Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0142

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Energy efficiency of energy geostructures – a reduced scale model

Performance énergétique des géostructures thermiques – approche physique sur modèle réduit

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ABSTRACT: The use of energy geostructures is more and more common to fulfil the energy demand of buildings. However, in France, there is no standard to regulate the development of such technology at city scale. It implies that the rule of the first come first served is applied without consideration of the possible thermal interaction between geothermal systems. Indeed, in the case of subsoil of dense urbanised area submitted to a groundwater flow, a thermal plume induced by an upstream energy geostructure can disturbed the thermal exchange of a downstream system. In order to study this behaviour, a reduced scale model of 400 m² including three structures with thermoactive diaphragm walls and a nine energy piles group has been built. This model called SENSE-CITY represents a city or, at least, a district where each building is equipped with energy geostructure. The controlled groundwater flow allows to study the thermal interaction between each structure and the effect of groundwater flow velocity on thermal performance. Thus, different hydraulic and thermal scenarios are studied. The ground and each energy geostructure are instrumented with optics fibre and punctual thermal sensors. The inlet and outlet heat fluid temperature are also measured. The results of such experiments provide a better insight of thermal performance of energy geostructures. Moreover, these results can lead to a global improvement of numerical thermo-hydraulic modelling.

RÉSUMÉ: Les géostructures thermiques sont de plus en plus utilisées pour subvenir aux besoins thermiques des bâtiments. Cependant, il n'existe aucune norme pour réguler le développement de cette technologie à l'échelle de la ville. Cela implique que la règle du premier arrivé, premier servi est appliquée sans considérer les possibles interactions thermiques entre plusieurs structures. En effet, dans le cas du sous-sol d'une zone fortement urbanisée soumise à un écoulement de nappe, un panache thermique provenant d'une géostructure thermique amont peut influencer les échanges thermiques d'une autre géostructure implantée à l'aval. Afin d'étudier ce phénomène, un modèle réduit de 400 m² incluant trois enceintes en parois moulées thermoactives et un groupe de neuf pieux énergétiques ont été construits. Ce modèle, dénommé SENSE-CITY représente une ville ou, du moins, un quartier où chaque bâtiment est équipé de géostructures thermiques. La possibilité d'imposer un écoulement contrôlé dans cette zone permet d'étudier les interactions thermiques entre chaque bâtiment. Plusieurs scénarios hydrauliques et thermiques sont ainsi étudiés. Toutes les structures et le terrain sont instrumentés à l'aide de fibre optique et de capteurs de température ponctuels. La température d'entrée et de sortie du fluide caloporteur est également mesurée. Les résultats de ces expérimentations fournissent un meilleur aperçu des performances thermiques des géostructures thermiques. De plus, ces résultats peuvent être utilisés pour calibrer et améliorer les modèles numériques thermo-hydrauliques.

Keywords: Energy geostructure; thermal interaction; thermoactive diaphragm wall; scale model

1 INTRODUCTION

Energy geostructures are part of shallow geothermal systems. They are based on the principle that the foundation of each building can be used as heat exchanger to produce heating and cooling. Thus, this technology can be implemented into deep foundations like piles, retaining walls, tunnels and slabs (Brandl, 2006; Adam and Markiewicz, 2009). With the development of energy geostructures, new types of buildings as metro station and tunnels are equipped with heat exchangers (Barla *et al*, 2016). The complexity and the interaction with the ground of such structures lead to review the concepts developed for energy piles (Fromentin and Pahud, 1997; CFMS and SYNTEC, 2017).

To properly design such geotechnical structures, thermal stress and strain and thermo-mechanical effects on the ground must be considered. Thus, many studies have been carried out on these subjects (Campanella and Mitchell, 1968; Laloui and Cekerevac, 2008; Bourne-Webb *et al*, 2009; Di Donna *et al*, 2016). However, to study the thermo-mechanical behaviour, it is essential to understand the temperature variation in the ground, in the structure and in the heat fluid due to the use of a heat pump. This cannot be easily done with analytical model (Signorelli *et al*, 2007; Xia *et al*, 2012; Zarrella *et al*, 2017), especially when the structure is submitted to a groundwater flow.

