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Energy tunnels for deicing of a bridge deck in Alpine region

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Abstract Roads and paved surfaces in cold climate are exposed to the formation of ice and snow deposition. These phenomena are related to high risks for vehicles and road users due to reduced friction. Deicing techniques are up to now mainly based on chemicals, especially salt. These substances induce chemical decay of concrete infrastructure elements and environmental harm. In order to overcome these drawbacks, the use of embedded hydraulic pipes with a hot carrier fluid below the paved surfaces has been proposed in last decades. This circuit can be part of a Ground Source Heat Pump (GSHP) system. Despite a number of examples of this technology have been proposed, very few of them included the application of energy tunnels. This paper focuses on the thermal activation of a tunnel lining in relation to an application for bridge deck deicing. A theoretical case study along an Alpine road has been considered as representative of a common situation of alternated bridges and tunnels. The numerical results show that the thermal activation of the tunnel lining can provide enough heat to keep the paved surface unfrozen even in protracted periods of low external temperatures.

Keywords: geothermal energy, deicing systems, energy tunnels

1 Introduction

Ice and snow removal are a compelling need to ensure road users safety. Suspended structures like bridges and viaducts are particularly prone to ice formation due to the lower thermal inertia compared to earth-contact structures. The need to avoid slippery surfaces is even more important when roads present a significant grade, e.g. hilly and mountainous areas such as the Alpine region. Plowing, traffic movement, natural melting and chemical treatment are common techniques used to this end (Zhou et al., 2014). Indeed road winter maintenance is often based on the use of chemicals and fine aggregates (Kuemmel, 1994) due to their faster action. Most common deicing chemicals are calcium and sodium chloride that however result in structural damages to pavements and concrete structures as well as environmental damages (Novotny et al., 2008; Corsi et al., 2010; Hintz and Relyea, 2017). Given these negative effects, a number of alternatives have been implemented including resistive electrical heaters embedded below the pavement, solar energy and pipes containing heating fluid (Fischer, 2010; Wu et al., 2015; Lai et al., 2015). In this latter case, heat originates from fossil fuels or renewable energy sources. Among them, geothermal energy has been proved to be effective (Mauro and Grossman, 2017). Geothermal energy collection has been obtained not only by means of borehole heat exchangers but also using energy geostructures in recent projects (Brandl, 2006). Among energy geostructures, energy tunnels are gaining attention in last years (Adam and Markiewicz, 2009; Barla and Perino, 2015; Barla et al., 2019). Thermal activation technology directly depends on the excavation method adopted (conventional or mechanized).

Furthermore, in mountainous and hilly regions, roads commonly run on an alternation of bridges and tunnels. In such conditions, only bridge deep foundations or tunnel linings can be thermally activated. Nonetheless application to deicing of the heat exchanged through the tunnel lining was taken into account in very few cases.

In this study the typical situation of an Alpine region road with a bridge passing through a gully and two adjacent mechanically excavated tunnels is analyzed. Thermal activation of the tunnel lining is studied by means of numerical simulation to assess the viability of a geothermal-based solution for bridge deck deicing.

2 The Turinella viaduct case study

To the aim of this study, a stretch of the “S.P. 23” access road to the Chisone valley (Italy) was investigated. The road was built in the framework of the infrastructure renovation for XX Winter Olympics Games held in Torino in 2006 (Kalamaras et al., 2005). The 5.1 km new road stretch includes the 50 m long “Turinella” viaduct enclosed between the “Craviale” (1055 m) and the “La Turina” (665 m) tunnels respectively. The viaduct allows to pass through the gully excavated by the “Rio Turinello” torrent.

The study area is located in the lowest portion of the Chisone Valley in the north-western Italian Alps. Fig. 1 shows a geological cross section along the axis of the S.P. 23 between the Craviale and La Turina tunnels.

The “Craviale” tunnel and the “Turinella” viaduct are completely comprised within the pre-quaternary metamorphic crystalline “Dora-Maira” rocks (fine grained gneiss and granite) while “La Turina” tunnel intersects gravels in sandy-silty matrix (alluvial/colluvial deposits) known as “Pinerolo” group. The contact zone between these two units is characterized by a layer of sandy gravels with meter-sized blocks and boulders derived from an ancient landslide. The contact between the gneissic-granitic complex and the alluvial-colluvial deposits is thus located about 100 m ahead from the ESE “La Turina” tunnel entrance (Fig. 1). This contact is however far from tunnel entrance with respect to possible thermal activation applications.

