# In Situ Measurement of Soil Thermal Properties. A New Prototype

*Angel Garcia-Fontanet[1*], Enrique Romero[2], Pedro Jiménez[1], Nuria Sau[2], Fernando Sossa[1]*

*[1]PRO GEO – Consultores Geotécnicos Asociados SL, Riera de Cassoles 20 2A, 08012 Barcelona, Spain*
*[2]CIMNE. Edifici C1-Campus Nord UPC. Gran Capità s/n. 08034 Barcelona Spain*
*[#]Corresponding author: agfm@progeo-cga.com*

## ABSTRACT

As part of the THERMALTUNNEL R&D, partially funded by Centro para el Desarrollo Tecnológico e Industrial (CDTI), a Spanish Ministry of Science and Innovation agency, PRO GEO has developed a soil penetration prototype that measures soil temperature and the thermal properties of the ground (thermal conductivity and specific heat) at different depths. The prototype is the size of a conventional CPT and contains an internal heat source with local thermocouples. A data acquisition system measures the temperature both in the prototype itself and in the surrounding ground through a penetration needle protruding from the main body of the prototype.

The thermal parameters are determined by analyzing the measured heating and cooling temperature curves using the finite element codes CODE_BRIGHT (Olivella et al., 1993) and G-PFEM (Monforte, 2018). In this later numerical code, a thermal analysis module has been incorporated within the framework of the project.

The operation of the prototype has been satisfactory in laboratory tests through a calibration chamber setup with granular soil under different controlled conditions of water saturation and porosity to assess the impact of those variables on the obtained values of soil thermal conductivity and specific heat. The back-analyzed parameters from the calibration chamber results have been compared with point tests (thermal conductivity and specific heat tests).

The project has been developed with the cooperation of CIMNE – International Centre for Numerical Methods in Engineering.

**Keywords:** ISC7; geothermal energy; in situ testing; soil thermal characterization; THM coupling

## 1. Introduction

This paper presents the preliminary design of a new probe prototype intended to evaluate the thermal properties (basically thermal conductivity and specific heat) in low-rigid soils that could be inspected from a geotechnical point of view with a static penetrometer (CPT).

At present, the thermal capacity of the ground is evaluated in a standard way with the Thermal Response Test, also known as TRT (Ghelin, 2002). Although it is a reliable test and it is widely used by the geothermal industry, it has the disadvantages related to its high cost and duration (usually on the order of 36 hours). The prototype that is presented in this paper tries to reduce the time of an eventual characterization and that the same can be carried out within the framework of a geotechnical survey.

## 2. Probe's concept

The prototype has the external appearance of a CPT and has an external steel casing.

The probe is driven into the ground at a constant speed up to the test depth. Once it is reached, a heat source powered by electrical energy is activated. This causes an increase in the temperature of the prototype and the surrounding terrain. The power of the heat source is regulated in such a way that the prototype reaches a temperature of 70 degrees Celsius within 20 minutes.

Once this temperature is reached, it remains constant and the heating process continues for 4 hours. Once this period has elapsed, the heaters are turned off, starting the cooling process of the probe and the surrounding ground.

During this non-isothermal process, a continuous measurement is made of the temperature of the probe and at various points of the ground located below the tip of the probe. The temperature measurement at various points on the ground located below the tip of the probe is achieved by means of a retractable element, housed inside the probe, which has a thermocouple at the tip.

An image of the probe is shown in Figure 1. As a result, the probe has the following components:

- A steel case.
- An electric thermal source.
- A set of hydraulic engines that allow the probe penetration in the soil and the extension of the monitoring elements.
- A set of thermal monitoring elements.
- A data recording system.

The result of the test is a set of time-temperature curves, which collect the readings from the different temperature sensors arranged in the probe and at various points on the ground under the tip. This information, together with the time-power curve of the heat generation source, allows the thermal parameters of the soil to be determined with the help of numerical methods.

