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Energy tunnels: concept and design aspects

Marco Barla *, Alice Di Donna

Department of Structural, Building and Geotechnical Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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Abstract

Geotechnical structures are increasingly employed as energy geostructures in Europe and worldwide. Besides being constructed for their primary structural role, they are equipped to exchange heat with the ground and supply thermal energy for heating and cooling of buildings and de-icing of infrastructures. This technology can play a fundamental role in the current challenge of addressing the increasing need for clean and renewable sources of energy. This study investigates the possibility of thermal activation of tunnel linings. Particularly, attention will be paid on a new energy segment, which can be used together with tunnel boring machine tunneling to create so-called *energy tunnels*. Thermal and mechanical designs need to be developed by making effective use of computational methods to quantify the exploitable heat and assess the possible consequences on the surrounding ground and the structure itself. Guidance on how to proceed in this direction will be provided in this study, showing how thermo-hydro and thermo-mechanical numerical analyses can be used to achieve a proper and effective design of energy tunnels. Two examples of possible applications will also be presented.

Keywords: Energy tunnel; Geothermal energy; Heating and cooling; Geotechnical design

Introduction

The increasing need for renewable energy sources has led to the expansion of shallow geothermal applications for heating and/or cooling of buildings. Shallow geothermal energy (<400 m depth) is used in many countries worldwide, with an increasing number of installations over the last decades. Together with the use of ground source heat pump and groundwater heat pump systems, as well as underground geotechnical structures such as deep and shallow foundations, diaphragm walls, tunnel linings, and anchors are being increasingly employed as energy geostructures by installing absorber pipes inside them (Barla & Di Donna, 2016a; Laloui & Di Donna, 2013). The integration of heat exchangers in structure elements that interface with the ground is particularly attractive because of the inherent cost saving involved in combining a required structural component with the harvesting of geothermal energy. Some practical applications of this technology are already operational particularly in Austria, Germany, United Kingdom and Switzerland (Brandl, 2006).

Tunnels are probably the least investigated energy geostructure (Barla & Perino, 2014). However, they could play a fundamental role in the current challenge of addressing the increasing need for clean and renewable sources of energy. Studies on thermal exploitation through tunnels were recently published (Barla, Di Donna, & Perino, 2016; Di Donna & Barla, 2016; Franzius & Pralle, 2011; Frodl, Franzius, & Bartl, 2010; Lee et al., 2012; Markiewicz & Adam, 2009; Moormann, Buhmann, Friedemann, Homuth, & Pralle, 2016; Nicholson, Chen, de Silva, Winter, & Winterling, 2014; Schneider & Moormann, 2010; Tinti et al., 2017; Wilhelm & Rybach, 2003; Zhang, Xia, Sun, Zou, & Xiao, 2013). Compared

* Corresponding author.
E-mail address: marco.barla@polito.it (M. Barla).

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to building foundations, tunnels involve a larger volume of ground and surface for heat exchange. Moreover, when mechanized tunneling is used, the tunnel segmental lining is precast in factory and then placed onsite by the tunnel boring machine (TBM). The segments can therefore be prepared and optimized for heat exchange. The system could also allow cooling the tunnel using the heat produced internally by fast moving trains or vehicles. This study is intended to describe the main characteristics that allow a tunnel lining to become a means of thermal exchange. Technological aspects are illustrated together with thermal and mechanical design aspects and examples of possible applications.

Energy tunnels

In general, a geotechnical structure can be thermally activated by embedding polyethylene pipes in its concrete body. The fluid flowing in the pipes constitutes the means for transferring heat from the ground to the buildings or vice versa through heat pumps (see Fig. 1). Similar to refrigerators, a heat pump operates on the basic principle that a fluid absorbs heat when it evaporates into gas, and likewise releases heat when it condenses back into liquid.

Thermoactive geostructures are systems that couple a primary structural role with that of ground heat exchanger, and thus, the operational depth depends on the position and dimension of the needed structure. This technology only requires a generally constant ground temperature over the year. Despite the seasonal fluctuations, this is satisfied in most continental Europe, where the ground temperature at depths higher than 5–8 m typically varies between 8 °C and 16 °C, but remains constant over the whole year, down to approximately 50 m. In such conditions, the ground operates as a heat source supplying warmth to buildings during winter, while functioning as a heat sink during summer when cooling is required.

