Journal of Rock Mechanics and Geotechnical Engineering 10 (2018) 1145–1153

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Assessment of thermal behaviour of thermo-active diaphragm walls based on monitoring data

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ARTICLE INFO

Article history:
Received 18 March 2018
Received in revised form
12 August 2018
Accepted 27 August 2018
Available online 22 September 2018

Keywords:
Heat transfer
Monitoring data
Near-surface geothermal energy
Energy geostructure

ABSTRACT

Thermo-active diaphragm walls have proved their effectiveness in the thermal conditioning of buildings and infrastructures. However, some aspects still need to be investigated in order to tailor methods and tools for an accurate prediction of their energy and structural performance. In this perspective, some issues are addressed that concern the definition of models for the numerical analysis, in particular issues about the modelling of geometry and thermal boundary conditions. Taking advantage of a monitoring programme on a real full-scale structure, this research focuses on the assessment of heat transfer process and thermal response of diaphragm wall and soil mass on the basis of field data. Understanding of the heat transfer process contributes to the definition of the time-dependent thermal boundary conditions at the excavation side. From the analysis of thermal gradients in the wall, the condition at the excavation side is recognised as a major factor that influences the heat transfer process, governing the direction of the heat flux in different seasons of operation of the geothermal system.

1. Introduction

World targets on the use of green and renewable energy sources and the reduction of greenhouse gas emissions are boosting towards the exploitation of the geothermal energy and of the subsoil for thermal energy storage in the sector of buildings and spaces for domestic, commercial and public services, a sector that has nowadays surpassed the sectors of industry and transport (International Energy Agency, 2014). Even at shallow depths, the ground thermal energy can be used for the thermal conditioning of buildings and infrastructures (Preene and Powrie, 2009; Hofinger et al., 2010; Amis, 2014), thus reducing the consumption of fossil fuels in a field that accounts for 40% of the total building energy demand (Pérez-Lombard et al., 2008; European Parliament and Council, 2010).

In this frame, the thermo-active geostructures represent an effective solution that permits the exploitation of geothermal energy at shallow depths and the use of the ground mass as a thermal energy reservoir. Being fully immersed or in contact with the subsoil and hosting heat exchanger pipes, usually fastened to the reinforcing cage, these geostructures exchange thermal energy with the ground by way of the circulating heat carrier fluid, that harvests heat in the season when heating is required and disperses heat in the season when cooling is required (Brandl, 2006; Laloui and Di Donna, 2013; Soga and Rui, 2016). These structures are therefore subjected to combined mechanical loads, related to the primary structural function they serve, and thermal loads from the secondary energetic function. The thermal loads are the result of thermal strains and stresses induced by the temperature variations and influenced by the constraints that the structure is subjected to, as from the surrounding earth mass and other connected structures. The challenge in the design of energy geostructures stems from the combined optimisation of their structural and energetic functions (Bourne-Webb et al., 2016a).

The use of the subsoil as heat source or sink can be associated with theoretically any kind of geostructures: deep and shallow foundations, diaphragm walls, tunnel liners, or anchors (Amis et al., 2010; Amatya et al., 2012; Zhang et al., 2013; Mimouni et al., 2014; Nam and Chae, 2014; Barla et al., 2016). In particular, the thermo-active diaphragm walls are conventional retaining structures designed for supporting deep surface excavations (basements, parking lots, metro stations, cut-and-cover tunnels, etc.). The base slabs of such underground excavations are also often equipped with heat exchangers.

The research on thermo-active diaphragm walls and the available experimental findings, although limited in number (Brandl,

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2018.08.002

2006; Adam and Markiewicz, 2009; Amis et al., 2010; Xia et al., 2012; Kürten et al., 2015a), highlighted the peculiar features of this kind of energy geostructure, for instance, with respect to the more common thermo-active pile, starting with the more complex geometry and boundary conditions.

Concerning full-scale applications, design details were reported by Amis et al. (2010) and Amis (2011) about Knightsbridge Palace Hotel project in London that includes, together with 50 energy piles, 150 m of thermo-active diaphragm walls, with 0.8 m thickness, 24 m of retained height and 12 m of full embedment. Amis et al. (2010) and Amis (2011) discussed the need for an accurate evaluation of the thermal potential along the wall perimeter and reported that the heat transfer, measured prior to and after the basement excavation, decreases as if the ground thermal conductivity underwent a 13% reduction, due to two thirds of the wall being exposed to the basement.

Other documented full-scale applications are Lainzer tunnel in Vienna, where an instrumented bored pile wall allowed to recognise that the exchanger pipes induce temperature variations smaller than those due to natural fluctuations (Brandl, 2006), and Shanghai Museum of Natural History, where tests on different loop arrangements in wall panels show that the energy performance can increase up to 40% when an optimal arrangement is adopted (Xia et al., 2012).

The energy performance and the geotechnical and structural consequences of the heat transfer process for diaphragm walls have been investigated also by thermal and thermo-mechanical numerical analyses (Bourne-Webb et al., 2016b; Rammal et al., 2016; Di Donna et al., 2017; Rui and Yin, 2018a). The results show that, for given hydro-geological conditions, the time-dependent thermal boundary conditions play a crucial role in determining the temperature field and the magnitude and direction of the heat fluxes. These conditions are for instance the thermal input from the secondary circuit (the time-dependent heat flux at the pipe inlet) and the temperature condition at the excavation side, and the latter is often of uncertainty and complex definition. In turn, they influence the energy performance and the structural internal actions of the diaphragm wall, in both the short- (transient regime in the initial years of operation) and the long-term regime (Bourne-Webb et al., 2016b). A long-term thermal drift can occur when there is no balance between extracted and injected thermal energies in the heating and cooling periods, respectively. An additional contribution to transient effects is expected in cohesive saturated soils, due to the hydro-mechanical coupling of their constitutive behaviour (Cekerevac and Laloui, 2004; Gawecka et al., 2017; Rui and Soga, 2018; Rui and Yin, 2018a, b).