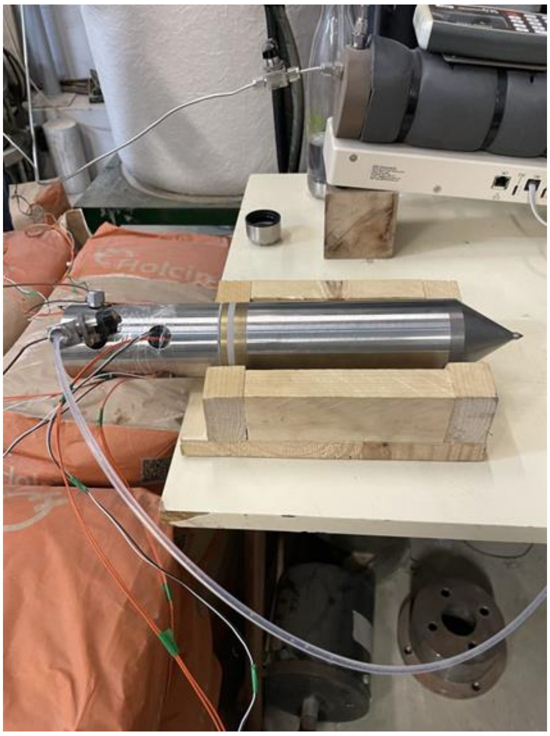

**Figure 1.** Image of the thermal probe.

## 3. R&D Project organization

The R&D project has been organized as follows:

- A set of numerical simulations has been carried out to determine the necessary features of the prototype and, in this way, have a basis for its design.
- Next, the design and construction of the probe prototype was carried out. This part of the process has been divided into two stages: firstly, the construction of a first prototype with the mechanical capabilities (penetration in the ground and deployment of the different auscultation devices at a certain distance from the tip of the probe) and, a once validated, the development of a second version in which thermal capacities (heating elements) and monitoring (measurement of probe and ground temperature) were incorporated.
- Finally, the operation of the probe prototype has been verified in the geotechnics laboratory of the Technical University of Catalonia.

The most relevant features of each step are explained below. No technological details of the probe design are given due to intellectual and industrial ownership requirements.

## 4. Numerical modelling

First, a numerical modelling of the test process was carried out using the finite element method. On the one hand, analyses were carried out with the CODE_BRIGHT program, capable of reproducing thermo-hydro-mechanical (THM) processes in partially saturated soils. In this case, a "wish in place" modelling was carried out, where the probe is already located at a certain depth and the penetration process is not reproduced. In figure 2 results from CODE_BRIGHT simulation are shown.

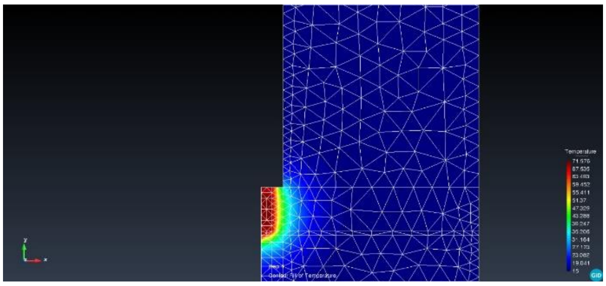

**Figure 2.** Temperature contours after 2 hours heating (CODE_BRIGHT)

On the other hand, it was considered interesting to reproduce the process of penetration of the probe into the ground, which implies the displacement of the ground by this element. This involved considering the regime of large deformations and the fact that the penetration process modified the geometry of the problem. For this purpose, the finite element code G-PFEM, developed by CIMNE, was used. As part of the R&D project, the thermal module was included in the program. Thus, the G-PFEM code was able to solve THM problems, although only for the saturated soil situation. In figure 3 results from G-PFEM simulations are shown.

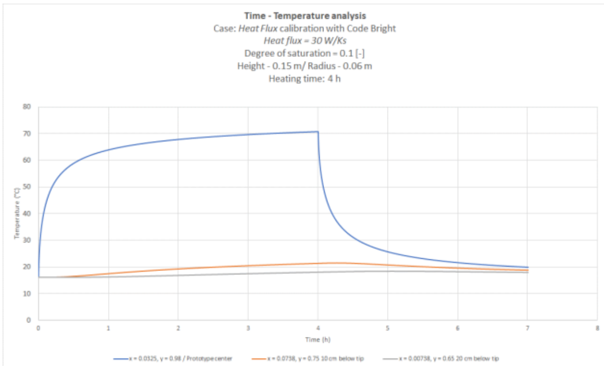


**Figure 3.** Temperature evolution in the probe (blue) and below the probe tip at 20 cm and 30 cm (orange and grey respectively).

