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# Thermal performance of a metro station in Turin equipped with energy geostructures

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ABSTRACT: High pollution levels combined with the lack of green spaces are hitting many cities leading to the exploitation of the underground for transportation. Given the need to foster local energy sources with low environmental impact, energy geostructures are more and more being explored. In this context, the promising outcomes of the experimental campaign on the thermal activation of tunnel segments carried out on Turin ML1 South Extension encouraged the authors to investigate applicability of energy geostructures for Turin ML2 project. This paper is intended to focus on the understanding of the thermo-hydraulic behaviour of a metro station equipped with energy diaphragm walls. A 3D FE numerical model reproducing the layout of the planned Mole-Giardini Reali station is used to study the energy exchange potential of the thermoactive walls. The quantification of the exploitable energy to meet the user demands of the station and of buildings above will be discussed on the basis of the results obtained.

## 1 INTRODUCTION

Today, lack of surface place represents a crucial issue not only in mega cities but in nearly all town and cities around the world. For this reason and given the need to reduce pollution as well as to preserve the living environment, in the last decades mankind has been encouraged to use and develop underground space. City traffic tunnels provide safe, environmentally sound, fast, and unobtrusive urban mass transit systems, clearing vehicles from surface streets, which may partially be used for other purposes, leaving room for recreation areas and playgrounds above ground (ITA-AITES, 2002).

The opportunity offered by a more intensive use of underground space also meets the need to foster local energy sources with a low environmental impact. Indeed, around one-third of global energy use is related to buildings and, of this, more than 70% is devoted to the production of thermal energy (REN21, 2022). Yet, despite strengthened commitments to climate change, the share of renewables for heating and cooling is very limited.

In this perspective, energy geostructures are more and more being explored thanks to their peculiar characteristics that make them economically convenient and sustainable (Brandl, 2006; Laloui and Di Donna, 2013; Barla et al., 2016). They are low enthalpy, closed-loop geothermal systems that use geotechnical structures, such as piles, walls or tunnels, adequately instrumented with a net of pipe loops to exchange heat with the ground. The possibility to thermally activate metro tunnels and stations is highly attractive and research on this topic is increasing (Delerablée et al., 2018; Zannin, 2022).

This paper will focus on the understanding of the thermo-hydraulic behaviour of a metro station of Turin Metro Line 2 equipped with energy diaphragm walls. After a brief description of the project, currently at the outlined design stage, a 3D FE numerical model reproducing the layout of the planned Mole-Giardini Reali station will be described with the goal to study the energy exchange potential of the thermoactive walls over time.

## 2 TURIN METRO LINE 2 PROJECT

Turin Metro Line 2 will connect the city from North to South over nearly 30 km, intersecting Metro Line 1 at Porta Nuova station. With its “Y” configuration it will be characterized by 32 stations and three main sections including the central one and the two North and South extensions. The infrastructure will help strengthen the links between the main city hubs, including the automotive plant in Mirafiori, the university centers of the Einaudi Campus and Politecnico di Torino, the downtown area, and the San Giovanni Bosco hospital. Line 2 will connect with the existing local railway service thanks to three transfer points at Zappata, Rebaudengo and Porta Nuova stations.

Currently, the outlined design of the first functional section of Turin Metro Line 2, included between Rebaudengo (pk 15 + 614.56) and Politecnico stations (pk 5 + 906.81), is ongoing (Figure 1). It is about 9.7 km long and includes 13 underground stations and 12 inter-section wells with ventilation, emergency exit and rescue access functions.