Three-dimensional (3D) numerical analyses also highlighted that the heat transfer is generally not uniformly distributed in the plane of the wall, but it rather depends on the exchanger pipe layout and on the possible coexistence of warmer and cooler vertical cross-sections. Different thermo-mechanical consequences are obtained in different vertical cross-sections, which interact during thermal expansion or contraction (Sterpi et al., 2017). Therefore, thermally induced compressive and tensile stresses can coexist in the wall at the same time, contrary to the usual understanding that heating induces a compressive state and cooling induces a tensile state. A similar result has been predicted also in thermo-active piles, despite their more limited cross-sectional area (Abdelaziz and Ozudogru, 2016).

In general, the computational models are effective as tools for the prediction and optimisation of the energy and structural performance (Rammal et al., 2016; Di Donna et al., 2017), but they usually require a preliminary accurate calibration of their input variables.

Finally, given the peculiar characteristics of geometry, constraints and thermal boundary conditions of thermo-active diaphragm walls, analytical heat transfer models developed for borehole heat exchangers or thermo-active piles cannot be extended to diaphragm walls and suitable design methods need to be introduced (Sun et al., 2013; Kürten et al., 2015b).

These considerations underline the need for a better understanding of the heat transfer process and of the role of key parameters in thermo-active diaphragm walls. The monitoring of full-scale, not experimental, geostructures helps in getting insights into these aspects and can provide a calibration database for further refinement of the numerical modelling.

In this perspective, a recent residential building located in Northern Italy and designed in conformity with the zero-energy concept was taken as a case study. The geothermal circuit integrated into the perimeter diaphragm walls and basement slab was equipped with a comprehensive sensor system for a continuous inspection of its operation. A specific set of monitoring data helped to understand the role of temperatures at the domain boundaries in the short term (first and second years of operation). From these field observations, some indications are given about a numerical modelling approach that accounts for the key factors that influence the energy performance.

2. Thermo-active diaphragm wall and monitoring system

A zero-energy residential building was recently built in the city centre of Tradate, located in northwest of Italy, on a hill side, at 300 m above sea level (Bertani and Todeschini, 2016). The building has a six storeys elevation and a three-floor basement that reaches the depth of 10.8 m. The excavation has an almost square shape, it is covered by a base slab of about 40 m in side length and 0.5 m in thickness, and it is supported by two pairs of facing diaphragm walls, formed with panels of 2.4 m in width, 15.2 m in height and 0.5 m in thickness (cross-section and front view in Fig. 1). Each panel is equipped with two pre-stressed anchors, which are destressed at the end of the construction, since their action is then applied by horizontal struts built in the floor slabs. The connection between the wall and the basement changes along the wall perimeter: one side of the perimeter is separated from the basement by way of a 0.5–1 m large gap in direct contact with the ground surface air, other parts are separated by way of a similar gap which however is closed at the ground surface, others are in continuity with the basement, and finally a part delimits the garage ramp and connects with the air by way of a central shaft. Consequently, the structural connection of the wall with intermediate levels of the basement is not continuous, though basically there are isolated struts or continuous slabs at the two depths of 7 m and 10 m.

The base slab and the diaphragm walls are equipped with heat exchangers, thus resulting in a surface equal to about 1700 m^2 for the former and about 2400 m^2 for the latter. However, out of this total 4100 m^2, 3300 m^2 represent surfaces which are exposed to the excavation on one face (i.e. 80%, corresponding to the entire base slab plus two thirds of the walls), while only 800 m^2 are fully embedded in the ground (i.e. 20%, corresponding to a third of the walls). These values highlight the major influence that the thermal condition within the basement might have on the overall energy performance.

Each panel of the diaphragm wall, 2.4 m wide, hosts two exchanger pipes that occupy the left and right parts of the panel, for a width of 0.8 m each (front view in Fig. 1). Each high density polyethylene (HDPE) pipe has internal and external diameters of 1.6 cm and 2 cm, respectively; it is fixed to the reinforcing steel cage on the soil side and is arranged to form a coil loop made of six vertical branches, having about 0.16 m distance from each other. On the left in Fig. 1, the layout of the loop at the top and at the bottom

