Measurement of soil temperature with depth using multiple sensor arrays

Marialetizia Zizzi*, *Gaetano* Elia, *Osvaldo* Bottiglieri, *Federica* Cotecchia

Technical University of Bari DICATECh, Via Orabona 4,70125, Bari, Italy
**Corresponding author: marialetizia.zizzi@uniba.it*

ABSTRACT

Accurate measurement of soil temperature is essential for the diagnosis of various environmental processes and their impact on ecosystems. Indeed, continuous monitoring of temperature profiles with depth provides valuable understanding of the soil thermal response, which could support studies related to climate change, hydrology, agriculture, and geothermal energy. The paper describes an innovative installation procedure of temperature strings (CS225) to measure the temperature field of an undisturbed soil deposit at different depths in real time. The strings consisted of multiple temperature probes connected in series, placed at specific depths within the soil profile. The CS225 probes require little maintenance and no initial calibration, guaranteeing a high accuracy and resolution of the temperature measurements.
The initial field measurements have shown a good performance of the probes, which have been able to detect the gradual decrease of soil temperature and the reduction of oscillations with depth. Further research will include the detailed analysis of the influence of ambient wind speed, solar radiation and soil moisture on the heat transfer from the ground surface to the deeper soil layers, as well as laboratory tests and numerical analysis.

Keywords: thermal site characterization; temperature strings; in-situ monitoring.

1. Introduction

The acquisition of ground temperature data is essential in different fields, such as geotechnical engineering, hydrology but also in environmental sciences and agriculture.

From a phenomenological point of view, it is well known that, at the surface level, the ground temperature is influenced by factors such as solar radiation, ambient air temperature and soil cover type (Shah et al., 2019). These factors impact the rate of heat exchange between the atmosphere and the soil surface. However, it is important to note that the soil temperature exhibits consistent variation within the shallow layers of the soil deposit, up to 1 meter from the ground level. Moving to lower depths (between 1 and 8 m b.g.l.), the temperature fluctuation reduces. In the deeper zone, from a depth of approximately 15-20 m, the ground temperature remains relatively constant, equal to the annual mean air temperature, usually called “undisturbed ground temperature” (UGT).

Referring to slope stability, soil temperature in the shallow layers could influence the evaporation rates and soil infiltration capacities, which impact the water balance at both shallow and larger depths. Consequently, the thermo-hydro-mechanical constitutive properties of the materials, as well as the soil cover type, are of key relevance for the analysis of weather-induced landslide activities (Stasi et al., 2022). Accurate temperature measurements may also help in the estimation of the evapotranspiration rates and for the modelling of water flow processes.

Moreover, the UGT is a critical parameter in the design of ground heat exchangers, in the context of shallow geothermal systems. Several methods are available for the estimation of UGT, the best known being the thermal response test, or TRT (Gehlin and Nordell, 2003). The test represents also a good method to determine the ground thermal properties, such as the in-situ soil thermal conductivity.

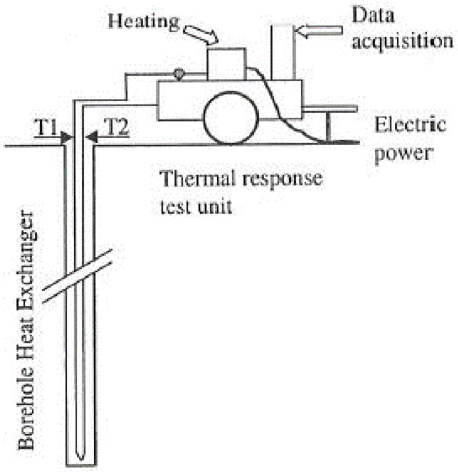

Figure 1. Thermal Response Test equipment (Gehlin and Nordell, 2003).

The test equipment comprises a U-tube borehole heat exchanger, connected to a circulating pump and a heating system (Fig. 1). The method is based on reaching the thermal equilibrium between the borehole fluid and the surrounding ground. UGT is derived by circulating a carrier fluid through the heat exchangers, without switching on the heating system. Temperature measurements of the outlet fluid are recorded by a data-logger every minute throughout the test. To be representative, the test must last approximately 7 days (Matsson et. al., 2007). Even without pumping out the heat during the whole procedure, a little amount of heat will be gained during the test due to the operation of the circulating pump, thus leading to an overestimation of the UGT (Gehlin and Nordell, 2003). Thus, a direct measurement of UGT through temperature probes in the soil deposit can eliminate the uncertainties related to the widely used TRT system, leading to a correct design of ground heat exchangers.

