Impact of temperature cyclic variations on bearing capacities of a sensitive soil

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Abstract. The incorporation of heat exchangers in geostructures produces a cyclic variation of the temperature in the adjacent soil. Therefore, there are important questions about the effect of temperature variations on hydro-mechanical soil parameters. In this study, the mini-pressuremeter tests were conducted in laboratory on a homogeneous material submitted to different thermal loading (1 to 40 °C). The tested material, an illitic soil, is compacted in a thermo-regulated container at optimal water content (31.3 %) and 90% of maximal dry density (1.29 Mg/m^3). Only six tests are performed in each container to prevent edge effects and the influence between the tests. The impact of temperature variation on creep pressure (p_f), limit pressure (p_l) and pressuremeter modulus (E_p) were determined. A decrease in creep pressure and limit pressure with increasing temperature was observed, while the variation of pressuremeter modulus was less pronounced. The first cycle induced more important parameter variations than the subsequent cycles.

Keywords. Geothermal energy, Laboratory tests, Pressuremeter, Temperature, Compacted soils, Illite.

1. Introduction

The incorporation of heat exchangers in geostructures leads to a temperature variation in the adjacent soil over a range from 4 to 30 °C [1].Consequently, there are important questions about the effect of temperature variations on hydro-mechanical soil properties and load transfer in the pile.

In the case of energy piles, on the one hand, the thermal expansion or contraction of the pile causes additional thermal stress in the pile which can influence the load transfer, and consequently the skin friction and the end bearing [2], [3]. On the other hand, the cyclic thermal variation imposed to the soil may affect its hydro-mechanical properties. Thus, the behaviour of an energy pile is directly related to the coupling of thermal, hydraulic and mechanical phenomenon.

Different in situ and laboratory studies were conducted to study the behaviour of energy piles and their thermo-mechanical response [4]–[8]. In all these studies, the effect of temperature on the soil parameters has been neglected. However, a thermal variation may have an impact on the shear strength, yielding and critical-state soil properties [9]–[14]. This phenomenon, named the thermal softening, may have an impact on the bearing capacity of the pile. The bearing capacity calculations of deep foundations are actually based on pressuremeter or penetrometer testing results. In this study, the mini-pressuremeter tests were conducted in laboratory on a solid submitted to different thermal loading (1 to 40 °C). Thus, in this study, a mini-pressuremeter test adapted from the pressuremeter test, is used to quantify the temperature effect on the mechanical behavior of the soil.

In the following sections, the material and the developed experimental device are first described. Then, the results are detailed and the impact of thermal variations on the pressuremeter parameters is discussed.

2. Material and method

In this part, the studied material is first presented, then experimental device is described and finally the mini-pressuremeter tests are detailed.

2.1. Basic characterization of the material

The tested material is an illitic soil named Arginotech® that contains 77% illite, 10% kaolinite, 12% calcite and traces of quartz and feldspar according to the furnisher. Mini-penetration tests, realised on this soil by Eslami et al. [15] showed the sensitivity of this material to thermal variations.

The particle-size distribution of the soil was determined using a laser Malvern Mastersizer 2000® device (Figure 1a). Almost 85% of the particles of the illitic material are smaller than 0.002 mm (clay particles). Its liquid limit (LL), its plastic limit (PL) and its plasticity index (PI) are 65%, 34%, and 31% respectively [16]. A optimum water content of 31.3% and A maximum dry density of 1.43 Mg/m^3 are obtained standard Proctor curve for the material [17] (Figure 1b).

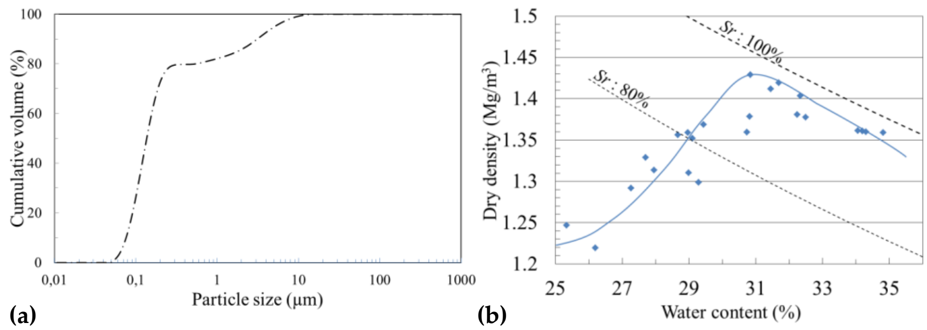

Figure 1. Characteristic of the studied illitic soil: a) particle size distribution and b) compaction curve, S_r: The degree of saturation.

