Thermal characterization of a geothermal precast pile in Valencia (Spain)

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Keywords: geothermal precast pile, thermal characterization, thermal conductivity, thermal response test.

ABSTRACT

The geothermal use of pile foundations represents a useful, efficient and cost effective method of installing ground heat exchangers for cooling and heating buildings, which may potentially favour a decrease in installation cost, considering that it involves a minimal impact on the piling program.

A new research and development project has been recently launched in Spain to undertake some studies on this complex matter (PITERM PROJECT). The experiment, consists of a specifically designed, constructed and fully monitored geothermal precast pile driven at Polytechnic University of Valencia Campus. The pile was subjected to two types of loading: mechanical and thermal. The mechanical load was applied by means of a mechanical frame anchored to the ground, as element of reaction, the three anchors being used to induce an active compressive force. The thermal load was provided by a reversible heat pump, with a data logger to record the outflow and return temperatures (thermal response test installation).

This paper presents the thermal characterization of the thermal precast pile in terms of an average thermal conductivity value for the ground around the pile (ground) and a thermal resistivity value (Rb) for the precast pile by means of two different approaches. Firstly, an in situ thermal characterization of the system pile-ground was done by the thermal response test installation. Secondly, 550 thermal conductivity measurements were performed by the "thermal needle method" in samples extracted from the cores obtained from a geothermal drilling conducted 2 m away from the thermal pile. Controlled variation of factors such as the degree of saturation – moisture and dry density allowed to assign a thermal conductivity range to each geological level. Once the stratigraphic profile is known, the average thermal conductivity of the ground around the pile can be determined by weighting the thermal conductivity with the thickness of each geological strata.

1. INTRODUCTION

Energy piles (thermo-active piles or geothermal piles) are foundations with double usefulness: to support the loads of the building and to serve as a heat exchanger with the ground. The geothermal use of pile foundations is a useful, efficient and cost effective method of installing ground heat exchangers for cooling and heating buildings. The key factor in the sustainability of thermo-active foundations systems is utilizing geo-structures that are already needed for structural purposes. This way, coupling piles with ground source heat pumps only requires a low extra over cost for geothermal installation, and it supposes a minimal impact on the piling program. They constitute a growing energy technology that improve the energy efficiency of heating and cooling systems in building and have been widely developed and researched in recent years [Laloui et al. 2003, 2006, 2011, Brandl et al. 2006, Amis et al. 2008, Bourne-Webb et al. 2009, Amatya et al. 2012] but it is still necessary to understand how the thermal and mechanical loads affect the mechanical behaviour of the pile. On the other hand, as this is a relatively new technology, robust standards and guidelines have not yet been developed for the design of these systems.

Although it is widely accepted that energy piles foundations are an efficient solution for long-term carbon emission reduction and sustainable construction, they have received only partial acceptance, because of concerns regarding the impact of cyclic thermal changes on their serviceability. In this sense, specific research is still needed to better understand how the thermal loads affect the pile behaviour: changes in vertical strains, stresses and axial loads along the pile, changes in shear stresses between pile shaft and soil, movements at head and toe of pile, changes in soil strength parameters, influence of ground lithological profile and water table position, effects of constrictions at head and toe of pile, possible associated phenomena regarding soil consolidation or negative skin friction, etc.

A research and development project in energy piles was performed in Spain from 2011 to 2015 (PITERM PROJECT). The purpose of this experiment was to improve the knowledge and understanding the effects of cooling and heating on precast piles subjected to mechanical loads in terms of mechanical, geotechnical and thermal actions.

2. PILE DESIGN, CONSTRUCTION AND INSTALLATION

A geothermal precast concrete pile was specifically designed and constructed at the Rodio-Kronsa factory (Fig. 1).

