Use of Universal Kriging as a tool to estimate mountain temperature distribution affected by underground infrastructures: the case of the Brenner Base Tunnel

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ABSTRACT

Mountains represent huge low enthalpy geothermal reservoirs. The correct estimation of underground temperature values is relevant for both the design of the tunnel ventilation system and for the assessment of the potential exploitation of geothermal energy. An accurate three-dimensional (3D) model of the ground temperature distribution can be therefore considered as an important goal in the preliminary design stage of mountain tunnels.

Numerical modelling and spatial interpolation of the available temperature data need an appropriate estimation methodology, due to the generally limited number of values compared to the dimension of the investigated area. The common deterministic temperature models, based on local surface datasets, average geothermal heat flux and underground thermal properties, possibly integrated with borehole data, cannot be considered sufficiently accurate. The traditional interpolations are generally characterised by low accuracy since they do not take into account the spatial structure of data (i. e. the distance among them). This drawback can be avoided using geostatistical approaches such as Universal Kriging (UK).

The UK method, presented in this paper, is a valuable tool for the improvement of temperature measurement interpolation at different depths. In particular, it allows an unbiased estimation of the distribution of the mountain temperature.

This type of model can also be continuously updated with new temperature data measured during construction, allowing the estimation of the temperature inside the tunnel at locations that may also be very far from the entrance. Finally, the estimation of the temperature variance, which is possible with this technique, provides a local probability mapping and shows the uncertainty of the temperature estimates.

The present work illustrates the application of this methodology to the Italian segment of the Brenner Base Tunnel. In this particular case, the temperature distribution model was added to the specific Geographic Information System available for the underground infrastructure.

1. INTRODUCTION

The low enthalpy geothermal potential in mountainous regions is significant as it is stored both in subsurface waters and in rock mass (Rybach, 1995). Infrastructures in mountain environments can exploit part of this energy, by installing absorber pipes in the ground and in the support systems or by taking advantage of the water drained by the excavations. The use of absorber pipes inside the lining (a technique usually known as “energy lining”) is particularly favourable because it reduces the investment costs with respect to conventional geothermal closed loop (borehole heat exchangers) and open loop (well doublets) solutions. Energy lining is usually coupled with heat pumps in order to provide heating and cooling to final users (Di Donna and Laloui, 2013).

Although the feasibility and economic convenience of the energy geostructures has been proved (Barla and Perino, 2012), nonetheless the correct prediction of the exploitable energy becomes of fundamental importance to finalise the investment value and the real benefits and incomes of each project, both in urban and mountain environments (Delmastro et al., 2016). As for other closed loop systems, the exploitable energy of the energy lining is strongly affected by the natural temperature distribution in the rock mass (Carslaw and Jaeger, 1959).

This paper presents a three-dimensional approach, based on geostatistical techniques, for the prediction of rock mass temperature in mountain environments affected by the presence of a tunnel. The study focuses on the case study of the Mules access tunnel of the Brenner Base Tunnel (BBT) system, for which an energy lining is hypothesised to exploit the available geothermal energy.

The method proposed in this paper can be generalised and used elsewhere for different energy geostructures applications and projects, especially when located in mountain environment, for which the spatial variability of rock mass temperature, due to the natural orographic, geological and hydrogeological conditions, should not be neglected.

2. OVERVIEW OF THE BRENNER BASE TUNNEL

The Brenner Base Tunnel (BBT), part of the European Corridor TEN SCAN-MED, is a railway line through the Eastern Alps that will connect the town of Fortezza - Franzensfeste (Italy) to the city of Innsbruck (Austria). The overall infrastructure length is about 55 km and the entire project includes the construction of about 230 km of tunnels, characterised by different elevations: the tunnels start from 743 m a.s.l. at Fortezza, subsequently reaching peak elevation at 794 m a.s.l. near the Brenner Pass and finally reaching the city of Innsbruck at 609 m a.s.l. The maximum tunnel overburden is about 1.600 m a.s.l. The BBT is scheduled to be operational in 2026 and it is composed by (Figure 1):

- 2 (in progress) main single-direction railway tunnels, referred as East and West tunnels;
- 1 (in progress) exploratory tunnel excavated in advance for geological and geomechanical investigation;
- 4 (built) access tunnels (Ampass, Ahrental, Wolf and Mules), for logistic purposes during tunnel construction phase and as emergency escape routes during the operational phase;
- 3 (planned) emergency stations (Innsbruck, St. Jodok and Campo di Trens – Freienfeld).

The BBT tunnels cross many different geological units and faults. Figure 2 shows the geological map relative to the Italian side of BBT.

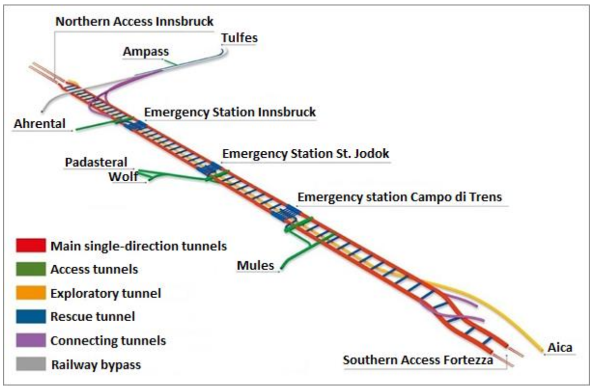

Figure 1: Layout of BBT system.

