On the thermal activation of Turin metro Line 2 tunnels

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Abstract The Turin metro Line 2 will extend for nearly 28 km and include 26 stations. It will connect the SW suburbs of the city to the NE ones. The excavation will be performed by means of TBM and Cut & Cover techniques and, once concluded, will host a fully automated driverless light metro. This paper will describe the feasibility study carried out to assess the energy potential of the thermal activation of the line by using an innovative tunnel lining segment (ENERTUN) recently patented and tested in real operating conditions. A novel methodology was adopted, involving thermo-hydraulic 3D FE numerical analyses to identify the geothermal potential for the different sections of the line. A study of the possible collectors for the thermal energy produced was also performed considering the planned stations, the existing buildings and the future urban developments.

Keywords: energy tunnel, geothermal energy, metro line

1 Introduction

Low enthalpy geothermal systems have always been largely used for space heating. Such applications offer one of the best ways for providing sustainable energy in urban environment where the ground can be used as heat source and/or energy storage reservoir. Shallow geostructures like foundations, diaphragm walls, tunnel linings and anchors, have recently been proposed and employed as heat exchangers (Brandl, 2006; Laloui & Di Donna, 2013). The thermal activation is obtained by embedding absorber pipes where a circulating heat carrier fluid transfers heat from or to the ground, for winter heating or summer cooling respectively.
A number of examples of foundation slabs, piles and diaphragm walls used for heating and cooling purposes of large buildings exist, particularly in Austria, Germany, the UK and Switzerland (Adam & Markiewicz, 2009; Bourne-Webb et al., 2009; Brandl, 2006;

Pahud, 2013; Xia et al., 2012). The application of this technology to tunnels is limited to a few case studies (Markiewicz & Adam, 2003; Frodl et al., 2010; Franzius & Pralle, 2011; Schneider & Moormann, 2010). Nevertheless, an increasing number of scientific studies showing the feasibility and the efficiency of geothermal tunnel activation reveals the growing interest in these applications (Adam & Markiewicz, 2009; Barla et al., 2016; Barla & Perino, 2014; Di Donna & Barla, 2016; Franzius & Pralle, 2011; Nicholson et al., 2014; Zhang et al., 2013).
Given the increasing number of tunnels excavated by means of TBMs, a novel energy tunnel precast segmental lining, named ENERTUN, has been designed and patented (Patent number: 102016000020821) at Politecnico di Torino (Barla & Di Donna, 2016; 2018). Compared to previous configurations (Franzius & Pralle, 2011), ENERTUN is characterized by a more efficient layout of the net of pipes which reduces bends and, subsequently, the hydraulic head losses by about 20-30%. Moreover, thermo-hydraulic numerical analyses have shown that such a configuration results to be more efficient in terms of heat exchange when a ground water flow is present.
ENERTUN segments were recently tested in an experimental site installed in the tunnel of Turin metro Line 1 (Barla et al., 2019) allowing to evaluate the performance of the technology. The promising outcomes from the experimental site encouraged the adoption of the ENERTUN technology for the thermal activation of the Line 2 tunnels.
This paper will describe the procedure that was adopted in the feasibility study to assess the energy potential resulting from the thermal activation of the Line 2. The objective is to quantify, by means of Finite Element Thermo-Hydro simulations, the heat that could be extracted from and injected into the ground by the geothermal activation of the tunnel linings. Finally, the potential receivers for the thermal energy extracted from the ground were identified considering the metro stations, the existing buildings and future urban developments.

2 Turin metro line 2

The city of Turin is undergoing a renovation of its rail transportation system. Currently, the rail network is constituted by the underground metropolitan railway system and by the Line 1.
The automatic driverless Turin metro Line 2 will represent a new fundamental line for the metropolitan transport network, connecting the southwest area of the city to the northeast districts. The total length of the new line will be about 15.7 km completely underground. Three railway stations will be connected by the metro line: Zappata FS, Porta Nuova FS (direct interchange with Line 1) and Rebaudengo FS, linking the regional railway transport with the underground system. Significant line extensions to an additional length of up to 12.2 km, have been foreseen in basic design by the city of Turin towards San Mauro (North-East), and Orbassano (South-West). The main tunnel line will be built by TBM from Anselmetti to Bologna stations for a total of roughly 10.2 km and by Cut & Cover (C&C) for a length of 3.0 km from Bologna to Rebaudengo (terminal station).