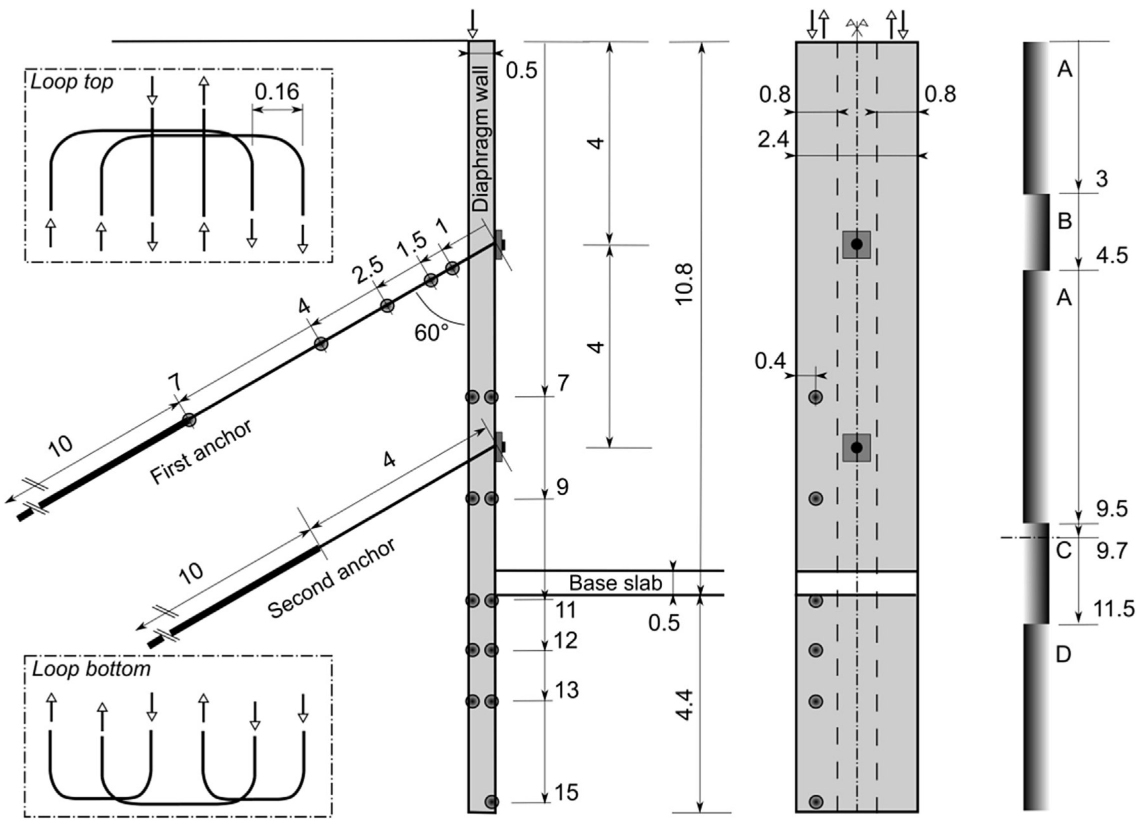

Fig. 1. Cross-section and front view of the anchored diaphragm wall panel and positions of the temperature sensors (dots) along the upper anchor, at the soil side and at the excavation side of the wall. On the right: soil layers and depths. On the left: details of the top and bottom parts of the loop (unit: m).

of the cage is shown. The total length of each exchanger pipe is about 90 m.

From the geognostic report, the soil can be broadly classified as a gravelly sand with silt, of low to medium density, with a distinction in five fairly horizontal layers (on the right in Fig. 1), which are characterised by the grain size contents: (A) coarse gravel: 10%–20%, sand: 60%–70%, silt: 15%–20%; (B) gravel: 20%–30%, coarse sand: 60%–70% silt: 5%–10%; (C) gravel: 40%–50%, sand: 40%–50%, silt: 5%–10%; and (D) fine gravel: 35%, sand: 50%; silt: 15%–20%. The water table is found at 9.7 m depth, and a perched water table saturates layer B. It can be assumed that the soil mass is in a nearly saturated condition also between 4.5 m and 9.7 m.

Since its activation (July 2015), apart from short periods of inactivity (i.e. in August 2015), the geothermal system was continuously monitored by a series of sensors measuring, for the diaphragm walls and the base slab separately, the thermal power, the fluid mass flow rate, and the fluid temperatures at the inlet and outlet of the exchanger pipes. This allowed to analyse the two sources separately and to eventually establish that the contribution of the base slab was less important. As an example, during winter in 2015–2016, the average monthly heat power per unit surface was in the range of 12.5–14.9 W/m^2 for the diaphragm wall and 3.2–8.6 W/m^2 for the base slab, i.e. the heat extracted by the wall was on average 2.7 times higher than the one extracted by the slab.

To investigate the temperature variations induced by the geothermal system in the wall at various depths, a set of sensors was inserted into reserved empty tubes, equal to those used as heat exchangers, fastened to the reinforcing steel cage at the soil side and at the excavation side, respectively labelled SS and ES. The tubes were not grouted to avoid damages to the sensors; the presence of air is expected not to delay or alter significantly the measurements, since the thermal capacity of the small air volume is negligible compared with that of the surrounding concrete volume, and the buoyancy effects or thermal stratification in the air volume are reasonably negligible, given the limited vertical temperature gradient in the wall at the soil side. Additional temperature sensors were fixed along the upper anchor (sensors AS) to investigate transient and permanent temperature variations in the ground (Fig. 1).

As to the instrumentation, the temperatures were measured by class A, three-wire connection, PT100 platinum resistance thermometers, with accuracy of about 0.15 °C (at 0 °C) that could increase up to about 0.3 °C as final recorded value. The sensitivity to the measured temperatures is 0.01 °C and the sampling time is 1 min. The fluid flow rate was measured by flow meters, integrated in the hydraulic pumps of the circulation system.

The data acquisition and control are integrated in a purposely designed building management system (Tecnoel s.r.l., Italy). The full set-up was designed to serve the built-in digital automation system; for a more systematic investigation on the thermal and thermo-mechanical responses of the diaphragm walls, a different set-up could be designed (e.g. Amatya et al., 2012; Murphy et al., 2015; Faizal et al., 2016).

3. Monitoring data of thermal response

Through monitoring the temperatures at various positions within the wall and in the soil mass, temperature fluctuations due to natural seasonal effects can be recognised. However, temperature differences between different positions within the wall also indicate thermal gradients and heat fluxes, and give insights into the thermal response of the diaphragm wall.