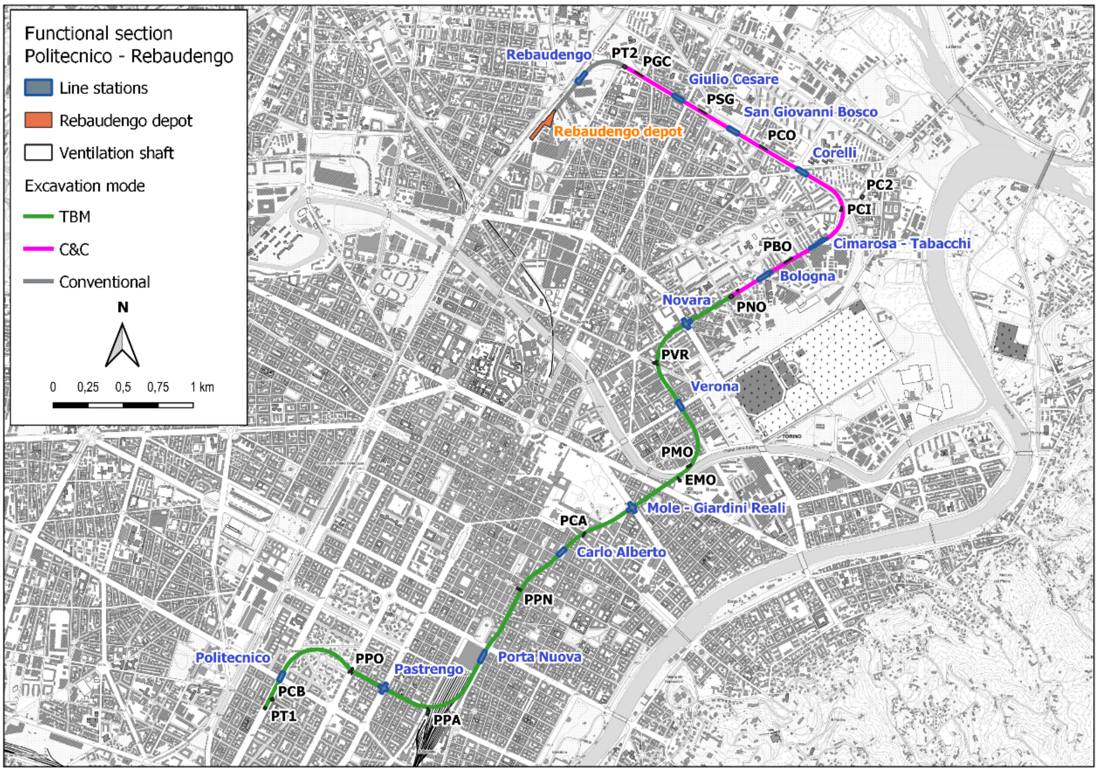


Figure 1. Key-plan of Turin Metro Line 2 – functional section Politecnico-Rebaudengo with indication of the excavation modes.

As shown in Figure 1, the line will consist of a natural tunnel section close to Rebaudengo station (576 m), an artificial section made by means of Cut&Cover technique (C&C) at one or two levels from the PT2 shaft to the Novara well PNO (about 3.0 km) and a section excavated by mechanized excavation (about 5.6 km) through the use of a Tunnel Boring Machine (TBM) with an excavation diameter of about 10.0 m. A terminal well (PT1) for the extraction of the TBM will be located in the Politecnico rear station. The Rebaudengo rear-station building, as anticipated, will have the function of depot-workshop for scheduled routine maintenance on the trains, as well as the parking of 7 trains in prearranged stalls and a total of 10 trains at the end of the service. The crossroads in the North branch towards San Mauro Torinese will be set up.

The project was developed with a strong focus on environmental sustainability. Indeed, among the solutions adopted and given the promising outcomes of the experimental campaign on the thermal activation of tunnel lining segments carried out on Turin ML1 South Extension (Barla et al. 2019), authors were encouraged to investigate the applicability of energy geostructures for the project of Turin ML2.

## 3 NUMERICAL MODEL OF THE MOLE-GIARDINI REALI STATION

Thermal activation of Turin Metro Line 2 will include not only the tunnels excavated by TBM and C&C, but also the 13 stations. In the following, the case study of the Mole-Giardini Reali metro station will be studied by describing geometry, material properties, initial and boundary conditions of the thermo-hydraulic finite-element numerical model built. Such model allows to capture the key aspects of the problem by coupling both thermal and hydraulic physics, i.e. heat transfer and fluid flow. The equations governing the thermo-hydraulic problem are mass conservation, Darcy's velocity law and energy conservation. It is thus possible to account for conductive heat transfer, mainly in the solid elements (ground, concrete structural elements) and partially in the heat carrier fluid in the pipes, and convective heat transfer in the heat carrier fluid, at walls intrados and in the ground (through groundwater flow in the shallow aquifer). The aim is to evaluate the thermal performance of the station and to understand the energy exchange potential of the thermoactive walls over time due to the above-mentioned heat transfer mechanisms.