Figure 1: Precast pile at the factory Rodio-Kronsa

This test pile, made of reinforced concrete with characteristic resistance (fck) of 50 N/mm2 and a Young modulus of 31314.27 N/mm2 ($E=8500\cdot(fck)^{1/3}$), with a square cross section of 35 cm side and a total length of 17.4 m, was made of two pieces 8.70 m long each, connected by a joint. To activate it thermally, two polyethylene tubes were installed vertically within a steel pipe, 11.3 cm nominal diameter, located in the centre of the pile with a double U-shaped configuration to permit the passage of the heat carrying fluid.

Ground conditions of the testing site in Valencia were taken into account to the foundation design: A superficial fill layer of sandy gravel (1m thick); a second layer of stiff clay (1 m thick); a 6 m thick layer of soft and black organic clays; a 3 m thick layer of loose sands; and below depth 11 m, layers of sandy gravels extended up to a depth of at least 27 m, interlayered with some stiff clays levels (Fig 3). The ground water table is located at a depth of 2.0 m. Under these lithological conditions, the pile should work transferring loads to the soil levels located at more than 11 m of depth.

The ultimate compressive resistance of the pile, calculated from ground test results by the method established in the Spanish Building Code [CTE 2006], was 2568,2 kN. Subsequently, a service compression load of 981 kN was decided at the pile head.

The pile was fully instrumented before being cast in the factory. The aim of the instrumentation was to monitor the distributions of temperature and axial strain with depth, as well as the supply and return temperatures of the heat exchanger fluid. Pairs of vibrating wire concrete-embedment strain gauges (VWSG) were oriented longitudinally and attached to the lateral reinforcing bars at seven different depths along the pile, then cast in concrete during construction (Fig. 2). Each VWSG contained a thermistor to monitor temperature in the concrete at each sensor location.

Figure 2: VWSG attached to the reinforcement bar

With the aim of comparing with the conventional instrumentation, Optical Fibre Sensors (OFS) were installed to measure temperature and vertical strain each 2 m along the length of the pile. Schematics of the foundation, the embedded sensors and the geological profile is shown in Fig. 3 and Fig. 4.

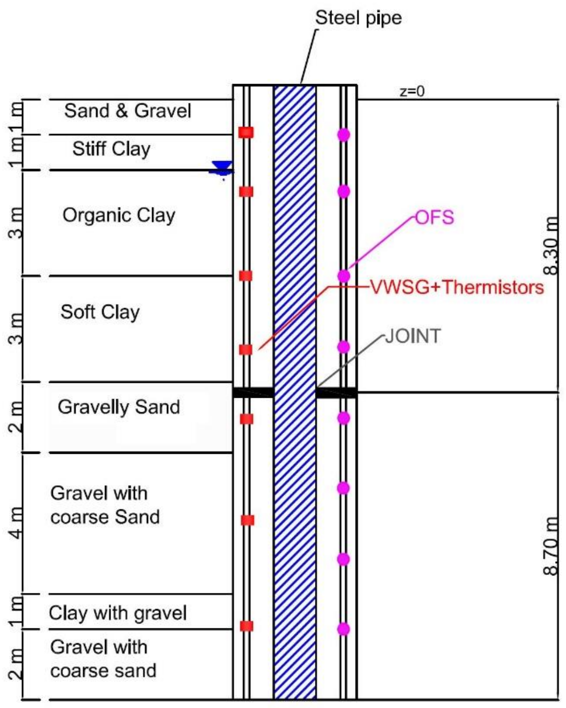


Figure 3: Soil profile and instrumentation

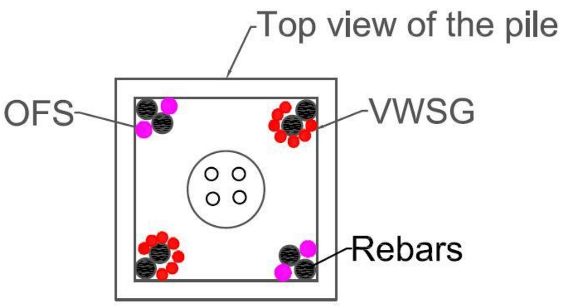


Figure 4: Top view of the pile

The pile was driven into the soil the 27th of June, 2012 in Valencia. Driving tests were carried out to assess the ultimate vertical compressive resistance, resulting in a base resistance of 1800 kN and a shaft resistance of 711 kN. The pile was then subjected first to static load tests, and secondly to thermal tests by maintaining the mechanical service load of 981 kN. Therefore, two types of load application systems were needed: mechanical and thermal.