The numerical simulations have been carried out considering the normalized quartzite sand supplied by the HOLCIM company, due to its homogeneous mineralogical composition and particle size distribution (0.2-0.6 mm).

A set of laboratory tests were carried out in UPC laboratory. Those tests were aimed to determine thermal conductivity, specific heat, and water retention curve.

A solid phase thermal conductivity of 7.7 W/m$^2$ K was obtained, together with a solid phase specific heat of

748 J/kg K. Solid particle density was estimated in 2650 k/m$^3$. Therefore, the obtained values are in good agreement with the technical references (De Vries, 1963).

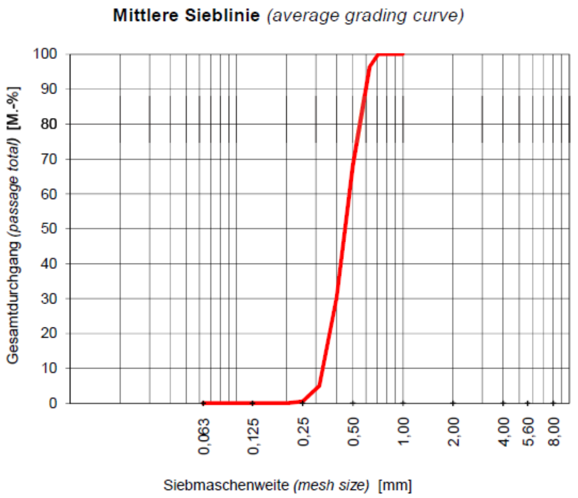


**Figure 4.** Particle size distribution. Holcim sand.

Water retention curve was parametrized with a van Genuchten (1980) model. In the laboratory tests, a desaturation suction of 2 kPa was obtained from lab tests, together with a residual degree of saturation of 2.4%. Test results are shown in figure 5.

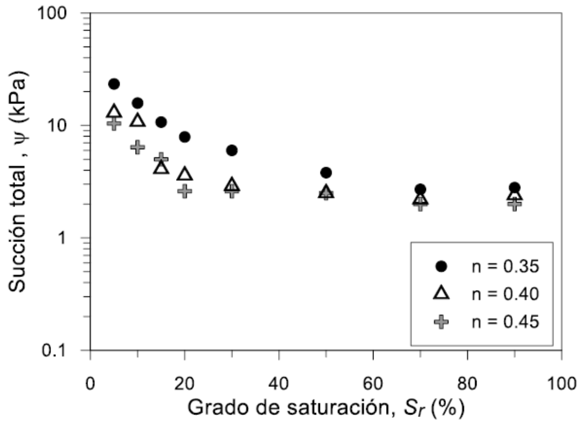


**Figure 5.** Water retention curve (degree of saturation-matric suction). Holcim sand.

This sand is the one that will be used in the laboratory tests described in the next section. In addition, numerical simulations were carried out with an initial porosity of 0.35 and four cases of degree of saturation: 0.1, 0.5, 0.9 and 1.0.

Full saturation conditions were simulated both with CODE_BRIGHT and G-PFEM codes, while the partial saturation conditions were only simulated with CODE_BRIGHT.

As it could be expected, as the degree of saturation increases, also does the thermal conductivity, because of air poor conductivity. Consequently, for increasing degrees of saturation it is necessary to increase the power applied to achieve an appreciable change in the temperature field of the ground.

To achieve meaningful results under a wide range of soil saturation, numerical simulations showed that a maximum electrical power of 200 W was required.

## 5. Prototype experimental tests

Once the different versions of the prototype were built, they were tested in the geotechnical laboratory of the UPC, with the aim of verifying the correct functioning of the different functionalities: mechanical penetration capacity of the probe and the extensible elements, as well as the electrical system and temperature measurement.