Indeed, to study the thermal activation for the bridge deck deicing, limited tunnel lengths equal to 50 m from both the entrances of the Craviale and La Turina tunnels were selected. The choice of activating the initial section of both tunnels was adopted in order to limit the pipes network overall length and hence the thermal and head losses in the hydraulic circuits.

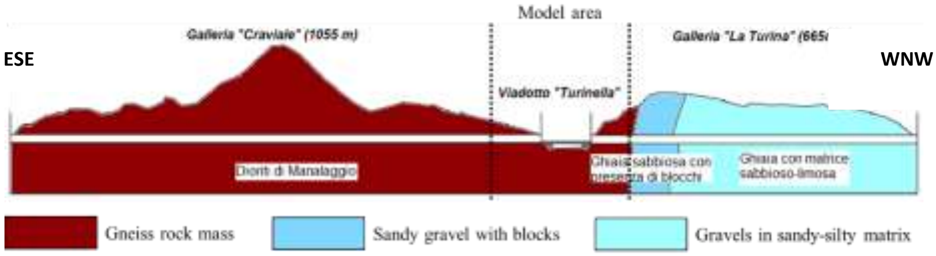


Fig. 1 Geological longitudinal cross section of the S.P.23 road axis between "Craviale" and "La Turina" tunnels.

Both the tunnels were constructed by conventional excavation method and are characterized by an internal radius of 6.3 m. Different cross sections were designed in line with the construction management process through observational method. In the Dora-Maira metamorphic crystalline rock mass the preliminary lining consisted of 15-20 cm thickness fiber reinforced shotcrete layer, completed by MN24 swellex dowels and 2IPN160 steel ribs where necessary. The final lining is a 70 cm thick reinforced concrete layer.
Tunnels entrances coincide with the viaduct abutments whose lengths are equal to 25 m. The "Turinella" viaduct is completely included in a straight section of the road and is a box structured 50.0 m long and 13.0 m wide bridge. Transversal slope is obtained by a variable thickness bituminous pavement.
This detailed geometrical information is adopted to properly assess the thermal activation performance of tunnel lining by means of high-resolution 3D Thermo-Hydro numerical models.

3 Numerical modelling of tunnels thermal activation

Thermal activation of the tunnel linings as deicing technology for bridge deck was analyzed with reference to the settings of the "Turinella" viaduct (Italy). For the sake of this study a 200 m long portion of the "S.P. 23" was reproduced by means of 3D Thermo-Hydro finite element models using the finite element code FEFLOW® (Diersch, 2009). The extremely variable ground surface was carefully reproduced and the model meshing resulted in about 1.9 million elements (Fig. 2). The pipe network was modelled in detail at the interface between primary and secondary lining, within the bridge deck exactly below the pavement layers and along the abutments and the tunnel entrances. Two distinct circuits were included, assuming both tunnels to operate deicing on half of the bridge deck length. Pipes were modelled through high hydraulic conductivity monodimensional elements, namely "discrete features" (Fig. 2) to reproduce 32 mm diameter-polyethylene tubes. To simulate the heat carrier fluid circulation, an interruption on the pipe network had to be included at the supposed location of circulation pump. Their location was assumed in the vicinity of the tunnel entrances where some technical room is often present to host the technological systems.

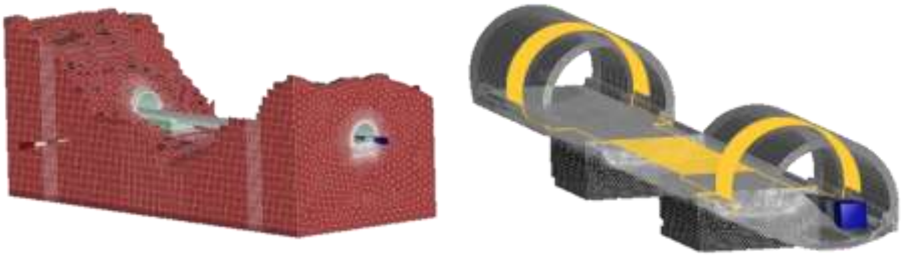


Fig. 2 Numerical model of the “Turinella” viaduct, the “La Turina” and “Craviale” tunnels. Ground surface overview (left); sketch of the embedded pipe network (right).

