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Heating and cooling an energy pile under working load in Valencia

María de Groot[1], Cristina de Santiago[1], Fernando Pardo[1], José Luis Arcos[2], Francisco Martín[2], Javier Urchueguía[3], Borja Badenes[3]

[1] Laboratorio de Geotecnia (CEDEX). C/ Alfonso XII 3 y 5. 28014 – Madrid, Spain

2 Grupo Rodio-Kronsa. C/ Velázquez 50. 2800 – Madrid, Spain

3 Instituto de Matemática Pura y Aplicada (UPV). C/ Camino de Vera s/n. 46022 - Valencia, Spain

maria.degroot@cedex.es

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ABSTRACT

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

Throughout the last years (since 2006), however, a number of studies have identified that temperature changes in piles lead to variations in shaft resistance and axial loads. This entails that heating-cooling load alternation on the building foundations can induce significant modifications in the soil-structure interaction, leading to additional stresses in the piles and decrease of the lateral friction.

In this sense, specific research is still needed to better understand the totality of the loads affecting the pile: **mechanical actions,** from both external loads and stress concentrations in concrete; **geotechnical actions** originated in soil consolidation or uplift movements and shaft friction variations and finally **thermal actions** giving rise to small expansion/contraction phenomena in the pile.

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 Valencia University Campus. The pile will be subject to two types of loading: mechanical and thermal.

The mechanical load will be 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 will be provided by a reversible heat pump, with a data logger to record the outflow and return temperatures. A borehole located at 0.5 m of the test pile will allow measuring the temperature depth-distribution in the adjacent soil mass.

The testing set is fully instrumented in order to register the response of the pile to mechanical and thermal load changes: extensometers and fiber optic sensors to measure vertical strain and temperature distribution through the test pile and the variations in the shaft resistance mobilized as a result of cooling and heating.

The most reliable way to demonstrate that the repetitive heating and cooling cycles do not affect the bearing capacity of the pile is to perform both static load tests before and after the thermal actions.

With these results, the response of the pile and surrounding soil during the test will be analyzed, and modeled through numerical simulation, being the aim to propose an adequate method of design that takes into account the thermal and mechanical effects in thermo-activated piles.

1. INTRODUCTION

Energy piles are foundations with double usefulness: to support the loads of the building and to serve as a heat exchanger with the ground. These elements are equipped with a system of pipes installed within concrete structures, with a heat carrier fluid that circulates through it, that can extract heat from the ground to satisfy the need for heat during the winter and can reject excess heat during the summer. If the groundwater flow is large enough that will provide a thermal regeneration of the ground and a natural thermal recharge occur.

This technology has already been used in Europe (Laloui et al. 2003, 2006; Brandl, 2006; Amis et al., 2008; Bourne-Webb et al., 2009; Laloui & di Donna, 2011; Amatya et al., 2012) but it is still necessary to understand how the thermal and mechanical load affects the mechanical properties of the pile.

The purpose of the trial is to apply a mechanical and a thermal load. The mechanical load will be 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 will be provided by a reversible heat pump, with a data logger to record the outflow and return temperatures.

2. PILE-SOIL INTERACTION UNDER MECHANICAL AND THERMAL LOAD

When a pile under working load is heated or cooled, a complex behaviour is imposed upon the pile that varies with ground conditions and different degrees of end restraint. The heating of a pile induce expansion while cooling induces contraction leading to displacements of the pile butt, changes in foundation side friction, or mechanical distress in the concrete. The total strain due to mechanical and thermal loads is:

$$\varepsilon_T = \varepsilon_m + \varepsilon_{th}$$

Where ε_m is the strain due to a mechanical load and ε_{th} is the strain due to the thermal loads

If the pile is unrestrained, the change in temperature induces a uniform free strain (Peron, Knellwolf, & Laloui, 2011):

$$\varepsilon_{th,f} = \alpha \cdot \Delta T$$

Where α is the coefficient of thermal expansion of the pile. In general case a part of the pile is constraint by the surrounding soil and the structure. If the pile constraint a blocked strain caused by a temperature difference is finally produced:

$$\varepsilon_{th,o} = n \cdot \alpha \cdot \Delta T$$

Where is the ratio of this two vertical strains, the degree of freedom of the structure (Bochon 1992,Laloui, 2011):

$$n = \varepsilon_{th,c} / \varepsilon_{th,f}$$

The degree of freedom is theorically zero when the pile is completely blocked and one when the pile is completely free to move. Normally n ranges from 0-1.

