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Effect of thermal loads on precast concrete thermopile

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Abstract (150 words)

The paper describes the thermo-mechanical behaviour of an experimental precast driven pile, properly instrumented and prepared to operate as a heat exchanger foundation element under the simultaneous action of mechanical and thermal loads. Firstly, in situ static vertical load tests were carried out to analyse the pile mechanical behaviour. Afterwards, two thermal tests were performed under constant mechanical load. A first thermal test was carried out to characterize the pile-ground system. By means of the second thermal test, the conditions of the pile in a geothermal installation of an office building operating in cooling mode were simulated. The influence of the thermal loads on the structural and geotechnical performance of the pile is subsequently analysed. Heating the pile leads to increases in axial and end-bearing loads, changes in shear stresses distribution and reduction of factors of safety for compressive ground resistance and for structural resistance of the pile.

Keywords chosen from ICE Publishing list

Piles & piling; Energy; Buildings, structures & design.

List of notation

U_z	is the vertical displacement
Δl	is the total vertical lengthening/shortening of the pile
q_c	is the constant heat injection rate used for the response test (W/m)
T_0	is the undisturbed ground temperature (ºC)
t	is the duration of the heat injection (s)
R_b	is the borehole (pile) radius
γ	is Euler's constant (0.5772)
λ	is the thermal conductivity (W/m·K)
α	is the thermal diffusivity (m^2/s)

1. Introduction

Under the auspices of the Spanish National R&D programs, the PITERM research project was undertaken in 2012 to study the thermo-mechanical behaviour of an experimental driven pile, properly instrumented and prepared to operate as a heat exchanger foundation element under the simultaneous action of mechanical and thermal loads. One of the main objectives of the study was to analyse the influence of the thermal loads on the structural and geotechnical performance of the pile. A considerable lack of knowledge exists nowadays concerning the transference phenomena of heat and load between a geothermal pile and the surrounding ground under the combined actions of mechanical and thermal actions, in terms of restrictions of movement at head, shaft and base of the pile, generation of internal stresses and deformations and about how these affect the stress-strain state of the whole. Though similar kind of tests had been already performed on cast-in-situ piles (Laloui, L. et al., 2003; Brandl, H., 2006; Bourne-Webb, P., et al., 2009), very little information was available at the time on the behaviour of thermally activated prefabricated driven piles. Even presently, the available information about precast concrete thermopile behaviour is very scarce. In this project, prior to thermal activation of the experimental pile, two in situ static vertical load tests were carried out to analyse its mechanical behaviour as foundation element. Afterwards, under the service constant mechanical load, several thermal tests were performed.

2. Test set up

Detailed description of the pile, ground and driving procedure can be found in De Groot Viana (2017). The 17.4m long reinforced concrete pile, fabricated at Rodio-Kronsa factory in Madrid, with a square cross section of 35 cm side and a total length of 17.4 m, was made of two pieces, each of them 8.7 m long, connected by a joint (Figure 1a). A steel pipe, with a diameter of 11.3 cm, was used to create a vertical circular hole at the centre of the pile (Figure 1b), in order to install, after driving, two polyethylene tubes with a double U-shaped configuration to permit the passage of the heat carrying fluid for thermal activation of the pile. The pile was driven in the city of Valencia, into deltaic deposits. At the site a borehole, with undisturbed sampling and SPT tests, and a dynamic probing super heavy test were done, showing the following soil profile: A superficial fill layer of compacted sandy gravel, about 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 layers of dense sandy gravels, interlayered with some stiff clays levels between 11 and at least 27 m of depth (Table 1). The ground water table was located at a depth of 2.0 m. From the ground investigation results, an ultimate compression resistance of the pile of 2571 kN (611 kN for shaft and 1960 kN for base resistance) was calculated (Pardo de Santayana et al., 2016) following the Spanish Building Code (Ministerio de Vivienda, 2006). Subsequently, a service compression load of 1000 kN at the pile head was decided for the experimental pile.

