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Analysis of vertical ground heat exchangers: the new CaRM tool

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Abstract

The ground source heat pump systems are worldwide used for space heating and cooling of buildings. The energy efficiency of the heat pump depends on the temperature of the heat carrier fluid on the ground side, which is affected by the annual ground load profile and the arrangement of the boreholes.
This paper conducts long-term analysis of two office buildings with unbalanced load profiles in Italy. Work focuses the effects of the heat imbalance on the heat pump entering fluid temperature over ten simulated years. A detailed numerical simulation tool was used to conduct the analysis.

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Keywords: Ground source heat pump systems; Heat exchanger; Heat pump; Borehole.

1. Introduction

In the last decades, the ground source heat pump (GSHP) systems have shown to be a green technology so they are worldwide used for space heating and cooling of buildings [1]. This is mainly due to the advantage of the use of the ground or groundwater as a heat source-sink for the heat pump compared to other thermal sources used in the common heat pump systems as the outdoor air. On the other side, the main disadvantage of GSHPs compared to conventional systems is the higher initial cost due to geotechnical inquiries and inspections on the ground and groundwater features

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and the thermal-physical characterization, together to the efforts needed for drilling operations of borehole ground heat exchangers or wells for extracting of the groundwater.

Several analytical models analyze the thermal behaviour of borehole heat exchangers. For instance, the infinite- [2-3] and finite-line [4-5] source model represent the borehole with a line of uniform heat flux. Another commonly adopted approach is the cylindrical heat source [2], which is usually used to analyze the thermal performance of energy piles.

A range of simulation tools is available to analyze a borehole heat exchangers. The TRNSYS simulation environment [6] for borehole heat exchangers takes the approach proposed by Hellström [7]. EnergyPlus software [8] simulates the borehole heat exchangers and uses long- [9] and short-time g-functions [10], that can be provided directly by users. Other software packages, such as EED (Earth Energy Designer) [11] and GLHEPRO [12] are based on Eskilson's work [9].

This work aims to analyze the long-term thermal performance of two real Italian GSHP systems. For this purpose, the measured ground load profile is used as an input for different either numerical or analytical models.

Nomenclature

a	Thermal diffusivity (m^2/s)
BHE	Borehole heat exchanger
F_{sc}	Short-circuit heat loss factor (-)
NB	Number of boreholes in a borefield (-)
PLF	Part-load factor during the design month (-)
q_a	Net annual average ground heat rate (W)
q_g	Ground heat load in design conditions (W)
q'	Heat transfer rate per unit length (W/m)
r	Radius (m)
R_{ga}	Thermal resistances corresponding to the annual pulse (m K/ W)
R_{gm}	Thermal resistances corresponding to the monthly pulse (m K/ W)
R_{gd}	Thermal resistances corresponding to the daily pulse (m K/ W)
T	Temperature (K)
T_g	Undisturbed ground temperature (K)
T_p	Penalty temperature (K)
λ	Thermal conductivity (W/(m K))
τ	Time (s)

Subscripts

ave	Averaged	g	Ground
b	Building, Borehole	h	Heating
c	Cluster, Cooling	in	Inlet
D	Design	out	Outlet
f	Fluid	s	Single open-field BHE

2. Models

The home-developed CaRM numerical simulation tool has been used. The approach of CaRM is based on the electrical analogy. The domain (which is made of ground, grouting material and ground heat exchanger) is discretized with thermal capacitances and thermal resistances that link the thermal nodes (see Fig. 1). Then, for each thermal node the heat balance equation is written, obtaining a linear system with as many equations as unknown temperatures. The CaRM tool has been highly improved from the first release reported in [13]; in the present work, its last release [14] has been used. The new approach also considers the axial heat transfer along the depth direction (within both the ground and grouting material) and the effect of the weather at the ground level, modelling the convection, short- and long-wave radiation heat transfer.