This paper describes the installation of temperature strings into an undisturbed soil to measure the temperature field up to 15 m depth in real time and presents the first acquired measurements.

2. The geo-mechanical contest of the test site: the Pisciolo hillslope

The test site, named “Pisciolo slope”, is located on the right bank of the Ofanto river, within the territory of the municipality of Melfi (PZ). The area of the hillslope, characterized by landslide processes, extends longitudinally from an elevation of 250 m to approximately 510 m above sea level, with an average slope of 12%. Within this area, 14 landslide bodies were identified by Cotecchia et al. (2014), which interact with strategic infrastructures at the toe of the slope, including an underground water supply pipeline (Fig. 2).

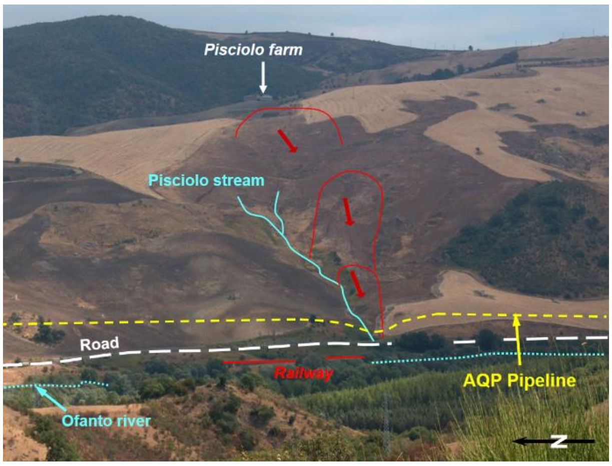

Figure 2. The Pisciolo hillslope (Cotecchia et al., 2014).

To mitigate the risk of compromising the water supply, due to repeated displacements of the pipeline at depth, a campaign of in-situ geotechnical investigations and laboratory tests was conducted in 2019, aimed at designing landslide mitigation measures. To this aim, the reconstruction of the geomechanical and geomorphological characteristics of the slope, the study of the failure mechanisms and the subsequent monitoring of the landslide processes were accomplished. The slope was found to be affected by slope-vegetation-atmosphere interaction, which can cause an increase in piezometric loads at depth related to the rainfall events of the winter season. From a geological point of view, the hillslope is composed by sedimentary successions which have been deposited in a marine basin prior to the orogenic phase (Cretaceous–Miocene). In particular, the slope is made of structurally complex fissured clays (known as scaly clays), which have been characterized by Cotecchia et al. 2014, with occasional interbedded fractured rocks. The lithological-structural and geomorphological map reported in Fig. 3 (Cotecchia et al., 2014) shows the location of the three key soil complexes forming the slope. The top one is the Numidian Flysch, N, composed by quartz sandstones and clayey levels, while the bottom complex, R, is made of scaly clays of the Red Flysch formation, including a series of calcarenite blocks. The middle transition complex, T, i.e. the Paola Doce formation, is made of laminated fissured clays, locally silty or sandy, including disarranged rock blocks, from centimetres to metres thick. The rock inclusions and levels vary from being calcareous to silico-clastic when moving from the bottom to the top of the Paola Doce complex. Therefore, two sub-complexes could be distinguished within the transition complex: an upper zone (ST), rich in quartz sandstone interbedding, and the lower one (CT), less rich in rock intervals, that, in this case, are mainly calcareous. After the deposition and orogenic phase, these sedimentary successions experienced folding and faulting processes during the Apennine orogenesis. The samples tested in the laboratory by Cotecchia et al. (2014) were mainly retrieved from the clayey layers of either the ST or the CT transition sub-complexes, whose presence is dominant in the hillslope.