The pile was instrumented internally to monitor the distributions of temperature and strains during the tests (Figure 2). Details of the internal instrumentation can be found in De Groot Viana, M. (2017) and in de Santiago et al. (2016). In short, to measure axial strain and temperature distributions along the pile, vibrating wire concrete-embedment strain gauges (VWSG), provided with thermistors, and optical fibre sensors (OFS) were attached to the reinforcing bars at different depths (see Figure 1b, Figure 3). As the pile had to be driven in two pieces, the joint element (see Figure 2c) had to be specially designed for this project in order to allow the connection of the instrumentation cables (VWSG and OFS) from the lower half of the pile to the upper half during the driving operation (see Figure 2d).

The pile was driven in the ground on June 27th 2012. 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, by following the CAPWAP method (Pardo de Santayana et al., 2016). Two types of load application systems were needed for the tests: mechanical and thermal. The mechanical load was applied by means of a hydraulic jack and an anchored metallic frame, as element of reaction, fixed to the ground by means of three 25 m long, 5º inclined anchors. A calibrated load cell measured the real load throughout the test (Figure 4). The thermal load was provided by a thermal installation, 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 5).

Once the pile was driven into the soil, the heat exchanger tubes were placed in the central hole of the pile, and this was subsequently filled with high thermal conductivity mortar (Figure 6). Finally, additional sensors were installed outside the pile to monitor the pile behaviour during the tests (Table 2).

3. Static vertical load tests

Two static vertical load tests, A and B, were carried out according to the load-time scheme shown in Figure 7. As optical fibre sensor readings were not properly taken during test A, a second test (test B) had to be done. Five load cycles (1C to 5C) were applied during test A, which was performed on 01/15/13 and lasted 24 hours. Test B was carried out on 03/29/13 and lasted 5 hours; at the end of this test a constant vertical load of 1000 kN was constantly kept at the pile head for the following stages of the study. Detailed analysis of the mechanical behaviour of the pile during these two static load tests can be consulted in Pardo de Santayana et al. (2016).

From the pile internal vertical strain measurements provided by the VWSG and OFS sensors, the vertical strain distribution along the pile, and, hence, the axial load profile at every step of the tests could be determined, as well as the pile total shortening. From the external instrumentation devices the pile head settlement was also measured. Figure 8 shows the evolution of the pile head settlement (U_z) from the lectures done with the 4 external 4 LVDT sensors, as well as the vertical shortening of the pile (Δl) during test A. Maximum head settlement value recorded was 7.8 mm (under 1000 kN of load), whereas maximum shortening of the pile was 4.2 mm. A permanent settlement of about 2 mm was observed after unloading at the end of this test A. By the contrary, no additional permanent settlement was observed during test B. Figure 9 shows the evolution of the vertical strain vs. depth curves during test A. As it can be observed in the figure, very similar strain vs. depth curves were obtained for a same level of head load in the different cycles of the test; also, it can be noted that for the same load, strains remained, in general, slightly higher in the unloading curve than in the loading one, being this difference bigger in the first cycles of the test; on the other hand, after 10 hours of keeping a constant load of 1000 kN on the pile head (cycle 4), the strain curves did not experienced any change; at the end of test A, the initial strain level was practically recovered, especially in the upper 10 m. Figure 10 shows the load vs settlement plot registered at pile head during test A. A comparison between maximum values of pile head settlement, base settlement (at depth 16.2m) and shortening of the pile during tests A and B can be seen in Table 3; the about 2 mm of difference of pile head and pile base settlements between both tests corresponds to the permanent settlement registered in test A. Figure 11 shows the evolution of the axial load vs. depth profiles in the pile during test B, determined from the vertical strains measured by the OFS devices.

Test A and B results showed that along the upper 10 to 12 meters of the ground (soft soils) the pile hardly transferred load to the surrounding soils. The pile was transmitting about 600 kN of load to the base and about 400 kN of load through the shaft, particularly along the lower meters of the pile. This means that the pile was working with a base safety factor of the order of 3.1 and with a shaft safety factor of about 1.7, whereas the global factor of safety for compressive resistance of the pile was 2.5 under the applied 1000 kN service vertical load.