### 3.1 *Geometry and pipes layout*

The Mole-Giardini Reali station is a 4-level underground building with the station platform running along the tunnel route. The three-dimensional BIM model of the station is shown in Figure 2 from which it is evident that the main chamber of the structure consists of an articulated series of diaphragm walls that reach various depths (max about 37.0 m from the ground surface). Along the shorter sides of the station, there are the entrances to the atrium level and further technical rooms (fire prevention, ventilation, etc.) which extend down to the underground level -1.

On the basis of the presence of these artifacts and the different depths of the diaphragm walls, 7 sections (*a*, *b*, *d*, *e*, *f*, *h*, *i*) have been identified that can be fully activated for a depth of approximately 33.5 and 37.2 m, in addition to the two sections *c* and *g* which can be activated only in the upper portion of the tunnel (14.7 m long) as shown in Figure 2. The total number of potentially thermally activable diaphragm wall panels, each 2.80 m large, is 48.

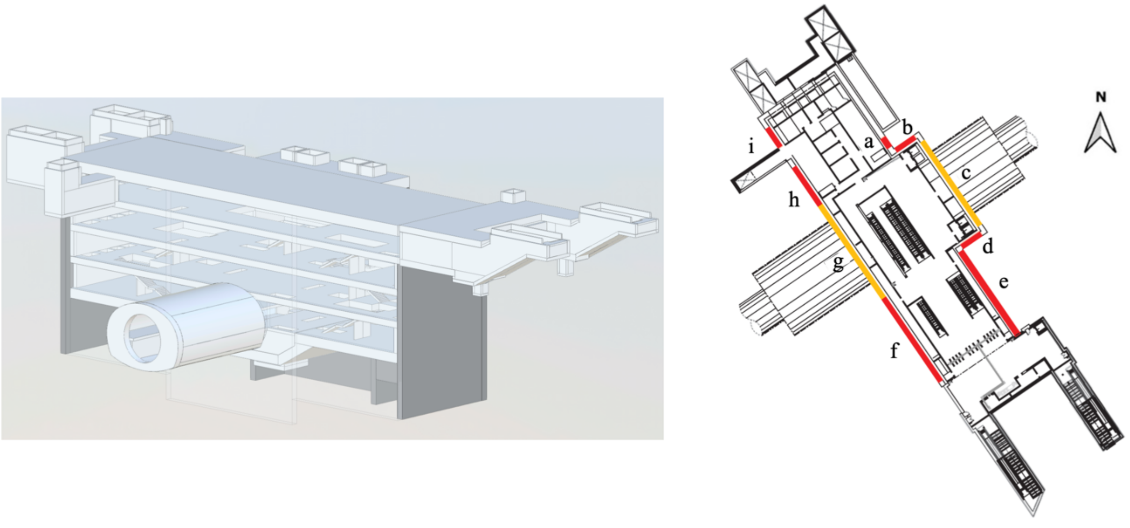


Figure 2. 3D BIM model of the Mole-Giardini Reali station (left) and plan of the atrium level with indication of the thermally activated diaphragm walls (right).

The geometry of the model was obtained by longitudinal extrusion of the vertical section (Figure 3a). The size of the model is such to define a compromise between calculation time and influence of the boundary conditions. The resulting dimensions are a width of 405 m, a height of 71.8 m and a thickness of 343 m.

Hydraulic circuits were included within the vertical diaphragm walls for the simulation of the structures' thermal activation (Figure 3b). The circuits were simulated by highly conductive one-dimensional elements (called "discrete features") characterized by an external diameter of 20 mm and 2 mm thick, with 3 U-shaped branches per panel equally spaced. The pipes are embedded in concrete at 6 cm from the ground.

