CPTU temperature sounding: The potential to identify flowing groundwater by thermal anomalies

By Sondre Gjengedal, Priscilla Paniagua and Martin Keiserås Haugen

Sondre Gjengedal (Ph.D) is a hydrogeologist and researcher at the Norwegian Geotechnical Institute (NGI), Trondheim, Norway.
Priscilla Paniagua (Ph.D) is a geotechnical engineer and researcher at the Norwegian Geotechnical Institute (NGI), Trondheim, Norway.
Martin Keiserås Haugen (M.Sc) is a geotechnical engineer and researcher at the Norwegian Geotechnical Institute (NGI), Trondheim, Norway.

Sammendrag

CPTU sondering med temperatur; potensial for å identifisere strømmende grunnvann med termiske anomalier. Å bruke temperaturdataene fra trykksonderinger med poretrykksmålinger (CPTU) viser seg lovende som et verktøy som muliggjøre påvisning av permeable soner i løsmasser der det faktisk forekommer grunnvannstrømning. CPTU-data fra tre ulike geotekniske prosjekter i Norge blir presentert, hvor prosjektene viser tre vidt forskjellige scenarier når det gjelder temperaturresponser i løsmasser. I to av prosjektene er det påvist temperaturavvik i forbindelse med forekomst av grovere løsmasselag innenfor leirdominerte sedimenter. Trendene til temperaturdataene i disse anomaliene viser temperaturøkninger innenfor et begrenset område, som ikke kan forklares av de vanlige kjente årsakene, eksempelvis friksjonsgenerering av varme eller feilaktige lagringsforhold for CPTU sonden før sondering. Det antas at disse uregelmessighetene er en indikasjon på forekomsten av grunnvannstrømning innenfor disse permeable lagene. Metodikken, potensialet og begrensningene til CPTU-metoden for å oppdage en slik anomali, når det gjelder datainnsamling og datatolkning, blir presentert.

Summary

The use of the temperature data from piezocone penetration tests with pore pressure measurements (CPTU) show promise as a tool that can enable the detection of permeable zones where there occurs actual groundwater flow. CPTU data from three different geotechnical projects in Norway are presented, showing three widely different scenarios in terms of temperature responses in soil. In two of the projects there are detected temperature anomalies in conjunction with the occurrence of coarser soil layers within clay dominated strata. The trend of the temperature data in these anomalies show elevated temperatures that are not explainable by more commonly known causes, such as frictionally generated heat or faulty storage conditions of the CPTU probe before sounding. It is hypothesised that these anomalies are indicative of the occurrence of groundwater flow within these permeable layers. The methodology, potential

and limitations of the CPTU method for detecting such an anomaly, in terms of data acquisition and data interpretation, are presented.

Introduction

The concept of "*energy geostructures*" is now seeing increased attention in Norway. Energy geo-structures are infrastructure and building assemblies, such as *energy piles*, *energy walls*, *energy tunnels*, *energy slabs,* and other subsurface installations that are installed below ground for a variety of construction or foundation purposes (Laloui & Loria, 2019). As opposed to the more common geothermal system in Norway, the borehole energy wells that are drilled several hundred meters deep into bedrock, energy geostructures are often installed relatively close to the surface, i.e. from 2 – 50 meters depth. In Norway's cold climate this yields a particular challenge for the adoption of energy geostructures into new projects, because the soil temperatures, at such shallow depths, tend to be close to zero in certain periods of the year. This yields a challenge because there exist limited quantities of heat in the soil to be used by the geothermal system before the ground is in risk of freezing, potentially causing ground settlement and property damage.

To mitigate this risk, it is recommended that an energy geostructure system constructed in Norway is designed as a thermal energy storage system, where excess heat from the building is used to heat the ground during the summer, elevating the ground temperature before wintertime, thus avoiding freezing (Gjengedal & Bjørnarå, 2024). Employing energy geostructures in this manner will be particularly beneficial for a building that have both cooling and heating demands, enabling the building to regenerate a portion of its energy from the summer to the winter season.