4. Thermal load tests

4.1 Pile-ground system thermal characterization test

The thermal characterization of the experimental pile was done by a heat injection test, simulating the thermal pile behaviour working in cooling mode. Once the working load was applied (1000 kN), two TRT were performed to characterize the installation. Taking into account the pile geometry (Table 4) and the GSHPA recommendations (GSHPA, 2012), the test duration was longer than usual. The extended testing time ensures that the pile thermal resistance has reached a near steady state behaviour.

The pile 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 5.

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 *Tf* (t) follows the trend described by Equation 1 (Eskilson, 1987):

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

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 (s) denotes the duration of the heat injection, 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 a linear equation (Equation 2):

$$T_f(t) = k \cdot x(t) + m$$

2.

where k is the slope of the line and it is related with the ground thermal conductivity according to Equation 3:

$$k = \frac{1}{4\pi\lambda}$$

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 (Equation 4):

$$m = T_0 + R_b q_c$$

4.

and finally, the time-dependent term (Equation 5):

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

5.

being t_0 equal to:

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

6.

The measurements recorded during the tests allow inferring the ground thermal conductivity and the pile thermal resistance by means of a heat transfer model such as has been described above. Figure 12 shows the evolution of the average fluid temperature against time recorded during testing.

As the evolution of the fluid temperature is logarithmic (Figure 13), the ground thermal conductivity (λ) can be evaluated by plotting the fluid temperature against *ln (t)* and determining the slope of the line *k* (Equation 7):

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

7.

Equations 8 and 9 were obtained for the two test performed, Test 1 and Test 2, and correspond to the fitting line equations defined in Figure 13:

Test 1:

$T_f(t) = 0.029 \cdot x + 31.7$

8.

Test 2:

$T_f(t) = 0.029 \cdot x + 25.3$

9.

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

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

10.

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

11.

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 (*Rb*) can be determined:

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

12.

Compared to other works (Lennon, Watt & Suckling, 2009; Wood, Liu & S.B, 2010; Park et al., 2013) the PITERM pile thermal resistance value calculated is in agreement with them, as shown in Table 6. A more detailed description of the thermal characterization of the pile as heat exchanger can be found in De Santiago et al. (2016).

4.2. Thermo-mechanical performance test

Once characterized the mechanical behaviour of the pile by means of the static loading tests A and B and the thermal pile-ground system, and keeping a constant service load of 1000 kN at the top of the pile, a thermo-mechanical performance test was performed in order to both assess the thermal behaviour of the experimental pile as heat exchanger, and to analyse the effect of the introduction of a thermal load on the mechanical behaviour of the pile as a foundation element. This first test, designed as test C, was carried out therefore between the 26th of June and the 10th of July of 2013, under a constant vertical load of 1000 kN and a series of thermal action stages (Table 7), as shown in Figure 14, applied by means of the heat exchange internal tubes, simulating its use in summer mode (cooling the building and heating up the foundation). Three different heat injection rates, relatively high, were used, and a series of monitoring moments (C_0, C_a, C_b, C_c, C_d and C_e) were used for the analysis (Table 8).

Figure 15 shows the temperature/depth curves measured at the selected moments inside the pile during test C. Figure 16 shows the upwards vertical movements registered at the head of the pile during the test, which reflected the evolution of temperatures. A maximum vertical ascending movement of 1.23 mm was measured in moment C_b, representing 0.0073 % of the pile length and approximately 1/3 of the free dilation that the pile would have experienced if there were no restrictions by the surrounding ground.

The application of heat during test C induced the pile to dilate, and tension vertical strains were registered by means of the internal devices. By integrating the vertical strains measured along the pile length, a maximum pile extension of 1.6 mm was obtained in moment C_b; by taking into account this value, together with the 1.23 mm vertical movement measured at the pile head, a maximum vertical movement (downwards) of -0.37 mm was determined for the pile base (see Table 3).