2.2. Experimental device and methods

To perform mini-pressuremeter tests at controlled temperatures, an homogeneous solid with a large volume is required as well as an experimental device to impose thermal variations to the solid. In this part, the developed methodology to obtain a meter-scale solid with homogeneous properties (temperature, water content and dry densities) is described.

First of all, water is added to the material in a large capacity fixed-speed mixer (38 rpm) in order to reach the target water content (w_{OPN} = 31.3%). The wet material is stored in 8 plastic drums for a minimum period of 5 days to ensure a good homogenization. A pneumatic compactor is used to compact the material in a cylindrical stainless steel container of 800 mm in height and 600 mm in diameter (Figure 2a). The compactor applied dynamic forces on a metallic plate of 4 mm in thick and 600 mm in diameter to allow a homogeneous compaction. The results of the preliminary series lead to the choice of a compaction in 11 layers of 70 mm in thickness.

A stainless steel tube is welded to the outside of the container. Insulating sleeves are placed on the tube in order to reduce heat exchange with the surrounding atmosphere. The top of the massif is insulated with a plastic film to preserve the initial water content. Finally, the assembly is placed in a box made of extruded polystyrene plates of 40 mm thick to reinforce the insulation. The stainless steel tube is connected to a thermoregulator to allow the circulation of an ethylene-glycol water solution at the target temperature in the tube (1 to 40 °C). Figure 2b shows the total parts of the developed experimental device in order to perform the mini-pressuremeter tests.

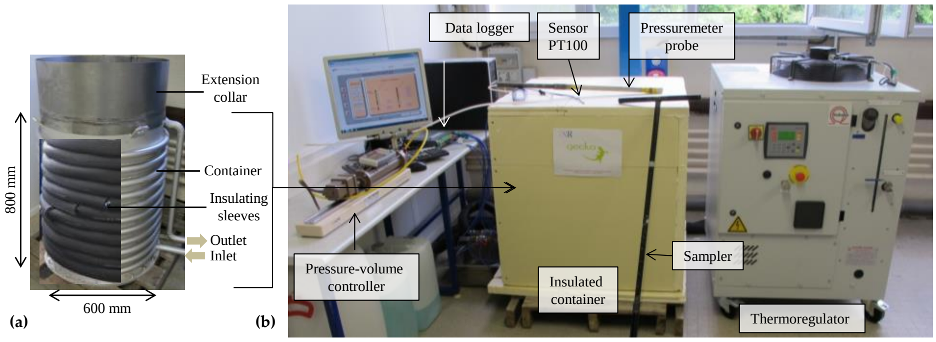

Figure 2. (a) Thermo-regulated metric scale container; (b) Total parts of developed experimental device.

Seven thermal sensors PT100 are positioned within the solid at various depths and various distances from the wall of the container. The sensors are plugged to a data logger in order to monitor the temperature evolution inside the compacted soil during the temperature variations.

2.3. Mini-pressuremeter tests

Only six mini-pressuremeter tests are performed in each solid to prevent edge effects and cross-influence between the tests. The test points are positioned on a concentric circle twice smaller than the container (Figure 3). The pressuremeter tests are conducted with an APAGEO® mini-pressuremeter probe of 380 mm in height and 28 mm in diameter. Before each pressuremeter test, a core with a diameter equal to the mini-pressuremeter probe is made using a core sampler. The 630 mm core is divided into smaller pieces to measure the water content and the density of the material as a function of the depth. The center of the probe is positioned in the middle of the height of the compacted soil (385 mm). The probe is connected to a pressure-volume controller brand GDS®. The pressure controlled test consists in applying increasing pressure with equal increments of 25 kPa for at least 1 minute. The equilibrium volume is measured for each increment and the volume versus pressure curve is plotted. The test is stopped when the imposed volume reached 140,000 mm^3.