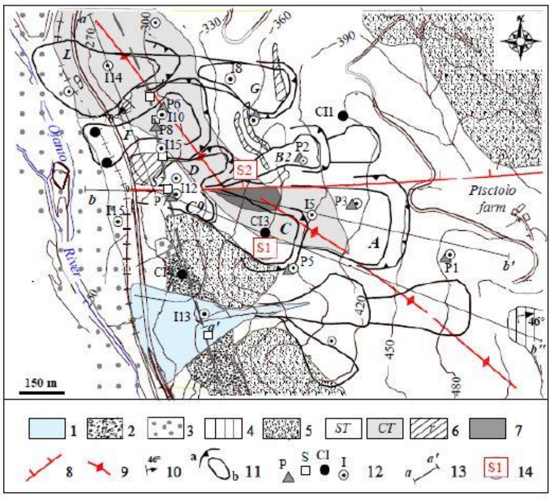

Figure 3. Schematic lithological-structural and geomorphological map of Pisciolo hillslope (Cotecchia et. al., 2014): 1) fan deposit; 2) debris deposit; 3) alluvial deposit; 4) Pliocene succession; 5) N Complex; 6) T Complex: ST-sandy sub-complex, CT-calcareous sub-complex, r-rocky strata 7) R Complex; 8) fault; 9) anticline axis; 10) attitude strata; 11) landslide: a-crown, b- body; 12) P: continuously cored borehole equipped with piezometers, S: GPS sensor; CI: continuous cored boreholes equipped with inclinometer casing, I: destructive borehole equipped with inclinometer casing; 13) section line 14) site of shallow sampling.

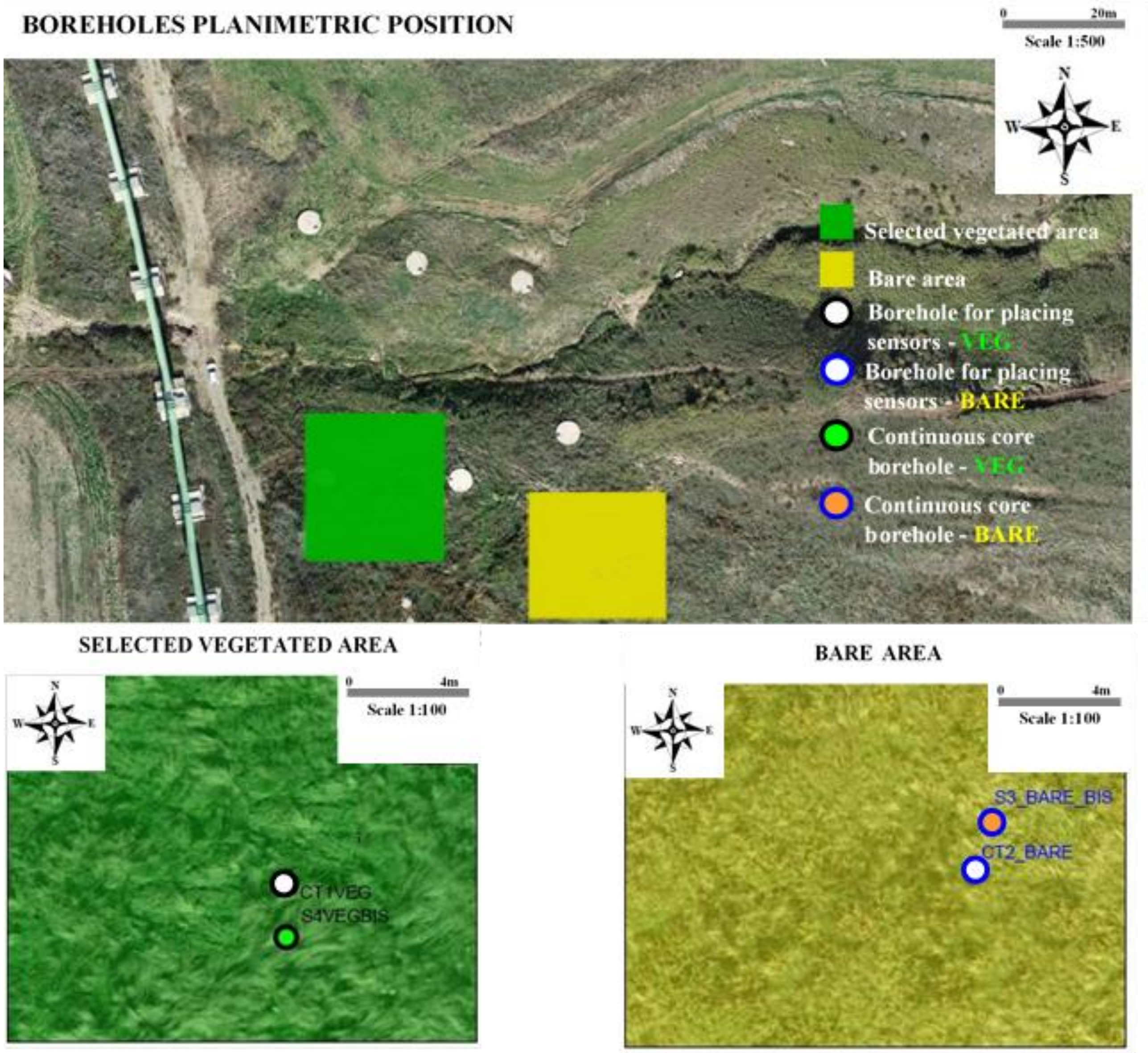

Figure 4. Planimetric view of the boreholes executed during the 2023 campaign.