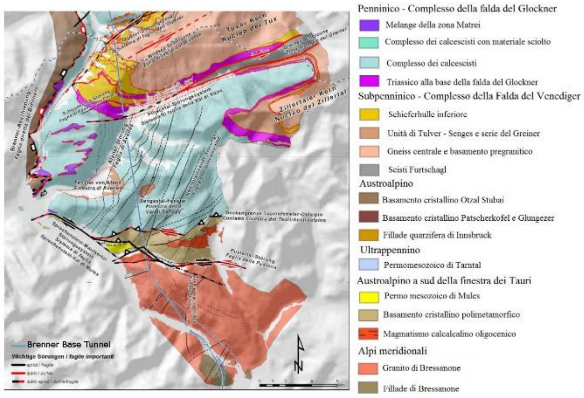

Figure 2: Geological map showing the main units and faults for the Italian side of BBT.

3. THE ENERGY LINING IN THE BRENNER BASE TUNNEL CONTEXT

The energy lining represents an innovative and relatively recent solution for low enthalpy geothermal energy exploitation. The functional principle consists in extracting heat from the rock mass through a closed loop circuit installed within the tunnel lining, to be used for different purposes, usually combined with a heat pump. The few existing applications and case studies refer to the use of the energy lining potential for heating and cooling of nearby final structures (Franzius et al., 2011) and for the natural cooling of the tunnel, with consequent reduction in ventilation needs (Nicholson et al., 2014).

Tunnelling methods can influence the selection of energy lining types, mainly in relation to the installation timing of the geothermal pipes inside the lining. The most common possibilities are:

- installation of geothermal pipes directly within the precast segments of the final lining. This solution can be adopted when the excavation is performed using a tunnel boring machine (TBM) (Rehau and Zublin, 2011);

- installation of geothermal pipes between the primary lining and the geotextile used for waterproofing. It is a valuable alternative when drill and blast or punctual mechanised excavation systems are used (Bouazza and Adam, 2012).

The Mules access tunnel was excavated with drill and blast technique inside the Brixen granite and at the moment is supported by a shotcrete layer. A part of this tunnel, characterised by a length of around 1.5 km and a slope of 9%, was already selected by the Authors of this paper for verifying the possibility of installation of geothermal pipes between the primary lining and the geotextile (Casale, 2015; Boldini et al., 2016; Lanconelli, 2016). Figure 3 shows a schematic representation of the geothermal closed loop circuit inside the tunnel, as designed after a preliminary feasibility study.

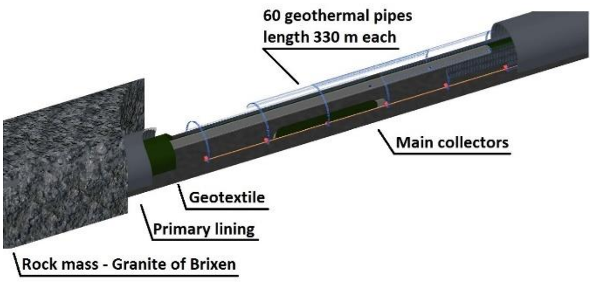

Figure 3: Three-dimensional scheme of the energy lining pre-designed for the Mules access tunnel.

4. THREE-DIMENSIONAL RECONSTRUCTION OF ROCK MASS AND TUNNEL THERMAL BEHAVIOUR

The estimation of temperature distribution in a rock mass should be achieved by a combined approach, based on deterministic equations that simplify the physical phenomena and a probabilistic modelling, able to tackle the natural variability and the abnormal points.

4.1. Part I: Deterministic modelling

Many Authors addressed the topic of heat transfer in subsoil and rock mass, and the related temperature distribution assessment, in different climatic, geographical and hydrogeological contexts (Kusuda and Achenbach, 1965; Turcotte and Schubert, 1982; Baggs, 1983). Some studies also took into account the thermal effect due to the presence of underground infrastructures and buildings (Mihalakakou et al., 1995). In recent times, the topic increased in popularity because of the renewed interest in using natural subsoil insulation to reduce energy consumptions of underground buildings, with particular attention to the agronomics sectors (Mazarron et al., 2012; Tinti et al., 2014; Tinti et al., 2015), and the increase in exploitation of geothermal energy from shallow geoexchangers and energy geostructures. For both applications, the knowledge of vertical temperature variations and the building-exchanger thermal interaction should be kept under control in the design phases (Bandos et al., 2009; Laloui and Di Donna, 2014). Equation [1] shows the well-known analytical model of temperature distribution in the subsoil, space-time dependent, which merges the ambient temperature wave with the rock mass thermal properties and the geothermal gradient:

$$T_g(d,t) = T_m - A \cdot \exp\left[-d \cdot \sqrt{\left(\frac{\pi}{T \cdot \alpha}\right)}\right] \cdot \cos\left[\frac{2 \cdot \pi}{T} \cdot \left(t - t_{T_0} - \frac{d}{2} \cdot \sqrt{\left(\frac{T}{\pi \cdot \alpha}\right)}\right)\right] + \vec{\nabla} T(\lambda, h) \cdot d \quad [1]$$

where T_m is the annual average temperature (°C), A is the wave amplitude (°C), T is the wave period (d), d is depth (m), t is time (d), t_{T0} is the time of minimum temperature (d), α is the equivalent thermal diffusivity of the rock mass (m^2/d) and $\vec{\nabla} T$ is the geothermal gradient (°C/m), depending on the geothermal heat flow h (W/m^2) and the equivalent thermal conductivity of rock mass λ (W/m·K).

