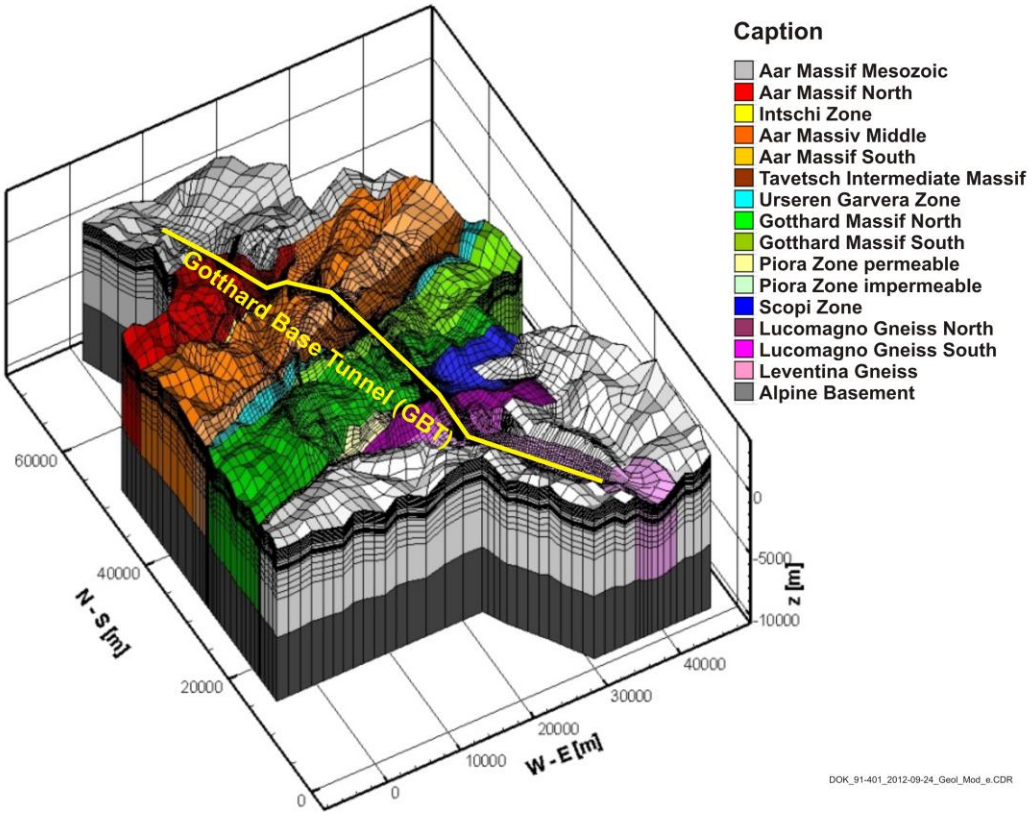

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Figure 2. Discretized model domain (about 200’000 finite elements) with the geologic/hydrogeologic units for the numerical rock temperature prediction

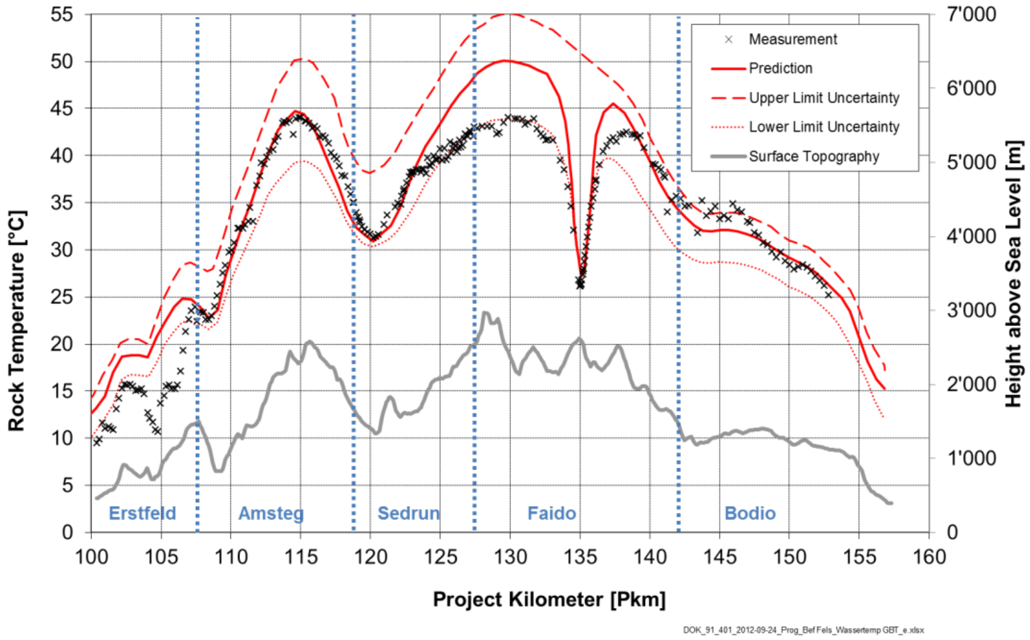

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Figure 3. Rock temperature prediction (red continuous line) with uncertainty band (dashed - dotted red), measured rock temperatures (black symbols) at tunnel depth, and surface elevation (gray line) along the GBT trace