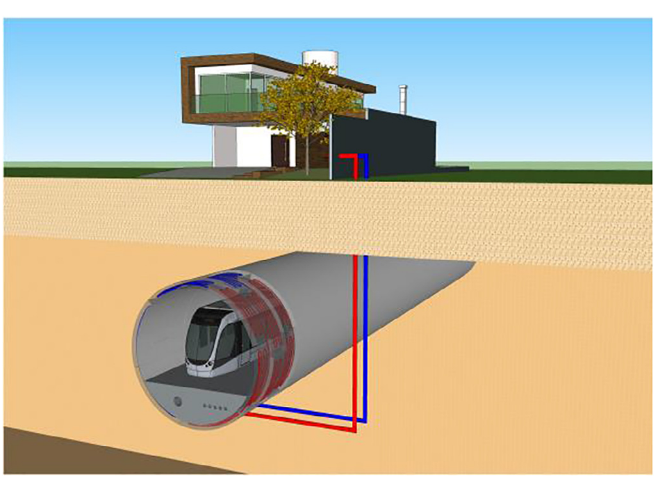

Fig. 1. Schematic example of the thermal activation of the tunnel segmental lining and its connection to a heat pump system in the above building.

In the case of energy tunnels, the heat exchanged at the tunnel level can be transferred to the surface by placing pipes into the ventilation shafts or through the portals. The stations of metro tunnels can also be used for this purpose. Depending on the surface heat requirements, and taking advantage of the many connections to the surface existing in metro tunnels, the pipeline length can be optimized in order to reduce heat losses and the system can be used to allow heat distribution at the district scale. Alternatively, the heat exchange can also be used for tunnel cooling to improve self-sustainability of the infrastructure.

The different local conditions and features of tunnels permit a simple classification into "cold" and "hot" tunnels in terms of their thermal conditions.

In cold tunnels, the air temperature is relatively low (approximately 15 °C) all year round, and the frequency of trains passing through is moderate so that it cannot significantly increase the temperature in the tunnel. This type of tunnel normally has a large internal diameter in the range 10–12 m. The prevailing temperatures in the tunnel only have a limited effect on the temperature in the surrounding ground. Road tunnels can also belong to this category.

Hot tunnels, on the other hand, usually show high internal temperatures. Urban tunnels (underground railways) with typical internal diameters of approximately 7 m may have summer temperatures of approximately 30 °C. Numerous stations and a rapid cycle frequency of trains lead to additional heat input from braking and starting. This increases the air temperatures in the tunnel, which warms the ground. Moreover, deep Alpine tunnels could be heated by the ground itself, which at depth can be encountered at temperatures between 30 °C and 50 °C.

Both cold and hot tunnels can take advantage of thermal activation. Two different methods for the instrumentation of tunnel linings for geothermal exploitation have already been suggested. In the case of conventional tunneling methods (e.g., New Austrian Tunneling Method), absorber pipes can be attached to non-woven geosynthetics offsite and then placed between the primary and secondary linings. This was the first technology to be implemented in energy tunnels and makes in situ installation easily achievable (Markiewicz & Adam, 2009). However, when mechanized tunneling is used, the tunnel lining segments are precast in factory and then placed onsite by the TBM. They can be therefore prepared and optimized for heat exchange by including hydraulic circuits in the cast concrete (Barla et al., 2016; Frodl et al., 2010; Nicholson et al., 2014). A schematic representation of a segmental lining equipped according to this second method is shown in Fig. 2. The circuit of each segment is linked to those of the adjacent ones by hydraulic connections to form lining ring circuits. Each ring is usually made of 6–7 segments. Two or more rings can be hydraulically connected in parallel forming a subcircuit. Each circuit made of two or more rings is then connected to the main conduit that directs the heat carrier fluid from them to the heat pump and vice versa. This is

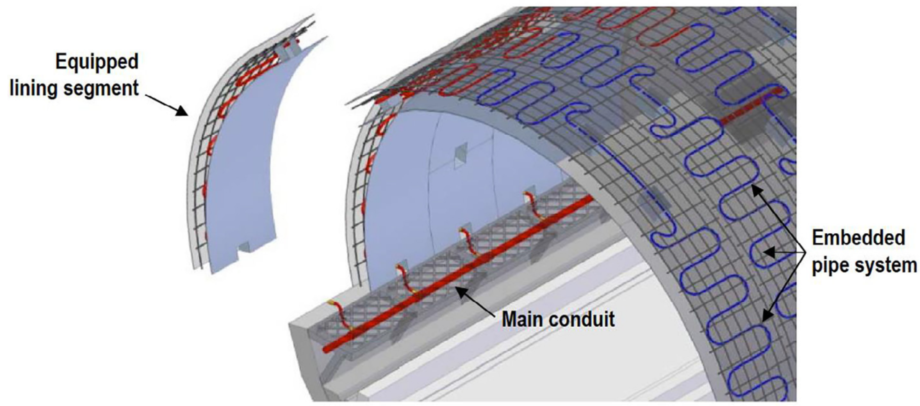

Fig. 2. Schematic representation of a tunnel segmental lining equipped as ground heat exchanger (Barla and Perino, 2014; Barla et al., 2016).

done in order to reduce the number of connections on the main conduit and the consequent significant head losses. The pipes for these applications are fabricated from reticulated polyethylene (Pe-Xa) and are composed of three strata: the inner stratum with high-density polyethylene, the intermediate stratum in polymeric material, and the outer stratum that is formed by a barrier in ethylene vinyl alcohol (EVOH), which avoids permeability to oxygen. The pipes are able to withstand high pressures and temperatures, resist corrosion and guarantee high durability. The thermo-fluid is propylene glycol mixed with water, which can work down to a temperature of −20 °C.