Figure 4 shows the typical trend of isotherms below the mountain surface calculated through the application of Equation [1] to the real climate and geological values of the Eastern Alps.

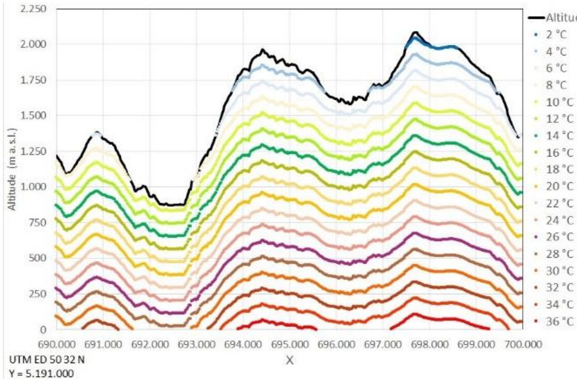

Figure 4: Standard behaviour of isotherms in a section of Eastern Alps, intersecting the Mules access tunnel, of the BBT system.

In the case of an energy lining, also the role played by the airflow at the support intrados has to be considered. A possible mathematical expression for the air temperature inside a tunnel is the following (Zhang et al., 2013):

$$T_{airflow} = T_a + A_v \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot t + \varphi\right) \quad [2]$$

where T_a is the annual mean temperature of air in the tunnel (°C), A_v is the wave amplitude in the tunnel (°C) and φ is the initial phase.

The airflow generates a convective heat transfer in the tunnel, which can be analysed by turbulent flow models and CFD simulations (Tan et al., 2014).

In order to compute the entire temperature field around a tunnel, the combination between conduction heat transfer models for the ground and convective heat transfer models for the airflow should be carried out. This combination is particularly important in mountain environment, where different coverages along the tunnel length are usual. In literature some examples of simplified analytical models on the determination of air temperature inside underground buildings exist (Mazarron and Canas, 2008). Following these examples, a simplified analytical equation expressing the temperature distribution at the tunnel lining intrados as a function of the chainage PK (km) and the time t is proposed as the following:

$$T_t(PK,t) = T_a \cdot \omega_a + T_g(PK,d,t) \cdot \omega_g - A_v \cdot \exp\left[-PK \cdot \sqrt{\left(\frac{\pi}{T \cdot \beta}\right)}\right] \cdot \cos\left[\frac{2 \cdot \pi}{T} \cdot \left(t - t_{T_0} - \frac{PK}{2} \cdot \sqrt{\left(\frac{T}{\pi \cdot \beta}\right)}\right)\right] \quad [3]$$

where ω_a and ω_g are the percentage weights identifying the contributions of air and rock mass temperature to the temperature of the tunnel lining; the percentage vary according to the different position on the lining (top and bottom); T_g (PK,d,t) is the estimated temperature of rock mass at different locations, depths and times, β is a parameter comprehensive of the different thermal effects within the tunnel, having the dimension of thermal diffusivity (km^2/d); all other parameters were already defined in Equation [1] and Equation [2].

4.2. Part II: Probabilistic modelling

Kriging is a widely used method of spatial interpolation, especially in earth and environmental sciences. The main aim of the kriging method is to estimate a variable over a domain, starting from the measured and known values, which are spatially localised. The interpolation parameters are selected to optimise the best-fitting criterion, whose characteristics are based on the sample data (Chiles and Delfiner, 1999). The kriging method uses a function based on a covariance or variogram model derived from the data. The variogram describes the spatial variability of the known data in a finite region. The experimental variogram $\gamma(h)$ is defined as follows:

$$\gamma(h)=\frac{1}{2}Var\left[Z(\tilde{x})-Z(\tilde{x}+h)\right] \qquad [4]$$

where $\tilde{x}$ is the spatial vector, representing the x,y,z coordinate, $Z(\tilde{x})$ is the spatial variable and h is the spatial lag between known data points.

The universal kriging (UK) method is used when the spatial variation of any continuous attribute is too irregular to be modelled by a simple, smooth mathematical function. Instead, the variation can be better described by a stochastic surface. In most cases, the mean of the regionalised variable is not constant across the entire study area and in this case, using a geostatistical technical language, the variable is defined as non-stationary. A non-stationary regionalised variable is split in two components (Davis, 1973):

$$Z(\tilde{x})=D(\tilde{x})+Y(\tilde{x}) \qquad [5]$$

where $D(\tilde{x})$ is the drift, consisting in the mean or expected value of the regionalised variable and $Y(\tilde{x})$ is the residual, being the difference between the actual measurements and the drift.

The UK method is able to manage these types of variables and does not require the removal of possible local trends from the data.