Looking at positions within the wall (Fig. 2), one can observe that, for a given depth above the base slab (for instance −7 m), the temperature measured at the soil side (sensor SS7) follows the same trend as that measured at the excavation side (ES7), but is slightly attenuated. This attenuation is due to the mitigating effect that the soil mass has on the soil side of the wall, while the excavation side is directly influenced by the temperature variations of the basement. Consequently, at a depth above the base slab, the temperature gradient along the cross horizontal axis and the associated heat flux change direction depending on the season are considered: in winter, the heat flux is directed towards the basement side, being characterised by lower temperatures; conversely, in summer, the heat flux is directed towards the soil side, since the basement is characterised by higher temperatures. In both cases, the basement acts negatively for the heat exchange of the geothermal system, representing a heat sink in winter and a heat source in summer. The maximum temperature difference between sensors SS7 and ES7 (Fig. 2) is equal to 2 °C in winter and −1.5 °C in summer, corresponding to thermal gradients of 5 °C/m and −3.75 °C/m, respectively, if a 40 cm distance is assumed between the two sensors.

On the contrary, Fig. 3 shows that the temperatures at depths below the base slab (for instance −13 m) are no longer influenced by the basement but rather by the presence of the heat exchanger, circulating hot fluid in summer and cold fluid in winter. In fact, the comparison between sensors SS13 and ES13 shows that, at the soil side, the temperature is lower in winter and higher in summer, and the two values approximately coincide during the idle periods of May and September. At these depths, the whole soil mass, fully surrounding the wall, positively contributes to the heat transfer with the geothermal system, effectively representing a heat source in winter and a heat sink in summer. The maximum temperature difference between sensors SS13 and ES13 is equal to −2 °C in winter and 2.5 °C in summer, corresponding to thermal gradients of −5 °C/m and 6.25 °C/m, respectively.

Note that these observations are not general but apply to the thermo-active diaphragm wall at hand in the monitored seasons, given specific seasonal thermal loads (heat carrier fluid temperatures) and boundary conditions (basement temperatures). For instance, with respect to the temperature of the basement, a hotter fluid could circulate in summer or a colder fluid in winter, thus reversing the heat flux directions in the exposed part of the wall.

The relevant effect of the basement temperature condition is confirmed also in Fig. 4, where the temperatures measured at various depths at the excavation side are compared: above the base slab (sensors ES7 and ES9), the basement condition highly influences the temperatures, and below the base slab (sensors ES11, ES13 and ES15), the effect is attenuated due to the mitigating action of the soil mass. However, the similar difference is not observed at positions closer to the soil mass and to the exchanger pipe (from SS7 to SS13), as shown in Fig. 5.

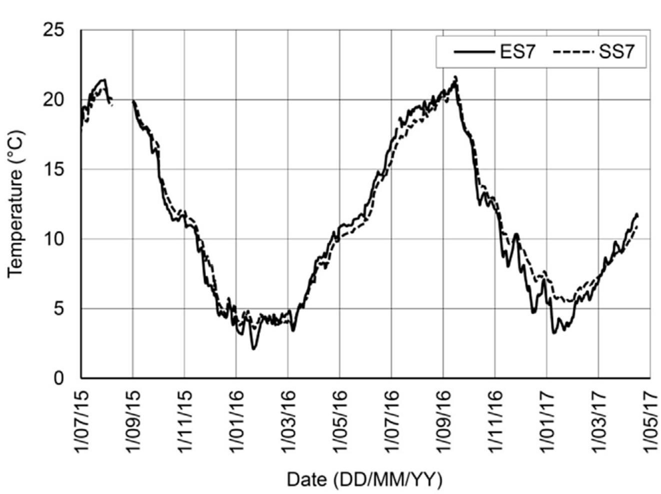

Fig. 2. Temperatures monitored by sensors ES7 and SS7 at same depth above the base slab.

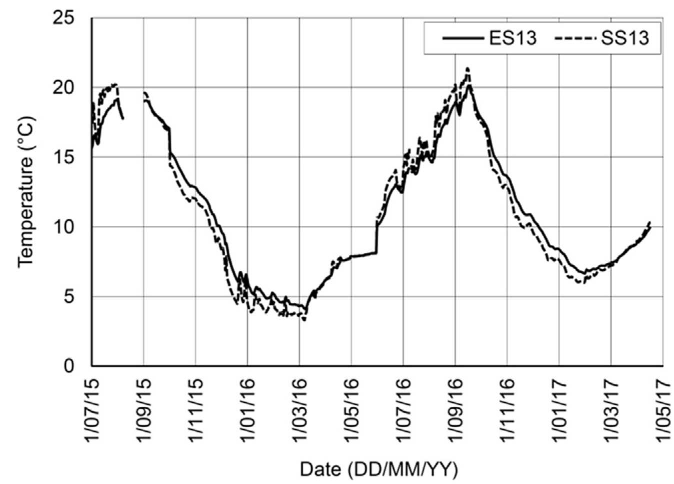

Fig. 3. Temperatures monitored by sensors ES13 and SS13 at same depth below the base slab.

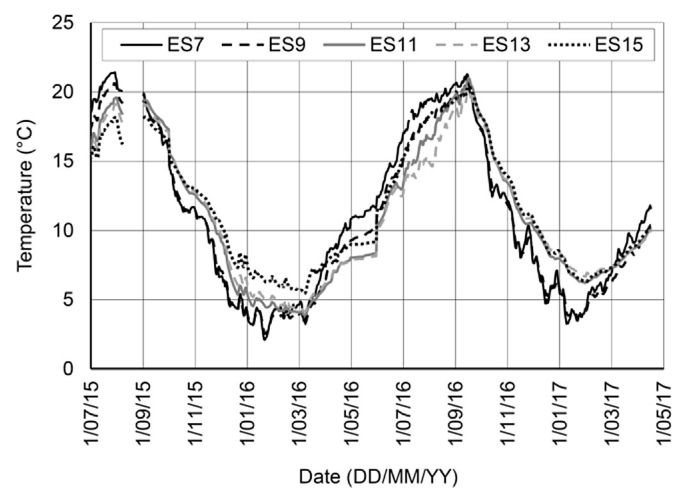

Fig. 4. Temperatures monitored by sensors ES7-ES15 at the excavation side.