The tunnel excavated in TBM was also modeled, neglecting however the concrete lining, which was appropriately considered in the boundary conditions adopted (see Chapter 3.3). Also the linings cover and the base slab have not been modeled explicitly, for simplicity, but appropriate boundary conditions have been chosen here. Finally, the distribution of spaces inside the station has been neglected as it is not believed this will affect the heat exchange process.

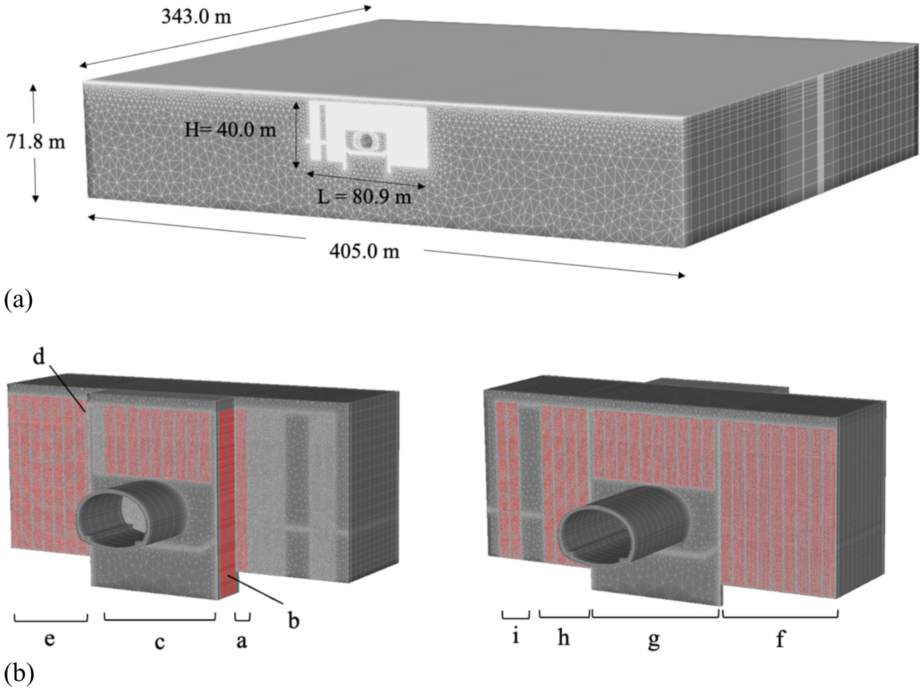


Figure 3. View and main sizes of the 3D thermo-hydraulic numerical model of the Mole-Giardini Reali station (a) and hydraulic circuits geometry, view from North-East and from South-West (b).

## 3.2 *Material properties*

To define the key material properties characterizing the area surrounding the Mole-Giardini Reali station, reference was made to the procedure and parametrization described in Barla et al. (2022). In detail, the parameters considered relevant are the groundwater table position (F), the undisturbed ground temperature (T), the groundwater flow direction (DF), the piezometric gradient (I), and the geological setting (Geo). Such parameters were evaluated as an average of those existing in a representative surrounding of the station with size given by two times the maximum width $m$ and the maximum length $n$ of the station itself (Figure 4). Such boundaries are the same chosen for the model domain in Figure 3a.

The input data for the determination of parameters F, T, DF, I and Geo were derived from the design documentation available and from specific thermo-hydro-geological investigation. In particular, regarding F, DF and I reference was made to the October 2021 groundwater level shown in the project documentation deriving from the analysis of bibliographic data, of the piezometric surveys carried out during the feasibility study and of the results of a campaign to measure the groundwater level carried out in the same month of October 2021. This aquifer level is located within the lower half of the band of maximum seasonal excursion of the aquifer which has been identified as being approximately 2 m. The thermal parameters of the aquifer (T) derive from measurement campaigns carried out on piezometers in 2022. For the detailed stratigraphy of the ground around the tunnel (Geo parameter) reference was made to the reconstruction of the subsoil along the tunnel based on the results of all the direct and indirect investigations carried out within the feasibility and the outlined design.