The course of the measured rock temperatures follows generally the variation of overburden. The maximum temperatures were found with ca. 44 °C at project km 115 and 130. The lowest rock temperatures have been measured in the vicinity of the North portal Erstfeld with 10 °C. No temperature measurements are available from a few tunnel kilometers before the South portal Bodio. A dominant feature is the temperature depression, most pronounced at project km135. It is caused by the downward movement of cold precipitation from the surface through the permeable carbonatic rocks of the Piora zone. For further details see Rybach and Busslinger (1999).

During tunnel construction, numerous rock samples were taken, on which thermal conductivity (including determination of anisotropy) as well as heat capacity and density measurements have been performed. The results are helpful for the interpretation of the rock temperature measurements; see below.

4 Comparison prediction / measurements

Generally, there is a good match between predicted and measured rock temperatures; the deviations remain largely within the tolerance as indicated by the prognosis uncertainty band. Figure 4 displays the absolute difference between prediction and findings as individual values as well as an interpolated curve. For perfect compliance all values should be 0 °C. The interpolated curve remains between -2 °C and +8 °C. The deviations generally do not follow the course of surface topography (the largest deviation is at smallest coverage).

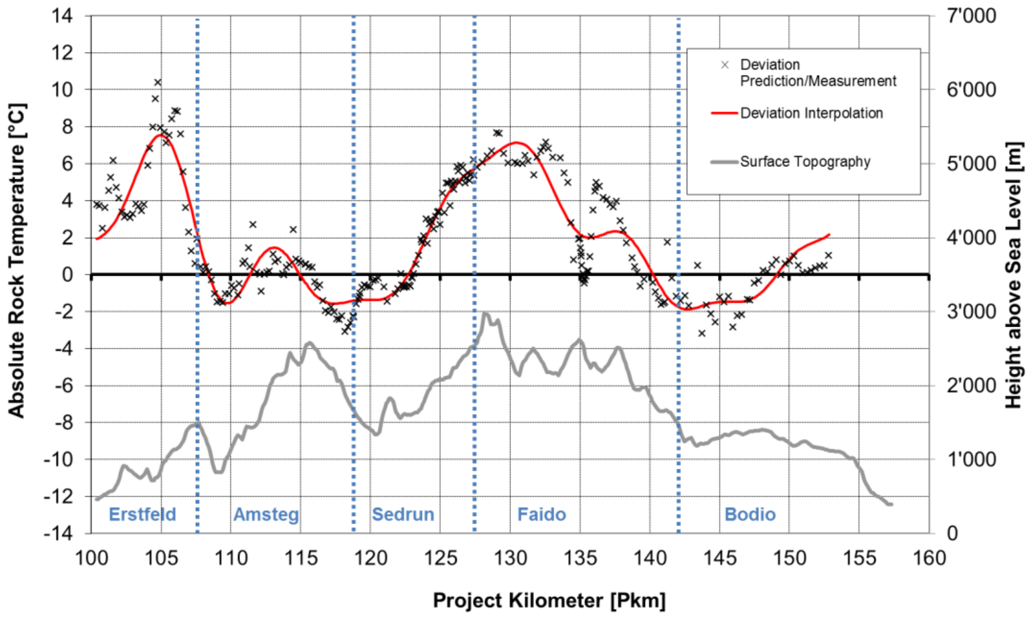

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Figure 4. Absolute deviation in °C between prediction and measurement: individual values and interpolated trend in red (trigonometric fit - Fourier series, 0th to 8th terms)

The differences between predicted and measured rock temperatures are positive as well as negative, without any systematic character.

The real quality of the prediction becomes evident from Figure 5: here, the relative deviations are plotted. Perfect match would be 0 % all over the tunnel trace. The deviations are generally small, only at two places above 10 %. In the following, the deviations are commented section-wise. Here it must be emphasized that the tunnel temperature measurements were taken as reported, without any accuracy checks (equipment calibration and measurement practice were not assessed).