3 Adopted methodology

On the basis of existing information and additional investigation taking place during the design of the new Line 2, the following data were collected:

- geometrical characteristics of the line;
- construction technology and procedures (TBM, C&C);
- geological longitudinal profile along the tunnel;
- geotechnical and hydrogeological characteristics (Geotechnical Units) including permeability and effective porosity of the ground;
- thermal parameters of the subsoil (i.e. conductivity, thermal capacity, diffusivity);
- shallow groundwater characteristics along the line, i.e. piezometric levels, ground water flow direction and underground water temperature.

Once the global geometrical, geotechnical, thermal and hydrogeological picture of the subsoil around the tunnel was gathered, the line was subdivided in a number of homogeneous sections for that pertaining to the geothermal behaviour of the tunnel following the procedure described in Baralis et al. (2018). For the TBM sections, the whole precasted tunnel lining will be activated by means of the ENERTUN system while for the C&C sections only the vertical diaphragms walls will be activated.
Therefore, the excavation method (TBM, C&C), the direction and velocity of the ground-water flow and the geothermal subsoil conditions will be relevant. Coupled Thermo-Hydro Finite Element numerical models were then built for each homogeneous section and adopted to study the geothermal potential. Interpretation of the Thermo-Hydro numerical analyses allowed to determine the thermal energy produced (kWh) and the energy efficiency for each homogeneous section. Thus the Line 2 overall deliverable geothermal potential was assessed.
As a final step, a spatial analysis on the area interested by the ML2 construction was performed in order to evaluate potential users of the heat energy. This procedure was carried out through GIS analysis with the aim of identifying potential thermal energy users located in the surroundings of selected extraction points i.e. the stations and the ventilation shafts where there is enough room for heat pump installation. Based on GSHP plant technical feasibility issues, potential users have to be located sufficiently close to the above-mentioned energy extraction points. Hence, a buffer zone of 100 m around the stations and ventilation shafts was evaluated. The following sections will show the details of the numerical models used for the geothermal potential as well as the overall results of the modelling.

4 Numerical models for evaluating tunnel thermal potential

With the purpose of quantifying the exploitable heat and studying the influence of the geo-thermal activation of the tunnel on the surrounding subsoil, three-dimensional Thermo-Hydro finite element models were used to reproduce both ENERTUN tunnel rings (for TBM sections) as well as diaphragms walls (for C&C sections) equipped with heat absorber pipes. In particular the FEM software FEFLOW® was used to this purpose. The reader can refer to the software manual (Diersch, 2009) for the whole mathematical formulation. 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).

To this aim, the geometry of the problem needs to be reproduced accurately, together with the groundwater regime. Fig. 1 shows two 3D models representative of a TBM stretch (section n° 72) and of a C&C one (section n° 7) respectively.

All the TBM sections were modeled using the same geometry. From a thermal point of view, they were considered as deep tunnels thus neglecting the thermal surface variations since the minimum tunnel cover is 8.90 m, i.e. close to the maximum depth affected by seasonal thermal fluctuations (Brandl, 2006; Vasilescu et al., 2018).

The model dimensions were chosen both to avoid the influence of the boundaries conditions and to correctly reproduce the geometry of a series of 9 precast lining rings.

For each ring the thermally activated tunnel's lining was simulated using 6 elements of 1.5 m length and 40 cm thickness in accordance to the design specifications. The pipes have a diameter of 20 mm and a thickness of 2 mm and are positioned through each lining ring according to the ENERTUN configuration. An average mortar layer with thickness of 10 cm was also modeled around the excavation. The thermal activation of three groups of three rings in series was considered.

For that pertaining to the C&C numerical models, the cyclic trend of air temperature on the surface needed to be considered given the relatively shallow depths. The C&C cross sections are heterogeneous in terms of the depths reached, the structures width and the internal distribution of the spaces. This dimensional heterogeneity was traced back to representative average sections. To reduce the computational burden and influence from the boundaries' conditions the models span between 152.0 m and 167.1 m in width and between 49.0 m and 70.0 m in height. The boundaries were located at a distance of 70 m from the diaphragm walls while the lower edge of the model was placed 30 m deeper from the base of the same diaphragms. Finally, the thickness of the model was 22.5 m, corresponding to 15 wall modules of 1.5 m each.