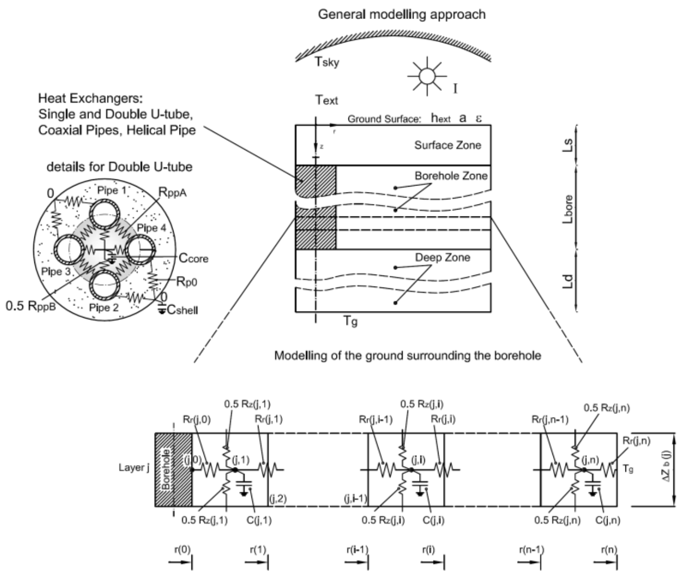


Fig. 1. The approach of CaRM.

The two real GSHP systems were also analyzed making use of the approach proposed by Kavanaugh and Rafferty [15], well-known as ASHRAE method. According to this approach, starting from heating-cooling loads of the building, the total borehole length can be directly calculated. In order to consider the change of the ground temperature in the long-term, the ASHRAE method considers a parameter named penalty temperature (T_p), which depends on the annual heat imbalance and the arrangement of the borehole field. Kavanaugh and Rafferty calculated this parameter making use of the net annual average heat rate to the ground and the infinite line source model. According to the ASHRAE method, the designers calculate two total borehole lengths: the first one to match the heating loads (Equation (1)) of the building and the second one for cooling loads (Equation (2)):

$$L_h = \frac{q_a \cdot R_{ga} + q_{g,h_D} \cdot \left[R_b + \left(PLF_{m,h_D} \cdot R_{gm}\right) + \left(R_{gd} \cdot F_{sc}\right)\right]}{T_g - \left(\dfrac{T_{fi} + T_{fo}}{2}\right)_{h_D} - T_p} \quad (1)$$

$$L_c = \frac{q_a \cdot R_{ga} + q_{g,c_D} \cdot \left[R_b + \left(PLF_{m,c_D} \cdot R_{gm}\right) + \left(R_{gd} \cdot F_{sc}\right)\right]}{T_g - \left(\dfrac{T_{fi} + T_{fo}}{2}\right)_{c_D} - T_p} \quad (2)$$

where the heat loads and the penalty temperature are positive values in heating mode and negative in cooling.

Another possibility for the assessment of the ground temperature of a borehole field in the long-term is to use analytical models. The most simple of these is surely the infinite line source model. According to this model, the temperature field around the borehole heat exchanger is a function of time and distance from the axis of the borehole (i.e. radius), which is expressed in the following Equation (3):

$$T^q(r,\tau) - T_g = \frac{q'}{4\pi\lambda}\int_{\frac{r^2}{4a\tau}}^{\infty}\frac{e^{-u}}{u}du = \frac{q'}{4\pi\lambda_g}E_1\left(\frac{r^2}{4a_g\tau}\right) \quad (3)$$

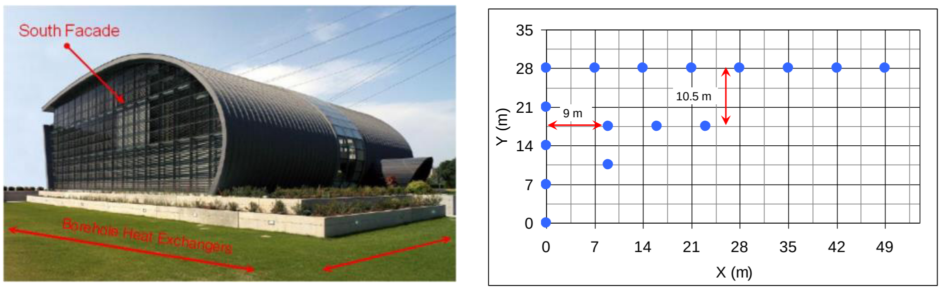
where the superscript in T^q points out that a uniform and constant heat rate q' is assumed.

In order to calculate the 2-D temperature distribution in the borehole field, the heat rate q' in Equation (3) can be assumed equal to the net annual average heat rate q_a' reported in Equations (1) and (2) of the ASHRAE method. This procedure has been implemented by Authors within a calculation sheet named LENGTH (Low ENthalpy Ground THermal exchange).