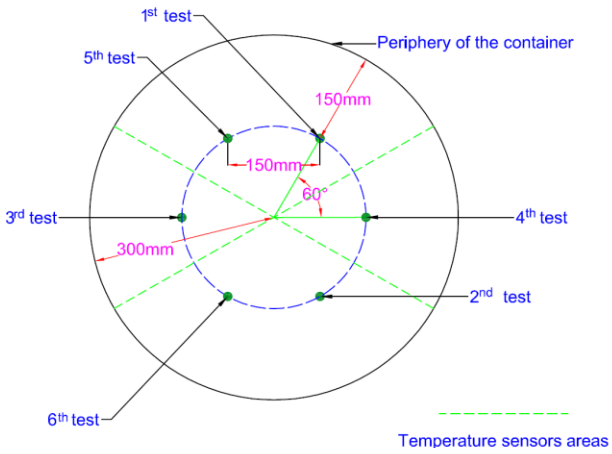

Figure 3. Positions of the test points and thermal sensor in the solid.

Immediately after the pressuremeter test at a given temperature, the borehole is filled with the same material, at the same water content, to avoid influencing the following tests. The effect of temperature variations on the resistance of the mini-pressuremeter membrane is measured by placing the probe in a climatic chamber at a given temperature during the calibration test of the membrane resistance.

3. Results

In the framework of our project, a preliminary series and four test series (six pressuremeter tests for each series) are conducted. In this paper only the two last test series, which aim to quantify the effect of a cyclic thermal variation on the pressuremeter parameters, are presented. The performed tests in each solid are numbered as follows Xx; with X, the massif temperature when performing test (i.e. 1, 20 or 40 °C) and x, the test index that increments for each new test at the same temperature.

The results of the preliminary test series show a good repeatability of the tests and allow estimating the uncertainty of each measured parameter according to the Student's t-distribution for a 90% accuracy: E_p: ±10%, p_f: ±5%, p_l: ±5%.

The selected test series, named series I and series II, consists in tests at 20, 1 and 40 °C. The initial temperature of the massif is 20 °C and the massif was successively brought to 1 and 40 °C, each step lasts at least 70 hours (**Figure 4** and **Figure 5**). The thermal equilibrium is reached for each step before performing the mini-pressuremeter test.

The Table 1 and the Table 2 present all the obtained parameters and properties. The average water contents and the average dry densities variations according to the thermal solicitation are lower than 1%: the solids are homogeneous.

The mini-pressuremeter tests are conducted at the end of the selected steps as shown in the Figure 4 and Figure 5. The pressuremeter curves (Figure 6) are consistent with the three pressuremeter domains. A softening takes place after heating the solid at 40 °C and a hardening is observed after cooling it at 1 °C, whatever the order of testing.

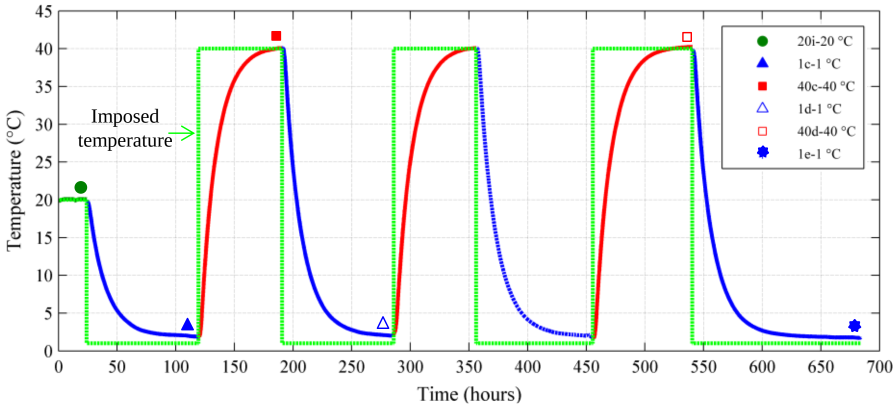

Figure 4. Temperature variation at 150 mm from the edge of the solid and the chronology of series I.

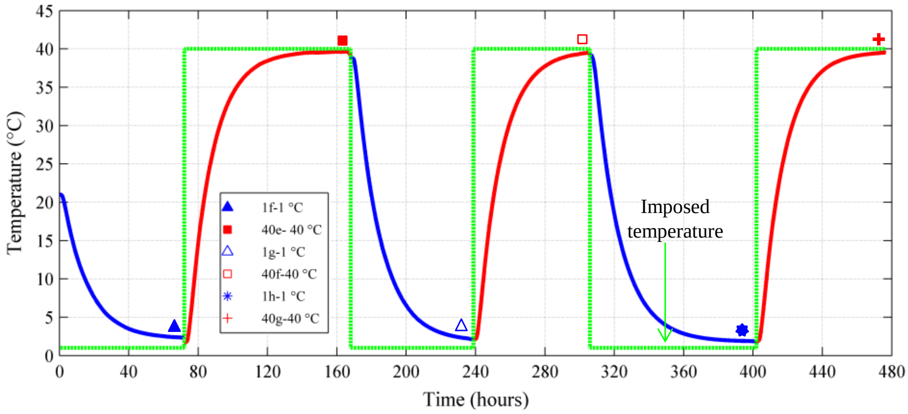

Figure 5. Temperature variation at 150 mm from the edge of the solid and the chronology of series II.