Geothermal segments of this type developed by Rehau AG + Co and Ed. Züblin AG (Zentrale Technik) companies were used for the first time in a 54 m long section of the 3.5 km long Jenbach Tunnel in Tyrol, Austria. The tunnel has been supplying geothermal energy to a building belonging to the local council since 2012 (Frodl et al., 2010; Moormann et al., 2016). The same system was previously tested by activating four rings of a new high-speed railway tunnel in Germany for a field trial between May and September 2009 prior to the tunnel opening, using a temporary heat pump and monitoring system. However, these events did not trigger a systematic application of the technology.

More recently, a new energy segment (ENERTUN) was proposed at the Politecnico di Torino (Barla & Di Donna, 2016b; Patent priority No. 102016000020821). Owing to an innovative geometry of the pipes, which are positioned so that their main direction is perpendicular to the tunnel axis, it is possible to reduce head losses and increase efficiency, especially when the groundwater flow is perpendicular to the tunnel axis. The decrease in terms of head losses is between 20% and 30% for each tunnel ring compared to previously described segments. Moreover, by maintaining the same material properties, geometry, and ground conditions, the increase in thermal exchange is in the order of 5% to 10% as presented in Table 1, where results of thermo-hydro (TH) coupled finite element analysis are shown. The numerical model was used to simulate the behavior of the thermally activated tunnel ring and determine the exploitable heat in W/m^2. Another improvement of the new energy segmental lining is that it is conceived to be flexibly adapted to three different configurations, namely ground, air, and ground and air (see Fig. 3). The first one is designed to exchange heat with the ground, the second one with the air inside the tunnel, and the third one has a double circuit, which enables heat exchange with both the ground and air. Depending on the requirement, the most appropriate configuration can be adopted allowing optimization of heat exchange.

Thermal and mechanical design

Thermal activation of segmental lining implies two additional efforts for tunnel designers. First, the exploitable heat should be quantified (i.e., its efficiency); second, mechanical effects on the structural element should be assessed to guarantee a limited influence on the long-term behavior of the structure (i.e., its integrity). This requires TH and thermo-mechanical (TM) coupled analyses. A fully thermo-hydro-mechanical (THM) coupled analysis could be adopted to study both efficiency and integrity problems; however, THM is usually neglected because the overall increase in complexity and computational time is not counterbalanced by a major improvement in the results for this type of application. For this reason, in the following, TH and TM analyses will be described only. TH analyses were performed by using the finite element software FEFLOW© (Diersch, 2009). The TH problem is governed by mass conservation, energy conservation equations, and Darcy's velocity law, written in the Eulerian coordinate system for a saturated medium composed of a solid and a liquid (water) phase. TM analyses were performed by using the finite difference software FLAC (Itasca, 2016). Only conduction is considered in the following analyses and the heat transfer computation is coupled to the mechanical one at any time during a transient simulation, so that thermally induced stresses and strains can be evaluated. The coupling occurs in one direction only, i.e., the temperature may

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Table 1
Heat exchange comparison between the two segmental linings design.

Pipes main direction with respect to tunnel axis	Q [W]	q [W/m^2]	q [W/m]
Parallel	1670.79	52.76	1193.42
Perpendicular (ENERTUN)	1773.49	56.00	1266.78

result in stress changes, but mechanical changes in the body resulting from force application do not result in temperature change. This restriction is considered to be acceptable, because the energy changes for quasi-static mechanical problems are usually negligible.

Quantification of heat exploitation (thermal design)

In order to quantify the exploitable heat, a three-dimensional TH finite element model can be used to reproduce a limited number of ENERTUN tunnel rings equipped with heat absorber pipes, as shown in the example in Fig. 4. To this aim, the geometry of the problem needs to be reproduced accurately, together with the groundwater condition. In the example shown, a difference in piezometric head is given between the two sides of the model causing a flow perpendicular to the tunnel axis as a function of ground hydraulic conductivity. For the simulation of the absorber pipes installed in the tunnel lining, one-dimensional discrete feature elements provided in FEFLOW© were adopted. The use of these elements to simulate pipes in geothermal systems has been validated and good agreement was found compared to analytical solutions (Diersch, 2009). The conservation of mass and energy is also satisfied for these elements, while the fluid flow inside them is described by the Hagen–Poiseuille law. Accordingly, fluid particles are assumed to move in pure translation with constant velocity, similar to what occurs in circular tubes.

Once initial conditions are achieved, the analysis is conducted by applying an initial temperature and velocity to the inlet of the piping system and measuring the outlet temperature at equilibrium.

