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Application of energy tunnels to an urban environment

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ABSTRACT

Deep and shallow foundations, diaphragm walls, tunnel linings and anchors are being increasingly employed as energy geostructures in Europe and all around the world. Besides being constructed for their primary structural role, they are equipped to be able 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 paper investigates the possibility of thermal activation of a new section under construction of the Metro Torino line 1 (Italy) to heat and cool adjacent buildings. The design and optimization of the geothermal plant, the quantification of the exploitable heat and the assessment of the eventual consequences on the surrounding ground are here discussed. For this purpose, thermo-hydro finite element analyses, able to capture the key aspects of the problem, were conducted. A 3D model is devoted to study the efficiency of the system, reproducing one ring of the instrumented tunnel segmental lining, while a 2D large scale model of the Torino aquifer is conceived to investigate the sustainability of the technology in terms of effects on the surrounding environment. Based on the results of the computations, it can be anticipated that, thanks to the favorable underground water flow conditions in Torino, the system would allow 53 and 74 W per square meter of tunnel lining to be exchanged during winter and summer respectively.

1. Introduction

Underground geotechnical structures, such as deep and shallow foundations, diaphragm walls, tunnel linings and anchors are being increasingly employed as energy geostructures, in Europe and all around the world (Laloui and Di Donna, 2013). They have the double role of providing structural stability and exchange heat with the ground to supply thermal energy for heating and cooling of buildings and de-icing of infrastructures. The thermal activation is achieved by installing absorber pipes in the geostructures, in which a circulating fluid extracts or injects heat from or into the ground. These systems belong to the category of low enthalpy geothermal plants and are associated with heat pumps. A number of practical applications of this technology are already operational especially in Austria, Germany, United Kingdom and Switzerland (Adam, 2009; Bourne-Webb et al., 2009; Brandl, 2006; Pahud, 2013; Riederer et al., 2007; SIA DO 190, 2005; Brandl, 1998, 2009). Most of them are related to energy piles and retaining walls as their implementation in real projects is supported by a wider scientific background which provides the means for a proper design both in terms of energy efficiency optimization (Gao et al., 2008; Suryatriyastuti et al., 2013) and geotechnical assessment (Amatya et al., 2012; Di Donna and Laloui, 2015; Dupray et al., 2014; Knellwolf et al., 2011; Laloui et al., 2003; McCartney, 2013; Mimouni et al., 2013; Mimouni and Laloui, 2014; Suryatriyastuti et al., 2012; Bourne-Webb et al., 2009). A recently growing interest for the application of this technology to tunnel linings resulted in a number of scientific works devoted to investigate the feasibility and efficiency of such systems (Barla and Perino, 2014a,b; Dupray et al., 2013; Franzius and Pralle, 2011; Lee et al., 2012; Nicholson et al., 2013; Zhang et al., 2013). Compared with building foundations, energy tunnels have the advantage of involving a larger volume of ground and surface for heat exchange. Two cases can be distinguished: cold and hot tunnels. In the first case, the temperature of the air inside the tunnel is similar to that of the ground, while in the second case, it is higher due to the passage of trains, cars or HV cables. The needed ventilation for hot tunnels might be presumably partially substituted by the geothermal plant.

However, the cases of real implementation of energy tunnels are limited, for the moment, to Austria and Germany (Adam and Markiewicz, 2009; Schneider and Moormann, 2010; Franzius and Pralle, 2011). This is probably because the ratio between the initial cost of installation and the energy advantages in the operational

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phase, which strongly depend on the specific site, is not completely assessed. This is certainly the case in Italy and was the reason driving the research project whose results are presented in this paper. The work was carried out in the framework of a feasibility study called ENERTUN and supported by a European fund for the Regione Piemonte (Italy). The project investigated the thermal activation of a new section under construction of the South Extension of the Metro Torino line 1 and use the system for heating and cooling the adjacent buildings. The main goals were the design and optimization of the geothermal plant, the quantification of the extractable heat and the assessment of the tunnel thermal activation consequences on the surrounding ground. For these purposes, two finite element models were developed and thermo-hydro analyses were conducted. A 3D model was devoted to study the efficiency of the system by reproducing a portion of the instrumented tunnel lining, while a 2D large scale model of the Torino aquifer was conceived to investigate the sustainability of the technology in terms of effects on the surrounding environment.

The main features of energy tunnel technology are briefly presented in the next section. Then, the case study of the Metro Torino line 1 and the numerical models developed to simulate the thermal activation of the tunnels are illustrated in detail. Finally, the results obtained are discussed focusing on the system efficiency and long-term sustainability.