Table 1. Pressuremeter parameters for the series I: temperature cycling (20-1-40-1-40-1-40-1 °C).

Test	Temperature (°C)	w (%)	ρ_d (Mg/m3)	p_f (kPa)	p_l (kPa)	E_p (MPa)
20i	20	31.4	1.25	103	240	5.51
1c	1	31.4	1.26	124	303	5.73
40c	40	32.1	1.25	125	236	7.68
1d	1	31.7	1.25	123	337	4.16
40d	40	31.5	1.28	143	270	6.85
1e	1	31.6	1.24	133	310	5.66

Table 2. Pressuremeter parameters for the series II: temperature cycling (20-1-40-1-40-1-40 °C).

Test	Temperature (°C)	w (%)	ρ_d (Mg/m^3)	p_f (kPa)	p_l (kPa)	E_p (MPa)
40e	40	31.2	1.30	174	305	6.24
1g	1	31.5	1.24	170	357	6.97
40f	40	31.2	1.28	170	307	6.18
1h	1	31.0	1.24	160	344	6.16
40g	40	31.1	1.25	153	276	5.76

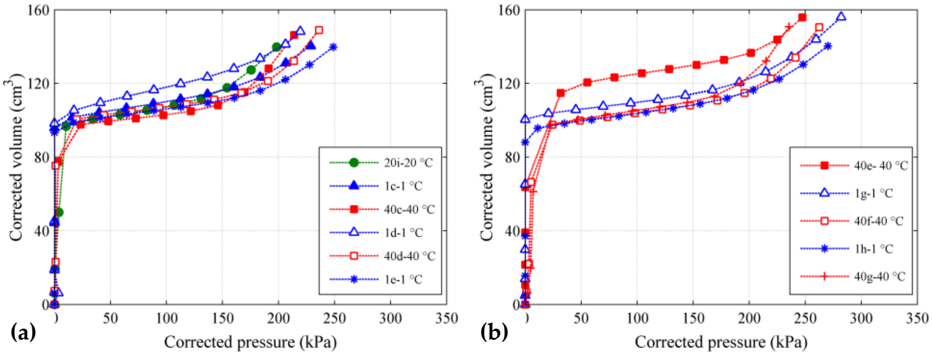

Figure 6. Pressuremeter curves: (a) series I; (b) series II.

The pressuremeter parameters are calculated for each step of each series and presented in Figure 7. In series I, p_f increases slightly with cooling the massif from 20 to 1 °C, then it remains almost constant with cycles of cooling/heating (1-40-1 °C). p_l increases with heating and decreases with cooling. In series II, the first value at 20 °C was not acquired and the test 1f was inoperable; in Figure 7, the values are estimated according to the similarity between series I and series II. The hypothesis states that the relative difference between 40c parameters and 1c parameter is the same than between 40e parameters and 1f parameters. The same method was used to place 20j parameters.

The parameters evolution these two series are compatible. After the first thermal cycle, the evolution of p_f over the imposed thermal variation is under the parameter uncertainty; this parameter reaches a stable value (Figure 7a, b). The evolution of p_l is slightly different, the thermal impact remains measurable even if its impact is totally reversible. Its evolution rate is estimated at 1.5 kPa/°C in the studied temperature range (1-40 °C) (Figure 7c, d). These results are consistent with the contraction of the elastic domain (yield locus) with the increasing temperature is shown in the literature with oedometric or triaxial tests for various clay materials [9]–[14].

The variation of E_p with temperature is lower than the other pressuremeter parameters (Figure 7e, f). The E_p evolution for series I solid seems not relevant because its evolution is erratic. On the contrary, a slight E_p decrease, consistent with the previous tests, is measured when series II is warmed.

4. Conclusions

The objective of this paper is to quantify the effect of cyclic temperature variations on parameters linked to the pile design. A protocol allowing the realization of mini-pressuremeter test in laboratory conditions was developed. The evolution of the pressuremeter modulus (E_p), the creep pressure (p_f) and the limit pressure (p_l) were measured according to the temperature variations on a soil selected for its high sensitivity to temperature variations.