Based on these studies and to improve the understanding of thermo-hydraulic behaviour of energy geostructures and the thermal interaction at district scale between different shallow geothermal systems, a reduced scale model called SENSE-CITY has been built at IFSTTAR, France (see section 2). In this model, the heat pump, the concrete of the energy geostructures and the ground are fully monitored in terms of temperature and groundwater flow velocity. This study does not consider the mechanical behaviour of such structure. The first data provide an insight on the effect of the groundwater flow on the temperature distribution in the concrete and in the ground. In the first part of this paper, SENSE-CITY geometry and composition are described. The second part corresponds to the thermal and hydraulic characterisation of the materials. In a third part, the first results of thermal activation are shown and analysed.

2 DESCRIPTION OF SENSE-CITY

SENSE-CITY is a reduced scale model of a district with a total area of 400 m². It consists in a climatic chamber where, for instance, temperature and humidity are controlled. The range of temperature is -10°C to +40°C. Two houses and one building have been built inside the chamber (see Figure 1). Beneath each building at least one type of energy geostructure has been installed. Thus, three structures with diaphragm walls and a group of nine piles compose the system. They are all connected to a heat pump link to a heating floor in the building.

Figure 1. Illustration of SENSE-CITY

To control the groundwater flow, all the underground systems, as the energy geostructures, are installed in an impermeable reservoir of concrete full of granular materials (see section 3). Moreover, a pumping and an injection system allow to develop a groundwater flow at different velocity.

2.1 Geometry

The reservoir is a square of inner dimension 20 m by 2.5 m depth. The three thermoactive diaphragm walls structures and the nine piles have the same geometry (see Table 1).

Table 1. Geometry of energy geostructures

Energy geo-structure type	Thermoactive diaphragm wall	Energy Pile
Length [m]	2.5	-
Width [m]	2.5	-
Depth [m]	2.0	2.0
Thickness [m]	0.2	-
Diameter [m]	-	0.2
Spacing [m]	-	0.6
Heat exchanger length [m]	62.4	4.1

The intrados of the diaphragm walls contain the same granular material than the extrados part. It means that it represents the embedded part of a real diaphragm wall.

Concerning the heat exchanger, it is a classical PEHD tube with an external diameter of 25 mm and an internal diameter of 20.4 mm. They are installed at the centre of each wall and are all independent. It implies that it is possible to activate separately the different walls of each structure (see Figure 2). The spacing of each loop is 30 cm.

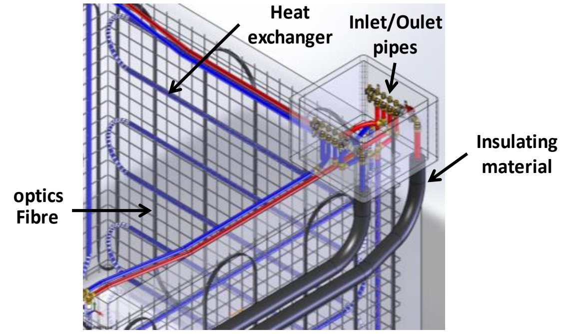

Figure 2. Position of heat exchanger pipes

To simulate thermal interaction between different energy geostructures, thanks to the groundwater flow direction, they can interact by group of two (see Figure 3).

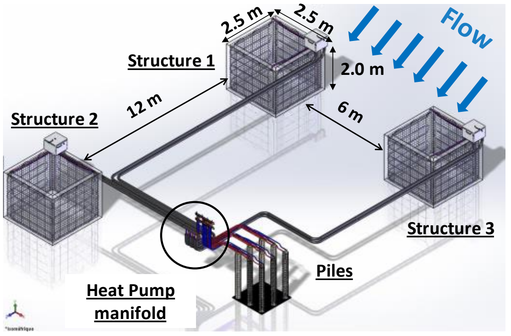

Figure 3. Disposition of energy geostructures

2.2 Monitoring system

To measure the variation of temperature in all the model, different types of sensor are used (see Table 2).