In this case study, the drift $D(\tilde{x})$ indicates the standard temperature in a point, according to climate, rock coverage, rock type and local geothermal heat flux; on the other hand, the residual $Y(\tilde{x})$ designates the local variations, due to measured local temperature anomalies, inhomogeneity of thermal rock properties and modifications of temperature distribution caused by the tunnel presence.

The model is able therefore to predict the natural rock mass temperature as well as the temperature variation inside the tunnel for different stages of advancement.

The model can be also progressively updated by new data collected during excavation, after new tests and in relation to additional utilisation stages of the tunnel.

5. MODEL APPLICATION TO THE MULES ACCESS TUNNEL

The UK estimation technique is used in this paper to recreate the entire three-dimensional temperature field of the Alp region affected by the presence of the Mules access tunnel. This knowledge is very useful for estimating the energy amount which would be actually exploitable by the energy lining system showed in Figure 3.

5.1. Preliminary data and measurements

The starting point for any temperature estimation in a mountain environment consists in getting a number of meaningful data. Many data were collected from BBT documentation, some others by open access information and finally through specific in situ and laboratory measurements. The complete set of data used consists in:

BBT documentation:

- geological and hydrogeological information on the Mules area (BBT SE, 2014; BBT SE, 2015);
- temperature logging inside monitoring boreholes during geophysical exploration (BBT SE, 2006);
- temperature logging of drainage water during excavation (BBT SE, 2011).

Open access information:

- weather data of the study area (Province of Bolzano, 2015);
- geothermal heat flow in the study area (UNMIG, 2015).

New measurements:

- thermal conductivity and diffusivity laboratory tests on some samples of the hosting rock (Brixen granite) and of the shotcrete preliminary lining (Figure 5);

Figure 5: Rock and shotcrete samples for laboratory thermal conductivity and diffusivity tests.

- in situ campaign (July, November and December 2015) of temperature measurements inside the tunnel with an infrared thermometer, calibrated by a contact thermometer (Figure 6).

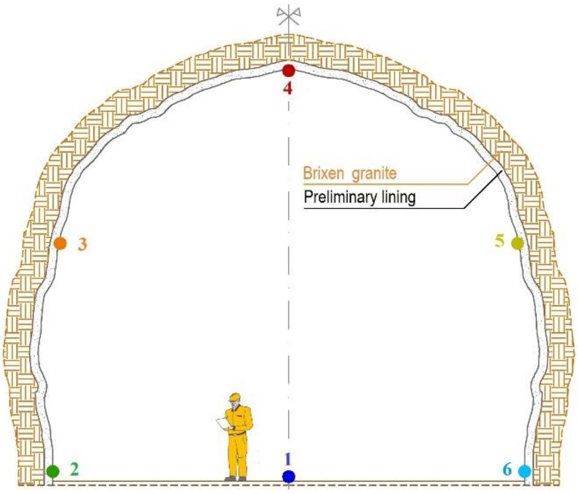

Figure 6: Measuring points of temperature in the tunnel.

5.2. Estimation of rock mass temperature

In the present case study, different information and data sets were used for the estimation of rock mass temperature. The geological and hydrogeological information were used to assess the general thermal properties of the area (almost exclusively made up of Brixen granite, see Figure 2), subsequently calibrated with the laboratory measurements of thermal conductivity and diffusivity on the 4 rock samples of Brixen granite. The weather data were used as top points at the ground level for the estimation of the vertical temperature behaviour. Geothermal heat flow provided the magnitude of the geothermal gradient of the area. The specific trend data were obtained from the temperature logging inside the monitoring borehole Mu-B-04 situated near the Mules access tunnel. The temperature data in the depth range 440 m - 716 m were taken as valuable measurements of the drift, being not affected by airflow movements. According to the geological information, and to simplify the methodology, the area of the estimation was considered as homogenous. The statistical analysis of the rock mass temperature is presented in Figure 7.

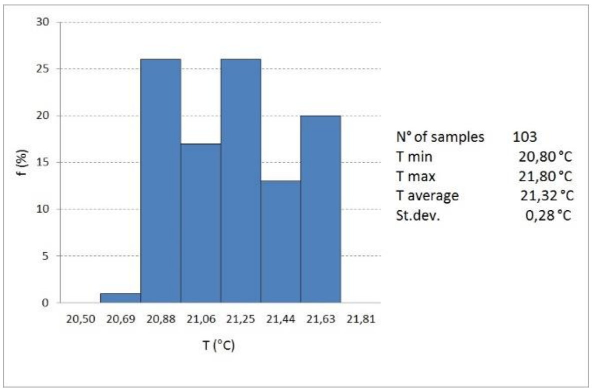

Figure 7: Histogram of the temperature obtained from the borehole data.

According to the physical increase of temperature with depth, and considering other influencing parameters (density, rock thermal conductivity, volume and height of the mountain), the temperature trend reflects a gradual increase, clearly shown by the experimental variogram, with the presence of a drift. The interpolation variogram model represents the basic structural behaviour of rock mass temperature around Mules access tunnel. The experimental and model variograms obtained by the borehole data are given in Figure 8.