The thermal activation of the diaphragm walls was provided by two separate hydraulic circuits, one for each side. Pipes are embedded vertically inside the wall, with 25 cm spacing to form an "U" geometry and have equal characteristic to those of TBM sections. Similarly to TBM sections, pipes are supposed to be installed at a distance of 5 cm from the concrete extrados and 3 groups of 5 modules were connected in series.

Both for the TBM and the C&C sections two different simulations were carried out, i.e. winter, where the heat is extracted from the ground, and summer configuration, where the heat is injected in the subsoil.

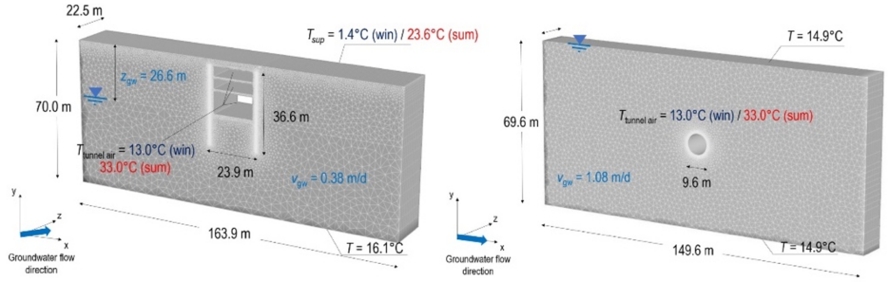

Fig.1 Examples of thermo-hydraulic FEM numerical model for TBM and C&C sections (n° 72 and n° 7 respectively).

5 Overall geothermal potential of the line

The interpretation of the results of the different thermo-hydro FEM numerical simulations carried out allowed to assess the geotherml potential of the different sections of Line 2. Fig. 2 shows, as an example, a summary of the results obtained along the alignment for that pertaining to winter configuration. The thermal energy exploited is expressed in terms of W/m of tunnel length. To obtain a simple and intuitive visualization of the thermal contributions, five classes were adopted. Class 1 (< 200 W/m) represents the less favorable conditions for ground heat extraction/injection while class 5 (> 800 W/m) is the most suitable. The velocity of the groundwater flow and the piezometric level to the tunnel position were found to be the most influencing parameters for heat exchange.

It is interesting to note that the numerical simulations showed a substantial difference between summer and winter thermal exchange for the TBM sections while the thermal exchange during summer and winter for the C&C sections was comparable. The minor summer performance for TBM sections is caused by the strong influence exerted by the air tunnel operating temperature equal to 33°C. During winter the internal air tunnel temperature equal to 13°C is similar to the ground temperature and its influence on the thermal exchange is therefore negligible. For C&C sections on the contrary the similarity of winter and summer results is caused by the higher thickness of the diaphragms compared to the TBM tunnel lining (120 cm vs. 40 cm) which insulate the pipe systems from the short-term temperature air changes.

Finally, a total of 1740 potential users of the heat exchanged with the ground were identified, i.e. public and private buildings whose surface is located for at least 50% into the 100 m buffer zones. Fig. 3 shows an example of the potential users' identification for the tunnel section between Novara and Giulio Cesare stations. The majority of the cadastral units identified correspond to residential buildings (1590 elements equal to 91.45% of the total), followed by industrial buildings (84 elements equal to 4.8% of the total) and commercial ones (33 elements, equal to 1.9% of the total). The remaining buildings (32, equal to 1.85% of the total) were assumed as strategic public buildings, (i.e. schools, hospitals, post offices, police/fire houses, etc.)