The mechanical load was applied by means of a metallic frame, as element of reaction, fixed to the ground by means of three 25 m long anchors, with an inclination of 5º. The compressive force was applied to the pile head by a hydraulic jack. A calibrated load cell measured the real load throughout the test (Fig. 5).

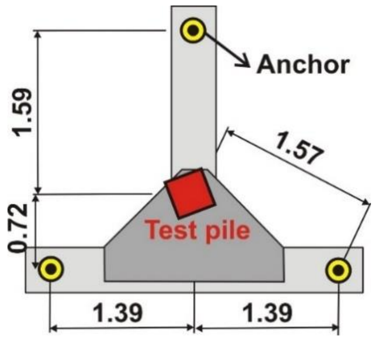


Figure 5: Scheme of the mechanical loading system

The thermal load was provided by a thermal installation (Fig. 6), formed by a reversible heat pump, a tank, a three-way valve for regulating the temperature of the injected water, a flowmeter and temperature probes with a data logger to record the inflow and outflow temperatures during the test.

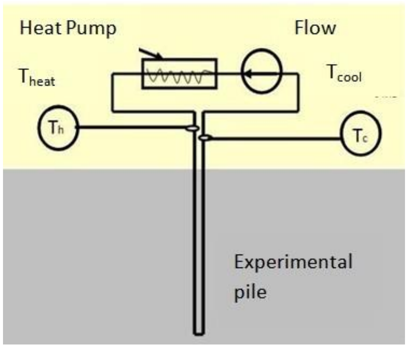
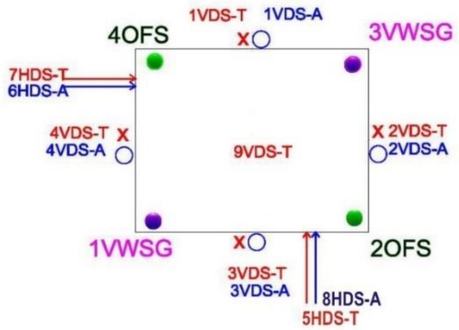


Figure 6: Thermal loading system

Once the pile was driven into the soil and thermally activated, the steel pipe located in the center of the pile was filled with high thermal conductivity mortar (λ = 2.1 W/mK) made up of quartz sand and sulphate resistant cement. The characteristic resistance of this grout material is almost equal to that of the concrete used in the pile.

The initial temperatures recorded by all the sensors prior to start the initial load test were between 17ºC and 21ºC. Below 10.40 m depth the ground temperature remains constant at 19ºC.

Finally, additional sensors were installed outside the pile, in strategic points of the loading frame and anchors, in order to monitor the pile behavior during the thermal and mechanical loads (Fig. 7 and Table 1).



$VDS\text{-}_T$: Vertical displacement transducer: LVDT
$VDS\text{-}_A$: Vertical displacement analog dial gauge
$HDS\text{-}_T$: Horizontal displacement transducer: LVDT
$HDS\text{-}_A$: Horizontal displacement analog dial gauge
OFS: Optical fibre sensors
VWSG: Vibrating wire strain gages

Figure 7: External sensors on the pile head

Table 1: Total monitoring during the study

Test element	Monitoring
Test pile (external)	4 analog dial gauges for vertical pile head displacements 4 electronic transducers (LVDT) for vertical pile head displacements 2 analog dial gauges for horizontal pile head displacements 2 electronic transducers (LVDT) for horizontal pile head displacements 1 LVDT to loading frame Load cell
Test pile (internal)	VWSG at seven levels in rebars diametrically opposed over 17 m length of pile OFS cables, 2 loops for strain and temperature measurement at the same time placed each loop diametrically opposed
Anchors	VWSG in each anchor to measure strain and temperature