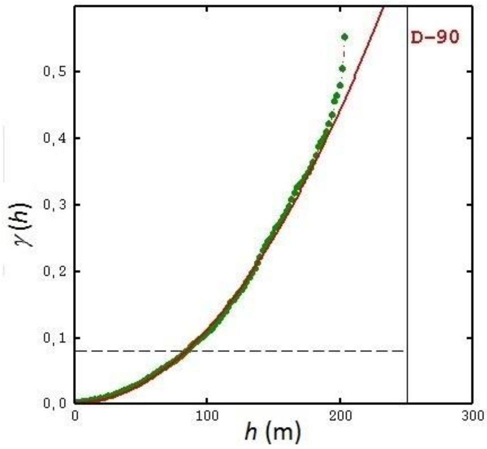

Figure 8: Experimental variogram and related model of the temperature obtained from the borehole Mu-B-04 data.

According to the variogram model of Figure 8, an increasing variability with the vertical direction can be observed. It indicates the presence of a space-varying mean, the drift $D(\tilde{x})$, representing the trend of data; when $D(\tilde{x})$ is present, the analysis should be performed using the UK approach (see paragraph 4.2).

It was then possible to calculate the entire temperature distribution around the Mules access tunnel in three dimensions. Figures from 9 to 12 show the horizontal sections of the UK results - temperature estimation and related standard deviation - at two different levels, respectively nearby the highest and the lowest elevation of the part of the Mules access tunnel considered.

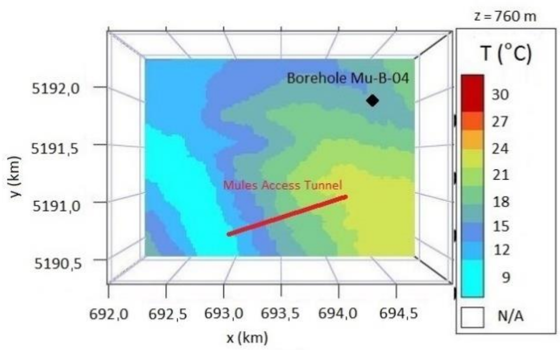

Figure 9: Horizontal section of the UK temperature estimation results at *z* = 760 m a.s.l., nearby the lowest elevation part of the Mules access tunnel considered.

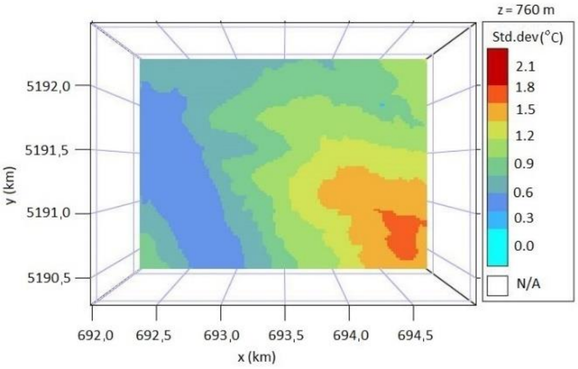

Figure 10: Horizontal section of the UK estimation standard deviation results at *z* = 760 m a.s.l..

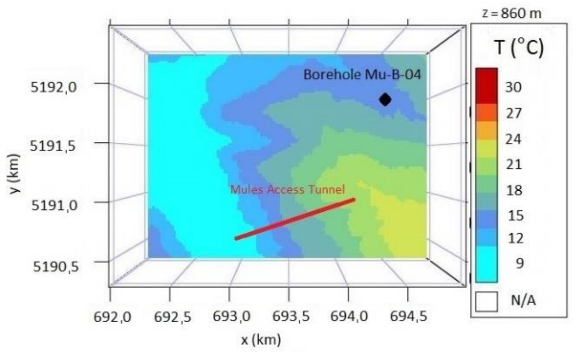

Figure 11: Horizontal section of the UK temperature estimation results at *z* = 860 m a.s.l., nearby the highest elevation part of the Mules access tunnel considered.

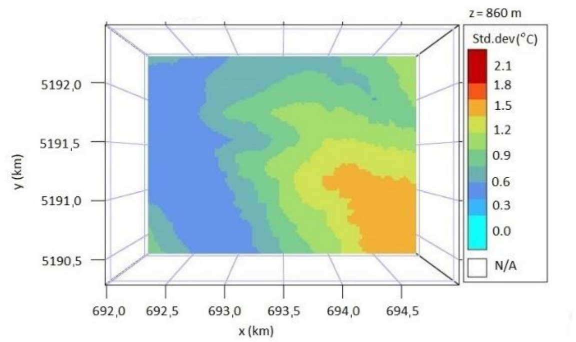

Figure 12: Horizontal section of the UK estimation standard deviation results at *z* = 860 m a.s.l..

The map of estimation standard deviation indicates the degree of confidence of results. Since the initial temperature data have the same spacing, with the exception of the temperature trend in Mu-B-04, the map of standard deviation variance only varies based on the coverage of the mountain. According to the estimation performed, the rock mass temperature at the lining extrados of the Mules access tunnel is shown in Figure 13.