The difference between the free and constaint stress brings a vertical support reaction,balanced by a proportional increased in the vertical stress in the pile:

$$\sigma = -E_{pile} \cdot (\varepsilon_{th,f} - \varepsilon_{th,c})$$

The negative sign corresponds to compression. This additional stress depends on each layer of the soil, leading a mobilization of the side friction at the pile-soil interface during cooling and heating.

During thermal loads radial stress can occur, in small diameters is not critical but in large diameters can be important.

2.1. Improvements in the thermo-mechanical behaviour understanding

Laloui (2008) resume the state of geotechnical knowledge in heat exchangers piles and mentioned the following issues:

- What are the thermal fluctuations ($\Delta T=30^oC$) lon g term effects on the bearing capacity of the foundation soil?
- What are the limit temperatures in the piles from wich bearing capacity of friction piles starts to decrease?Is there a long term fatigue effect?
- Can a -3^oC fluid temperature inside the pile have a long term effect on the concrete resistance if the latter has no sufficient porosity due to special design mixture formula?

Later, Soga (2011) summarized the new goals for the understanding in heat exchanger piles:

- Is the stress in the concrete smaller than the strenght?
- Are the mobilised shaft friction and the end bearing pressure smaller than the design limits?
- Is the pile movement acceptable during the thermal loads?

3. EXPERIMENTAL TEST IN SPAIN (PITERM)

A research and development project in energy piles is taking place in Spain (PITERM PROJECT).The purpose of this experiment is to improve the knowledge and understanding the effects of cooling and heating on precast piles under mechanical loads in terms of mechanical, geotechnical and thermal actions.

3.1. Pile design and construction

The trial is taking place in Valencia with a geothermal precast square hollow pile with polyethylene tubes installed vertically in a pipe located in the center of the pile with a double U-shaped configuration to permit the passage of the heat carrying fluid. The test pile was made of two pieces with a length of 8,70 m each connected by a joint , a total of 17 m pile is used with 35 cm in square section. The working load of the pile is 1893 kN. The nominal diameter of the hollow is 12, 2 cm, the material used for the manufacture of the pipe that was placed inside the pile is steel (Illustration 2). The pile was made with reinforced concrete with characteristic resistance (fck) of 50N/mm2, The Young modulus of the concrete is 31314, 27 N/mm2 (E=8500· (fck) 1/3).



Figure 1: Precast pile in the factory Rodio-Kronsa



Figure 2: Steel pipe used in the precast pile

The pile was fully instrumented before it was concreting in the pile factory. The instrumentation chosen for the response of the pile to mechanical and thermal load changes consist in Vibrating Wire Extensometers (VWSG) at seven levels in reinforcement bars (rebars) diametrically opposed over 17 m length of pile with thermistors. The aim is to measure vertical strain, temperature and shaft resistance each 2 meters.



Figure 3: VWSG used and in rebar

To compare with the conventional instrumentation it has been used Optical Fiber Sensors (OFS) that will measure temperature and vertical strain each 2 meters along the length of the pile. There is a large variety of fiber optic sensors for monitoring, for this test it is used Fiber Bragg-Grating sensor, with a single cable, it is possible to measure strain and temperature at different locations in the cable.2 loops has been used to measure at the same time in rebars diametrically opposed.