Table 2. Type of thermal sensor and position

Sensor	PT100	Fibre optics
Concrete	X	X
Vertical profile in the ground	X	-
Horizontal profile in the ground	-	X
Inlet/outlet temperature	X	-
Soil/structure interface	-	X

X: sensor; -: no sensor

Mini-diver inside three piezometers and a flowmeter at the circulating groundwater flow pump provide data on the groundwater flow level and velocity.

2.2.1 PT100

PT100 are platinum thermistance with a value of 100 Ω at 0°C. In SENSE-CITY, the values given by these sensors are the references. For instance, it is used to calibrate the optics fibre.

Moreover, PT100 are used to measure the inlet and outlet fluid temperature for each energy geostructure. These temperatures allow to calculate the heat exchange thanks to Equation 1.

$$Q = m.C_v.(T_{in} - T_{out}) \tag{1}$$

where Q is the value of the heat exchange (W), m the flow rate inside the pipes (m^3/s), C_v the volumetric heat capacity (J/m^3.K), T_{in} and T_{out} are respectively the inlet and outlet fluid temperature (K).

There is also five PT100 at different depth by piezometer at three different position. It provides the vertical temperature profile in the ground of SENSE-CITY (see Figure 4).

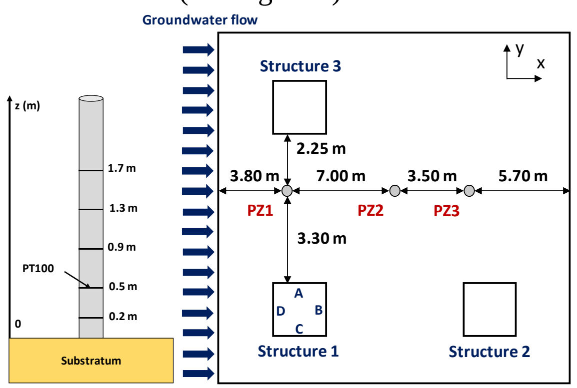

Figure 4. PT100 position on piezometer

Furthermore, inside the structure 1 walls A and D (see Figure 5), five PT100 by wall have been placed to measure the temperature gradient inside the concrete. Data from these sensors will also provide some insights on the thermal behaviour of walls perpendicular or parallel to a groundwater flow. Moreover, walls A and D correspond respectively to the inlet and outlet fluid.

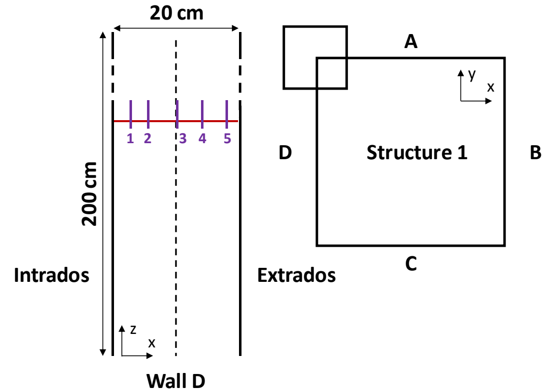

Figure 5. PT100 position in concrete

2.2.2 Fibre optics

To have a more global view of the thermal filed in SENSE-CITY ground and structure concrete, continuous fibre optics have been installed:

- Horizontal profile in the ground: 340 m at 1.60 m depth;
- Concrete: 69 m/structure at wall mid plane;
- Soil/structure interface: 69 m/structure with the same pattern as the one in the concrete.

The serial assembly allows to monitor the entirety of the system all at once.