The temperature profiles monitored within the wall are shown in Fig. 6, with reference to both excavation and soil side and to two representative conditions of the year, i.e. those characterised by low ground surface temperatures (January 2016) and high temperatures (August 2016). It is worth noting that the average low and high ground surface temperatures monitored on site by the Environmental Protection Agency (ARPA-Lombardia, Italy) were equal to 3.1 °C and 23 °C, respectively. It turns out that the temperature within the wall at the excavation side is very close to the outdoor temperature in winter (Fig. 6a), whereas it is few degrees Celsius cooler in summer (Fig. 6b).

The thermal gradient along depth is almost negligible on the soil side (0.02–0.24 °C/m) and very limited on the excavation side (0.41–0.53 °C/m). The deepest position (ES15) is less influenced by the temperature fluctuations and therefore has the highest value in winter and the lowest in summer. Fig. 6 also allows to recognise how the horizontal thermal gradient and the consequent

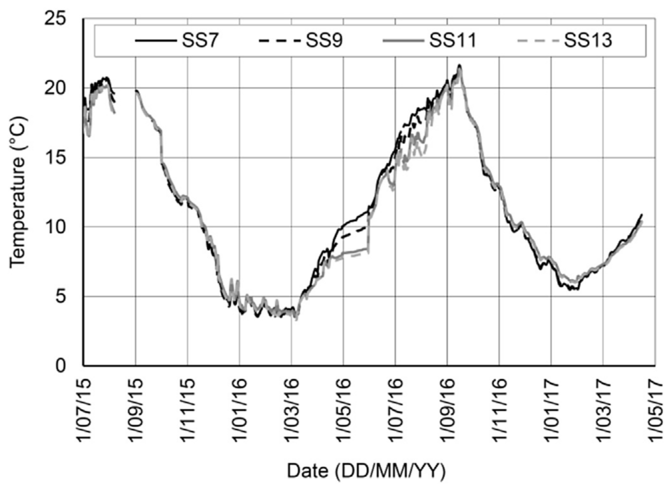

Fig. 5. Temperatures monitored by sensors SS7-SS13 at the soil side.

horizontal heat flux between the exchanger pipe and the basement change direction when moving from a position above the base slab (depth < 10.3 m) to a position below (depth > 10.8 m).

Finally, the temperature variations monitored at the positions along the upper anchor are reported in Fig. 7. As expected, the sensors record temperature fluctuations that are both damped and delayed with respect to the thermal input at the wall surface, and this effect increases with increasing distance (from AS1 to AS7). It should be also noted that even the deepest position (AS7), reaching a depth of 7.5 m from the ground surface and a distance of 6 m from the excavation side, turns out to lay within the zone of influence of both boundaries, according to the analytical solutions of the heat transfer in a semi-infinite space subjected to sinusoidal temperature variation at the surface. For example, the equation proposed by Hillel (2004) leads to temperature fluctuations in the ranges of 12.3 °C–14.5 °C and 12.8 °C–14 °C for the depths of 6 m and 7.5 m, respectively, when assuming surface temperatures having average of 13.4 °C and amplitude of 21.5 °C (these values are justified in Section 4.2), a soil mass thermal conductivity of 2.2 W/(m °C) and a volumetric heat capacity of 3170 kJ/(m^3 °C) (soil thermal properties assumed after Sterpi et al., 2017).

4. Modelling aspects

4.1. Model geometry

The numerical modelling of a diaphragm wall is generally based on a two-dimensional (2D) plane strain geometry, which refers to the vertical cross-section of the structure. The thermal input of the wall is sometimes modelled through a simple temperature distribution, within either the whole wall or the modelled pipe, which can be time-dependent and variable with depth. In this case, a purely conductive heat transfer mechanism is considered (Bourne-Webb et al., 2016b; Rui and Yin, 2018a). Alternatively, the exchanger pipe is explicitly modelled with convective elements, connecting inlet and outlet positions according to the real loop layout, and the heat carrier fluid flow is prescribed by way of its properties (mass flow rate and fluid temperature at the pipe inlet). This refined modelling requires a 3D geometry, with a very fine discretisation to adapt to the small size of the pipe, and it normally requires a high computational effort. A refined modelling is for instance recommended for parametric analyses and design optimisation (Sterpi et al., 2014; Cecinato and Loveridge, 2015; Di Donna et al., 2017). An explicit modelling of the ground heat exchangers can also be coupled with an integrated simulation approach, as a support to automated strategies of operation and control of the geothermal system (Rui et al., 2018).