As the pile tends to dilate during heating, the surrounding soil restricts this tendency and new shear stresses appear at the pile shaft/soil interface opposing dilation. Consequently, compression stresses of thermal origin are generated along the pile, and additional axial loads appear, relatively to the axial load distribution generated by the 1000 kN mechanical load applied to the pile head. In Figure 17 total (thermal+mechanical) axial load profiles along the pile during test C are presented. As shown in the figure, the axial loads tend to a value of 1000 kN at the top of the pile, where no additional stresses were generated, as restriction to dilation did not exist there.

The results show a maximum increase of about 400 kN in axial load in the pile, corresponding to moment C_b, which can be considered a considerable value, if compared to the 1000 kN of mechanical load. This increase is maximum and homogeneous along a pile section between 4 to 12 m of depth, approximately, revealing that the ground is not taking any load form the pile in that section. Due to the characteristics of the soil profile, resistance to dilation is only efficient at both ends of the pile: at the base, where the gravel layers are located; and at the upper 3 to 4 meters, where the artificial fills and the stiff unsaturated clay layer are located; the opposition to pile expansion at this upper level was somehow unexpected, because no significant resistance to the mechanical loads in the previous tests was registered; the explanation for this behaviour remains unclear, but several factors might have contributed to this fact: the extension and compaction of a superficial gravel layer to condition the site after the first tests, a certain lowering of the water level during the summer time when test C was carried out, or thermal and dilation effects at the stiff upper ground levels.

Of the additional 400 kN of axial load generated at the middle section of the pile due to the thermal action, about 340 kN are supported by the pile base. This means that the base load increased from 600 kN, due to the mechanical action, to about 940 kN, due to the combined effect of the mechanical and thermal actions, implying that a considerable reduction of the pile base resistance factor of safety actually occurs (from a value of 3.1 to a value of about 1.9). Clearly, this increase in axial load also affects the factor of safety for structural failure. It should be noted that a second pile-ground system thermal characterization test (test D), similar to test C, was carried out in September of 2013 with identical results to test C.

4.3 Building cooling mode simulation test

Test E consisted of 14 daily cycles of thermal loads, in cooling mode, applied at a lower power rate than in test C. Maximum thermal injected power ratio was 80 W/m, therefore, simulating in a more realistic way a real geothermal pile of an office building installation. The test was carried out between 22/10/2013 and 4/11/2013, simulating daily cooling of the building from 07:00 till 21:00, except for Sundays, and keeping constant the mechanical load of 1000 kN at pile top. Figure 18 shows a scheme of the injected thermal power during a normal day, with a maximum in the morning, a midday interval and another power injection during the afternoon. Figure 19 shows the scheme of the whole test.

Results obtained in test E regarding vertical movements (see Table 3), vertical strains, stresses and axial loads were similar to those of test C, though of lesser extent as a consequence of the lower injected power. Actually, the maximum increase of temperature in the pile during this test did not reach 5°C at any depth. As to the evolution of these magnitudes with the number of cycles, a trend to stabilization was observed towards the end of the test. The evolution of vertical movements at pile head is shown in Figure 20; maximum value was about 0.4 mm; lower peaks correspond to Sundays, when no heat injection was applied. The maximum values of the axial load in the pile were registered at moments E_{ne} (see Fig. 18), corresponding to 21:00 hours, when higher temperatures were reached in each cycle. These values were of the order of 1150 kN, considerable lower than those determined in test C (Figure 21). The maximum axial load at the base of the pile was about 720 kN, therefore 20% higher that the values measured without thermal load in tests A and B. Considering an end-bearing resistance of 1800 kN, during test E the pile base resistance factor of safety diminished from about 3.1 (without thermal loads) to a value of 2.5.