As part of the slope-vegetation-atmosphere interaction study and with the aim of designing possible landslide mitigation measures, part of the slope was planted with deep-rooted crops (called, hereafter, selected vegetation) to determine the efficacy of the vegetation in modifying the hydraulic balance in the slope and reducing the amount of water infiltrating in the soil (Tagarelli and Cotecchia, 2022). All the variables governing the hydraulic balance were monitored (such as suction, volumetric water content, soil temperature, solar radiation, wind speed) through an advanced network of sensors and probes.

3. Upgrade of the monitoring system

In 2023, an upgrade of the monitoring system already existing in the Pisciolo test site has been designed to measure other soil state variables, such as the temperature, and use the site as a pilot case study for the thermal characterization of the soils at different depths. During this new campaign, two temperature strings manufactured by Campbell Scientific (named CS225) were installed along two boreholes, approximatively 50 m distant, one located in deep-rooted vegetation area and one in the bare area (Fig. 4). The sensors have been placed at 6, 9, 12 and 15m depth (CT1VEG and CT2_BARE). The field work has also involved the execution of two continuous core boreholes (up to 15m depth) for the geotechnical characterization of the soils (S4VEGBIS and S3_BARE_BIS). Four undisturbed samples have been retrieved from each borehole in the proximity of the temperature measurement points, at depths from 5.70 to 6.30 m, 8.70 - 9.30, 11.70 - 12.30, and 14.70 - 15.30 m. The eight samples will be used for an unconventional laboratory investigation, as described in last section of this paper.

4. Technical features of the CS225 probe

The CS225 temperature string (Fig. 5) operates with advanced digital sensor technology (Campbell Scientific, 2017). This temperature monitoring system is composed by temperature probes encapsulated within a robust steel-reinforced cable. Each CS225 unit is custom-manufactured, according to the specific requirements of the user.

Figure 5. CS225 temperature string (Campbell Scientific, 2017).

The CS225 is well-suited for a wide range of applications that necessitate temperature profiling. Its cable assembly is completely sealed, allowing for burial, submersion, or direct integration into structures. The CS225 temperature strings give accurate and stable measurements (Table 1).

Table 1. CS225 main features

Operating range [°C]	–55 to 85 °C
Accuracy	±0.2 °C over –40 to 85 °C
Resolution	0.0078 °C
Output protocol	SDI-12 1.3
Maximum cable length	152 m (500 ft)

The CS225 string uses the SDI-12 digital technology, which is a communication protocol designed for the purpose of facilitating the transmission of data from intelligent sensors used to monitor environmental parameters. These instruments are characterized by a low-power consumption (12 volts) and an easy utilization in remote locations. The protocol adheres to a client-server architecture, in which a data logger sends the request for data to the intelligent sensors, each sensor being uniquely identified by an assigned address. Temperature sensors with SDI-12 acquisition technology offer significant advantages over traditional analog-acquired thermocouples. In terms of precision, SDI-12 boasts a resolution of 12 bits or higher, eliminating the analog-to-digital conversion errors typical of thermocouples. Furthermore, SDI-12 reduces noise and electrical interference, ensuring a more stable and reliable signal.

5. Installation procedure of the CS225 probes

For measurement accuracy, it is crucial to install the CS225 probes in direct contact with the medium under investigation, i.e. the soil.

For this reason, the two boreholes have been drilled with a non-standard core sampler of 66 mm diameter, to facilitate the spontaneous closure of the hole after the installation of the CS225 temperature string (Fig. 6).

The total length of the boreholes is 15 m and they have been initially supported by 13 slots of 1 m length casing each.

Figure 6. Core sampler.

A PVC guide tube has been used to keep the entire array of sensors in its position during the installation phases (Fig. 7a – 7b).

Figure 7. Installation of the CS225 probes on the PVC guide (a) and of the casing (b).