The 2D plane strain modelling could be accurate as far as the thermal gradient in the longitudinal direction (the plane of the wall) is negligible. However, since the pipe loop is not uniformly arranged within the wall (Fig. 1), different vertical cross-sections undergo different temperature variations. Therefore, the most accurate analysis requires a 3D model, also when aimed at assessing

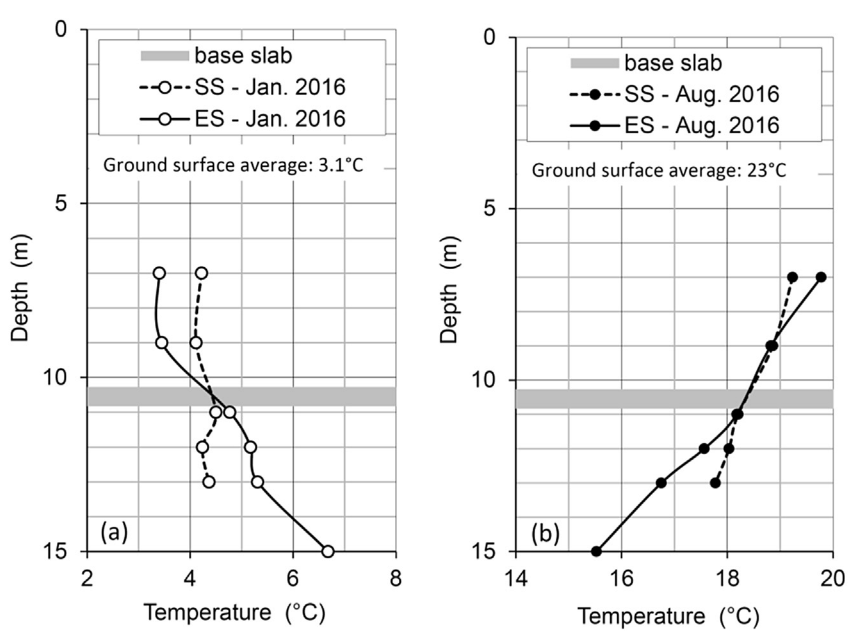

Fig. 6. Monitored temperature profiles within the wall at the soil (SS) and excavation (ES) sides: average values in (a) January 2016 and (b) August 2016. The average ground surface temperatures monitored by the Environmental Protection Agency ARPA are also reported.

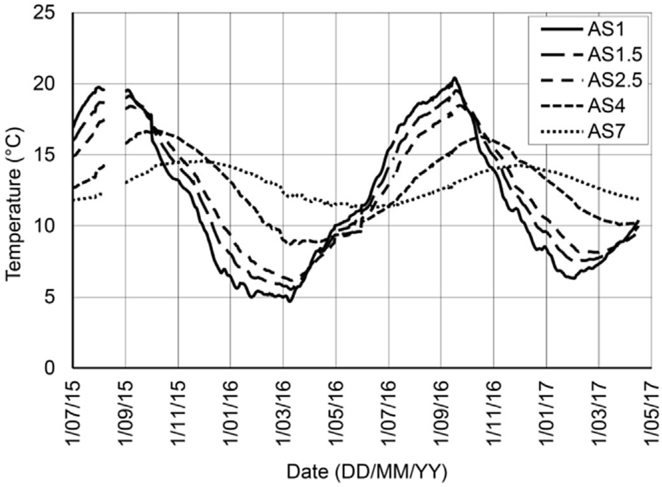

Fig. 7. Monitored temperatures along the anchor from AS1 to AS7.

the thermally induced stress–strain fields. On the real geometry, it is usually possible to recognise vertical symmetry planes in the thermo-active wall, due to the repeated sequence of similar panels, so as to reduce the 3D domain to a thin slice of the entire structure. In the case currently considered, the out of plane dimension of the domain could be reduced to 1.2 m, representing half of the single panel, hosting one heat exchanger loop.

For the analysis of the energy performance, the thermal conditions required by the numerical modelling consist of an initial temperature field $T(\underline{x}, 0)$ and prescribed values of temperature $T(\underline{x}_B, t)$ at given boundaries $\underline{x}_B$: a constant value at the ground base and time-dependent values at the ground surface, the basement surfaces, and the inlet of the exchanger pipe, when modelled with convective elements. The latter must be completed with an input on the fluid velocity (or mass flow rate), to correctly assign the heat flux coming from the building secondary circuit. The lateral sides and the front and back faces of 3D domain are assumed as adiabatic boundaries, since they are symmetry planes.

If the fluid velocity at the pipe inlet is set to zero, the analysis under these same thermal boundary conditions provides the temperature field in the undisturbed state (initial state). This assumption entails that the excavation and construction time is long enough to let the soil mass reach a dynamic equilibrium condition before activating the geothermal system.

4.2. Thermal boundary conditions

The thermal boundary conditions required by the numerical modelling can be obtained based on site environmental data and monitoring data of the thermo-active wall.

In the studied case, the Environmental Protection Agency ARPA provided the ground surface air temperatures at the site, as daily average, from which the weekly and yearly average values were computed (shown with different dots in Fig. 8). An average yearly cyclic variation, with reference to the period 2010–2015, can be computed and then considered as boundary condition at the ground surface (shown with a solid line in Fig. 8). In a more rigorous approach, the temperature at the ground surface should be estimated from the air temperature considering several processes, i.e. convection heat transfer, radiative heat transfer, absorption of solar radiation and possibly latent heat transfer. However, the modelling of these processes requires the knowledge of outdoor environment parameters and the ground surface exposure. In lack of this detailed information, a simplified approach can consider the main outdoor parameter only, i.e. the dry bulb temperature.

The cyclic temperature variation provided by ARPA ranges between 3 °C and 24.5 °C, with amplitude of 21.5 °C and average of 13.4 °C. It must be noted that a season can be characterised by temperatures largely lower (i.e. winter in 2011–2012) or higher (i.e. summer in 2015) than the assumed average, thus affecting the results. At the base of the modelled domain, the constant value 13.4 °C must be assigned, equal to the yearly average value at the ground surface, in order to have a thermally stable system.