The tests were carried out in a reinforced polyester tank with a truncated cone shape, with a lower diameter of 0.59 m and an upper diameter of 0.68 m, with a height of 0.86 m. This container was filled with Holcim sand, which was compacted with a conventional needle vibrator for concrete. In each test, the porosity was calculated and the amount of water necessary to achieve the target degree of saturation was added.

An INSTROM press with a thrust capacity of 2000 kN was used as a thrust element.

An image of the tank filled with sand and the INSTROM press is shown in figure 6.

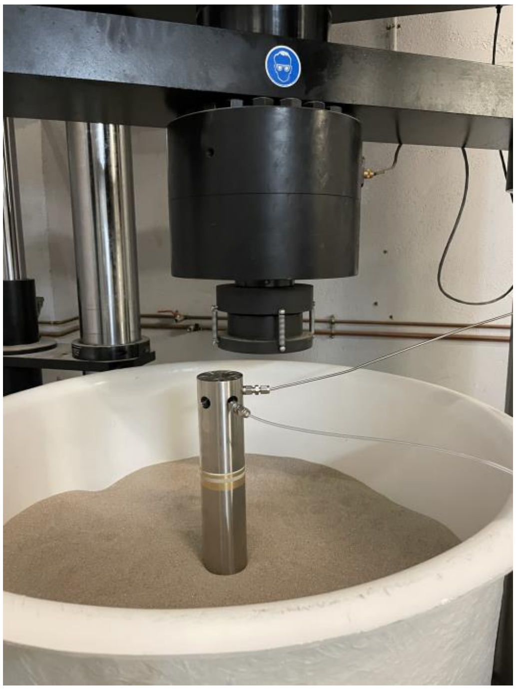

**Figure 6.** Sand container with prototype and INSTROM press.

In the first stage of testing, aimed at checking the mechanical behavior of the probe, it was found that the probe penetrated well into the ground and that the retractable element was deployed correctly and that it was housed normally again inside the probe. In figures 7 and 8 it is respectively shown an example of the stress penetration of the probe and the tip measurement extension.

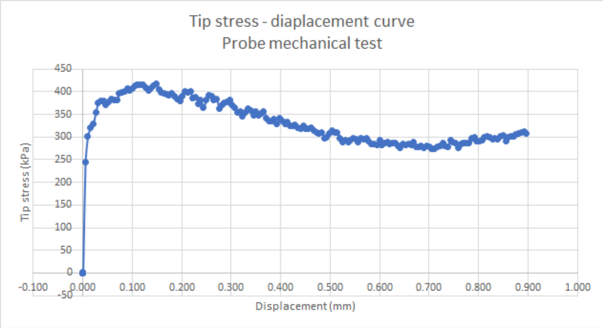


**Figure 7.** Displacement – penetration stress for the probe.

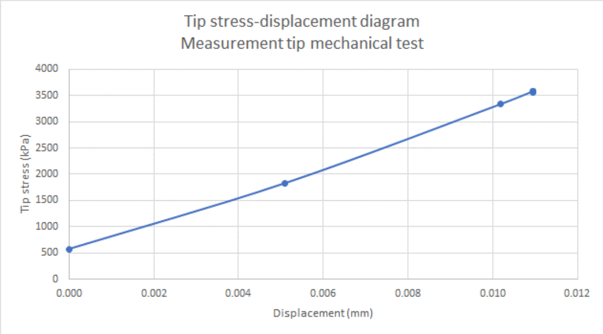


**Figure 8.** Displacement – penetration stress for the measurement tip.

In a second stage, the heat generation and temperature measurement functionalities in the probe and in the field were checked. Due to the practical difficulty of handling a mass of completely saturated sand in the laboratory, the tests were carried out with degrees of saturation 0.40 and 0.60.

A power of 200 W was applied to the heaters, as predicted by the numerical simulations, until they reached a temperature of 73-74 ºC, sufficient for the probe-soil contact to be at a temperature of 70 ºC, as also was predicted by the numerical simulations.

The initial soil temperature was 25 ºC, consistent with that existing in the test room at the time the test was carried out, and somewhat higher than that which usually exists on the ground in the Mediterranean area (16 ºC). It is understood that this difference does not represent a significant problem in the experimental validation process of the probe prototype.