2.2.3 Groundwater flow velocity

The groundwater flow is controlled by a pump which pumps and injects water from one side to the opposite with the same flow. Thus, it is possible to generate a groundwater flow with velocity from 0 to more than 1 m/day. To control the flow velocity, a flowmeter has been installed close to the pumping system.

Moreover, each piezometer is equipped with a mini-diver to measure the water table level. The hydraulic gradient allows to determine a macroscopic fluid velocity (Darcy, 1856) thanks to Darcy law (see Equation 2).

$$\vec{v}_D = -k.\vec{\imath} \quad (2)$$

where $\vec{v}_D$ is the Darcy velocity (m/s), k the hydraulic conductivity (m/s) and $\vec{\imath}$ the hydraulic gradient (m/m).

3 THERMAL AND HYDRAULIC CARACTERISATION

The whole system is monitored with multiple sensors. However, to analyse the thermo-hydraulic behaviour of the ground and of the energy geostructures, some laboratory and *in situ* tests have to be performed.

3.1 Geology

The geological nature of the material used as ground is an essential parameter to estimate in a first approach of the global behaviour of the system. In the case of SENSE-CITY, the idea was to simulate a ground with relatively high hydraulic and thermal conductivity. Indeed, these conditions are favourable to geothermal systems.

That is why, in a first approach, a crushed material with sandy particle distribution has been chosen. The particle size distribution curve is the following (see Figure 6).

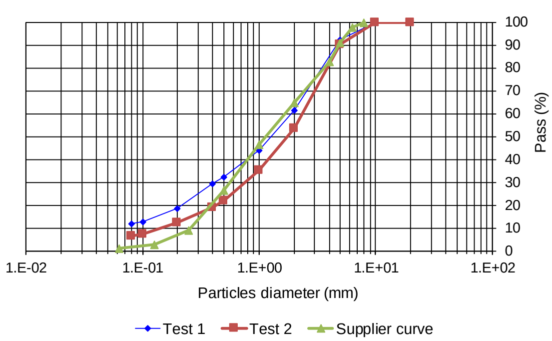

Figure 6. Particle size distribution curve

The two tests show more fine grains than the curve given by the quarry owner. It implies a relatively lower hydraulic and thermal conductivity (Kersten, 1949).

A X-ray diffractometer test will be performed to analyse the mineral composition of this material.

3.2 Thermal conductivity

One of the main parameters when dealing with shallow geothermal systems is the thermal conductivity of the materials. To measure this parameter, series of needle probe tests (Low *et al*, 2014) have been performed at different density and water content (see Figure 7).

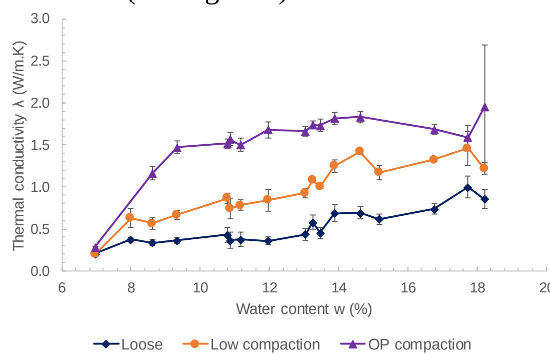

Figure 7. Thermal conductivity at different water content and density

The three states of density are:

- Loose = *i.e.* without compaction;
- Low compaction = 30% of optimum proctor test energy of compaction;
- OP compaction = optimum proctor test energy of compaction.

These results are in accordance with the literature (Winterkorn, 1962; Brandon et Mitchell, 1989; Tarnawski et Leong, 2000). An increase of density and water content implies an increase of thermal conductivity. In SENSE-CITY, the ground is saturated and compacted. The effective value of thermal conductivity considered for this material is 1.8 W/m.K. Thanks to Kersten empirical formulation of thermal conductivity for clay and sand (see Equation 3), the thermal conductivity of SENSE-CITY ground is similar to clayey or silty soil (see Figure 8).

$$\begin{cases} \lambda_{clay} = 0.1442.(0.9.\log(w) - 0.2).10^{0.6243\rho_d} \\ \lambda_{sand} = 0.1442.(0.7.\log(w) + 0.4).10^{0.6243\rho_d} \end{cases} \quad (3)$$

where λ_{clay} is the theoretical thermal conductivity of clay (W/m.K), λ_{sand} the theoretical thermal conductivity of sand (W/m.K), w the water content (-) and ρ_d the dry density of the material (kg/m^3).