A first analysis (Step A in Fig. 3) was employed to evaluate the thermal evolution along the year at the tunnel’s extrados, at the pavement surface and within the rock mass without thermal activation. To this end appropriate Dirichlet boundary conditions were imposed to the elements pertaining to the external air by interpolation of climate data with a sinusoidal function, while initial rock mass temperature was set to 11.5°C, namely the mean annual air temperature. Internal air influence was neglected for the sake of simplicity, assuming ventilation to be absent. Material properties adopted in the models are listed in Table 1.

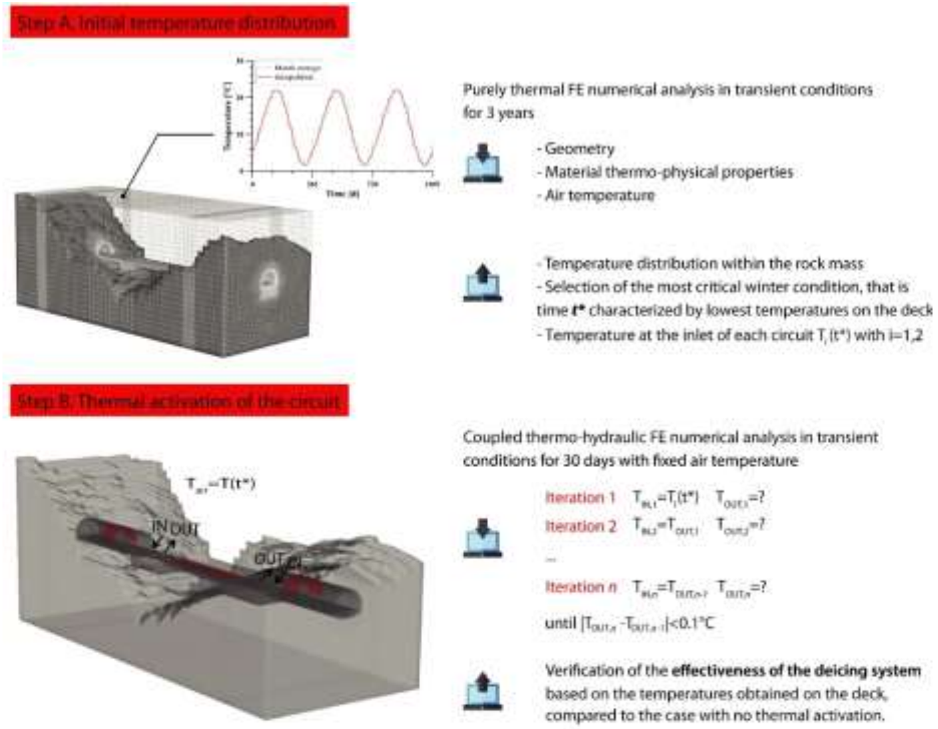
Table 1 Materials thermal properties adopted in the models

	Concrete	Asphalt	Rock mass	Air	Heat carrier fluid
Thermal conductivity λ [W/mK]	2.3	0.64	3.5	0.53	0.38
Thermal capacity ρc [J/m^{3}K]	2.19	0.92	2.16	0.001	2.16

By means of this analysis, temperature at the location of the tunnel heat exchanger was evaluated. First analysis also served to determine the time at which the minimum temperature on the bridge deck was reached.

The temperature field obtained at this time was later adopted to analyze the operations of the free heating circuits (Step B). Activation of the geothermal installation was studied for a period of 30 days. External extreme air temperature of -3°C were assumed during the whole period. Heat carrier fluid was assumed to circulate within the pipes with a velocity of 0.4 ms^{-1}.

In free heating mode the temperature at the inlet side is virtually equal to the one at the outlet end of the circuit and hence varies continuously. Thus the thermal evolution within the model was evaluated by iterating the analyses until the difference recorded at the outlet ends of the circuit was negligible with respect to previous iteration. A threshold value of 0.1°C was chosen. Indeed, the temperature profile of the fluid at the outlet side was afterwards employed as input at the inlet side of the subsequent model run. The process was continued until the difference in two subsequent runs did not exceed the above mentioned threshold value. The methodology is briefly depicted in Fig. 3.