Figure 4: OFS sensors in rebars

3.2 Test site location

Ground conditions relevant to the foundation design are typical for Valencia: A superficial fill layer of sand gravel (1m thick), a second layer of stiff clay (1 m thick), at 2 m depth there is a layer of organic soft black clay (6 m thick), below it there are 9 m of gravel and sand, with an interlayer of 1 m of clay and gravel at 14 m depth. The pile works as an end bearing pile.

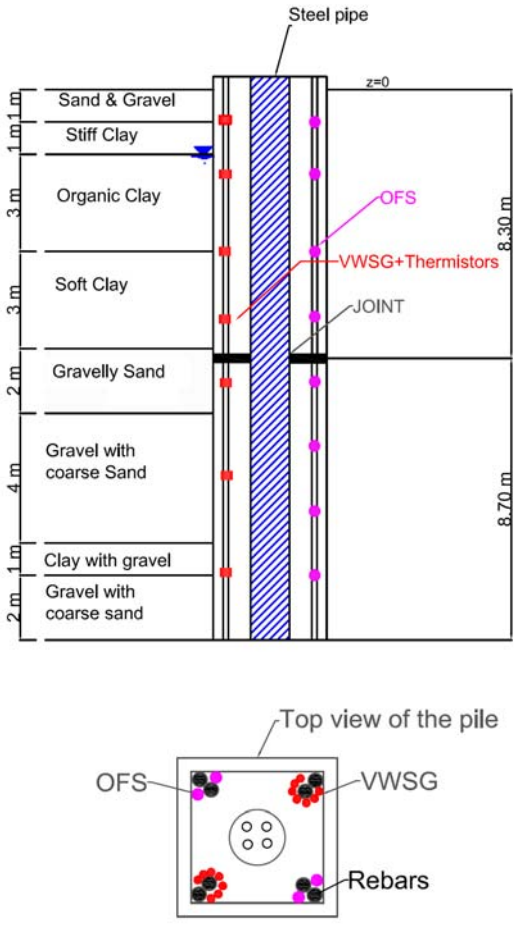


Figure 5: Soil profile and instrumentation details

A thermistors array was installed within an adjacent borehole that has been formed about 2 m from the test pile to allow near-field temperature profiling to be undertaken, in order to follow in real time the thermal behavior of the adjacent soil mass. It will be useful to provide a picture of the temperature change as it is not carrying any mechanical load.

The three anchors being used to induce an active compressive force were instrumented with VWSG for the static load test.

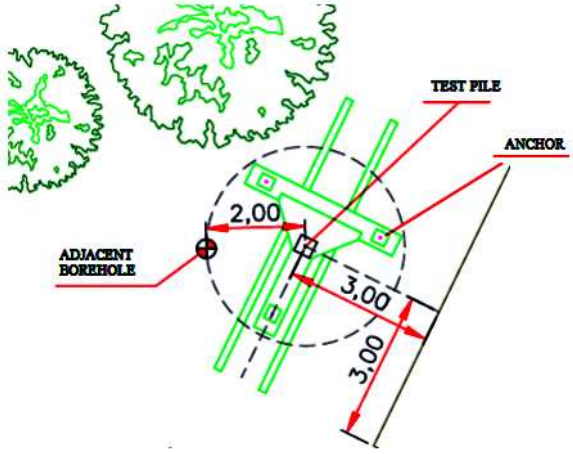


Figure 6: Top view of the test

3.3. Pile driving

The pile was driven into the soil the 27th of June, 2012 in Valencia.

In order to obtain ground information throughout the piling process, a Pile-Penetrometer Test was performed through monitoring the number of blows necessary to drive the pile 20 cm into the ground. This way, the Pile-Penetrometer Test becomes a powerful ground investigation technique, providing a certain index equivalent to N_{SPT} value, connected with the ground resistance during installation.

Figure 7 shows the profile of the ground resistance to penetration during the driving process of the pile.