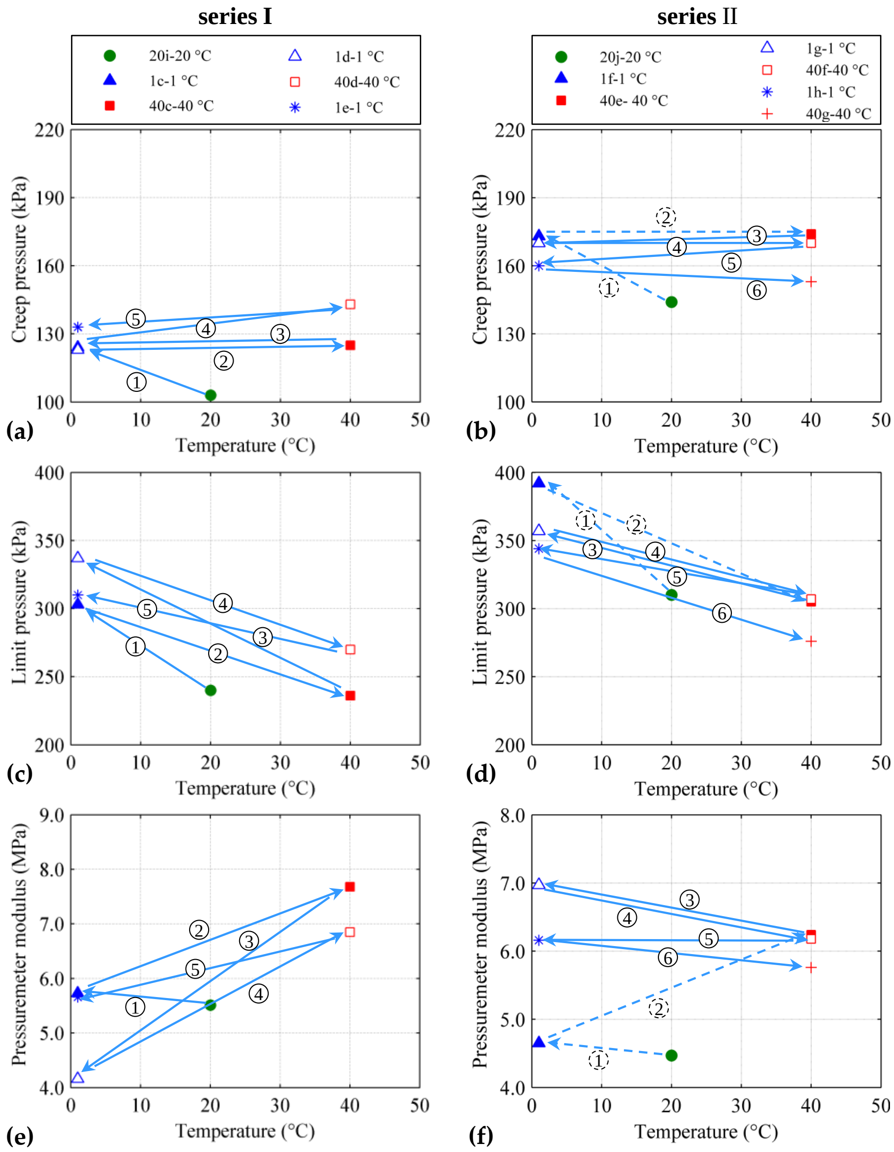

Figure 7. Variation of creep pressure (p_f) (a-b), limit pressure (p_l) (c-d) and pressuremeter modulus (E_p) (e-f) with temperature for series I and II. Dotted lines correspond to estimated parameters.

The results of the mini-pressuremeter tests on the compacted illitic soil showed a decrease in the creep pressure and the limit pressure as temperature increases (thermal softening), while the variation of the pressuremeter modulus is less significant, probably due to the sensitivity of this parameter to the test conditions. For the following cycles, the effect of the temperature variation is lower. After more than one cycle, p_f seemed to reach an equilibrium value independent of the temperature. The p_l keeps its temperature dependence beyond the 1st cycle but it evolution is reversible and the evolution rate is 1.5 kPa/°C in the studied temperature range (1- 40 °C).

The limit pressure is the key parameter of calculating ultimate load of piles, so the evolution of this parameter with temperature variation would be taking into account to calculate the bearing capacity of geothermal piles built in sensitive soils.

5. ACKNOWLEDGEMENTS

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