The Fiber Optics Sensors, based on fiber Bragg grating (FBG) technology, are intended exclusively for embedding in concrete structures. Although the technical sheet of these sensors offer nominal wavelength for 22ºC (λ_{22}) and a temperature sensitivity constant value (S_t) of 23.8 pm/ºC, a lab-calibration was performed prior to their installation within the energy pile. In this manner, all the individual real λ_{22} and S_t values were determined to allow the later conversion of the raw signals into temperature and strain values.

As for the VWSG sensors, the ideal methodology to measure the global thermal correction factor would have involved measuring the axial heave of the energy pile during heating before applying the mechanical load of 1000 kN and comparing this with the measured thermal axial strains using a soil-structure interaction analysis such as that of Knellwolf et al. (2011). In the absence of this type of test, the calibration factor given by the factory (12.2 μm/m·ºC) was used in calculations.

3. FIELD ASESSMENT OF THERMAL PERFORMANCE

Energy pile (EP) design needs to integrate geotechnical, structural and thermal considerations. The geothermal heat exchange capacity of an energy pile is a key design parameter to dimension the geothermal loops and the heat pump system. Thermal characteristics of the ground as well as the heating and cooling loads from the structure need to be considered for the number of EPs that will be utilized as heat exchangers. Therefore, the thermal properties of the site need to be evaluated in addition to the geotechnical characterization for foundation design. In this project, the first test performed to evaluate the thermal behavior of the experimental EP has been a thermal response test (TRT).

TRT is a widely used field method for estimating soil thermal conductivity and the thermal resistance of traditional borehole heat exchangers (BHE). However, there is a lack of scientifically supported guidelines for analyzing TRT data from energy piles [Loveridge 2011]. Recently, the Ground Source Heat Pump Association (GSHPA) published a manual on the design and construction of energy piles [GSHPA 2012], including TRT guidelines for EP. Testing methods for BHE systems assume a high length to diameter ratio so that the shape of the borehole approaches a line source. The diameter of an energy pile is significantly larger and the depth is typically much less. The difference in geometry means that the testing practices of BHEs do not necessarily apply to EPs, for this reason, the GSHPA association has made some recommendations in regards to conducting TRTs for EP systems:

- When the potential use of EP systems is identified early in the design process a BHE can be constructed with a single loop and tested to find the local thermal properties.
- If the designed piles are no larger than 30cm in diameter, a TRT can be carried out using the recommendations made for a BHE system.
- If the EP system design consists of piles larger than 30 cm in diameter, the TRT should be extended to ensure that the thermal resistance of the pile is overcome. Furthermore, more sophisticated interpretation techniques can be applied.
- Once the EP is fully instrumented with strain gauges and temperature gauges, it is possible to conduct a complete stress-strain analysis as well as a thermal analysis in order to better understand the structural and thermal behaviour of the pile under

the superimposed action of coupled mechanical and thermal loads.

Since the experimental energy pile is square section 0.35 m side, and bearing in mind the recommendations of GSHPA, the field assessment of thermal performance in this project consists of two different tests: firstly, two bespoke TRT of longer duration (5 + 6 days) were performed to ensure that the thermal resistance of the pile is overcome. Then, as the EP is fully instrumented with VWSG extensometers, thermistors and Fiber Optics Sensors, a complete stress-strain analysis was undertaken in order to better understand the structural and thermal behaviour of the pile under the superimposed action of coupled mechanical and thermal loads.

3.1 Thermal loads generating facility

The main objective of the facility is to produce the thermal heat injection and to monitor the associated variables that allow to perform the thermal response test analysis.

In order to produce thermal loads, the appliance uses a reversible heat pump (cooling) or a thermal resistance (heating) and a hydraulic circuit. Several measurement elements and electronic circuits are necessary for the required data-logging and measurement control. The facility is shown in figure 8 schematically.