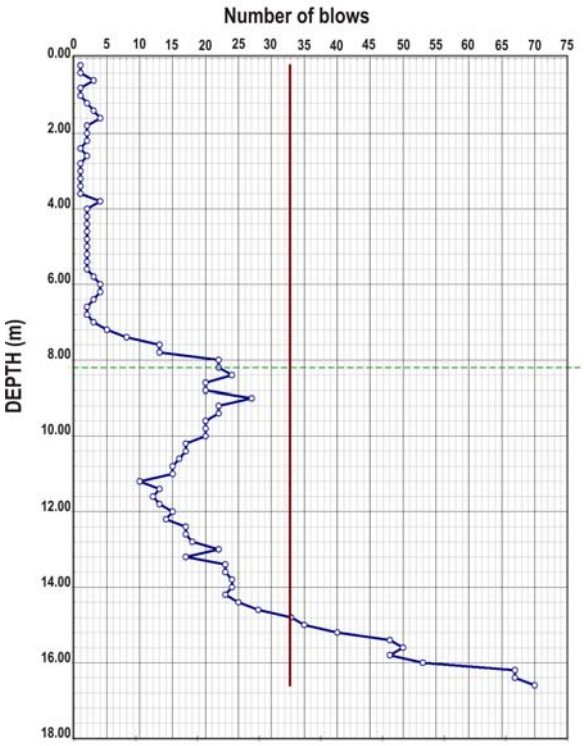


Figure 7: Pile penetrometer Test

With the aim of monitoring the drive system performance and driving stresses, during the pile installation, a High Strain Dynamic Test was performed by means of a Pile Driving Analyzer® (PDA).

The PDA calculates results from velocity and force signals obtained by accelerometers and strain transducers attached to the pile while the second half pile was being driven (Figure 8).

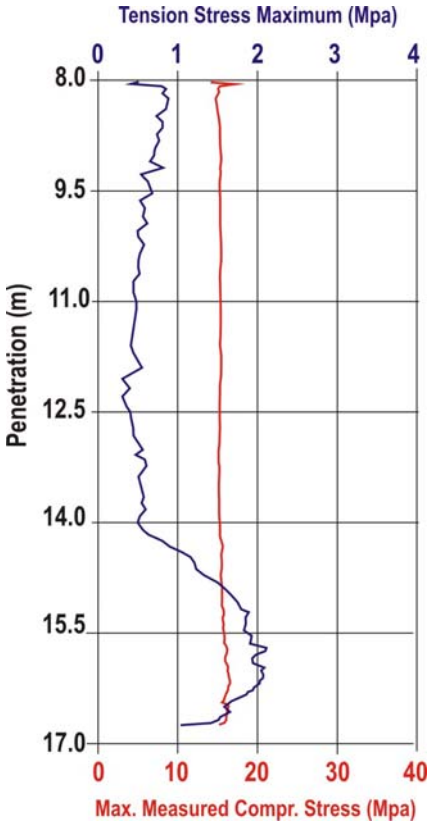


Figure 8: Results of compression and tension during the driving of the second part of the pile

Three hours later, the pile capacity was assessed by means of a second Dynamic Load Test during restrike driving. In this case, CAPWAP (CAse Pile Wave Analysis Program) analysis of PDA data was done to provide the soil resistance distribution along the foundation and simulate a static load test, taking as input the force and velocity data obtained with a Pile Driving Analyzer® (PDA). Extensive correlations between CAPWAP simulated and actual static load tests have proven the reliability of this method of determining pile capacity.