The heat Q (expressed in W) extracted during winter and injected during summer can be computed, given the difference between the inlet temperature T_{wi} (imposed) and outlet temperature T_{wo} (from numerical simulation result) of the pipe circuit, using the following equation:

$$Q = mc_w|T_{wo} - T_{wi}| \quad (1)$$

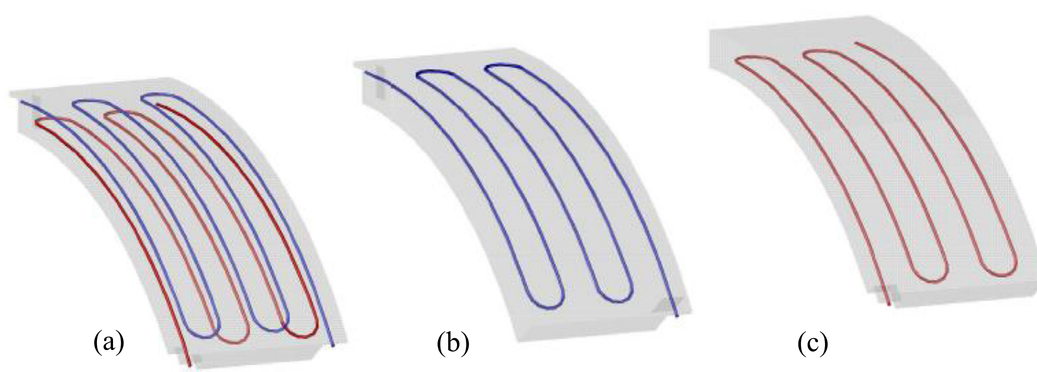

Fig. 3. Different configurations of the new energy segmental lining ENERTUN: (a) ground&air, (b) ground and (c) air.

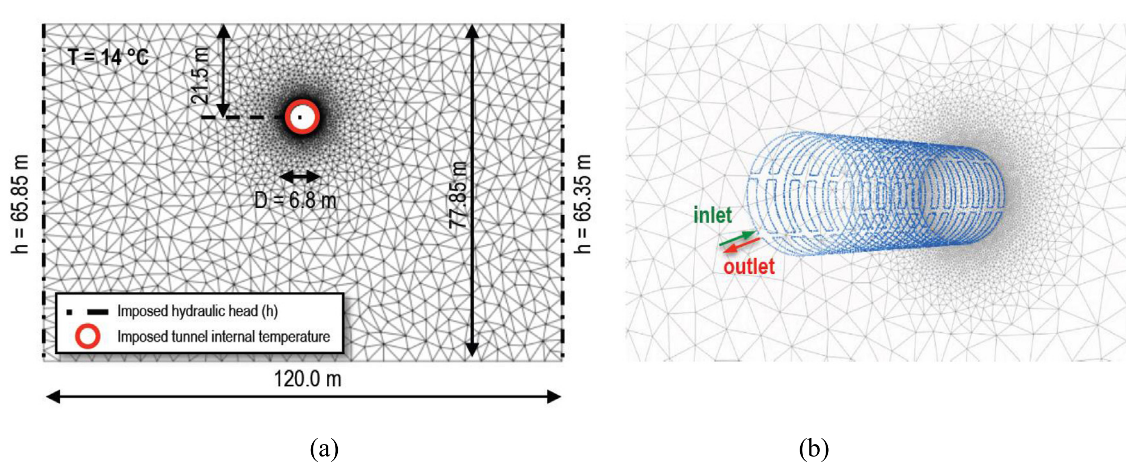

Fig. 4. Example of a 3D model of the energy ring: (a) size and boundary conditions, (b) detail of the discretisation of the piping system in the lining segments.

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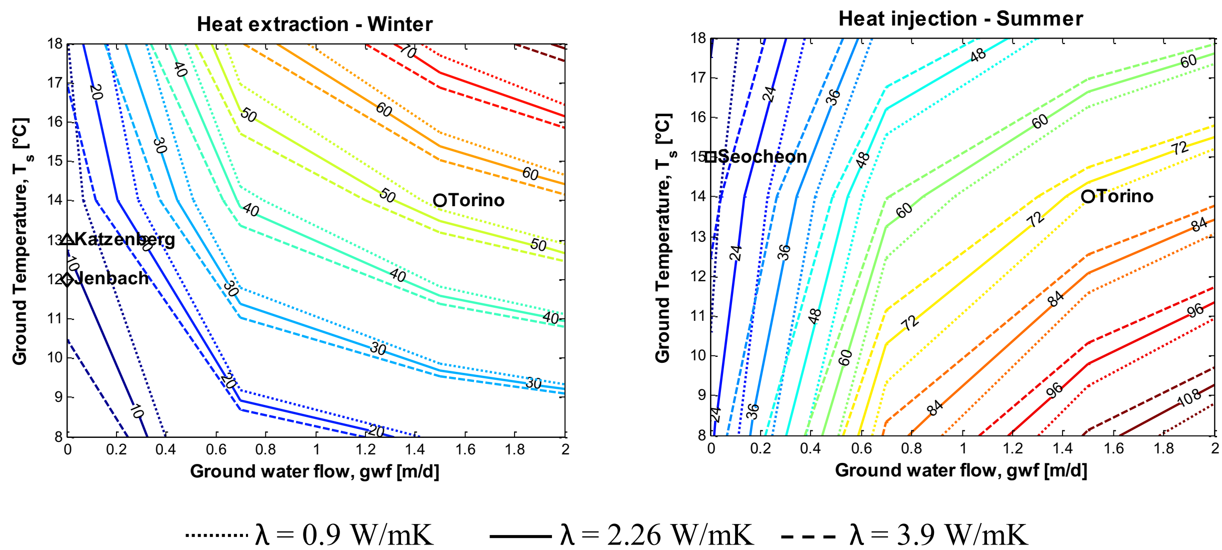