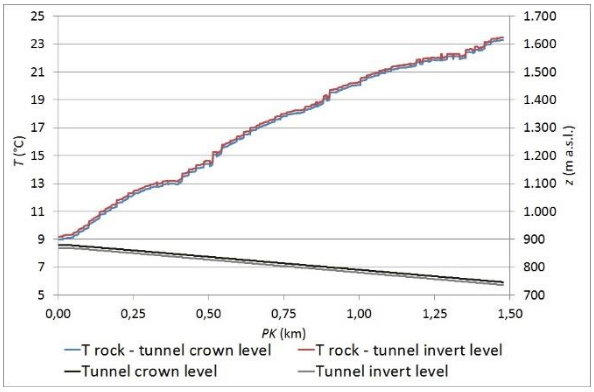

Figure 13: Estimation of the temperature of the rock mass along Mules access tunnel length.

5.3. Inverse model for the prediction of tunnel inside temperature

Three different databases were used to predict the temperature behaviour inside the tunnel as a function of the chainage *PK*, corresponding to the measurements carried out in July, November and December 2015. As previously shown in Figure 6, these latter were performed at six points of the tunnel section, three at the crown (points 3, 4 and 5) and three at the invert (points 1, 2 and 6).

The significant step for estimating the temperature distribution inside the tunnel in different months consisted in modelling the spatial structure starting from the experimental data taken at different *PK*.

The spatial variation of the temperature at the crown and invert of the lining intrados were analysed trough variograms considering the distance among measurements. Each month was analysed independently and an experimental variogram of the temperature variability was consequently calculated. From the analysis of the three experimental variograms, one unique structure of nested variogram model was hypothesised. This structure was then calibrated, by varying the range and sill, to the three experimental variograms related to the measurement campaigns carried out. It was possible to quantify the spatial variability of the temperature at the intrados of the primary lining.

The nested variogram model used is composed by a nugget effect (which identifies the non-structured part) coupled with K-Bessel and J-Bessel variogram models (which identify the temperature sinusoidal pattern at the tunnel portal, affected by external temperature and airflow) and a power model (which identifies the drift caused by the temperature increase due to the rock coverage). Figures from 14 to 19 show the experimental and model variograms related to the sample data of July, November and December 2015, at the crown and invert of the Mules access tunnel.

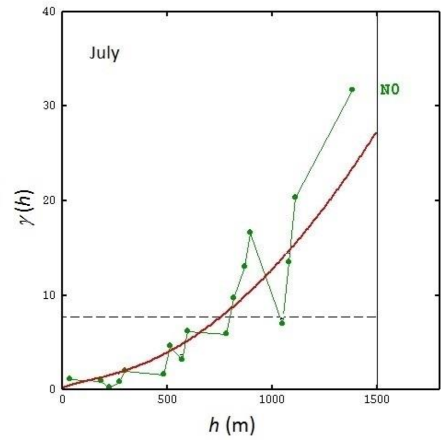

Figure 14: Experimental variogram and related model of the temperature obtained from the sample data collected at the crown of the Mules access tunnel (measurements points 3, 4 and 5) in July 2015.

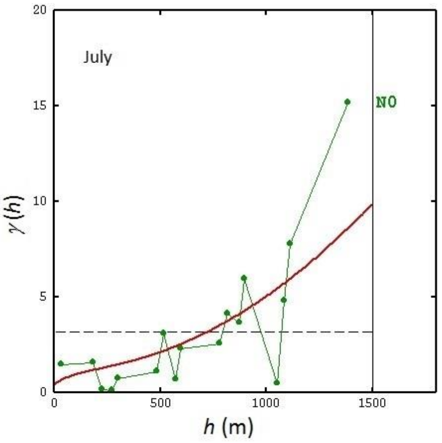

Figure 15: Experimental variogram and related model of the temperature obtained from the sample data collected at the invert of the Mules access tunnel (measurement points 1, 2 and 6) in July 2015.

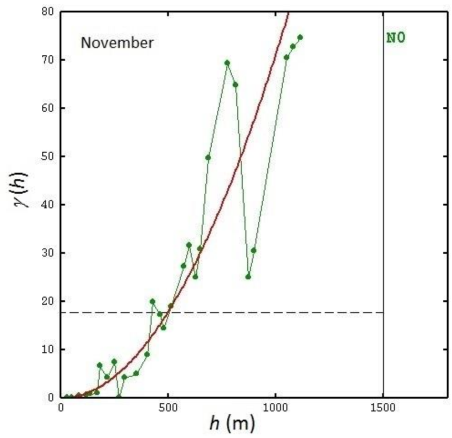

Figure 16: Experimental variogram and related model of the temperature obtained from the sample data collected at the crown of the Mules access tunnel in November 2015.

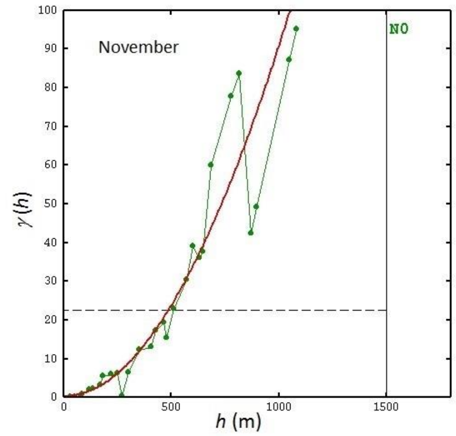

Figure 17: Experimental variogram and related model of the temperature obtained from the sample data collected at the invert of the Mules access tunnel in November 2015.