All such thermal energy storage systems rely on their efficiency and capacity to store the heat, meaning it is unfavourable to lose the heat to the surroundings, causing losses for the system as a whole (Nordell, 2015). Groundwater flow is one potential phenomenon that has the capacity to deplete thermal energy storages before the systems are able to make use of it. For instance, if a permeable soil layer occurs within the storage volume, that e.g. allow groundwater to flow through the energy pile foundation area, the groundwater will absorb the stored heat and remove it, thus depleting the storage capacity. The potential for groundwater flow through these systems should therefore be investigated at an early stage in the project development.

However, as with any ground source heating and cooling project, it is typically a financial hurdle to acquire site specific geological data at an early stage in the planning phase of projects (Gehlin, 2002; Akrouch et al., 2016). The piezocone penetration test with pore pressure measurements (CPTU, also known as cone penetration test) is a conventional geotechnical site investigation method that is often used in construction projects in Norway today (NGF, 2010). Its multisensory logging approach allow geotechnical engineers the interpretation of stratification (for example, the detection of permeable soil layers at a site), classification of soil type and evaluation of engineering soil parameters. It is used particularly for projects that involve load bearing or load altering measures, such as installation of piles or retaining structures. Nonetheless, the conventional CPTU parameters used today does not indicate whether there occurs groundwater flow within this permeable layer, or not.

A recent study at the Norwegian Geotechnical Institute has found signs that the CPTU can provide an early-stage approach for the evaluation of groundwater flow by employing the data from the integrated temperature sensor in the interpretation process, in addition to the standard CPTU parameters. This paper presents a theoretical framework for this hypothesis along with the findings where CPTU temperature data is evaluated in conjunction with the standardized logging parameters. The potential and limitations of the CPTU method in this respect, both in terms of data acquisition and data interpretation, will be presented. In addition, equipment limitations will be discussed.

Theory

The temperature within the subsurface is a site-specific property that vary depending on local climatic and geological conditions. Seasonal variations in air temperature cause the ground temperature to fluctuate and this fluctuation will often follow a distinct pattern. In the special case of using CPTU sounding for temperature logging, one must consider that the sounding occurs at a specific time of the year, triggering these seasonal trends to affect the results. One must therefore recognise which type of trends that should be expected from the soil at a given site and depth, and which trends that should not be expected at the time of sounding. Deviations from the expected trends, so called anomalies, might occur due to a variety of causes. Knowing how different phenomena affect the temperature recorded by the CPTU is therefore important, giving due cause to consider groundwater flow as possible explanation for the anomaly.

Luckily the expected ordinary trends have distinct signatures. In soil and rock, the conduction of heat, both to and from the surface, is governed by a soil's thermal properties and the local climatic conditions at a given location. Near the surface, i.e. the upper few centimetres of soil, the soil temperatures tend to fluctuate on a daily basis, while deeper sections of the soil profile will fluctuate with longer trends, following the larger seasonal temperature variations that occurs above ground. A typical yearly fluctuation is shown in Figure 1, where the annual envelope shows the maximum and minimum temperatures the soil obtains during the course of a year. The corresponding temperature data for each month is shown as individual profiles towards depth. The monthly profiles show that it takes time for the deeper soil to adjust to the surface temperature, displaying a gradual decline and increase towards depth with each consecutive month, lagging behind the seasons.

The fluctuations are particularly profound in the upper section of the soil, i.e. above 3-meters depth where the fluctuations can be relatively large and vary by more than 10-30°C from the winter to the summer months. At greater depth the ground temperature, both in soil and in bedrock, trends towards a stable level all year round, shown here from approximately 13-meters depth and below (Figure 1). This stable temperature is typically reasonably similar to the local annual average air temperature at the surface at the given area, which in southern Norway is often around 5-8 °C. Below this depth the ground temperature is relatively constant, although a slight and gradual increase in temperature is observed towards greater depths (S1 and S2 in Figure 2). This gradual increase is due the geothermal gradient, and the temperature typically increase between 1.5-2.5 °C per 100 meters depth in Norway (Holmberg et al. 2018). The annual envelope shown in Figure 1 and the deeper trend shown in Figure 2 are in most cases the expected temperature profiles where there does not occur any anomalies, and in areas where there are no additional heat sources adjacent.