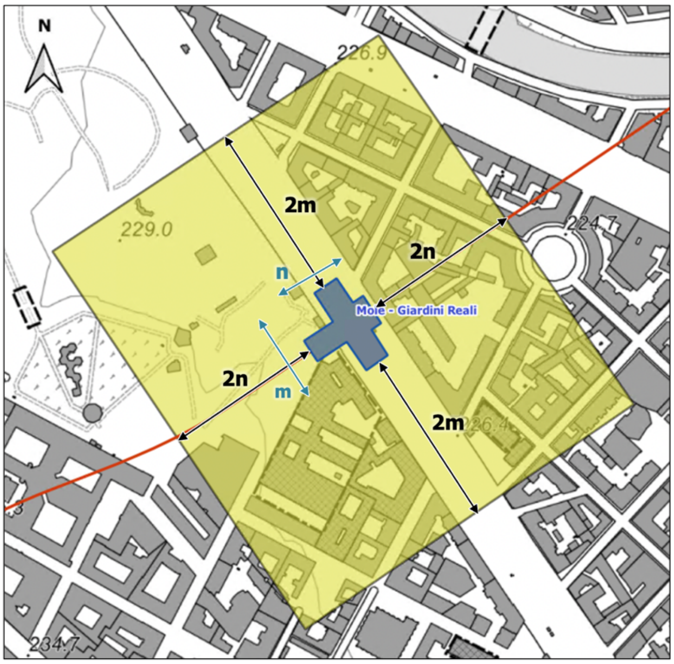


Figure 4. Extension of the area around the Mole-Giardini Reali station where the average parameters F, T, DF, I and GEO are evaluated.

According to the procedure described above, the piezometric surface resulted to be located at a depth of about 9.8 m. The groundwater direction is 79° with respect to the North axis (i.e. 23° clockwise with respect to the route direction) and the groundwater flow gradient is 0.56%. Undisturbed ground temperature corresponds to 15.5°C and the stratigraphy identified is characterized by two geological formations, sandy-gravel deposits (AFR) up to around 24 m depth and clay layers below (FAA). Thermo-hydraulic properties of such formations, as well as of concrete (from Insana and Barla, 2020), are shown in Table 1.

Table 1. Thermo-hydraulic properties of the different geological units involved in the numerical model and of concrete.

| Geological unit | Horizontal permeability $k_h$ [m/s] | Vertical to horizontal permeability ratio $k_v/k_h$ [-] | Effective porosity $n_e$ [-] | Thermal conductivity $\lambda$ [W/mK] | Thermal capacity $\rho c$ [J/(m$^3$K)] |
|---|---|---|---|---|---|
| AFR | $1.93 \cdot 10^{-3}$ | 0.05 | 0.175 | 4.22 | $2.60 \cdot 10^{6}$ |
| FAA | $1.00 \cdot 10^{-8}$ | 0.05 | 0.05 | 4.19 | $2.30 \cdot 10^{6}$ |
| Concrete | $1.00 \cdot 10^{-16}$ | 1 | 0 | 1.12 | $2.19 \cdot 10^{6}$ |

Horizontal permeability was defined based on literature data and on specific campaigns, namely in-hole Lefranc tests carried out in the framework of the feasibility and outlined design, pumping tests and slug tests. The permeability anisotropy ratio used derives from the numerical back-analyses of the pumping tests conducted on the extraction geothermal wells of the Intesa Sanpaolo Headquarters (Barla et al. 2012, 2013). This ratio is justified by the presence, at least within the AFR unit, of lenses made of material with different cementation levels characterized by lower permeability, especially in the vertical direction. Effective porosity values for the two geological-stratigraphic units were defined from data available in the literature (Celico, 1988). Thermal conductivity, intended as that of the solid phase, was obtained from a simple hand calculation accounting for the degree of saturation and the porosity based on the results on three in situ Thermal Response Tests (TRTs). Last but not least, the values of specific heat capacity adopted in this work were obtained from data available from literature (Eppelbaum et al. 2014) as the average of that of the different lithotypes present within the different units. The volumetric heat capacity of the different units was obtained starting from the specific heat capacity considering typical density values equal to 2600 and 2100 kg/m$^3$ respectively for the characteristic lithotypes of AFR and FAA.