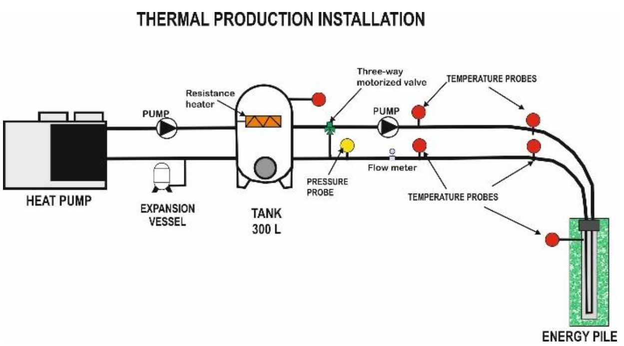


Figure 8: Thermal loads generating facility

Throughout the test, water is circulated into the thermo-active pile and heat is exchanged with the surrounding soil through the pipes located inside, in a thermo-hydraulic configuration alike any conventional BHE. The system contains two cycles of water flow:

- The primary cycle, which contains the heat exchanger pipes, installed in the pile, the primary circulation pump, a three-way valve for regulating the temperature of the injected water, a flow meter and various temperatures probes

- The secondary cycle, which contains the heat pump, a storage tank equipped with a thermal resistance, an expansion vessel and the secondary circulation pump.

The primary cycle is responsible for maintaining a constant power supply to the experimental pile, maintaining a constant temperature difference between inlet and outlet of the pipe installed in the pile in order to activate it thermally. For this purpose, the secondary circuit supplied water heated or cooled by the thermal resistance or the heat pump.

The temperatures of the heat exchange fluid entering and exiting the pile during heat pump operation were monitored using a pipe-plug thermocouples installed in the inlet and outlet ports of the manifold. The fluid will be able to extract or inject heat into the ground depending on the relationship between the temperatures of the heat carrier fluid and the ground around the pile at each moment throughout the test. Summarizing the main characteristics of the facility:

- Cold generation (heat pump) and heat generation (electric resistance).
- Regulation of the injected power by means of pulse width modulation.
- Monitoring of the flow, inlet and outlet temperature and pressure.
- Remote control of the process.
- Data logging.

3.2 Thermal characterization of the pile

The thermal characterization of the experimental pile was done by a heat injection test, simulating the thermal pile behavior working in cooling mode. Once the working load was applied (1000 kN), two TRT were performed to characterize the installation. Taking into account the EP geometry (Table 2) and the GSHPA recommendations, the tests duration was longer than usual. The extended testing time ensures that the pile thermal resistance has reached a near steady state behavior.

Table 2: Geometry of the tested energy pile

Pile length (m)	17.4
Square cross section side (m)	0.35
Active pipe length (m)	17
Heat exchanger type	Double U
Number of pipes	4
PE Pipe Outer Diameter (m)	25.0
PE Pipe Inner Diameter (m)	20.6

The EP characterization was carried out during 11 (5+6) days by introducing different power levels to the experimental pile (700 and 1400W). The temperatures of the heat exchange fluid entering and exiting the foundation during heat pump operation were monitored using pipe-plug thermocouples installed in the inlet and outlet ports of the manifold. In this manner, checking the temperature variations of the inlet and outlet pipes allowed to obtain the evolution of temperature over time. The main parameters applied during the test are presented in Table 3.