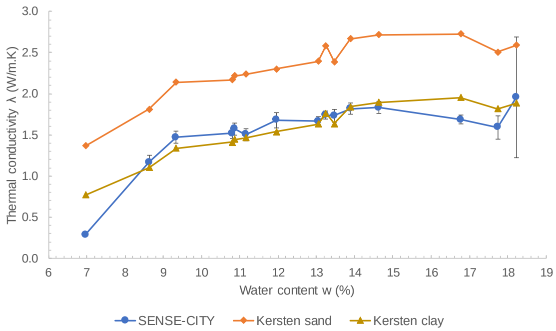

Figure 8. Comparison between Kersten conductivity and measured conductivity

3.3 Hydraulic conductivity

The hydraulic conductivity is an essential parameter in SENSE-CITY due to the groundwater flow control. To measure this parameter, laboratory permeability tests and *in situ* pumping tests have been performed.

The results between laboratory and in situ tests are consistent and provide a value of hydraulic conductivity between 9.10^{-5} m/s and 1.10^{-4} m/s. These values betray the hydraulic behaviour of a sand (Castany, 1982).

3.4 Conclusion on characterisation study

The material used in SENSE-CITY shows thermal properties close to silty or clayey soil with relatively low value of thermal conductivity. However, the hydraulic and granulometric characterisations show a behaviour close to sandy soil with high value of hydraulic conductivity.

These results imply that the granular skeleton of the material is coarse with a low value of quartz content. The X-ray diffractometer test should provide more robust conclusion.

4 THERMAL ACTIVATION

Now that the system is fully described in term of monitoring system and thermo-hydraulic properties, the results of the thermal activation of the different energy geostructures in SENSE-CITY can be fully analysed.

4.1 Studied scenario

The scenario presented in this paper is a heating of the building during eighteen days with a groundwater flow velocity of 1.0 m/day for eleven days and a hydrostatic state the days after. Only the structure 1 and 2 with diaphragm walls were activated.

The heat pump has run from 2:00 am to 22:00 pm. To have a constant energy demand during the heating period, the floor of the building is heated (*e.g.* 30°C) and kept at constant temperature (*e.g.* 18°C) by an independent cooling system. During four hours in the night, the system is turned off to simulate a thermal rest period.

The temperature in the heating fluid, in the concrete and in the ground, should decrease to fulfil the energy demand of the building. The stop of water flowing in the ground should provide some insights in the effect of groundwater flow on heat exchange.

4.2 Results

During this experiment, the optics fibre was not operational. In this paper, only data from PT100 are presented. Moreover, the PT100 T3 of the wall D was broken.

The Figure 9 presents the variation of inlet and outlet fluid temperature for the structure 1. It shows a slight decrease of temperature day after day. With groundwater flow, the parabolic curve slope reaches a value of -0.06°C/day. However, when the water flow is stopped, this value reach -0.15°C/day after few days. The first conclusion is that the natural thermal recharge due to the groundwater flow is non-negligible. The heat pump must decrease the fluid temperature faster to continue to fulfil the energy demand.