### 3.3 *Initial and boundary conditions*

The initial thermal conditions consist in defining the temperature throughout the model, equal to 15.5°C. As for the boundary conditions, a Dirichlet boundary condition was applied both on the upper and lower faces of the model and at the inlet of the pipe for the entire duration of the thermal activation. On the upper face, the temperature was set based on the annual time history recorded in 2021 at a weather station close to the future Mole-Giardini Reali metro. On the lower one it was set equal to 15.5°C, by virtue of the high depth and the absence of influence of seasonal thermal fluctuations. The temperature is 4°C in winter and 28°C in summer at the pipes' inlet. A Cauchy boundary condition was imposed at the tunnel extrados and along all the internal nodes of the station. The temperature at the tunnel extrados varies linearly between 9°C in winter and 24°C in summer, while in the station between 16°C in winter and 28°C in summer. The value of the heat transfer coefficients adopted for the Cauchy boundary conditions described above is equal to:

- 5.3 W/(m$^2$K) at the intrados of the station platform and the upper slab of the station, obtained from the calibration of a thermo-hydraulic finite element 3D model based on the results of the experimental tests carried out on the Enertun prototype installed in Piazza Bengasi (Insana and Barla, 2020; Insana, 2020);
- 1.83 W/(m$^2$K) along the extrados of the tunnel;
- 1.11 W/(m$^2$K) along the intrados of the diaphragm walls by the 80 cm thick concrete lining;
- 0.56 W/(m$^2$K) along the elements of the base slab in contact with the ground.

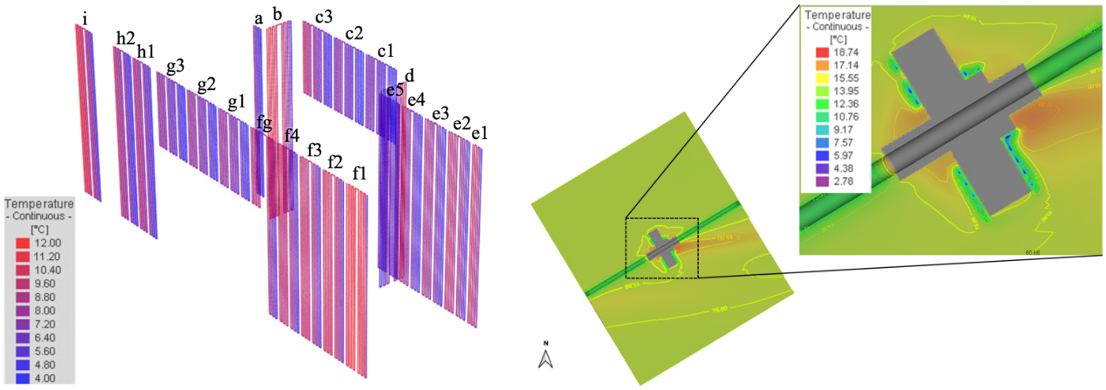
The latter three were calculated considering, through a series connection, the thermal resistance represented by a thickness not modeled of 0.40, 0.80, and 1.80 m and a thermal conductivity of 1.12 W/(mK).

The initial hydraulic conditions were obtained through a purely hydraulic steady-state analysis during which the hydraulic conductivity parameters of AFR, FAA and concrete were defined, and the hydraulic load was adequately fixed on all external vertical boundaries of the model. As a further hydraulic boundary condition, the velocity at the point of entry and exit from the pipes was set at 0.9 m/s exclusively during the thermal activation.

## 4 RESULTS AND DISCUSSION

The results obtained at the end of the 60 days-long thermal activation stage show a temperature differential between 3.0 and 7.2°C in winter (Figure 5a) and 2.0 and 7.4°C in summer for an average of 5.1 and 4.2°C respectively. The overall thermal power obtained in winter is 84.8 kW, higher than the one in summer of 70.0 kW. This is probably due to the higher winter temperature difference between the heat carrier fluid and the inner air temperature, equal to 12°C, whereas in summer such difference is null. Instead, temperature difference between the heat carrier fluid and the groundwater are comparable in summer and in winter.