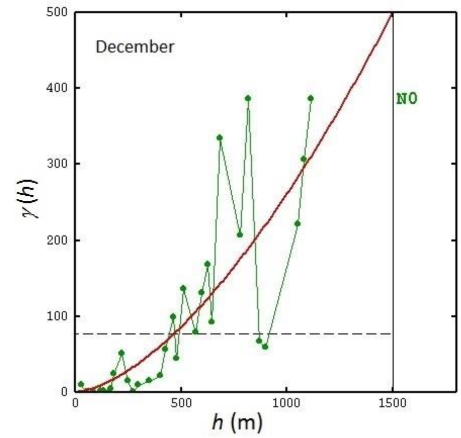

Figure 18: Experimental variogram and related model of the temperature obtained from the sample data collected at the crown of the Mules access tunnel in December 2015.

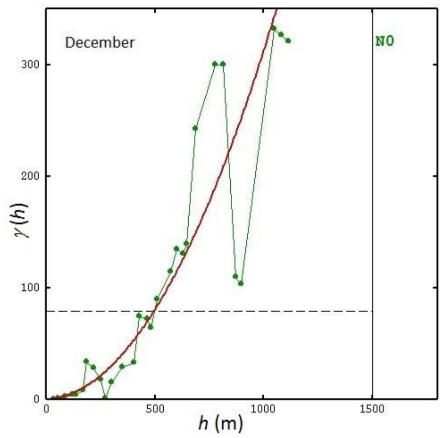

Figure 19: Experimental variogram and related model of the temperature obtained from the sample data collected at the invert of the Mules access tunnel in December 2015.

The variogram models were used in the UK, and a complete spatial estimation of temperatures for the three months considered was obtained. The estimation variance was also calculated and, together with the temperature trend along the tunnel axis, both at the crown and at the invert, it showed the coherency of the estimation with the spatial behaviour of the measurements. Results of the UK method highlight the spatial modification of the temperature inside the tunnel according to the different influential parameters such as the rock coverage and the external temperature seasonal variation along the year.

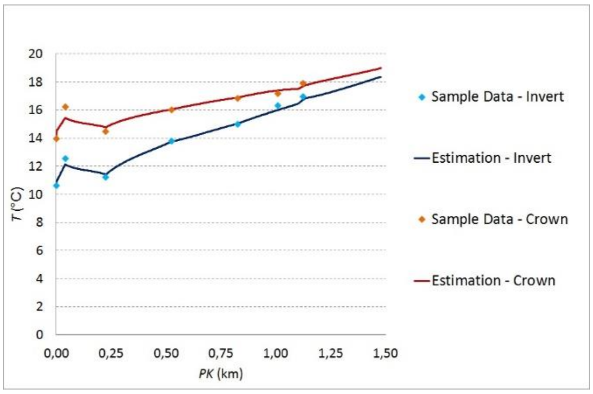

Figure 20: Comparison between temperature data and estimated trend along the crown and the invert of the Mules access tunnel. Month of July 2015.

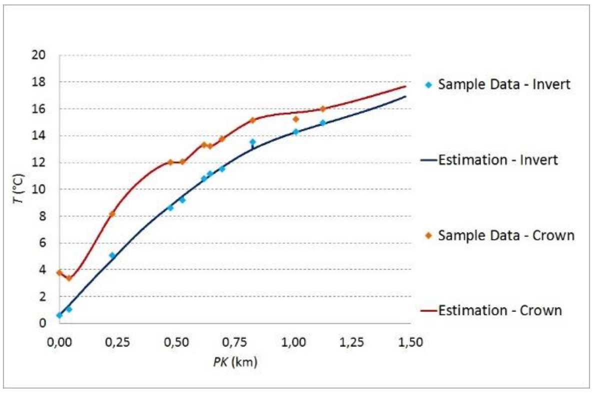

Figure 21: Comparison between temperature data and estimated trend along the crown and the invert of the Mules access tunnel. Month of November 2015.

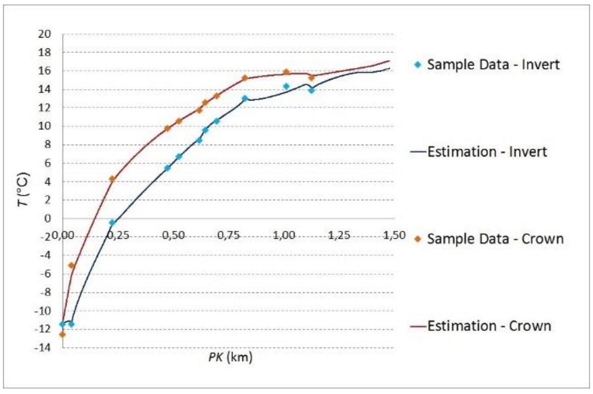

Figure 22: Comparison between temperature data and estimated trend along the crown and the invert of the Mules access tunnel. Month of December 2015.

Figures 20, 21 and 22 show the results in terms of temperature at the intrados of the lining (crown and invert) for the three months considered.