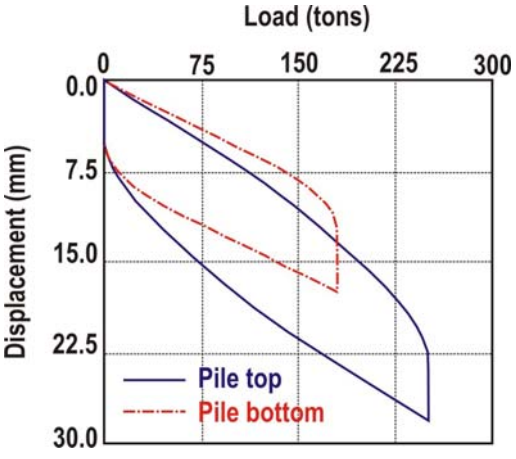


Figure 9: Load-Displacement relationship at the top and bottom of the pile, 3 hours after the driving process

The maximum load mobilized was 2500.8 kN, being 700.7 kN of them developed in the pile shaft and 1800.1 kN in the base of the pile.

Once the pile was driven in the soil, 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.

3.4. Static Load test

The Static Load Test (SLT) is the most definitive method of determining load capacity of a pile. It involves the direct measurement of pile head displacement in the response to a physically applied test load. It is the most fundamental form of pile load test and is considered as the bench-mark of pile performance.

A Static Load test was undertaken between the 15th and the 16th of January of 2013, in the load range 100kN to 1000 kN, prior to the thermal and mechanical trial.

The mechanical load is applied by means of a mechanical frame anchored to the ground (Figure 10), as element of reaction, and three anchors used to induce an active compressive force with a hydraulic jack of 100 tons. A calibrated load cell measures the real load throughout the test.

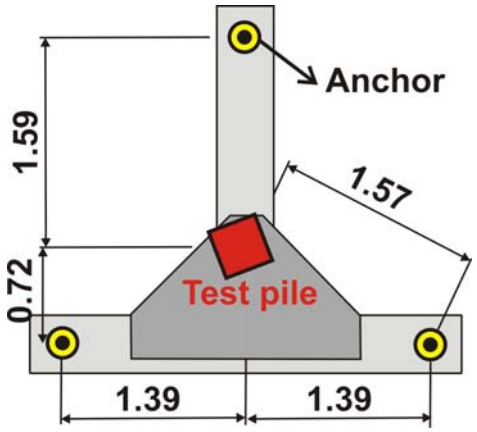


Figure 10: Mechanical loading scheme

The performance of the Static Load Test follows the load cycles shown in the Figure 11.

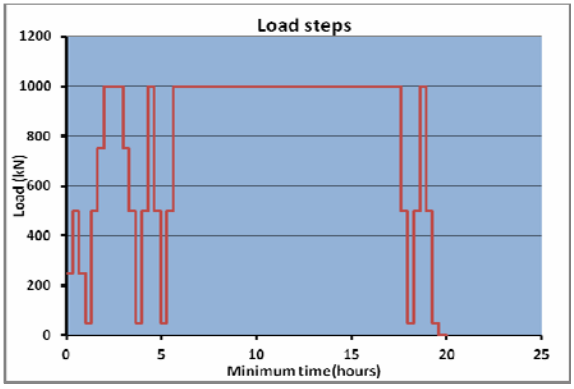


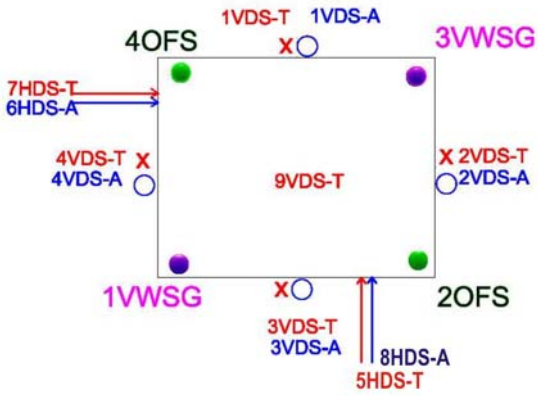
Figure 11: Load cycles defined in the SLT

During the Static Load Test, direct measurements of pile vertical and horizontal displacements /strains under the applied loading are taken by reading deflectometers (analog dial gauges), electronic transducers (LVDT's), Optical fiber sensors (OFS), Vibrating wire strain gages (VWSG). On the other hand, temperature is recorded by means of OFS and thermistors (Figure 12).