Purely thermal FE numerical analysis in transient conditions for 3 years

- Geometry
- Material thermo-physical properties
- Air temperature

- Temperature distribution within the rock mass
- Selection of the most critical winter condition, that is time **t*** characterized by lowest temperatures on the deck
- Temperature at the inlet of each circuit $T_i(t^*)$ with i=1,2

Coupled thermo-hydraulic FE numerical analysis in transient conditions for 30 days with fixed air temperature

Iteration 1 $T_{IN,1}=T_i(t^*)$ $T_{OUT,1}=?$
Iteration 2 $T_{IN,2}=T_{OUT,1}$ $T_{OUT,2}=?$
...
Iteration *n* $T_{IN,n}=T_{OUT,n-1}$ $T_{OUT,n}=?$
until $|T_{OUT,n}-T_{OUT,n-1}|<0.1°C$

Verification of the **effectiveness of the deicing system** based on the temperatures obtained on the deck, compared to the case with no thermal activation.

Fig. 3 Conceptual scheme of the steps performed to evaluate the effectiveness of the deicing system

4 Results

The temperature natural trends at the interface between primary and secondary lining was evaluated with a finite element model comprising a portion of 200 m of the “S.P. 23” road with careful geometrical reproduction of the highly variable ground surface. Numerical analysis extended to three years timespan, starting from the end of the winter season, resulted in decreasing influence of the external air temperature together with increasing distance to the tunnel entrances (Fig. 4).

Due to the considerably higher depth of the inner sections, temperature range decrease is more pronounced than direct proportionality to the distance to the tunnel entrance. Fig. 4 in fact shows a band of about 10 m where the temperature of the rock mass is significantly affected by external air, while at larger depths this influence is negligible. Indeed at 15 m from the entrance, temperature oscillates about 7.4°C on annual basis, while at 30 m distance this range significantly shrinks to just 1.2°C. In this application the pipe coil was assumed to be deployed within the tunnel starting at 10 m from tunnel entrance and extending on 5 meters length. It should be noted that larger distances would result slightly beneficial to the heat exchange within the tunnel lining.

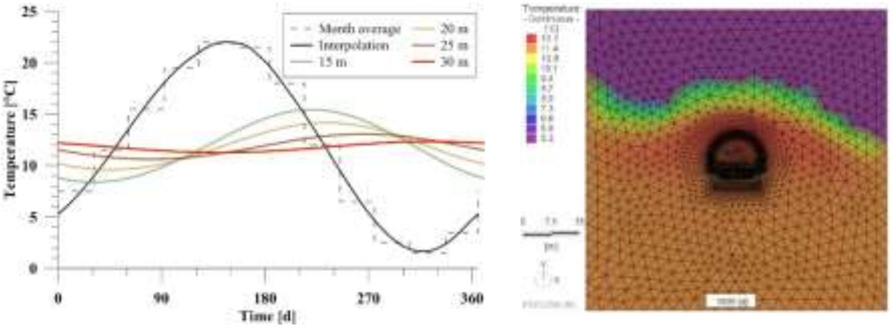


Fig. 4 Temperature trends at the “Craviale” tunnel crown without thermal activation at several distances from tunnel entrances. Picture on the right is referred to the cross section at 30 m from the entrance.

Temperature on the bridge paved surface oscillates according to the air temperature virtually being in thermal equilibrium with it as no external heat sources are considered (e.g. solar radiation). Indeed, the minimum temperature was found (1.7°C) at the center of the bridge deck in the coldest day of the year, corresponding to the 15th January.