5. Discussion

Heating the pile produces dilation deformations. As a result of the tendency of the surrounding soil to constrain the pile dilation, the mobilized shaft friction during heating shows an opposite response at the upper part, where the friction is negative (the soil is exerting a downwards force on the pile shaft), and the lower part of the pile, where the friction is positive (the soil is exerting an upwards load on the pile shaft). The opposition to pile dilation is not uniformly distributed along the pile depth, but depends on the ground profile, specifically on the existence of soft or stiff soil levels. Only those layers of stiff or very frictional materials will be able to oppose the pile dilation or contraction. On the other hand, at the depths where the pile is surrounded by soft soils, the opposition to thermal dilation or contraction of the pile will be negligible. In this experimental case, it appears that the opposition to pile dilation is concentrated at both ends of the pile, at the upper 2 to 3 metres, where the soil consists in artificial fills and stiff clays, and at the base area, where the soil is composed of coarse sands and gravels (Figure 22). This evidences the importance of the stratigraphic column in the thermo-mechanical behaviour of the system. This trend to dilation inverts when the pile cools down with respect to moments of maximum temperature (for instance, C_c and C_d moments, in test C, with respect to moment C_b). During this process, the soil tends also to show opposition to pile contraction at both ends.

In summary, pile/soil interface shear stresses generated due to heat injection into the pile during tests C and E are coherent with the theoretical model and explanations published by Bourne-Webb et al. (2009), with some specific peculiarities derived from the local geological profile, offering two levels of stiffer soils at both ends of the pile that constrain the potential pile deformation.

Table 8 summarizes the values of base and shaft resistance of the pile during tests A, B, C and E under the head load of 1000 kN, together with the ultimate values determined during the pile driving by the CAPWAP method. A can be seen, both static load tests, A and B, showed very similar results: the pile is working at a 60% of the ultimate base resistance and at 32-33% of the ultimate shaft resistance, which corresponds to safety factors of 3.1 and 1.7, respectively, and to a global safety factor of 2.5.

In tests C and E, when a thermal load is induced in the pile, the concepts of safety factor for base resistance, shaft resistance and global resistance have to be reconsidered. Assuming that the total vertical bearing capacity of the pile is of about 2500 kN, with a constant mechanical load of 1000 kN on the pile head, the global safety factor would be of 2.5. However, the pile is not working in the same way as if submitted only to the mechanical load. There is a tendency of the pile to dilate, when heated, or to compress, when cooled, which develops shear stresses at the pile shaft-ground contact of different sign along the pile. If those shear stresses are integrated along the whole length of the pile, positive and negative values cancel each other and the resultant axial load transmitted by the pile shaft to the ground is small. Analyzing the shear stresses by vertical sections, it could be seen, especially in test C, that the values determined are close to the shear strength values of the pile-soil interface at different depths That means that in relation to the pile shaft bearing capacity, the margin of safety for eventual additional loads applied at the pile head would be limited to changes of sign of the interface shear stresses at the depths where, due to the thermal loads, they are not opposing the mechanical load. As to the pile base, when heating the pile, the concept of base safety factor can still be used by comparing the load that reaches that level with the ultimate base resistance. This base resistance factor of safety was reduced in tests C and E, with respect to tests A and B, from a value of, approximately, 3.1 to 2.0 and 2.5, respectively.

Attention should be also paid to the structural behavior of the pile itself, in relationship with the axial load. As previously shown, in tests C and E the maximum axial load in the pile increased in about 30% and 12 %, respectively, when compared with the maximum value of 1000 kN without thermal loads, and this fact should be taken into account when designing the thermopile. Table 9 shows the maximum values of the axial load and the depth at which it appears in tests C and E.

6. Conclusions

This work presents the results from a thermo-mechanical evaluation of an experimental full-scale precast concrete energy pile driven into deltaic deposits in the city of Valencia, Spain, and submitted to mechanical and thermal loads, simulating its use within a geothermal installation working on summer mode (cooling the building and heating the foundation). A series of innovative measures were introduced in the pile design in order, on the one hand, to install in it after driving the two polyethylene tubes with a double U-shaped configuration that were used later on for the thermal activation of the pile, and, on the other hand, to install and connect the internal instrumentation (VWSG and OFS) cables between the two 8.7 m long pieces of the driven pile. Data collected from internal and external instrumentation sensors allowed to assess the mechanical and thermo-mechanical behaviour of the pile in terms of internal axial strains, stresses and loads, and therefore shaft pile/soil interface shear stress values, as well as pile movements and deformations. Measurements of pile internal strains and head movements done during static load tests A and B were indispensable to understand the mechanical behaviour of the pile as foundation element, and to analyse the effect of thermal loads applied in tests C and E.