Fig. 5. Design charts for winter mode and summer mode (extracted and injected heat in W/m^2) – (experimental data from Franzius and Pralle (2011) and Lee et al. (2012)). (Di Donna and Barla, 2016).

where m is the mass flow rate in kg/s and c_w is the heat capacity of the circulating fluid.

This allows quantifying the exchangeable heat for the specific application.

Several parameters influence the heat exchange. Di Donna and Barla (2016) have investigated the effect of ground temperature, groundwater flow velocity, and thermal conductivity on the heat exchange by conducting a parametric analysis. Their results show the following:

- In the absence of groundwater flow, when the heat exchange occurs essentially by conduction, the soil thermal conductivity plays a primary role and the exchanged heat is more than doubled, ranging from 0.9 to 3.9 W/(m•K) for both summer and winter operational modes;
- When groundwater flow is present, the heat exchange results from a combination of conduction and convection, and the most influencing factor is the intensity of groundwater flow. With an increase from 0 to 2 m/d, the exchanged heat improves by a factor of 3 to 8 times. However, in the case of high groundwater flow velocity, the risk of thermal pollution should be assessed;
- The heat exchange improves by approximately 7%/°C of ground temperature, being more favorable in hot regions during winter and in cold regions during summer.

The obtained results were shown to be in good agreement with monitoring data available in the literature (Franzius & Pralle, 2011; Lee et al., 2012). To assist designers and city planners in evaluating the potential of heat exploitation from energy tunnels in relation to different site conditions, the two design charts shown in Fig. 5 were produced from parametric analyses. They can be used for a preliminary assessment of the potential energy exploitation in both summer and winter based on the specific site conditions where the system is to be installed. Once this preliminary evaluation is obtained, a detailed and site-specific thermal design should be conducted with the help of TH numerical analysis, as described above.

Assessment of thermo-mechanical effects (mechanical design)

To investigate the mechanical effects on the structural elements caused by temperature cyclic changes due to thermal activation of the tunnel lining, a TM analysis should be adopted. Again, the model should reproduce the geometry of the problem. The in situ state of stress needs to be reproduced and appropriate constitutive parameters adopted for the ground and structural elements. Moreover, the construction sequence needs to be simulated.

Fig. 6 shows an example of a finite difference mesh used to evaluate the influence of temperature on the long-term structural behavior of a tunnel lining. The pipes are included in the model with their real geometry. The temperature change in the pipes is applied as a boundary condition at the contour of the pipe. The temperature gradient is taken from the results of the TH analysis and is used as an input in this computation. In the example shown, the tunnel is excavated at a depth of 21.5 m with a diameter of 7.4 m. The lining has a thickness of 35 cm and the pipes are installed at 12.5 cm from the extrados.

Fig. 7 shows the results in terms of vertical and horizontal stress variations due to the activation of the thermal lining. A full summer–winter cycle is simulated with heat injection through the pipes in summer and heat extraction during winter. Typical temperatures for central European applications were adopted (inlet temperature in summer = 25.8 °C; inlet temperature in winter = 4.5 °C). Horizontal and vertical stresses decrease during heating with the segmental lining experiencing compression, whereas the