Concerning the temperature condition at the surfaces of the basement, it was discussed that a constant value is not realistic of many situations and could negatively affect the energy performance assessment (Soga et al., 2015; Bourne-Webb et al., 2016b; Rui and Yin, 2018a). Here, a first hypothesis is introduced that the basement, an unheated parking lot, is characterised by yearly cyclic temperatures having the same variation of the ground surface temperatures, with the same average value but damped amplitude. The damping coefficient can be calibrated based on the monitoring data during the first period, when the geothermal system was working at low capacity (mid-July to mid-October in 2015). In particular, it is assumed that, in that period, the temperature at the sensors embedded in the wall close to the excavation face (sensors ES7 and ES9) is equal to that within the basement without time delay.

Fig. 9 reports the temperatures monitored by ARPA and the corresponding curve assumed as ground surface condition (solid

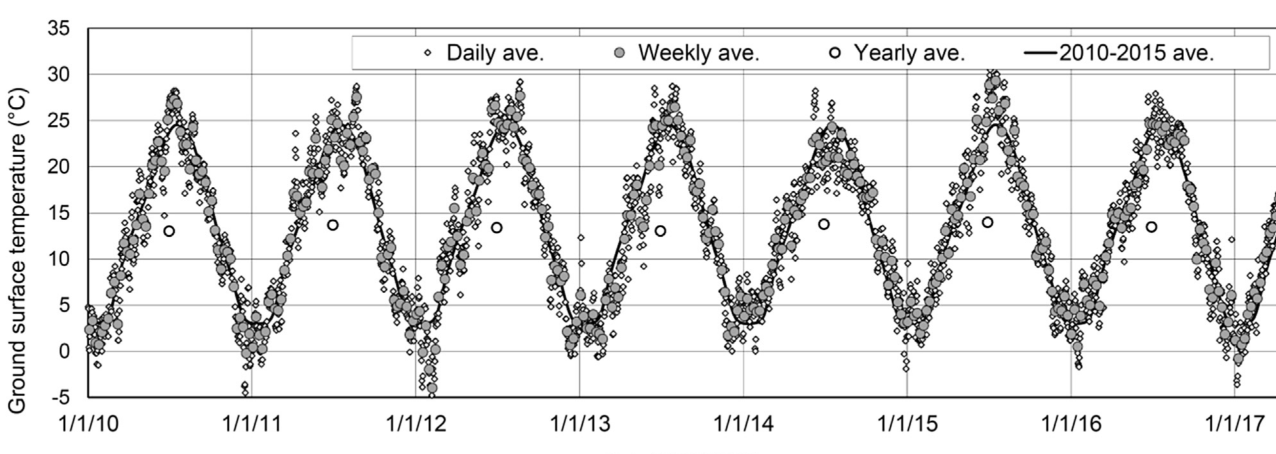

Fig. 8. Site monitoring of the ground surface air temperatures and their averages (ARPA-Lombardia, Italy).

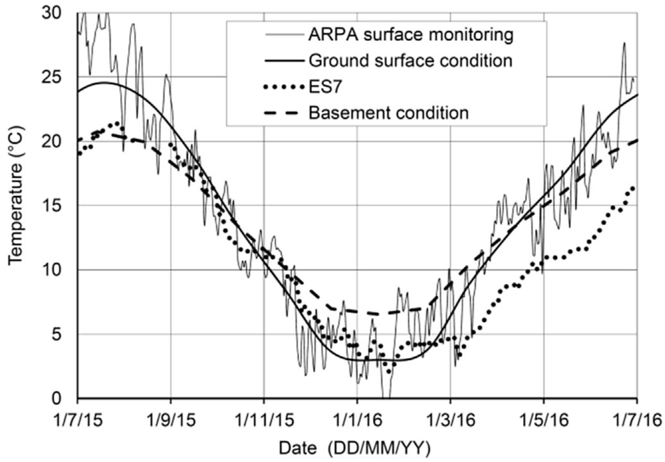

Fig. 9. Monitored temperatures at the surface (ARPA data) and at sensor ES7, compared with the assumed temperature conditions at the ground surface and the basement, respectively.

lines), together with the monitored temperature at sensor ES7 (dots) and the calibrated curve of the temperature variation within the basement (dashed line). The damping coefficient that led to an optimal calibration was found equal to 0.66. In the following, the comparison between thermal boundary conditions and monitored temperatures at the excavation side, above the base slab, is made with reference to sensor ES7, but it applies to sensor ES9 as well, the two providing very close temperature values (ref. Fig. 4).

Through observing the temperature variation at sensor ES7 during December 2015 and January 2016, it could be inferred that the wall side is in direct contact with the atmospheric temperatures, rather than a space where temperatures are mitigated. This can occur in case the gap between the wall and the basement effectively works as a natural ventilation path. The deviation between monitored ground surface and ES7 temperatures, starting in March 2016, proves that this hypothesis is arguable and the temperatures recorded by sensor ES7 might be affected by a combination of factors, not least the low temperatures of the circulating fluid operating in heating mode up to May 2016. It can be added also that the natural convection that takes up within the ventilation gap limits the downward flow of hot air in summer and eases the downward flow of cold air in winter, thus resulting in temperature differences between ground surface air and gap air, which are larger in summer than in winter. In fact, Fig. 6 also shows that the difference between the ground surface temperature provided by ARPA and the monitored temperature at the excavation side is equal to few degrees Celsius in August 2016 (Fig. 6b) and is negligible in January 2016 (Fig. 6a). If a damped temperature variation was assumed at the basement, with a damping coefficient of 0.66, the gap air temperature in August 2016 would be 19.7 °C, very close to temperatures actually monitored at the depths of 7 m and 9 m (between 19 °C and 20 °C), whereas the gap air temperature in January 2016 would be 6.6 °C, largely greater than the monitored value (about 3.4 °C).