2. Energy tunnels

Two different methods for the instrumentation of tunnel linings for geothermal exploitation have already been suggested. In the case of conventional tunnelling methods (e.g. New Austrian Tunnelling Method, NATM), absorber pipes can be attached to non-woven geosynthetics off site and then placed between the primary and secondary lining. This was the first technology to be implemented in energy tunnels and makes in-situ installation easily achievable (Adam and Markiewicz, 2009). However, when mechanized tunnelling is used, tunnel-lining segments are precast in factory and then placed on site by the Tunnel Boring Machine (TBM). They can be therefore prepared and optimized for heat exchange by including hydraulic circuits in the cast concrete (Franzius and Pralle, 2011; Barla and Perino, 2014). A schematic representation of a segmental lining equipped according to this second method is presented in Fig. 1. 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 sub circuit. Each circuit made of two or more rings is then connected to the main conduit which directs the heat carrier fluid from them to the heat pump and vice versa. This is 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 in reticulated polyethylene (Pe-Xa) and composed by three strata: the inner strata with high-density polyethylene, the intermediate strata in polymeric material and the outer strata 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 to corrosion and guarantee high durability. The thermo-fluid is a propylene glycol mixed with water that can work down to a temperature of −20 °C.

At the preliminary design stage, a critical aspect to be considered is represented by the heat carrier fluid temperature, compared to that of the undisturbed soil. This influences the required fluid flow rate and consequently the dimensioning of all the plant components. A high difference between the two temperatures results in a smaller, and thus cheaper, geothermal plant, but, at the same time, affects more significantly the thermal equilibrium of the ground and reduces the efficiency of the heat pump. Conversely, a low difference between the temperatures of the circulating fluid and the undisturbed soil allows for good performance of the heat pump but imposes a bigger, and thus more expensive, plant.

The optimized solution is obtained when the difference between the fluid outlet temperature, T_{wo}, and that of the undisturbed ground, T_g, is (Capozza et al., 2012):

$$|T_{wo} - T_g| = 6 \div 11^\circ\text{C} \quad \text{in heating regime} \tag{1}$$

$$|T_{wo} - T_g| = 11 \div 17^\circ\text{C} \quad \text{in cooling regime} \tag{2}$$

The difference between the inlet and outlet temperatures might be chosen ensuring turbulent flow regime inside the pipes (Reynolds number higher than 2300) and minimizing the head losses to avoid the use of too expensive pumping system. This is normally achieved if:

$$|T_{wo} - T_{wi}| = 3 \div 5\ ^\circ\text{C} \tag{3}$$

where T_{wi} is the fluid inlet temperature. Assuming these requirements as a starting point, the plant can be designed from both the geothermal and hydraulic point of view, including the choice of the appropriate heat pump.

3. The case study: the South extension of the Metro Torino line 1

The South extension of the Metro Torino line 1 connecting Fermi Station to Porta Nuova is operational since early 2006, while a second section was constructed between 2006 and 2011 to connect Porta Nuova and Lingotto stations. The total length of the line in service is about 13.4 km and includes 21 stations. A new South extension of the line (1.9 km and 2 stations) toward Piazza Bengasi is currently under construction. This latter is the portion considered for the purpose of this study, as it would provide a good opportunity to test the energy tunnel technology in the Torino subsoil. The tunnel is to be excavated by an approximately 8 m diameter (internal diameter 6.8 m and external diameter 7.4 m) shielded EPB TBM (Earth Pressure Balance Tunnel Boring Machine), with the exception of the section immediately after the Lingotto station (length of 125 m), already in operation. The average cover of the tunnel is 21.5 m and excavation takes place below the water table. From the thermal point of view, the tunnel is of a cold type as ventilation is guaranteed by a number of wells that inject external air into it. The tunnel lining is made of precast concrete rings (thickness 30 cm), each constituted by 7 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 order to allow for easy inspection during the tunnel lifetime, with the metro system in service, the inflow pipe and the outflow pipe is located in the sidewalls of the tunnel, below the security pedestrian footpath. In the specific case, the described system would allow to activate a total length of tunnel of 1350 m.

This study is supported by a wide knowledge and a large amount of data related to the Torino subsoil properties and conditions (Bottino and Civita, 1986; Barla and Barla, 2005, 2012; Barla and Vai, 1999). The metropolitan area, located at the western edge of the Po valley, has an overall surface of about 130 km^2, 80% of which are a level area enclosed by the rivers Stura di Lanzo, Po and Sangone, while the remaining 20% are made up by a hilly area connected to the low reliefs of Monferrato. The city area is situated on the end section of the great alluvium fan of the Dora Riparia river and, from the morphological point of view, appears to be almost flat with a weak dip starting from West and going toward East, with elevation ranging from 260–270 m a.s.l. to about 220 m a.s.l. (Bottino and Civita, 1986). The subsoil conditions in Torino are char-