The Table 1 summarizes the sensors installed to monitor the pile behavior.

Table 1: Instrumentation installed

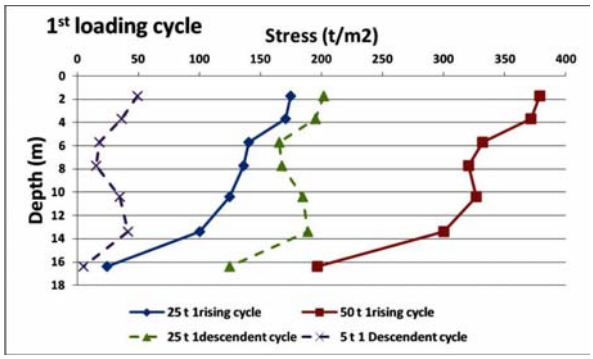
Test element	Monitoring
Test pile (external)	4 analog dial gauges for vertical pile head displacements 4 electronic transducers (LVDT) for vertical pile head displacements 2 analog dial gauges for horizontal pile head displacements 2 electronic transducers (LVDT) for horizontal pile head displacements 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
Adjacent Borehole	Thermistor array at six levels over 16 m

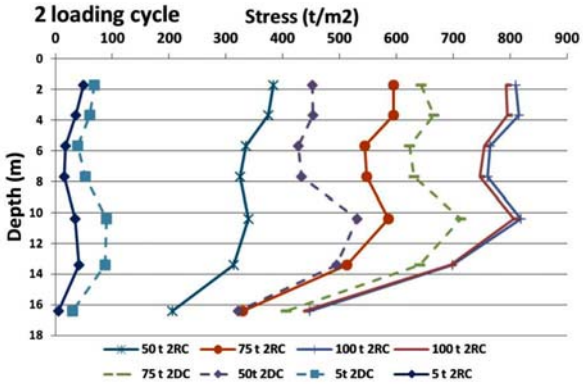


VDS-$_T$: Vertical displacement sensor - transducer: LVDT
VDS-$_A$: Vertical displacement sensor - analog dial gauge
HDS-$_T$: Horizontal displacement sensor - transducer: LVDT
HDS-$_A$: Horizontal displacement sensor – analog dial gauge
OFS: Optical fiber sensors
VWSG: Vibrating wire strain gages

Figure 12: Schematic layout of the instrumentation used during the static load test

The observed response during the four loading-unloading cycles, defined in the Figure 11, registered by the instrumentation listed in the Table 1, is shown below (Figure 13).