Table 3: Thermal response test parameters

	Test 1	Test 2
Temperature step	1ºC	2ºC
Flow rate	0,6 m^3/h (10 l/min).	0,6 m^3/h (10 l/min).
Fluid	Tap water	Tap water
Applied power	700 W	1.400 W
Heat injection rate	40 W/m	80 W/m
Duration	5 days	6 days

Considering the duration of the test, the energy pile can be approximated by a line source in a homogeneous medium as a first approximation for the thermal assessment. By the line source approximation, the evolution of the mean fluid temperature T_f (t) follow the trend described by the following equation (1) [Eskilson 1987]:

$$T_f(t) - T_0 = \frac{q_c}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r_b^2} - \gamma\right)\right) + q_c \cdot R_b = \frac{q_c}{4\pi\lambda}\ln(t) + q_c\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right] \quad [1]$$

Where q_c represents the constant heat injection rate used for the response test (W/m), T_0 the undisturbed ground temperature (ºC), t denotes the duration of the heat injection (s), r_b the borehole (pile) radius and γ is Euler's constant (0.5772).

A maximum error of a 10% for $t \geq 5r^2/\alpha$ is generally accepted in thermal response test applications [Gehlin 2002].

For a proper analysis, the previous equation is adapted to the equation for the line (2):

$$T_f(t) = k \cdot x(t) + m \quad [2]$$

- where k is the slope of the line and it is related with the ground thermal conductivity according to the following expression:

$$k = \frac{1}{4\pi\lambda} \quad [3]$$

- and m is the coordinate in the origin, which represents the value when the time is equal to 0. Considering the thermal resistance of the borehole a constant value over time:

$$m = T_0 + R_b q_c \quad [4]$$

- and finally, the time-dependent term:

$$x(t) = q_c\left(\ln\left(\frac{t}{t_0}\right) - \gamma\right) \quad [5]$$

Being $t_0 = \frac{r_0^2}{4\alpha}$

It is clearly evident that the equation (1) corresponds to equation (2) using the values in (3), (4) and (5).

The measurements recorded during the tests allow to infer the ground thermal conductivity and the pile thermal resistance by means of a heat transfer model such as has been described above. Fig. 9 shows the evolution of the average fluid temperature against time recorded during testing.

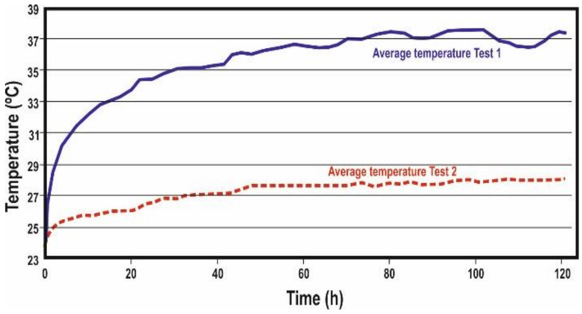


Figure 9: Average fluid temperature throughout TRT

As the evolution of the fluid temperature is logarithmic (Fig. 10), the ground thermal conductivity (λ) can be evaluated by plotting the fluid temperature against ln (t) and determining the slope of the line k:

$$\lambda = \frac{q_c}{4\pi k}$$

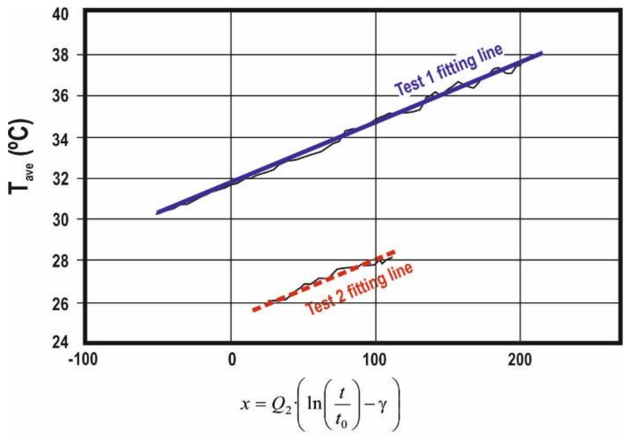


Figure 10: Semi logarithmic graph of average fluid temperature versus ln (t)

The equations obtained for the two test performed were:

Test 1: $0{,}029x + 31{,}7$

Test 2: $0{,}029x + 25{,}3$

The slope of the line is the same in both tests, as it only depends on the ground thermal conductivity:

$$k = \frac{1}{4\pi\lambda} = 0{,}029 \implies$$

$$\lambda = 2{,}7 \pm 11{,}7\% \ \mathrm{W/(mK)}$$

Once the ground thermal conductivity is known, the pile thermal resistance can be assessed on the basis of equation 3. This requires knowledge of the undisturbed ground temperature. In this case, as T_0 is the same for the two equations, the energy pile thermal resistance (R_b) can be determined:

$$R_b = 0{,}16 \pm 11{,}7\% \ mK/\mathrm{W}$$

Compared to other works [Lennon et al 2009, Wood et al 2010, Park et al 2013] the EP thermal resistance value calculated is similar, as shown in the following table (Table 4).

Table 4: Energy pile thermal resistance values

EP characteristics	Rb (mK/W)
Concrete driven Square cross section 0.27x0.27 m^2 Simple U pipe	0.17
Continuous auger pile 0.3 m Simple U pipe	0.22
Precast high strength concrete 0.4 outer and 0.12 inner hollow W shape pipe	0.131
Precast high strength concrete 0.4 outer and 0.12 inner hollow 3U shape pipe	0.098

4. LAB DETERMINATION OF THE GROUND THERMAL CONDUCTIVITY

As for obtaining soil thermal parameters, both in situ and laboratory methods can be used. In order to compare with TRT results, 11 samples extracted from the cores obtained from a drilling conducted at 2 m distance from the energy pile, were used to determine the thermal properties of the ground by lab measurement methods.

The thermal properties analyser KD2-PRO (DECAGON), allows to measure thermal properties by the thermal needle method (ASTM D 5334-08) or the dual-probe method (Bristow et al., 1994) indistinctly. In both methods, thermal properties are determined indirectly by measuring the rise or fall of temperature at the point of interest in response to a line source heat input.

550 thermal conductivity measurements were performed by inserting the thermal probes in different positions (Fig.11) in the core samples.

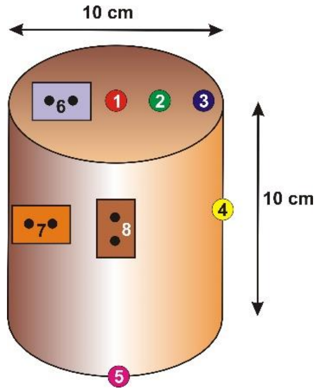


Figure 11: Different thermal probes and positions used to measure the thermal conductivity in the core samples

The core samples show different mineralogical and nature composition (granular and clayey). Furthermore, they were studied under different (moisture and density) compacting conditions, from completely dry to fully saturated state. The values ranges measured in all the samples, by different methods and probe positions, under different density and degree of saturation conditions, are shown in Table 5, including sample depth and soil classification following the Unified Soil Classification System (USCS).

Table 5: Thermal conductivity ranges obtained in the core samples

Sample	Depth (m)	U.S.C.S.	λ W/m·K
M-7411	1.2–1.3	CL	1.75–1.85
M-7412	3.2–3.4	CL	1.65-1.75
M-7413	3.8–3.9	CL	1.50-1.70
M-7414	4.8–5.0	SM	2.20-2.70
M-7415	5.5–5.6	ML	1.70-1.90
M-7416	6.0–6.2	SC	1.90-2.10
M-7417	7.4–7.55	CL	1.50-1.70
M-7418	9.4–9.6	SW	2.20-2.50
M-7419	12.6–13.2	GM	2.60-3.00
M-7420	14.0–14.2	GM	2.60-3.00
M-7421	19.2–19.4	CL	1.90-2.00

From the results obtained, the influence of factors such as the degree of saturation - moisture, dry density and type of material was verified. The thermal properties are very sensitive to the mineralogy, increasing with quartz percentage and diminishing with clay abundance. On the other hand, thermal conductivity increases with increasing bulk density for all soils as a result of particle contact enhancement as porosity is decreased. Furthermore, water content plays a major role in soil's thermal conductivity. As water content increases towards saturation, thermal conductivity increases.