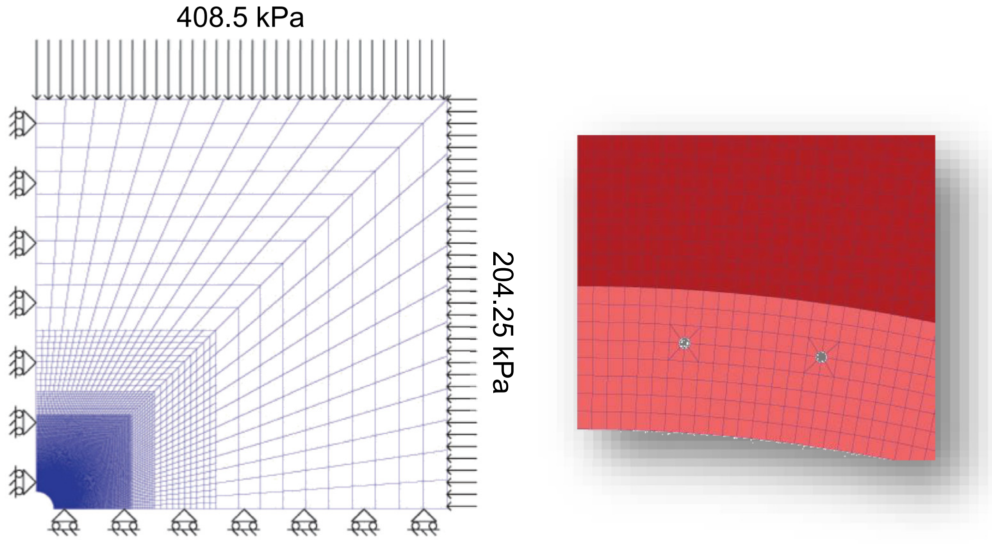

Fig. 6. Example of a FDM mesh for thermo mechanical analyses of the tunnel lining.

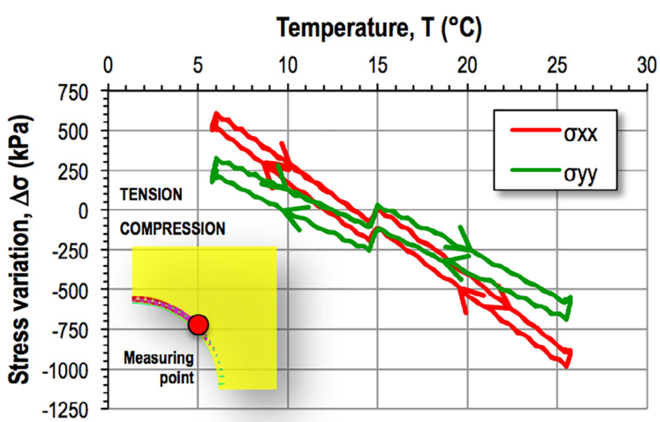

Fig. 7. Horizontal (σ_{xx}) and vertical (σ_{yy}) stresses versus temperature variations computed by the TM analysis.

contrary occurs during cooling. The stress change is shown to be in the order of less than 1 MPa, during the whole cycle for this specific application. This range of variation is in agreement with previous studies and findings (Mimouni, Dupray, & Laloui, 2013).

Based on the above, the mechanical design of the tunnel lining generally will not impose substantial variations with respect to normal procedures as the thermally induced loads are substantially negligible in either the short or long term. In the case of reinforced concrete, pipes would preferably be installed inside a steel cage in order not to reduce the concrete cover, and to conveniently separate them from the circumferential bending of steel rebars.

Examples of possible applications

The ENERTUN segmental lining can be used for district heating and cooling in urban areas (GROUND configuration) as well as to cool hot tunnels using the heat produced internally or the heat from the surrounding ground (AIR configuration). Particularly, tunnels in urban areas offer great potential for geothermal exploitation owing to the presence of consumers in the immediate vicinity. If the energy activation of tunnels is considered at an early stage of the planning of urban areas and in the design of tunnels, such a system is relatively easy to integrate into the design process, as shown above. Moreover, an urban tunnel will run for many kilometers under densely urbanized areas so that it can be effectively integrated to district heating systems.

In the case of hot tunnels, where the heat produced internally by fast moving trains or vehicles increases the internal air temperature, the thermal activation of the lining may be adopted for cooling. ENERTUN AIR can also be adopted in deep tunnels, where the ground geothermal gradient may cause the tunnel internal air temperature to rise above acceptable limits. In these cases, savings on costs of ventilation and cooling system may be obtained.

Two examples of potential applications of energy tunnels are briefly described below.

Shallow urban tunnels

as an example of an application to a shallow tunnel, Barla et al. (2016) studied the thermal activation of the lining of the Metro Torino tunnel. The south extension of the Metro Torino line 1 connecting the Lingotto Station to Piazza Bengasi (1.9 km and 2 stations) is currently under construction. This section was considered, as it would provide a good opportunity to test the energy tunnel technology in the Torino subsoil. Moreover, the tunnel lies completely below the groundwater and the groundwater flow direction is perpendicular to the tunnel axis, which are both favorable conditions for enhancing thermal exchange. The tunnel runs very close to a new 220 m tower under construction to host