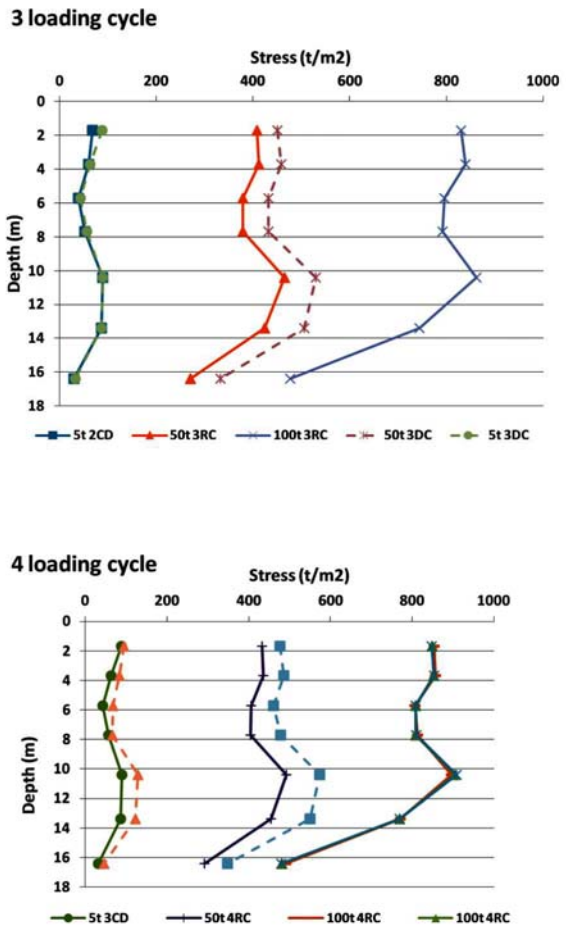


Figure 13: Profile of Load distribution during the load cycles

4. NEXT EXPERIMENTAL STEPS

Being the current status of the project stated in the previous section, there are still the most important experimental steps to perform, such as the thermal response test to characterize the thermal behaviour of the ground as well as the heat transfer between the ground and the heat carrier fluid trough the pile.

Strategically designed thermal loads (controlled heating and cooling of the pile) series will be applied without mechanical loads and, afterwards, with mechanical loads applied to the pile.

4.1. Thermal characterization of the pile

To start with the next test is necessary to reload to working load (1000 kN) and to carry out the characterization with a thermal response test. This is a mobile laboratory formed by a reversible heat pump, a tank, a three-way valve for regulating the temperature of the injected water, a flow meter and various temperatures probes (Figure 14).

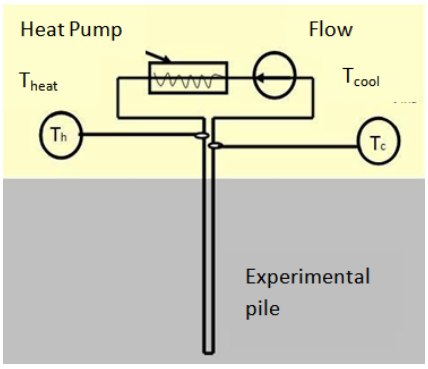


Figure 14: Thermal Response Test Scheme

The system contains two cycles of water flow:

- The primary cycle, which contains the heat exchanger pipes installed in the pile and the primary circulation pump.
- The secondary, which contains the heat pump, storage tank, control valve 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 heat pump.

The characterization of the experimental pile will be carried out 9 days by introducing different power levels to the pile (700, 1000 and 1400W) checking the temperature variations of the inlet and outlet pipes in order to obtain a curve evolution of temperature over time. The main target of this thermal test is to determine the power that will be used during the consequent trials (W/m). After this test, the temperature profile will be recorded to assure that reaches the thermal equilibrium again.

4.2. Thermal loads without and with mechanical load

This stage is meant to show the thermo-mechanical behavior of the pile under usual working loads, simulating its use within a geothermal installation. With this view, cooling will be injected to the pile, for a period of 15 days. After 5 days to let the ground stabilize again, heat will be injected to the pile, for a period of 15 days.

This thermal series will be repeated without and with mechanical load. Throughout the trials, all the geotechnical parameters will be registered, apart from temperatures, power and flow, to check the possible differences in the thermal and geotechnical behavior of the pile.

To finish with the experimental work on this pile, a second static load test will be performed in order to determine whether the bearing capacity of the pile has changed or not due to the thermal cycles applied before.

3.6. Future prototype

A second improved prototype of precast thermal pile is planned to be designed, fabricated and driven, after learning from the results obtained with the first one.

In this second thermal pile, pore water pressure transducers will be added to the general monitoring installed in the pile. The aim of this new approach is to measure the variations in the pore water pressure upon cooling and heating processes, depending on the density, porosity and hydraulic permeability of the ground layer, and the consequent variations in the effective stresses state.

4. CONCLUSIONS

The PITERM Project will last two years, finishing in June 2014. Hopefully this project will help to better understand the thermo-mechanical behaviour of a precast thermal pile under mechanical and thermal loads. Making good use of the results, it should be possible to develop a numerical analysis basis to take into account the thermal loads in the geotechnical design of thermal piles. The final objective would be to suggest its incorporation to the Spanish Technical Code for Building

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