Groundwater flow has in many situations been known to affect temperature levels in soil and rock (Anderson, 2005), e.g. altering the temperature in boreholes where a permeable fracture introduces groundwater to a well (Liebel et al., 2012). The effect of groundwater

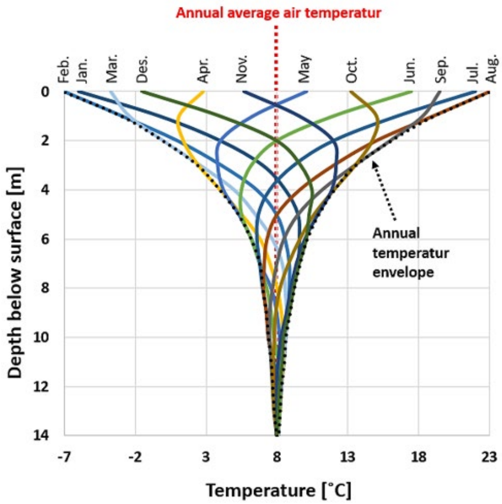


Figure 1. Typical temperature profiles towards depth for soils affected by the annual temperature fluctuations of surface weather and climate (modified after Kurylyk et al., 2015).

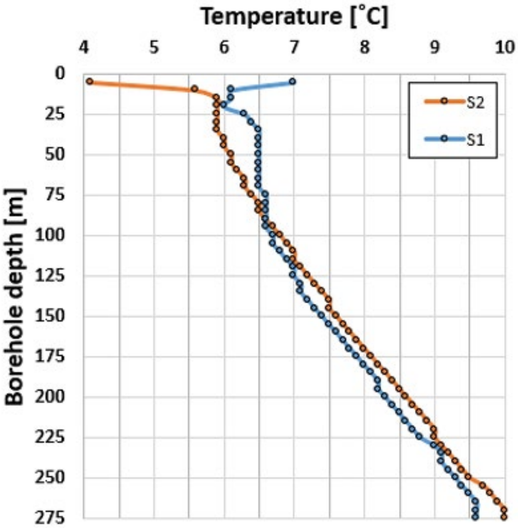


Figure 2. Two temperature profiles towards depth from a borehole in Skjåk, Oppland County, Norway (reproduced after Holmberg et al., 2018). Note the relatively large spread in the upper 10-meter sections of the borehole for the different profiles S1 and S2 that are taken on different times of the year.

flow on the temperature depends on which temperature the water has before entering the area, and thus the effect depends on the direction of flow. One example is seen in the data of Holmberg et al. (2018) in Figure 2, where the S1 datapoints deviate from the S2 data in the upper 100 meter of the borehole. This is due to entry of relatively warm groundwater, via a fracture at this depth, that flows upwards to another fracture at 35 meters depth, causing the temperature profile to deviate from the expected trend in the part of the profile where the flow occurs.

Furthermore, in urban areas with existing buildings and infrastructure, there might also be manmade heat sources that affects the soil temperature, influencing the local ground temperature around their foundations. A study by Liebel et al. (2011) display this for four boreholes in Oslo. Two boreholes drilled adjacent to an old school building display significantly higher temperatures in the subsurface than expected when compared to two other boreholes drilled at greater lateral distances from the building.

All these possible influences affect the shape of the annual envelope and temperature trends, which might thus be different in urban versus rural areas, and with or without groundwater flow. These phenomena must be considered when interpreting CPTU temperature data. The sampling methodology and data acquisition has also been found to affect the recordings and will be elaborated in the next section.

CPTU – data acquisition, sampling methodology and error sources

A cone penetration test (CPTU) is performed by pressing a cone-shaped probe (Figure 3) vertically downwards into the soil at a constant speed of 20 mm/s (EN ISO 22476-1:2012). The movement of the probe through the soil induce resistance forces in the soil and this resistance is measured by the probe. Standard CPTU probes have three main sensors that measure I) the cone resistance (q_c), II) the sleeve friction along the probe shaft (f_s) and III) a pressure transducer that measure the pore water pressure at the cone shoulder (u_2).