In the tests it was found that, for a power of 200 W, it was necessary to increase the duration of the test to 6 hours, instead of the 4 hours initially planned, with the technical alternative of increasing the power to avoid this extension of the heating period. However, good performance of the prototype could be confirmed, with behaviour very similar to that predicted by the numerical simulations (see figures 9 and 10). Specifically, it is observed that the measuring element, located 20 cm from the tip of the probe, measures an increase of 5 ºC, consistent with the modelling results and sufficient to estimate the ground thermal parameters.

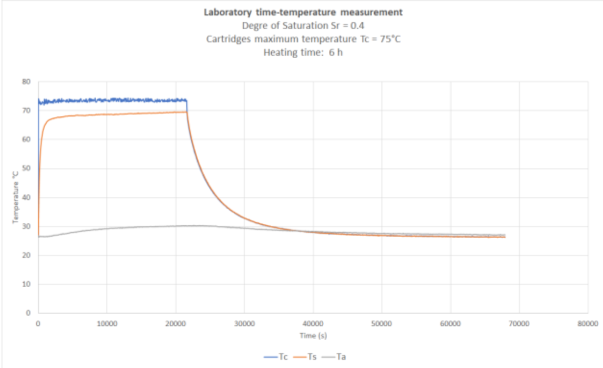


**Figure 9.** Laboratory test temperature time evolution. Saturation degree: 40% (in blue, heater, in orange probe-soil contact and in grey measurement tip).

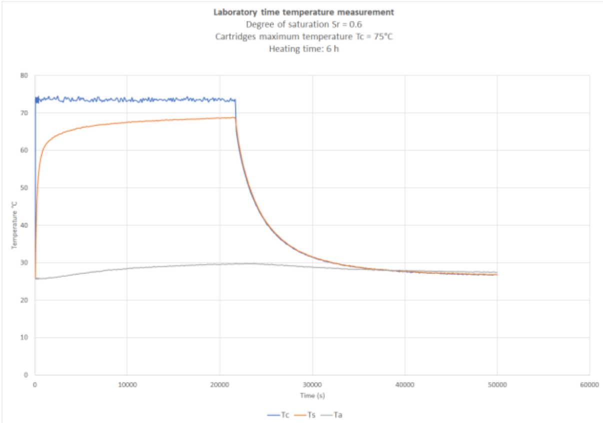


**Figure 10.** Laboratory test temperature time evolution. Saturation degree: 60% (in blue, heater, in orange probe-soil contact and in grey measurement tip).

## 6. Future tasks

Once the satisfactory behaviour of the prototype and the consistency of the results between the numerical simulations and the experimental results have been verified, it is considered necessary to deepen the following aspects:

- Improvement of the thrust equipment to ensure that the probe can reach depths of the order of several tens of meters.
- Test the behaviour of the probe under more heterogeneous ground conditions.

Some of those advances are currently being carried out in the framework of the R&D project.

## 7. Conclusions

The results presented above show a correct operation of the prototype, although work must continue on several aspects such as: a possible reduction in the duration of the test, the ability to work at depths of several tens of meters or the verification in soils that have a greater degree of heterogeneity.

## Acknowledgements

The authors are grateful for the financial support provided by funding agency CDTI. In addition, they want to express their gratitude to Prof. Marcos Arroyo and CIMNE researcher Dr. Luis Monforte for the implementation of the thermal formulation in G-PFEM code. Finally, we want to thank the companies Talleres Torrecillas and the company Bosso Engineering SL for their assistance during prototype construction.

## References

De Vries, D. A. (1963). “Thermal properties of soils.” *Physics of the plant environment*, W. R. Van Wijk, ed., Wiley, New York, 210–235.

Gehlin S. 2002. *Thermal Response Test, Method Development and Evaluation*. PhD Thesis. Luleå University of Technology. Sweden.

Monforte, L. 2018. *Insertion Problems in Geomechanics with the Particle Finite Element Method*, PhD Thesis. Technical University of Catalonia (UPC). Spain.

Olivella, S. Carrera, J., Gens E., Alonso E.E. 1993. “Non-isothermal Multiphase Flow of Brine and Gas through Saline Media.” Transport in Porous Media, volume 15: 271-293.