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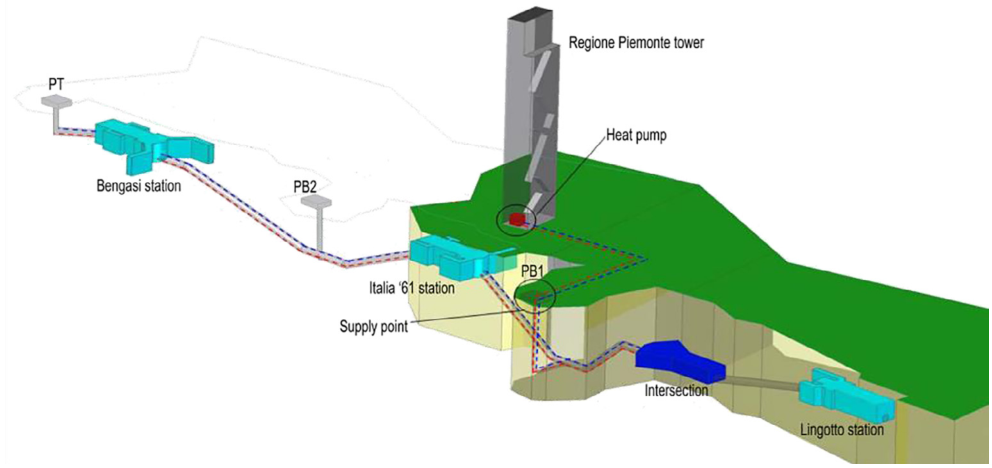

Fig. 8. View of the Turin Metro Line 1 South Extension tunnel alignment and the proposed geothermal plant connected to the Regione Piemonte tower (Barla and Perino, 2014).

Table 2
Extracted/injected heat in winter and summer.

Season	Total extracted/injected power, Q [kW]	Extracted/injected power per squared meter, Q [W/m^2]	Extracted/injected power per meter of tunnel, Q [W/m]
Winter	1.67	52.76	1193.42
Summer	2.34	73.87	1670.81

the new headquarters and offices of the Piemonte Regional Government (see Fig. 8). The possible use of the tunnels to exploit heat for the Regione Piemonte new tower was therefore investigated.

The tunnel is to be excavated by an approximately 8 m diameter (6.8 m internal diameter and 7.4 m external diameter) shielded earth pressure balance TBM, with the exception of the section immediately after the Lingotto station (length of 125 m), which is already in operation. The average cover of the tunnel is 21.5 m, and as mentioned, excavation takes place below the water table. From the thermal point of view, the tunnel is cold type as ventilation is guaranteed by a number of wells that inject external air into it. Monitoring data from the metro tunnel currently in service also confirm this condition. The tunnel lining is made of precast concrete rings (30 cm thickness), each comprising 6 segments mounted by the TBM itself. Cement foam is injected to guarantee full contact with the ground and the segments are appropriately sealed in order to avoid groundwater ingress. In this specific application, the described system would allow activating a total length of tunnel of 1350 m.

With the available data from geotechnical investigations and numerical analysis performed in the past, a geotechnical model for the subsoil conditions has been derived for the depth relevant to tunneling (Barla & Barla, 2012; Bottino & Civita, 1986). The hydraulic, hydro-dispersive, and thermal parameters of the aquifer are also known from in situ pumping tests and monitoring performed in an area of the city not far from the considered metro line (Barla et al., 2015). The groundwater level along the tunnel axis is known based on piezometric measurements, and predictions on long-term conditions have also been carried out. At the site, the water table surface is approximately 12 m below the ground level and the thickness of the aquifer is estimated as 22–23 m. The water in the aquifer has an average temperature of 14 °C and flows toward the Po River.

TH finite element analyses with the characteristics described in Section 3 were performed to quantify the potential for heat exchange. The exchangeable power computed is presented in Table 2. The thermal activation of the south extension of the Metro Torino tunnel lining is shown to be particularly more favorable compared to other case studies (Frodl et al., 2010). The main reason is the presence of the significant groundwater flow velocity perpendicular to the tunnel axis, which allows for a continuous thermal recharge of the ground, significantly improving the heat extraction and injection efficiency.

Owing to the favorable underground water flow conditions in Torino, the energy tunnel system would allow exchanging between 53 and 74 W/m^2 of tunnel lining in winter and in summer respectively. These figures would allow covering the energy needs of up to 1.67 kW in heating mode and 2.34 kW in cooling mode, considering the total tunnel length, which are in line with the heating and cooling demand of the new tower.

The influence on the surrounding ground in terms of temperature variation of the groundwater flow is within

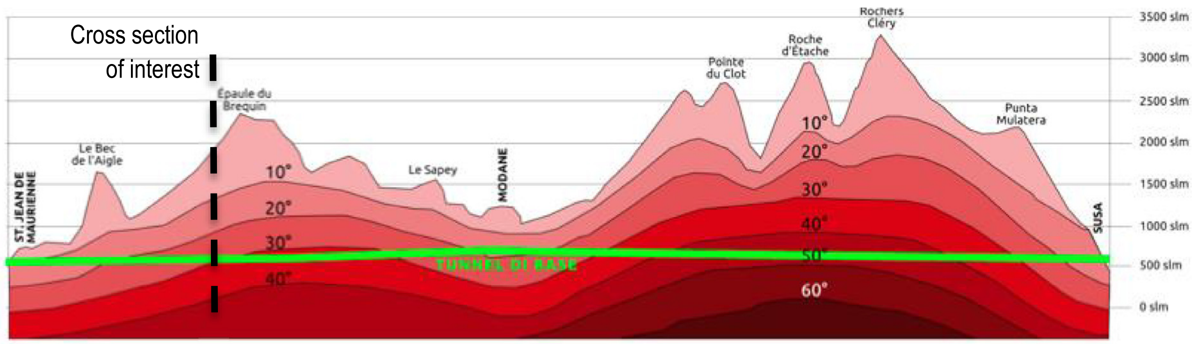

Fig. 9. Predicted temperature at depth for the Turin Lyon base tunnel (personal communication).