In March and April 2016, the temperature recorded by sensor ES7 tends to rise again due to the outdoor milder temperatures and a lower thermal demand from the geothermal system. The time delay observed in the wall temperature increase with respect to the one at the outdoor could depend on the fact that the cold air trapped in the void after winter is not easily conveyed upwards, and therefore, the warming up of the wall is delayed. In May 2016, the system is in idle period and the temperatures slowly rise due only to the effect of milder climate, while after June 1st they increase also because of the activation of the system in cooling mode.

This experimental evidence highlights the role of the environmental condition for the air within the wall-basement gap in the heat transfer process and energy performance of the wall.

It is also worth noting that the numerical simulation generally requires different time scales depending on the focus of the analysis, whether it is on the energy performance and design (short-time response, and fine integration time intervals) or on the thermo-mechanical response (larger integration time intervals), especially when the system operates in an intermittent regime, due to milder climate conditions and lower energy demand (Faizal et al., 2016; Rui et al., 2018).

4.3. *Ground mass thermal properties*

The soil nature and the ground water conditions are basic factors that influence the energy performance, as already well established for borehole heat exchangers and other thermo-active geostructures (Dupray et al., 2013; Suryatriyastuti et al., 2013; Angelotti et al., 2014; Vieira et al., 2017).

Customarily performed site surveying allows to estimate the soil physical and mechanical properties, but a direct estimation of the thermal properties would require a purposely devised investigation, such as thermal response tests. In the absence of the latter, the assumptions about soil thermal conductivity and specific heat can be based on the thermal properties of the single three phases of the natural soil, assuming a condition of porosity and water content and relying on literature data for the thermal properties of soil grains of various natures (Rees et al., 2000; Beier et al., 2011; Vieira et al., 2017).

In the case study, the monitoring data at positions embedded in the soil mass are of limited use for the calibration of the soil thermal properties. In fact, the temperatures along the anchor are affected by the coexistence of a variety of factors: the seasonal temperature variations at both the ground surface and the excavation side, the temperature variations of the heat carrier fluid, the thermal properties of the soil mass that govern the damped and delayed nature of the heat diffusion, and finally the thermal properties of the steel anchor that influence the heat transfer along its axis. The presence of these influential factors makes the calibration of the soil thermal properties difficult, starting from these monitoring data and lacking a real thermal response test at the site.

5. Conclusions

The interpretation of monitoring data from a real thermo-active diaphragm wall helps to understand the process of heat transfer, the role of the thermal boundary conditions and the factors that influence the thermal fluxes in this specific thermo-active structure. Ultimately, a better understanding helps the numerical modelling for the assessment and optimisation of the energy performance.

The monitoring data briefly presented and discussed in this study were limited to the temperature variations at positions within the wall and along an anchor, during the first two years of operation of the geothermal system. The data show that the temperatures are influenced by several factors that induce minor or major effects depending on the position being considered.

The most relevant conclusion, drawn from the analysis of data of this specific case study, concerns the influence of the thermal condition in the basement on the heat flux directions. While the surrounding soil mass always represents a positive contribution to the heat transfer with the circulating fluid (i.e. it acts as a heat source in heating periods and a heat sink in cooling periods), the basement represents a negative contribution in both heating and cooling operating modes. In fact, in the former case, the fluid disperses heat to the basement, thus reducing the heating potential to the secondary circuit, and in the latter case, it draws heat from the basement, thus reducing the cooling potential. The overall energy performance could be anyway satisfactory, especially if the heating and cooling of the basement space are part of the purposes of the geothermal system. In order to correctly predict the energy performance, the accurate calibration of this boundary condition is therefore highly recommended.

The interpretation of these monitoring data is limited by the fact that they are collected during a transient condition (the first two years of operation). On the one hand, they might be useful to set the undisturbed initial temperature field, and on the other hand, they do not represent the working condition of the geothermal system in the long term. In fact, since the heat injection and extraction are not balanced over the year, a thermal drift is expected to occur, influencing the temperature field and the overall energy performance in the first six to ten years after activation. The thermal drift is expected to be a gradual cooling of the ground mass, because for a residential building at the climatic conditions of this site, the thermal energy extracted in winter is in general higher than that injected in summer. This effect cannot be discerned in the brief time span as shown in Figs. 4–6, where the relatively high temperatures in winter of 2016–2017 (the second heating cycle) could be due to a random excess of heat injection in summer of 2016 (the first cooling cycle).

The calibration of the soil mass thermal properties is still an open issue. In the absence of thermal response tests carried out at the specific site, these properties could be preliminarily assumed by combining the information from the hydro-geological site survey with data bases collecting the estimated average thermal properties of soil/rock classes. A back-analysis approach, aimed at estimating the soil thermal properties by comparing numerical results with monitoring data, still requires the accurate definition of the several factors that influence the heat transfer process.

This research is currently in progress, with the continuous update of the monitoring data, for reaching the full definition of the numerical model.

Conflicts of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome.

Acknowledgements

The authors are grateful to Ing. G. Bertani (Ingg. Bertani e Baselli & C. SpA, Milano, Italy) and to Ing. L. Todeschini (Tecnoel s.r.l., Milano, Italy) for providing the case study and the monitoring data. The first author acknowledges the support of COST Action TU1405 GABI (Geothermal Applications for Building and Infrastructures).

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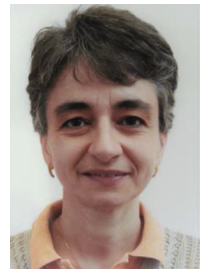

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