3. Case-studies

3.1. Case study A

The building is located in the city of Padova, near Venice in the north of Italy. It is a four-storey office building with a total floor area of 2,200 m^2. Three floors are above ground and one level is underground (see Fig. 2a). Approximately 90 people work inside this building. The north and south facades are completely glazed. Building construction was completed in 2003 and the whole building has been operational since 2004.



(a) (b)

Fig. 2. Case study A: (a) building, (b) borehole field.

The GSHP system consists of a heat pump and 16 boreholes. The heat pump is used for both space heating and cooling. The nominal thermal power of the heat pump is 70 kW in heating mode and 76 kW in cooling; besides the nominal energy efficiencies are equal to 4 (i.e. COP) and 4.2 (i.e. EER) in heating and cooling mode, respectively. The boreholes are 95 m long, 7 m apart and arranged in an L-shape as reported in Fig. 2b. The heat-carrier fluid inside the ground heat exchangers is pure water with a total constant mass flow rate equal to 5.84 kg/s. The characteristics of the ground heat exchangers are reported in Table 1.

The equivalent ground thermal conductivity was 1.9 W/(m K) and the volumetric heat capacity was 2.24 MJ/(m^3 K). The undisturbed ground temperature was assumed to be 14°C. The area's groundwater flow was considered negligible.

The building was monitored in 2013. As summary, the monthly ground energy loads are reported in Fig. 3a. The ratio between the annual energy extracted from the ground and that injected into it was about 0.4, which suggests that the ground's annual load profile is remarkably cooling dominant.

Table 1. Characteristics of the ground heat exchangers.

	Case-study A	Case-study B
Pipe		
Material	HDPE	HDPE
Thermal conductivity [W/(m K)]	0.40	0.40
Outside diameter [mm]	32.0	40.0
Inside diameter [mm]	26.0	34.0
Number of pipes [-]	4	4
Borehole diameter [mm]	140.0	152.0
Spacing between the pipes (center to center) [mm]	82.6	60.0
Borehole length [m]	95.0	100.0
Grout thermal conductivity [W/(m K)]	2.5	2.0
Grout thermal diffusivity [m^2/s]	0.676×10^{-6}	0.640×10^{-6}
Connection between the two U tubes	Parallel	Parallel

3.2. Case study B

The building is located near Milan, in the north of Italy. It is a five-storey office building with a total floor area of 23,000 m^2. Two floors are above ground and three levels are underground. Approximately 120 people work inside this building. About 60% of the external surface is made up of low thermal and acoustic exchange triple-glazing; high insulation concrete is used for the opaque share. The resulting global thermal transmittance is 0.44 W/(m^2 K).

The GSHP system consists of three heat pumps in parallel; each heat pump is characterized by nominal heating and cooling loads of about 100 kW and 135 kW respectively, with heating COP value of 4.1 and EER value of 5.5. The borehole field consists of 51 vertical ground heat exchangers. The boreholes are 100 m long, 7-9 m apart and arranged as reported in Fig. 4. The heat-carrier fluid inside the ground heat exchangers is pure water with a total constant mass flow rate equal to 20 kg/s. The characteristics of the ground heat exchangers are reported in Table 1.

Thermal response test was carried out during the design phase, so the thermal conductivity was 1.9 W/(m K) and the volumetric heat capacity was 2.0 MJ/(m^3 K). The undisturbed ground temperature was assumed to be 13.4°C. By previous analysis carried out in the same zone, the groundwater flow was considered negligible.

In 2013 the heat loads on the ground side were measured and they were used as input for the CaRM simulations. The monthly ground energy loads are reported in Fig. 3b. The ratio between the energy extracted from the ground and the energy injected into it was about 1.8, which means that the ground's annual load profile is highly heating dominant.