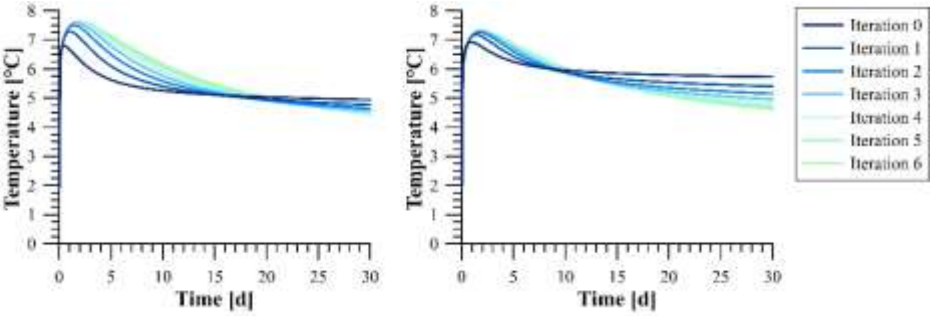


Fig. 5 Outlet temperature of Craviale tunnel (left) and La Turina tunnel (right) deicing circuits over 30 days for each iteration.

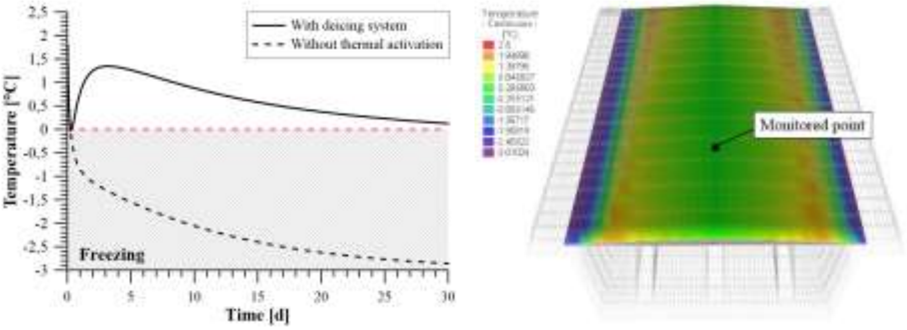


Fig. 6 Temperature profile at a selected location of the pavement surface (left). 3D visualization of the thermal status of the pavement after 30 days (right).

This temperature field was afterwards adopted as initial condition of the installation operation. An iterative approach was adopted to consider the dependency of the heat carrier fluid temperature at the circuit ends. In the first iteration the inlet temperature was assumed constantly equal to the initial condition. The two circuits hence slightly differ due to topographic surface near the inlet end differences (5.17°C in the case of the “Craviale” tunnel and 6.14°C for “La Turina” tunnel). The outlet thermal profile was then assumed as input parameter of the subsequent iteration. The iterations were continued until the criterion of 0.1°C difference in output of two consecutive iterations was met. It resulted that 6 iterations were needed for results convergence (Fig. 5). The comparison among the outlet temperatures shows that in the short term the initial assumption of constant temperature results to be conservative. On the contrary in the long term the same assumption may result in unrealistic values.

Fig. 6 shows the temperature profile of the last iteration on the paved surface at the bridge deck center together with the temperature profile obtained in the same conditions without heat carrier fluid circulation. The comparison of the two curves allows evaluating the efficiency and viability of this technological solution as deicing technique.

It is thus demonstrated that, even in extreme conditions, the pavement surface is kept above the freezing level for the entire time of the analysis equal to a 30 days timespan (Fig. 6). The temperature trend results to be decreasing at the very beginning of circulation, leading to a limit temperature slightly lower than freezing level. This might be due to the thermal inertia of the system. Its undesired effects should be thus avoided with anticipated activation of about 10 hours respect to the time when extreme conditions are expected.

5 Conclusions

An application of geothermal energy was studied in this paper related to the deicing needs of road infrastructures in Alpine and cold regions. In particular the heat exchange through tunnel linings was analyzed in relation to the “Turinella” viaduct deicing along the “S.P. 23” in the Chisone Valley (Italy). A numerical model was adopted to investigate at first the natural temperature in the rock mass interested by the tunnels. Marked thermal affection decrease was found together with the increasing distance to the entrance. The worst case thermal scenario resulting was then adopted as starting point for the simulation of free heating operations. Heat carrier circulation was simulated in further analyses with an iterative approach in order to consider temperature continuity at the inlet and outlet ends of the circuit. It resulted that the pavement temperatures are virtually always kept above the freezing point, except for the very first hours. It should thus be advisable to switch on the circulation of the circuit with proper advance when weather forecast indicate possible freezing.

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