As it is possible to see, the performance changes considerably depending on the circuit location and arrangement. A great role in this sense is played by groundwater flow whose natural velocity (around 0.93 m/d in the AFR formation) and direction is greatly altered by the presence of the station due to "dam effect". Figure 6 exemplifies the change in the Darcy's velocity around the metro station 6 m below the phreatic surface (around 16 m from the ground surface). The flow velocity increases on the lateral sides and decreases on the upstream and downstream sides of the station. Therefore, in correspondence of lateral sides the thermal recharge would be largely beneficial, making them more appropriate for energy geostructures installation. However, this was not possible due to the presence of artifacts, as described in Chapter 3.1. Notwithstanding, the better thermal performance of circuits close to the station corners ($e_1$, $f_1$ and $i$) is consistent with this observation. Also $c_3$ is positively affected by the change in groundwater flow.



(a) (b)

Figure 5. Temperature within the geothermal loops (a) and in a horizontal cross section at the tunnel axis depth (b) at the end of the heating season.

The thermal alteration produced by the presence of the station at the tunnel axis depth can be seen in Figure 5b. Compared to the situation with no thermal activation, it can be stated that the thermal field is slightly altered just in the station surroundings, up to a distance of about 4-5 m from the diaphragm walls extrados, because the groundwater flow is very slow where most of the circuits are located. The thermal plume that can be seen is in large part due to the tunnel and station internal air temperature. Likely, the thermal plume would have looked different in case of thermal activation of the shorter station sides.

The quantification of the exploitable energy allows understanding in which proportion the user demands of the buildings above and of the station itself could be possibly met. Based on the results obtained, up to 59 and 56% of the station thermal need (213 kW in winter and 302 kW in summer from the feasibility design) could be fulfilled by geothermal energy in winter and in summer respectively (assuming a heat pump with a coefficient of performance of 3). Alternatively, thermal energy could be delivered to users detected in a 100 m-radius buffer area around the station. In particular, 39 residential buildings, 2 schools and a post office have been identified thanks to a geospatial analysis.

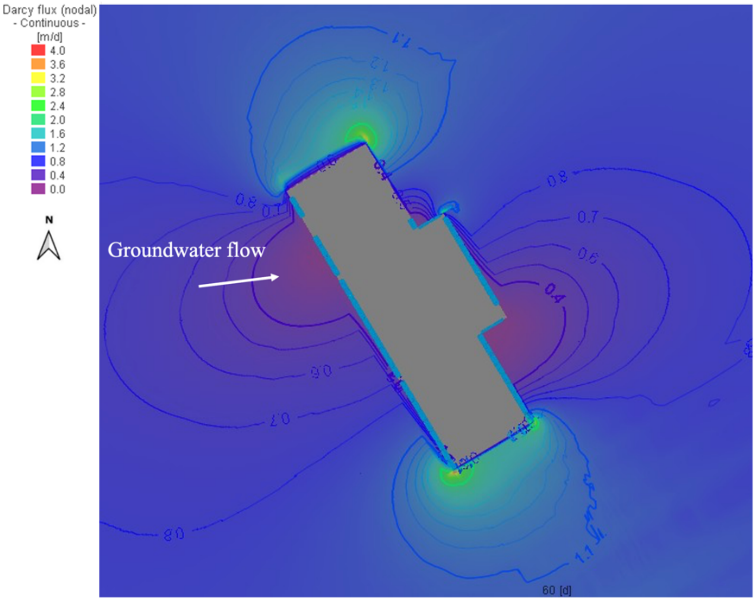


Figure 6. Darcy's velocity around the Mole-Giardini Reali station.

## 5 CONCLUSIONS

The underground expansion of urban transportation infrastructures brings environmentally positive spill-overs effects not only *per se*, because it reduces pollution and frees surface streets from vehicles, but also because it offers the opportunity to transform geostructures into heat exchangers to capture and store heat within the ground. The paper showed a possible application of energy diaphragm walls to the Mole-Giardini Reali metro station, one of the 13 stations planned within the first lot of Turin ML2 project. A 3D finite-element, thermo-hydraulic model reproducing the geometry and thermo-hydro-geological characteristics was built to assess the thermal performance of the energy walls. Based on the results obtained, a relevant thermal power otherwise unexplored was unraveled. Such energy could contribute to providing more than one-half of the station's thermal need in winter and in summer.

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