When thermal actions were applied to the precast driven experimental energy pile, the manner the pile resisted the mechanical loads was modified. It was verified that as the pile is heated or cooled, changes appear in the amount and sign of the shear stresses between pile shaft and surrounding soil, as the soil opposes free thermal dilation or contraction of the pile. As a consequence, the distribution of vertical stresses and axial loads along the pile is altered. The way in which these changes take place is strongly influenced, on the one hand, by the soil profile and, on the other, by the working mode of the pile and the distribution between skin-friction and end-bearing resistances. In this study, when the pile was heated, a significant increase in axial load along the pile was verified, as well as in end-bearing load, which caused an important reduction of the factor of safety for base resistance, especially in test C. The increase of axial load in the pile was in the order of 40% during test C and about 12% during test E. It is important to notice that the thermal loads applied during the test C, described in this paper, are higher than those that would be needed in a real case of geothermal exploration of a normal office or residential building founded on piles like the one used in this study, which would be closer to the loads applied in test E. Anyhow, these facts should be taken into account not only in relation to the compressive ground resistance design, but also for the design of the structural resistance of the pile. Further research is needed to improve the understanding of the thermo-mechanical behaviour of geothermal piles and to formalize proper design guidelines and safety factors for assuring the ultimate and serviceability limit states of this kind of energy foundations.

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Figure captions.

Figure 1. Soil profile and instrumentation.

Figure 2. View of pile at precast bench showing axial tube (2a); vibrating wire strain gauges and optical fibre sensors attached to reinforced bars (2b); and joint element (2c); and view of the process of connecting sensor cables during pile driving (2d).

Figure 3. Pile dimensions and distribution of internal instrumentation.

Figure 4. Scheme of the mechanical loading system on top of pile.

Figure 5. Scheme of the thermal loading system.

Figure 6. Driving process and introduction of heat exchanger tubes in the pile after driving.

Figure 7. Load-time schemes for tests A (a) and B (b).

Figure 8. Head settlements and pile shortening during test A.

Figure 9. Strain profiles during test A measured with VWSG; (notation example: 1 CC-250 kN = cycle 1; CC/CD, loading/unloading curves; 250 kN load step; curves 4CCa-1000kN and 4CCb-1000kN correspond, respectively, to beginning and end of step interval).

Figure 10. Load at pile head vs. load settlement during test A.

Figure 11. Axial load vs. depth curves during test B, from OFS devices; (notation example: 1 CC-250 kN = cycle 1; CC/CD, loading/unloading curves; 250 kN load step).

Figure 12. Average fluid temperature throughout TRT.

Figure 13. Average fluid temperature throughout the thermal test TRT as a function of a time-dependent term from the so called infinite line source approximation (ILS), mathematically expressed in equation 1.

Figure 14. Scheme of test C and identification of monitoring moments: C_0, Ca, Cb, Cc, Cd and Ce.

Figure 15. Temperature profile evolution during test C.

Figure 16. Pile head vertical movements measured by the 4 electronic transducers (V1, V3, V5 and V6) located at the 4 sides of the pile cross-section during test C.

Figure 17. Evolution of total (mechanical + thermal) axial load vs. depth curves during test C, from OFS devices.

Figure 18. Daily profile of power injection during test E, indicating points for data analysis.

Figure 19. Scheme of complete test E.

Figure 20. Vertical movements at head of pile during test E.

Figure 21. Evolution of total axial load at moment E_{ne} during test E (determined from FOS).

Figure 22. Shear stress at pile shaft-soil contact during test C (determined from FOS).

Table1. Soil parameters.