Starting from the collected data and the corresponding modelled distributions for the three considered months it was possible to reconstruct the temperature distribution within the tunnel all over the year, by using a simplified multi-parameter approximated approach, as the one presented in paragraph 4.1.

A non-linear regression technique on the periodic model expressed by Equation [3], was used to find the new parameter β, comprehensive of the thermal phenomena in the tunnel, and the percentage weights (ω_a, ω_g) to quantify the contribution of air and rock temperature. The technique uses optimisation algorithms based on differential equations and therefore involves the use of derivative of Equation [3] with respect to the unknown parameter.

The analysis uses the temperature spatial model presented in paragraph 5.2 as the fixed data set. Then, the estimated variation of temperature along the tunnel length during one reference year was calibrated by using the three temperature spatial models of July, November and December, reconstructed with the UK method.

Figures 23 and 24 illustrate the comparison between the time-space estimated behaviour of the temperature at the crown and invert, and the temperature models for the three months obtained starting from the measured data. The new comprehensive model is characterised by similar temperature trends for deeper tunnel sections. Some discrepancies between real values and estimated ones are still present, especially near the tunnel portal. This is mainly due to the convective effects caused by wind speed and intensity, which, not following a seasonal behaviour, cannot be correctly managed by the proposed new analytical model. Other specific factors, such as presence of vehicles, can alter the temperature distribution within the tunnel. These factors should be taken into account during the measurement campaigns.

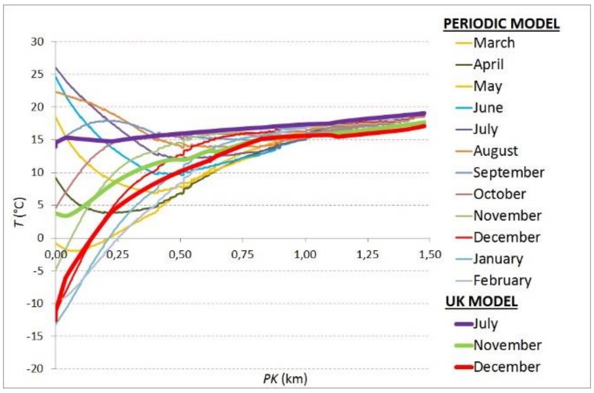

Figure 23: Temperature distribution along the tunnel crown according to the periodic temperature model and the punctual geostatistical models based on the real measurement values.

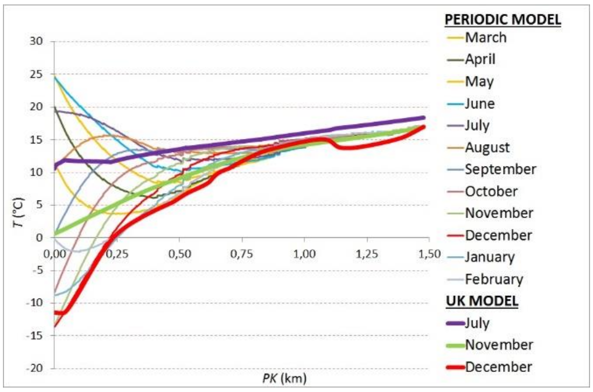

Figure 24: Temperature distribution along the tunnel invert according to the periodic temperature model and the punctual geostatistical models based on the real measurement values.

6. DISCUSSION AND CONCLUSIONS

When trying to assess the temperature distribution in a rock mass affected by the presence of large infrastructures, a comprehensive analytical model, taking into account all thermal phenomena influencing the data, is hard to find, especially in mountain environments, where many factors influence heat exchange. In the paper, a semi-probabilistic approach was proposed, calibrated against the available information and measurements. The approach and the results obtained for the Mules access tunnel are very much dependent on the specific situation. At this stage of knowledge, the convenience of the exact replication, to other similar cases, of the multi-step analysis method presented in this paper cannot be confirmed. Nonetheless, the semi-probabilistic approach can be easily adapted to other cases of mountain environments, starting from the physical constraints and the available information.

The paper presented a complete assessment of the temperature distribution in a rock mass affected by the presence of a tunnel in mountain environments, based on a combined use of deterministic and probabilistic methods. In particular, the use of the geostatistical drift as an appropriate solution to tackle both the physical trends and the spatial variability of the phenomenon was suggested. A new simplified analytical model was proposed for the estimation, through superposition of effects, of the temperature distribution within the tunnel.

The method was validated on the real case of the Mules access tunnel, part of the Brenner Base Tunnel system, for which a pre-feasibility study for the installation of an energy lining was performed.

The use of this approach makes possible to predict, with reasonable degrees of approximation, the distribution of temperatures in the rock mass and within the tunnel even during the excavation phases. For the particular case of the BBT system, the same calculations can be replicated also for the other tunnels consisting the network.

If the estimations of temperatures and thermal parameters are accurate, the economic benefits of the energy lining in mountain tunnels can be more precisely evaluated for both geothermal energy projects and the ventilation and cooling systems. Prediction errors can lead to underestimation of the investment costs or overestimation of the exploitable energy and circulating fluid working temperatures.

The Authors would suggest the computation of a three dimensional map of temperature distribution in the rock mass and inside the tunnel as a necessary tool for the design of a geothermal project and for the ventilation control of tunnels in mountain environment.

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