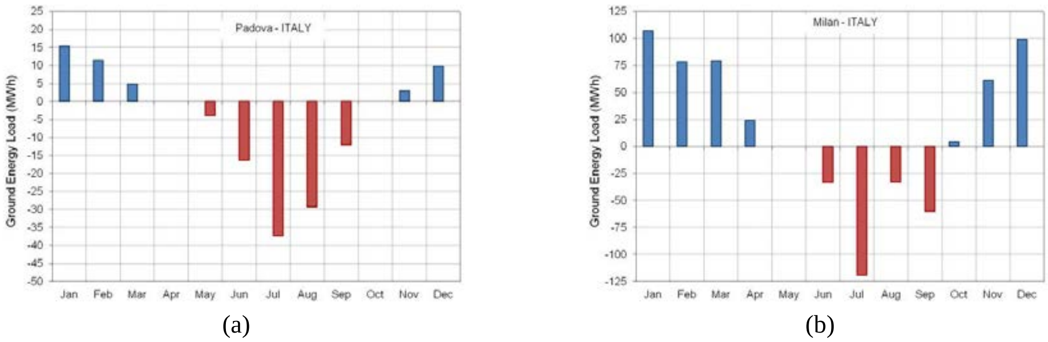


Fig. 3. Monthly ground energy load: (a) Case study A, (b) Case study B.

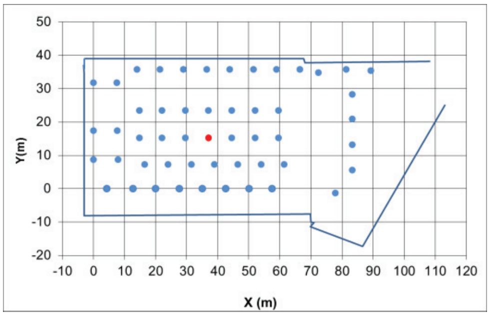


Fig. 4. Case study B: borehole field.

3.3. Computer simulations

For each case study, three types of simulations were carried out:

- *Type 1*. The borehole field was simulated as it was built and the measured ground heat loads were considered.
- *Type 2*. The ground heat loads were modified in order to decrease the effect of the thermal drift. For the Case study A, the energy injected during the cooling season was decreased so that the ratio between the energy extracted and that injected into the ground increased from 0.4 of *Type 1* to about 0.7. On the other side, in the case-study B, the energy extracted from the ground during the heating period was decreased in order to decrease the ratio between the extracted and injected energy from 1.8 to about 1.2.
- *Type 3*. The measured total ground heat loads of *Type 1* were used but the number of the boreholes was increased.

Table 2 summarizes all of the simulations carried out in this work (e.g. Case A-1 is the simulation of the case-study A with the assumptions of *Type 1*). The CaRM simulations were conducted over a ten-year period, with an hourly calculation time step.

Table 2. Characteristics of the ground heat exchangers.

	Type	Number of boreholes [-]	L_{bore} [m]	Notes
	1	16	95	Real Status (Extraction/Injection = 0.4)
Case Study A (Padova)	2	16	95	Extraction/Injection = 0.7
	3	20	95	Borehole number increased
	1	51	100	Real Status (Extraction/Injection = 1.8)
Case Study B (Milan)	2	51	100	Extraction/Injection = 1.2
	3	63	100	Borehole number increased

4. Results and discussion

4.1. CaRM results

This section presents the main results obtained with CaRM tool for the two case-studies A and B with the three simulation types. The time-histories of the entering fluid temperature (EFT) at heat pump on the ground side through the whole simulation period are reported in Figs. 5a-b-c, for Case A-1, Case A-2 and Case A-3 respectively, whereas Figs. 5d-e-f show the results for Case B-1, Case B-2 and Case B-3. As can be seen, in the real status of the plant system of Case A, the annual maximum value of EFT increased of about 5°C through ten operating years. On the other side, for the Case B, the annual minimum value of EFT decreases of about 6°C through ten simulated years.

When the heat imbalance of the ground load profile was reduced (i.e. according to the *Type 2* boundary conditions), the change of the temperature of the heat carrier fluid inside the ground heat exchangers was limited at about 1°C through ten years for both the case-studies.

When the number of borehole heat exchangers was increased and the same ground load profile of the simulations carried out with *Type 1* was used, the change of the fluid temperature through the time decreased at about 3°C in Case A-3 evaluated on the maximum temperature and 4°C in Case B-3 evaluated on the minimum temperature.