Depth (m)	Lithology	Geotechnical Parameters
0 – 1.00	Sandy gravel	ρ_{ap} = 18 kNt/m^3 c' = 0 kPa φ = 28º
1.00 – 2.00 F.L ∇	Stiff clay	ρ_{ap} = 20 kN/m^3 c' = 1 kPa φ = 26º c_u = 30 kPa
2.00 – 7.80	Soft and black organic clays	ρ_{ap} = 19 kN/m^3 c' = 5 kPa φ = 26º c_u = 20 kPa
7.80 – 26.0	Sandy gravels	ρ_{ap} = 22 kN/m^3 c'= 0-20 kPa φ = 35º c_u = 30 - 50 kPa

Table 2. Monitoring system.

Test element	Monitoring devices
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.
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.

Table 3. Comparison between maximum values of vertical movement (neg. sign = settlement) at head and toe of pile and pile shortening/extension during tests A, B, C and E.

	Test A (cycle 3)	Test B (cycle 2)	Test C (C_b)	Test E (cycle 2, E2a)
Max. head movement (mm)	-7,2	-5,3	+1,23	+0.18
Max. pile shortening (-)/ extension (+) (mm)	-4,1	-4,1	+1.6	+0.23
Max. base movement (mm)	-3,1	-1,2	-0.37	-0.05

Table 4. 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

Table 5. 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

Table 6. 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	0.131

W shape pipe	
Precast high strength concrete 0.4 outer and 0.12 inner hollow 3U shape pipe	0.098

Table 7. Stages of the test C.

	Stages		
	1	2	3
Initial date	26/6/2013	01/7/2013	05/7/2013
Initial hour	11:09	12:33	12:03
Final date	01/7/2013	05/7/2013	10/7/2013
Final hour	11:06	11:12	13:30
Fluid	Tap water		
ΔTºC	1ºC	3ºC	1.5ºC
Heating power (W)	700	2100	1050
Heat injection rate (W/m)	40	120	60

Table 8. Time schedule and monitoring moments selected during test C.

Moment	Date and hour	Observations	Surface temperature (ºC)
C_0	26/06/2013 10:57	Prior to test C	22.9
C_a	01/07/2013 12:27	After thermal equilibrium at stage 1	30.4
C_b	05/07/2013 12:27	After thermal equilibrium at stage 2	32.3
C_c	10/07/2013 14:30	After thermal equilibrium at stage 3	26.2
C_d	11/07/2013 11:54	End of test C	23.1
C_e	30/07/2013 10:07	19 days after end of test C	29.8

Table 9. Total pile head load, pile shaft load and pile base load in tests A, B, C, E (2nd cycle, point E_{2e}; 12th cycle, point E_{12e}), compared to pile ultimate bearing capacity, base resistance and shaft resistance (CAPWAP).

CAPWAP	Shaft resistance (kN)	Base resistance (kN)	Total bearing capacity (kN)
	711.3	1800	2511.3
	Shaft load (kN)	Base load (kN)	Total head load (kN)
Test A (VWSG)	412	588	1000
	58%	33%	40%
	S.F. = 1.7	S.F. = 3.1	S.F. = 2.5
Test B (VWSG)	455	545	1000
	64%	30%	40%
	S.F. = 1.6	S.F. = 3.4	S.F. = 2.5
Test B (OFS)	395	605	1000
	55%	34%	40%
	S.F. = 1.8	S.F. = 3.0	S.F. = 2.5
Test C (OFS)	70	930	1000
	10%	52%	40%

	-	S.F. = 1,9	-
Test E E2e (OFS)	307	693	1000
	49%	39%	40%
	-	C.S. = 2,6	-
Test E E12e (OFS)	280	720	1000
	40%	40%	40%
	-	C.S. = 2,5	-

Table 10. Maximum axial load registered in the pile during tests C and E, and corresponding depth.

Test	Maximum axial load (kN)	Depth (m)
Test C (VWSG)	1283	3,6
	1283	10,4
Test C (OFS)	1432	3,6
	1416	12,0
Test E cycle E_{2e} (VWSG)	1054	3,6
	1076	10,4
Test E cycle E_{2e} (OFS)	1097	3,6
	1097	12,0
Test E cycle E_{12e} (VWSG)	1114	3,6
	1100	10,4
Test E cycle E_{12e} (OFS)	1122	3,6
	1129	12,0