Subsequently, the temperature probes and the guide tube have been placed in each borehole, with the first sensor positioned at the bottom, i.e. at a depth of 15m from the ground level. The bottom part of the borehole has been filled with on-site material to block the cable and PVC tube assembly and also to ensure that the cable was inserted in a perfectly vertical direction (Fig. 8a – 8b). Finally, the casing slots have been removed and, to further enhance the direct contact between the measuring probes and the soil, the gap between the cable and the hole has been filled manually with on-site material. This procedure has minimally disturbed the hydro-mechanical setting of the measurement area. At the end of the installation, the electrical connections to the data-logger have been completed (Fig. 8c – 8d), employing IP68-rated protective systems able to guarantee a high level of shielding from environmental factors, even in demanding conditions.

Figure 8. CS225 placement in the borehole (a); filling operation with on-site material (b); the cable ready for the wiring phase (c); wiring procedure (d).

6. First acquired data

Temperature measurements have been obtained from the two sensor arrays (one located in a selected vegetation data and one in a bare vegetation area) at depths of 6, 9, 12, and 15 meters during a monitoring period starting from July 2023. In August, the monitoring has been interrupted along both boreholes, due to a malfunctioning data logger, while in September a big wild-fire developed in the site has caused important damages to the instrumentation, including the cables connecting the sensors to the data logger. In January 2024, the monitoring has partially resumed after replacing the fire-damaged cables.

Fig. 9 shows the monthly average temperature profiles obtained from the monitoring. The data reported in the figure have been integrated with those measured at shallower depths by sensors installed during previous research projects (Stasi, 2024). Overall, the two monitored boreholes exhibit a different temperature response. Lower temperature values have been recorded at each depth along the selected vegetation vertical compared to those measured in the bare vegetation area. Moreover, the recorded trend follows the expected cup-shaped pattern described in the literature (Ouzzane et al., 2015), with more pronounced temperature variations at shallow depths and less accentuated changes at greater depths. Nevertheless, a noticeable oscillation has been observed at a depth of 15 meters in both monitored boreholes, with a significantly more pronounced effect in the selected vegetation area. This can be attributed to several factors, including the spatial variability of the soil properties (moisture content, porosity, which directly affect thermal conductivity) or variations in groundwater flow patterns. Indeed, the literature suggests that the soil water content is one of the key state parameters which can significantly influence the thermal response of soils (Likos, 2014). The dependency on moisture content is appreciable due to the large contrast in the thermal conductivities of the solid, liquid, and gas phases.

7. Conclusions and future perspectives

The paper presents the installation procedure of two temperature strings (CS225) to measure the temperature field of an undisturbed soil deposit at different depths in real time. The initial field measurements have shown a good performance of the probes, which are able to detect the gradual decrease of the amplitude of soil temperature oscillation with the increase of depth. Moreover, the data indicates that the temperature measured along the vegetated area is lower than that recorded along the bare area.

Further research will consider laboratory and numerical work. Conducting laboratory experiments to characterize the thermal properties of the undisturbed soil samples, collected from the monitored depths, can in fact provide valuable insights. This will include i) the measurement of the thermal conductivity according to the transient line source method (ASTM, 2014); ii) the investigation of the influence of soil moisture content on the soil thermal behaviour. As regards this latter aspect, controlled drying and wetting tests on shallow soil samples can be conducted to establish a relation between the soil moisture content and the soil thermal conductivity. In addition, it is well known that the values of soil thermal conductivity are influenced by the confining pressure. With this perspective, the research group is developing an unconventional double-chamber triaxial cell to determine the drying (or wetting) thermal conductivity curves under controlled suction and confinement. Furthermore, developing numerical models to simulate the temperature profiles in the monitored areas can provide a deeper understanding of the observed differences. The laboratory data obtained from the thermal property characterization and soil-water tests will be used as input for the numerical models, whose results can help to validate the field measurements, identify the key influencing factors, and predict temperature distributions under various scenarios.