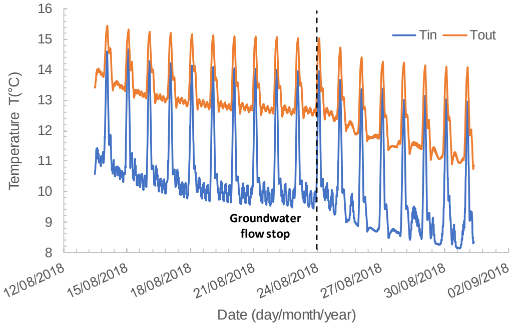

Figure 9. Inlet and outlet fluid temperature variation in structure 1

However, the difference between inlet and outlet temperature is constant on the whole period. It means that the heat power is constant over time thanks to Equation 1. Afterwards, this value is divided by the heat exchange surface of the structure to provide a heat flux. On average, the heat flux reaches 63 W/m². The structure 2 shows the same behaviour with higher values of temperature difference. Since the structure 2 is partially under the heating floor system (see Figure 1), heat losses from the building induce heat injection into the ground.

Concerning the concrete temperature, the same behaviour is observed as in the fluid but with higher temperature decrease over time (see Figure 10).

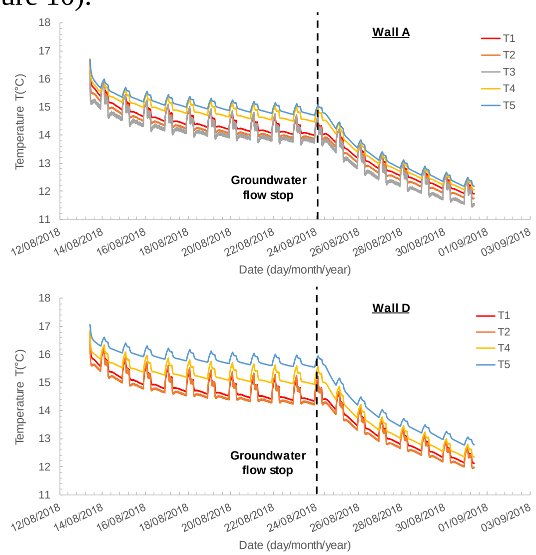

Figure 10. Concrete temperature variation for wall A and D of structure 1

This is due to the fact that the concrete specific heat is lower than the water one. It implies that, for the same energy, the variation of temperature is higher. Moreover, the concrete at the intrados and extrados face does not have the same behaviour. Thanks to the groundwater flow, the temperature at the extrados is higher than the intrados one. Furthermore, the wall D which is perpendicular to the groundwater flow presents higher value of temperature than the wall A which is parallel to the flow. Since the wall D is also the outlet pipes, it can explain this difference.

4.3 Analysis

In this experiment, the groundwater flow allows to reduce the temperature decrease due to the building heating. As the energy demand is constant, the heat pump keeps the difference between inlet and outlet temperature constant. However, the natural thermal recharge is not sufficient to stop the thermal drift. This observation is particularly true when the flow is stopped.

Moreover, the different walls do not have exactly the same behaviour. This can be due to their interaction with the groundwater flow. Indeed, the structures imply a dam effect.

5 CONCLUSIONS

To conclude, this paper presented the reduced scale model of energy geostructures called SENSE-CITY. The global systems were described with the geometry of the three structures of thermoactive diaphragm walls and the nine piles group. The injection and pumping system allow to control the groundwater flow.

Moreover, a set of thermal sensors as PT100 and fibre optics are used to monitor the whole system.

Furthermore, the thermal characterisation of the ground material show a behaviour close to a clay with a thermal conductivity of 1.8 W/m.K at saturation and optimum proctor density. However, the hydraulic conductivity is more like a sand with a value of 0.9-1.10^{-4} m/s.

At last, the thermal activation of the structure 1 and 2 shows that the groundwater flow improves the natural thermal recharge. Indeed, moving from 1 m/day to 0 m/day, for the same energy demand, the daily decrease of temperature is more than double.

The perspectives are to perform more scenarios and to collect the data from the fibre optics to improve the global view of the thermal field in SENSE-CITY and its thermo-hydraulic behaviour.

6 ACKNOWLEDGEMENTS

This work was carried out in the framework of a PhD thesis founded by IFSTTAR and the company Antea Group. The authors thank all the participant to the equipment SENSE-CITY.

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