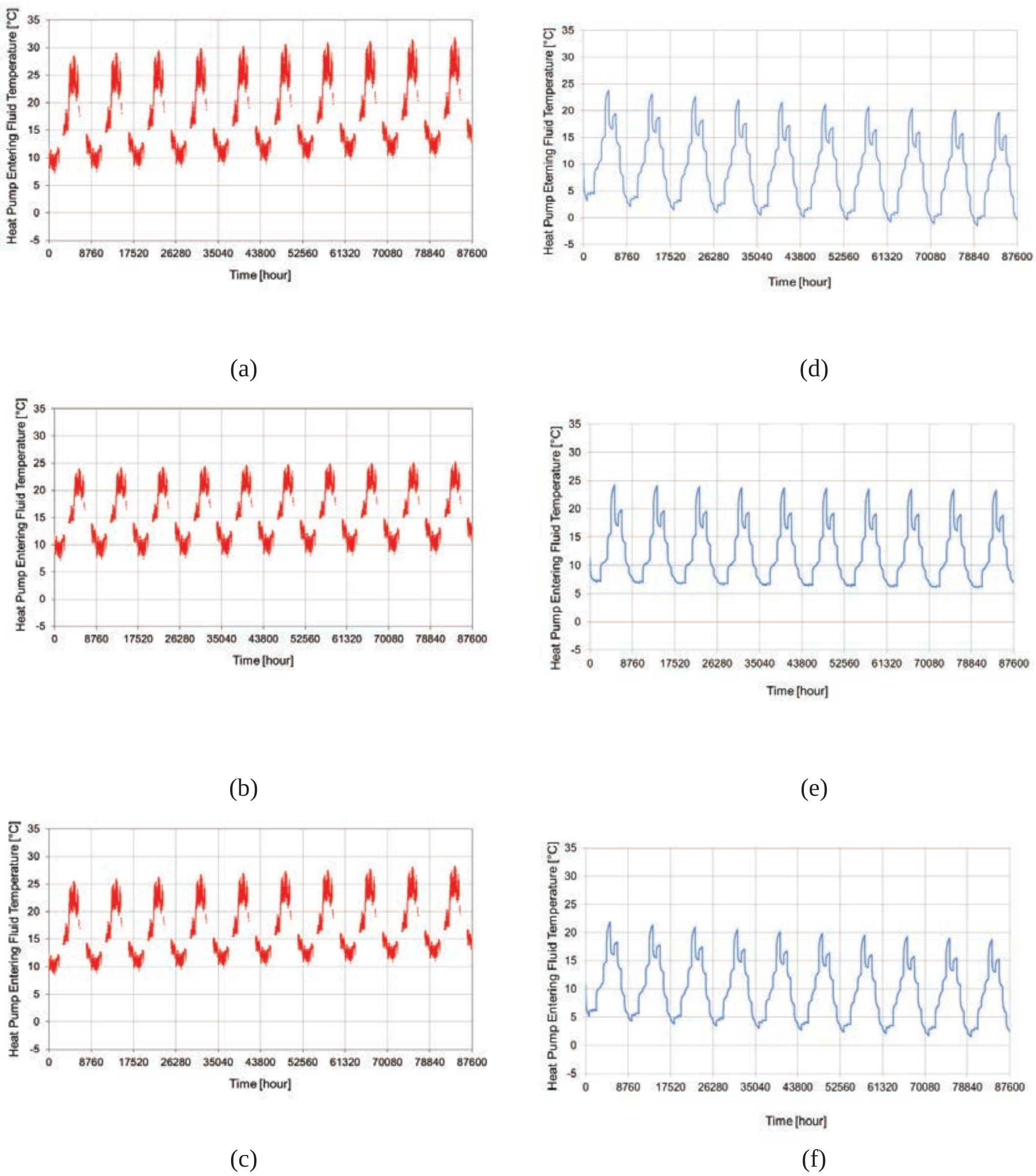


Fig. 5. Results: (a) Case A-1, (b) Case A-2, (c) Case A-3; (d) Case B-1, (e) Case B-2, (f) Case B-3.

4.2. Sizing according to ASHRAE

For the Case A the parameters required by ASHRAE method were calculated making use of the measured ground load profile through one year. In these conditions, the total borehole lengths calculated with Equations (1) and (2) were equal to 1056 m and 1472 m in order to fully match the heating and cooling loads of the building respectively.

The same check was also performed on the GSHP system placed near Milan (Case B), but the design values of 500 MWh and 360 MWh were adopted for the yearly heating and cooling loads to the heat pump group on the building side. A total borehole length of 5300 m was requested from the procedure, which fits with the actual value of 5100 m. The existing borehole field is then consistent with the good design practices suggested by ASHRAE. Of course, the measured operating conditions of the Case B are actually quite far from the design ones, as it was remarked in Sect. 3.2, and a patent undersized exchange length occurs in this case.