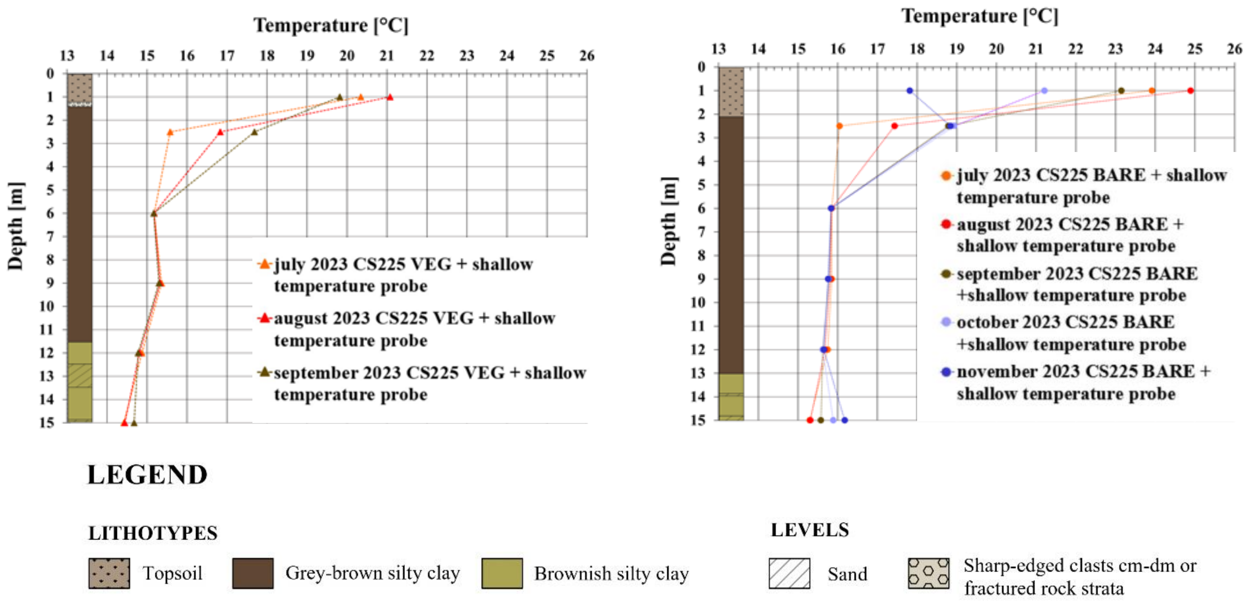

Figure 9. Monthly average temperature profiles with depth, in the selected vegetated (left side) and bare area (right side).

By combining field measurements with laboratory work, numerical modeling, and long-term monitoring, the research activity can contribute to a comprehensive understanding of the thermal behaviour of the soil and its implications for geotechnical engineers.

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References

ASTM Committee D18 "Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure", ASTM International, United States, 2014, https://doi.org/10.1520/D5334-22.

Campbell Scientific, "CS225 Temperature String Product Manual", Logan, Utah, 2017.

Cotecchia F., Vitone C., Santaloia F., Pedone G., Bottiglieri O. "Slope Instability Processes in Intensely Fissured Clays: Case Histories in the Southern Apennines", *Landslides* 12(5), pp. 877-93, 2014, https://doi.org/10.1007/s10346-014-0516-7.

Gehlin S., Nordell B., In: ASHRAE Transactions, "Determining undisturbed ground temperature for thermal response test". Chicago, Canada, 2003, 151-56, https://www.diva-portal.org/smash/get/diva2:1014062/FULLTEXT01.pdf.

Likos W. J. "Modelling Thermal Conductivity Dryout Curves from Soil-Water Characteristic Curves". *Journal of Geotechnical and Geoenvironmental Engineering*, 140 (5), pp. 1-13, 2014. 10.1061/(ASCE)GT.1943-5606.0001078.

Matsson N., Steinman G. Laloui L., "In-Situ Thermal Response Testing – New Developments", In: European Geothermal Congress 2007, Unterhaching, Germany, 2007.

Ouzzane M., Eslami-Nejad P., Badache M, e Aidoun Z., "New Correlations for the Prediction of the Undisturbed Ground Temperature". *Geothermics*, 53, pp. 379–384, 2015, https://doi.org/10.1016/j.geothermics.2014.08.001.

Shah S.K., Aye L., Rismanchi B. 2019. "Undisturbed ground temperature in Melbourne". In: 8th BSME International Conference on Thermal Engineering, Dhaka, Bangladesh, 2019, vol. 2121, Issue 1, https://doi.org/10.1063/1.5115928.

Stasi N., Tagarelli V., Cotecchia F., Cafaro F., "In situ and laboratory investigation of the saturated hydraulic conductivity of a clayey soil cover when bare or vegetated", In: IARG 2022, Caserta, Italy, 2022.

Stasi N., "Experimental and numerical study of Soil-Vegetation-Atmosphere interaction for the design of Nature-Based Solutions in landslide risk mitigation ", PhD Thesis, University of Bari - Technical University of Bari, 2024.

Tagarelli, V. and Cotecchia, F., "Preliminary Field Data of Selected Deep-Rooted Vegetation Effects on the Slope-Vegetation-Atmosphere Interaction: Results from an in-Situ Test", In: RIG, 2022, vol. 56, no. 1, pp. 62–83. 10.19199/2022.1.0557-1405.062.