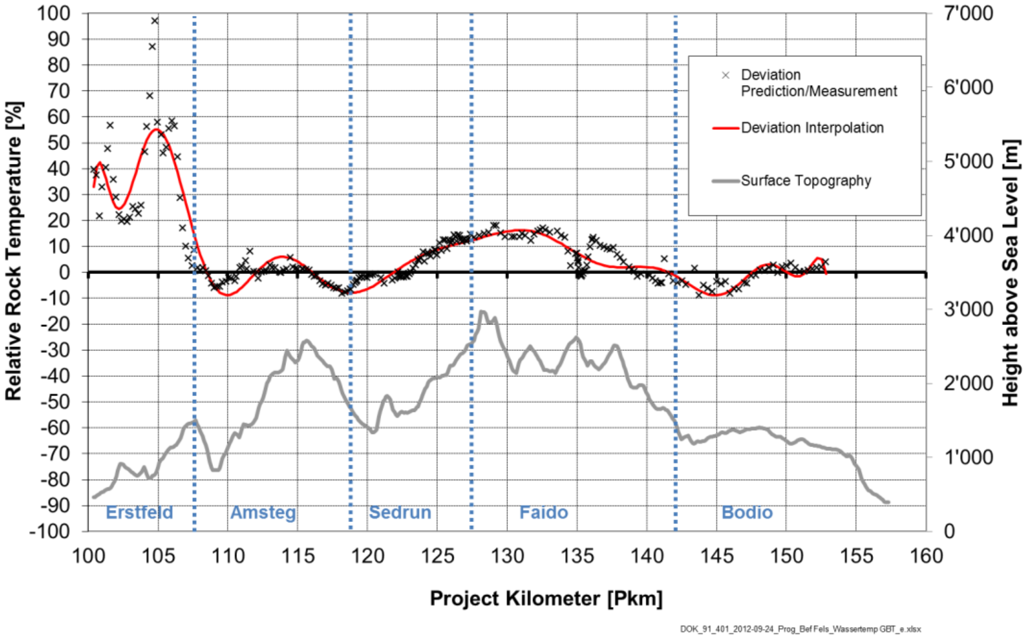

Figure 5. Relative deviation in % between prediction and measurement: individual values and interpolated trend in red (trigonometric fit - Fourier series, 0th to 8th terms)

4.1 Section Erstfeld (project km 100 – 106)

Between project km 100 and 103 the measured values follow the lower limit of the prediction (Figure 3), whereas around 105 project km the largest deviations occur at the lowest measured temperatures. The averaged difference reaches + 55 %, a single value has 100 % (a deviation of 10 °C yields 100 % difference at a temperature of only 10 °C). The surprisingly low actual rock temperatures can be attributed to the cooling effect of unexpected meteoric water, infiltrating from the near (<500 m vertical distance) surface. This is corroborated by the large, cold inflows (up to 280 l/s with < 10 °C) encountered in the same tunnel segment (project km 104 and 106) during construction. These highly remarkable hydrogeologic features were not yet known for the prediction modeling since they were found only later, during the excavation of the tunnel.

4.2 Section Amsteg (project km 106-118)

In this section, the deviations are positive as well as negative but very small, only a few %. The temperature measurements were already available for modeling and were used for calibration (Rybach et al. 2006).

4.3 Section Sedrun (project km 118-127)

According to Figure 3, the prediction and the measured temperatures coincide in the segment project km 119 and 123. Subsequently, the temperatures follow the lower limit of the prediction. The relatively low actual temperatures with the maximum difference of about 6 °C (15 % relative) at project km 127 are remarkable and in need of explanation.

The geologic documentation of the rock units found during tunneling (especially about their dip angles) and thermal conductivity measurements on samples taken by the project geologists revealed new insight about the course of rock temperatures in the segment project km 123-133. The fall angles found are about 25° steeper than used in the prediction calculations; this enhances the heat transfer towards the surface and thus lowers the rock temperature. The thermal conductivities found parallel to schistosity were significantly higher (not yet known at the time of the modeling); this also leads to lower rock temperatures. It is estimated that these effects decrease the rock temperatures by 5 – 10 °C. Significant water flow (up to 50 l/s encountered during tunneling) can be a further reason for the relatively low temperatures.

4.4 Section Faido (project km 127-142)

According to Figure 3, the measured values in the segment between project km 127 and 133 follow the lower limit of the prediction, thus the measured values were significantly lower than predicted. The maximum predicted values reach about 50 °C whereas the measurement at the same point (project km 130) amounts only to 43.5 °C. The absolute deviation is thus 6.5 °C, the relative deviation 15 %. Also in this segment, the lower than predicted temperatures can be attributed, as in section Sedrun, to higher rock thermal conductivities and steeper fall angles.

The great anomaly at project km 135, related to the Piora zone, was already known at the time of the predictive model calculations (Busslinger and Rybach 1997); between project km 133 and 136 as well as between project km 138 and 142, the measured temperatures fit the prediction well. In the remaining part of the section, the measurements reveal slightly higher temperatures than predicted.

4.5 Section Bodio (project km 142-157)

The measured temperatures between project km 142 and 147 show relatively large scatter. On average, they are higher than predicted by a few °C; this can be attributed to the fact that for the prediction steeper fall angles were taken than found during tunneling. Good agreement exists, however, between project km 147 and the end of measurements.