4.3. Thermal drift evaluation

For both cases, a more detailed evaluation of the thermal drift was performed over ten years. The quantity T_p known as “penalty temperature” was evaluated according to [16] with the following expression:

$$T_p = \left(\frac{1}{NB} \sum_{l=1}^{NB} T_{c,ave,l}(r_b) \right) - T_{s,ave}(r_b) \tag{4}$$

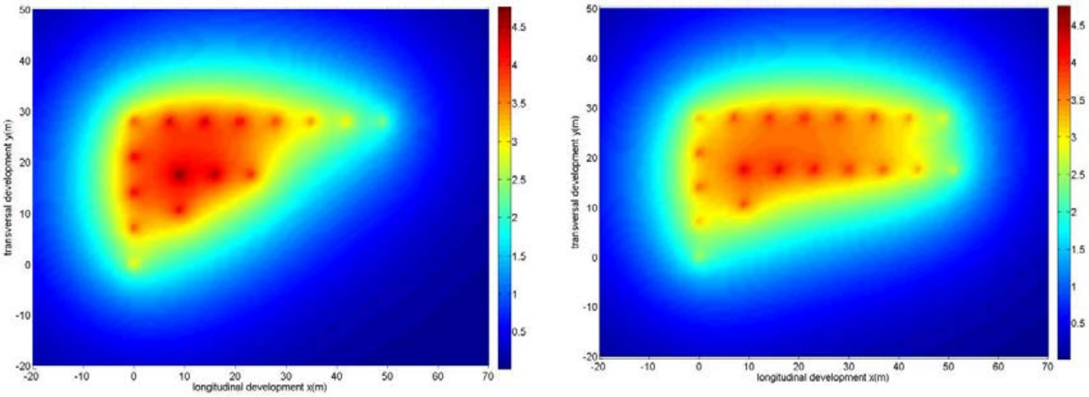
which substantially identifies T_p as the difference between the average temperature on the walls of the cluster of NB boreholes and the wall temperature of a single open-field BHE, being equal the exchanged thermal ratio.

To this purpose, the computer application termed LENGTH developed in the past by the Authors [16], allows the evaluation of the above quantities T_p for a borefield of vertical BHEs, regardless of the complexity of its horizontal layout and with/without involvement of groundwater flow.

The results are summarized in Table 3, which shows for each analyzed case the obtained values of T_p and the relevant annual average heat transfer rate per unit length q_a', which is assumed as positive value when the heat is injected into the ground and as negative when the heat is extracted from the ground. Some examples of graphic representation of the results by LENGTH are shown in Figs. 6 and 7.

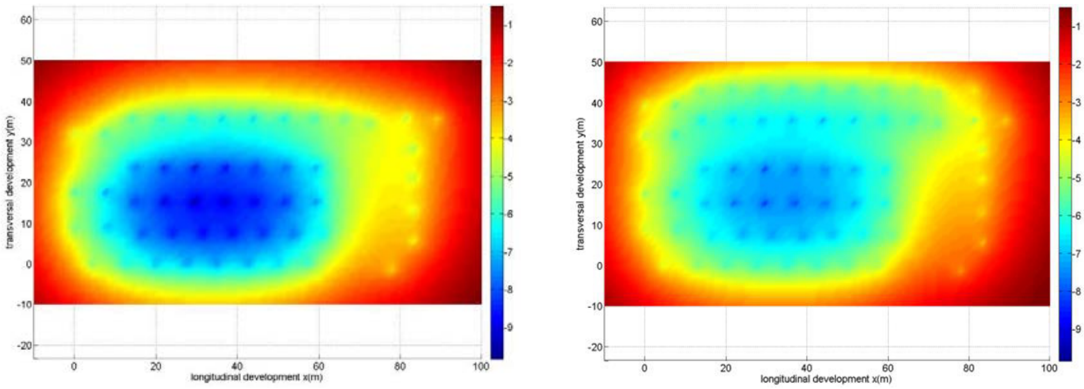
Table 3. Thermal drift results.