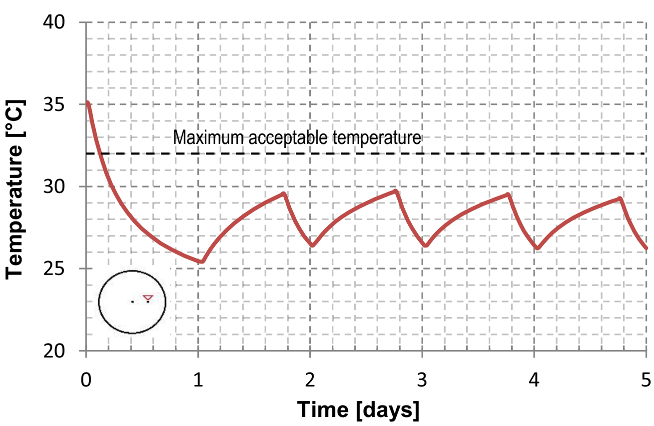

Fig. 10. Temperature in the tunnel during 4 on & off cycles of activation of the thermal lining.

5 °C at 10 m distance from the tunnel contour and fully recovered after the year-round cycle.

The additional cost required to activate the tunnel lining was computed to be less than 1% of the total cost of the project so that the thermal activation of the tunnel lining is 41% less expensive than using vertical piles with ground source heat pumps to cover the same energy requirement.

Because of the very promising results of the preliminary analyses above, a test site was recently installed in the tunnel under construction to validate the above findings and provide quantitative information for future installations (Barla, Di Donna, & Insana, 2017).

Deep mountain tunnels

As an example of an application for deep tunnel cooling using a cost effective alternative to ventilation systems, the base tunnel of the Turin–Lyon new railway track was considered. The predicted temperature longitudinal profile for this tunnel is shown in Fig. 9. For a number of kilometers, the natural ground temperature is expected to be higher than the acceptable limit (32 °C) and cooling will have to be implemented.

As a preliminary investigation, by again adopting TH finite element modeling, the efficiency of cooling was tested for the ground conditions expected for a cross section shown in Fig. 9. In this application, the piping system is installed at the intrados of the lining (ENERTUN AIR configuration, see Fig. 3c). Fig. 10 shows the computed temperature inside the tunnel after the application of the geothermal cooling system. To improve cost benefits, the system is considered active in cycles. After the first cooling activation, the system is switched off and on in time intervals that allow maintaining the temperature between 25 and 30 °C. As a preliminary evaluation, compared to a conventional ventilation system, the thermal activation of the tunnel lining would provide a cost saving between 10 k€/(km•year)$^{-1}$ and 20 k€/(km•year)$^{-1}$. Moreover, the system would allow for thermal exploitation, and possible users in the vicinity of the portals could use the heat extracted. The heat extracted for a kilometer of activation was computed with reference to the equilibrated condition after the first 50 days of operation and is shown to be approximately 6500 (MW•h)/year.

Conclusions

The advantage of integrating thermally active systems into geotechnical structures such as tunnels is that the structures are being built anyway, and thus, the additional cost is limited with respect to the overall cost.

The thermal activation of tunnel linings is therefore an interesting opportunity that could allow for exploiting the energy stored in the ground with significant economic and environmental benefits. Moreover, the innovation in thermally active segmental linings shown here (which allowed reducing head losses and increasing efficiency) leads to additional improvements in the thermal exchange and in the overall cost/benefit ratio of these applications. In terms of heat exchange, for example, thermally active tunnels could allow exchanging from approximately 10–20 W/m^2 when no groundwater flow is present, and up to 50–60 W/m^2 when there is significant groundwater flow.

For deep tunnels, the most promising application seems to be for cooling the internal tunnel air, whose temperature can increase to uncomfortable values if expensive constant control and ventilation systems are not implemented. Thermally active tunnel linings could allow reducing, if not avoiding, these costs with the added value of providing heat at the tunnel portals for potential users.

Nevertheless, heat extraction and heat injection through energy tunnels are best applied within urban areas, where the exchanged heat can be directly utilized by adjacent buildings and integrated into district heating and cooling systems. However, enhancing geothermal exploitation in urban areas requires city scale planning, interference evaluation, and regulation. Worldwide cities that will be able to handle these tasks will definitely benefit in terms of improved quality of life for their citizens.

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