5 Conclusion

Predicted and actually measured rock temperatures generally agree well along the GBT, mostly within ± 15 %. The differences do not depend on the rock coverage. The agreement proves that most of the assumptions applied in the prediction modeling have been correct.

Many new geologic and hydrogeologic findings as well as thermal conductivity measurements have been made during construction of the Gotthard Base Tunnel. On the basis of their consideration and comparison with the rock temperature measurements, the following conclusions can be made:

- The structural geologic input parameters as well as the rock thermal and hydraulic properties have been generally appropriate for the model calculations, as substantiated by the new findings;
- Significant differences between prediction and measurement occur only in two limited tunnel segments: 1) In tunnel section Erstfeld (cf. chapter 4.1) where the prediction overestimates rock temperature by up to 10 °C. The measured low values are due to cold meteoric water infiltration from the near mountain surface. During tunneling, large and cold inflows (280 l/s, 10 °C) were encountered in the same segment; 2) In segments of tunnel sections Sedrun and Faido (cf. chapters 4.3 and 4.4.), the prediction overestimates the measured conditions by max. 6.5 °C (relative discrepancy 15 %). This is due to the difference between the modeling input parameters and the reality as revealed by the observations during tunneling: notably, the structural dip was steeper than anticipated and higher thermal conductivity of the rocks lead to a cooler tunnel domain by several °C.

The tunnel section Faido comprises a spectacular geothermal anomaly at project km 135, related to the Mesozoic rocks of the Piora zone. The course of the rock temperatures disagree completely with the overburden thickness, see Figure 3. This was already evident during driving the Piora exploratory adit (prior to GBT): Contrary to common sense, tunnelers experienced a rock temperature drop while excavating deeper into the mountain range. Numerous special drillholes with temperature measurements revealed a pronounced cold zone, which was perfectly modeled by the prediction calculations (cf. Busslinger and Rybach 1999b). It was shown by Rybach and Busslinger (1999b) that the anomaly is caused by cold groundwater of surface origin, circulating in the higher, more permeable parts of the Piora zone perpendicular to the vertical plane through the GBT.

Based on the experiences described above, a number of recommendations can be made for upcoming tunneling projects.

6 Recommendations

Rock temperature predictions for deep tunnels can nowadays be made remarkably accurately. Special numerical modeling software is needed to reliably handle the complex conditions, processes, and boundary conditions. The example of the Piora thermal anomaly proves that deep groundwater circulation must be especially considered and treated.

In order to have a solid basis for the prediction, a close coordination of the providers of the input parameters like the geologic, hydrogeologic, and geothermal data of the project realm is needed from the very beginning. A project-specific understanding of the possible range of individual input values as well as of boundary conditions is indispensable (e.g. possible deviations in position, extent, and orientation of geologic units).

The temperature distribution over the earth surface in the project realm is a key boundary condition in the prediction modeling. Special methods had to be developed to describe the elevation dependence of surface temperatures in the Swiss Alps and, especially, in the realm of the Gotthard Base Tunnel (Rybach et al. 2006). These can now be applied for tunneling projects in pronounced topography.

For rock temperature predictions it is essential to have information about possible water inflow into the tunnels. Thermal effects of inflow (especially cooling by water infiltrating from near-surface) can be crucial (see e.g. Busslinger and Rybach 1999b and Chapter 4.1). Therefore, hydrogeologic data and inflow assessments are needed. Modeling techniques are nowadays available to predict the place and intensity of inflow and to estimate their thermal effects (Graf et al. 2002, Mégel et al. 2009).

On the other hand, warm inflowing waters form water-bearing zones under high cover can heat up work space; therefore, they are usually led (through insulated conduits) out to the portals. Possible energetic use of outflowing warm tunnel waters (e.g. for space heating or greenhouses) near the portals should be assessed already during early planning stages (Wilhelm and Rybach 2003).

Special emphasis must be given to the calibration of the rock temperature prediction along the tunnel axis. This requires the availability of reliable actual rock temperatures at selected places along the tunnel axis. It is therefore highly recommended to acquire corresponding data, already at early project stage, by means of special drillholes reaching the tunnel axis below highest rock cover (possibly deviated boreholes from the mountain flanks). Further information from the boreholes (petrophysical and thermal data) is certainly beneficial.

The example of the Gotthard Base Tunnel proves that reliable rock temperature prediction can be achieved also for terrains with high topographic relief, with further complexities like deep groundwater circulation or uplift/erosion.

Each tunnel builder equipped with a reliable rock temperature prediction holds an indispensable, powerful planning tool in his hands. It will enable him to accurately prepare necessary provisions (like cooling and ventilation) as well as discover possible deviations from geologic predictions (as fault zones with heavy water inflows) in advance.

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