	Type	T_p [°C]	q_a' [W/m]	Notes
	1	+2.6	4.4	Increasing ground temperature
Case Study A (Padova)	2	+0.8	1.4	Effective for thermal drift cut down
	3	+2.4	3.5	Not effective for thermal drift cut down
	1	-5.1	-4.6	Decreasing ground temperature
Case Study B (Milan)	2	-1.2	-1.1	Effective for thermal drift cut down
	3	-4.6	-3.7	Not effective for thermal drift cut down



(a) (b)

Fig. 6. Thermal drift field in the surrounding ground: (a) Case A-1, (b) Case A-3.



(a) (b)

Fig. 7. Thermal drift field in the surrounding ground: (a) Case B-1, (b) Case B-3.

5. Conclusions

These results can be so summarized.

- The thermal drift of the ground highly depends on the annual heat imbalance on the ground side. A rough evaluation of the thermal drift in the real status of the two case studies (Case A-1 and B-1) can be deduced from the trend of the minimum values of the borehole outlet temperature: an increase of about 5°C for the Case A (cooling dominant) and a decrease of 6°C for the Case B (heating dominant) were detected over the ten year's simulation.
- The decrease of the heat imbalance on the ground side is the key factor to decrease the effect of the thermal drift. In the case-studies analyzed the increase of the number of boreholes did not significantly affect the thermal drift.
- The thermal drift evaluated with the infinite line source method was in good agreement with the results of CaRM tool for both of the case studies analyzed.
- The results of the ASHRAE method and CaRM tool were comparable when the same heat loads were used.

Acknowledgements

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References

[1] Bayer P, Saner D, Bolay S, Rybach L, Blum P. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. Renewable and Sustainable Energy Reviews 16 (2012) 1256– 1267.
[2] Ingersoll LR, Zobel OJ, Ingersoll AC. Heat conduction: with engineering and geological applications. McGraw-Hill Book Co, New York, 1954.
[3] Carslaw HS, Jaeger JC. Conduction of Heat in Solids. Claremore Press, Oxford, 1959, Chapter X.
[4] Zeng HY, Diao NR, Fang ZH. A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer-Asian Research 31(7) (2002) 558-567.
[5] Lamarche L, Beauchamp B. A new contribution to the finite line-source model for geothermal boreholes. Energy and Buildings 39(2) (2007) 188–198.
[6] Klein S, Beckman W, Mitchell J, Duffie J, Duffie N, Freeman T et al. TRNSYS 16 – A transient system simulation program, User manual. University of Wisconsin, Madison (2004).
[7] Hellström G. Ground heat storage. Thermal analysis of duct storage systems: theory. Doctoral Thesis, Department of Mathematical Physics, University of Lund, Sweden, 1991.
[8] EnergyPlus Energy Simulation Software, U.S. Department of Energy-DOE, 2013: http://apps1.eere.energy.gov/buildings/energyplus/ .
[9] Eskilson P. Thermal analysis of heat extraction boreholes. Doctoral Thesis, Department of Mathematical Physics and Building Technology, University of Lund, Sweden, 1987.
[10] Yavuzturk C, Spitler JD. A short time step response factor model for vertical ground loop heat exchangers. ASHRAE Transactions 105(2) (1999) 475-485.
[11] Hellström G, Sanner B. Earth energy designer: software for dimensioning of deep boreholes for heat extraction. Department of Mathematical Physics, Lund University, Sweden, 1994.
[12] Spitler JD. GLHEPRO: a design tool for commercial building ground loop heat exchangers. In: Proceedings of the fourth international heat pumps in cold climates conference, Aylmer, Québec. August 17-18, 2000.
[13] De Carli M, Tonon M, Zarrella A, Zecchin R. A computational capacity resistance model (CaRM) for vertical ground coupled heat exchangers. Renewable Energy 35(7) (2010) 1537-1550.
[14] Zarrella A, Capozza A, De Carli M. Performance analysis of short helical borehole heat exchangers via integrated modelling of a borefield and a heat pump: A case study. Applied Thermal Engineering 61 (2013) 36-47.
[15] ASHRAE. ASHRAE handbook: HVAC applications, Geothermal Energy, 2011. Chapter 34.
[16] Capozza A, De Carli M, Zarrella A. Design of borehole heat exchangers for ground-source heat pumps: A literature review. methodology comparison and analysis on the penalty temperature. Energy and Buildings 55 (2012) 369-379.