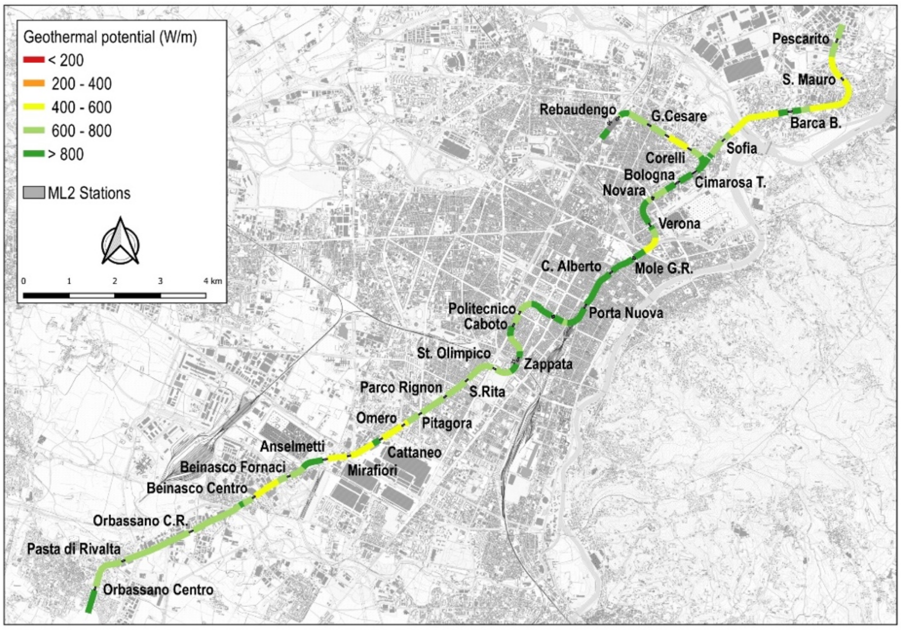

Fig. 2 Classification of the winter geothermal potential (W/m) for the Line 2

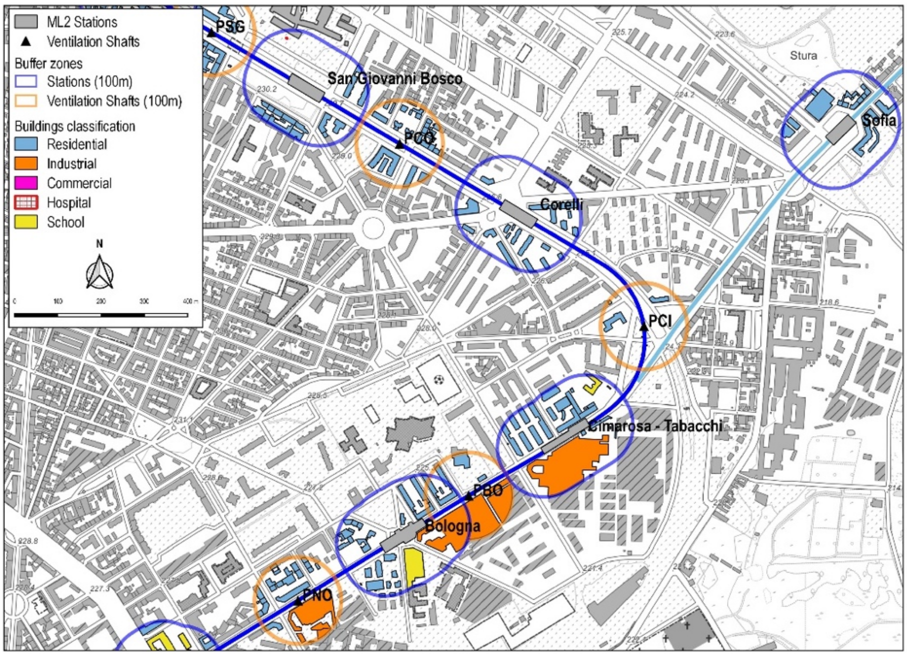

Fig. 3 Identification and classification of the potential users of the thermal heat extracted for the Novara – Giulio Cesare section

6 Conclusions

This paper discussed the beneficial opportunity offered by the thermal activation of Turin metro Line 2. Using 3D FEM models, the heat exchange between the ground and the structure could be simulated in detail, taking into account a considerable number of influencing factors including the geometry and the hydrogeological setting. Numerical analyses show that when groundwater flow exists, higher heat exchange rates and lower temperature variation in the surrounding soil are predictable.
Based on the results obtained, the thermal activation of the tunnels, would satisfy the heating/cooling demand of all the planned stations along the line. The thermal energy excess can be used for other potential users along the ML2. Further favorable perspective can be envisaged as it is generally known that the metro line construction can boost new urban and building development. An added value to the thermal activation of the metro structures is predictable in those areas of new urbanization or complete renovation. In these areas in fact connection to existing district heating is difficult due to technical reasons. Geothermal heat can thus provide an interesting option to reach the minimum law requirements in terms of energy from renewable sources. In this context, the metro Line 2 itself can be seen as a local district heating and cooling network.

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