Finally, a stratigraphic profile with thermal conductivities ranges of each geologic level was drawn (Fig. 12), considering the degree of saturation ranges evaluated in lab tests, in order to be compared and related to thermal response test.

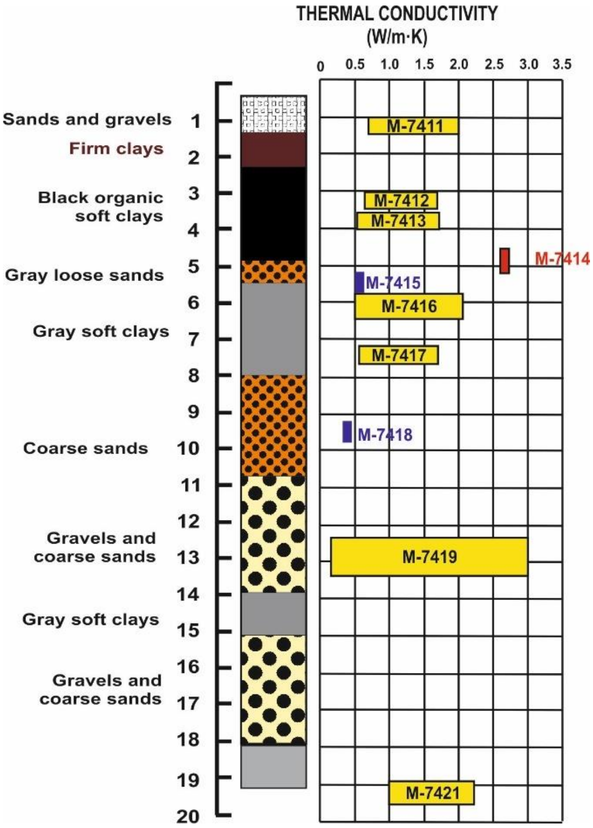


Figure 12: Thermal conductivity ranges corresponding to each geological level around the pile (red: only saturated state, blue: only dry state)

5. COMPARISON BETWEEN LAB DATA AND TRT DATA

Once the thickness strata and the specific thermal conductivity value corresponding to each level is known, under dry state for the geological materials above the water table and saturate state for the materials under it, it is possible to calculate the whole average thermal conductivity (λ_{calc}) by weighting the lab λ data (Table 6).

Table 6: Thickness and thermal conductivity values of the different geological levels

Materials	Thickness	Lab λ
Sands and gravels	1	0,77 (dry)
Dry firm clays	1	0,77 (dry)
Black organic soft clays	5.8	1,611 (sat)
Gray loose sands	6	3,267 (sat)
Gray soft clays	1.2	1,872 (sat)
Coarse sands	2	3,267 (sat)

The calculated ground thermal conductivity (λ_{calc}) is determined by weighting the lab λ data, by the thickness of the strata around the pile. This way, λ_{calc} results 2.31W/m·K, slightly below the value obtained from TRT (λ=2.7 ± 11.7% W/m·K) but, still coherent and compatible with usual values obtained in these geological materials.

6. CONCLUSIONS

This work presents the comparative analysis between two methods to characterize the ground thermal conductivity, a thermal response test done in a precast pile and a series of laboratory measurements. Validation and consistency of both methods serves to verify the standards of TRT performed in piles developed recently by the Ground Source Heat Pump Association (GSHPA).

The difference between the results obtained with both methods is less than 0.1 W/mK, considering the error range of the test site, being the values compatible with theoretical characteristics in these geological materials. It can be concluded that a time extended thermal response test measured in a pile estimates properly the thermal ground conductivity.

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Acknowledgements

We thank the Spanish Ministry of Economy and Competitiveness for its financial support, through the program INNPACTO 2011, for the design, installation and instrumentation of the geothermal pile in Valencia.

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD UNIÓN EUROPEA FONDO EUROPEO DE DESARROLLO REGIONAL "Una manera de hacer Europa"