In addition to these three sensors there is also a temperature sensor installed in most of the standard electric CPTU probes in Norway. The role of this temperature sensor is primarily to improve the readings of the main parameters (q_c, u_2, and *fs*), and the temperature data is implemented in the calibration algorithms in a data compensation sequence to help limit error readings due to the temperature dependant electronics. Most often this temperature data is not used by the geotechnical engineer for

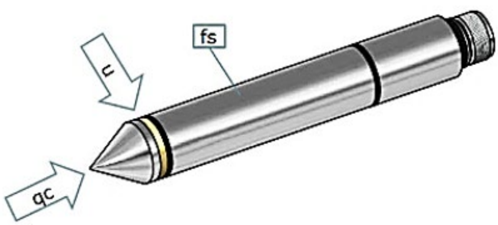


Figure 3. Sketch of a CPTU probe with location of measuring devices shown (Geotech AB, 2015). The u parameter is designated u_2 in this paper.

interpretation purposes, but in recent years the temperature data has typically been employed to evaluate the soil thermal properties for use in dimensioning of energy geostructures, for determining the soil thermal conductivity and volumetric heat capacity, so called T-CPTUs (Akrouch et al., 2016; Vardon et al., 2019).

The most common CPTU probes used by geotechnical drilling contractors in Norway are listed in Table 1. The accuracy of these temperature sensor and the recording resolution vary depending on the manufacturer and cone type used, which obviously will affect the reliability of the data accusation and data interpretation. The Geotech NOVA CPT has a recording accuracy of ±0.5 °C and display a data resolution of 0.1 °C, while the ENVI Memocone CPT unit has a recording accuracy of ±1.0 °C and display a data resolution of 0.6 °C. Presumably this varies depending on how precise the temperature compensation algorithm needs to be applied within the cone system configuration, but other manufacturer concerns might also determine the choice of component. Nevertheless, the better the recording resolution, the smaller the temperature anomalies that can be detectable by the cone, and consequently this can improve the interpretation process.

However, regardless of the sensor accuracy, the temperature sensor must also be allowed to adjust to the surrounding soil for the data to be sufficiently accurate. To limit the errors in the reading, the probe should be stored properly before use. This is specified in the production manual from the manufacturer (Geotech AB, 2015) which states that:

"Keep the probe stored in a dry place at a temperature as close to the ground temperature as possible (normally approx. +5°C). The probes are equipped with a system to compensate for temperature variations. Nonetheless, fast temperature changes might affect the accuracy of the sounding results…"

This guideline is often not followed up in practice by the drillers in Norway. Usually, the CPTU probe is stored in ambient temperature before sounding, which cause the probe temperature to be markedly different than the soil temperature before the test. The initial cone temperature therefore depends on the temperature at that specific time and date of installation, and might vary markedly depending on time of day, time of year, climate and season. This inevitably cause errors in the recording with respect to the *in-situ* temperatures in the ground.

Yet another error source is the potential for the sounding to generate heat. The calculation methods employed by most T-CPTU studies rely on heat generated due to friction along the cone tip and shaft during sounding (Akrouch et al., 2016; Vardon et al., 2019; Vardon and Peuchen, 2020; Xiaoyan et al., 2022). Heat is mainly found to be generated in sand and coarser soils during sounding, whereas clay and silt do not generally produce significant heat. As this heat generation in sand might represent an anomaly, it also represents a potential error source when trying to identify groundwater flow in the soil, particularly since groundwater flow primarily also occur in sandy and gravely soils. However, frictional heat will dissipate when the cone stops, whereas this should not necessarily occur for groundwater flow anomalies.

To determine the cause of the temperature anomaly it is thus relevant to evaluate the

Table 1. Typical CPTU cones used in Norway (pers.com ENVI services and Geotech services, 2024).

Manufacturer (country)	CPT type CPT diameter	Temperature sensor type	Measurement Range	Measurement Accuracy	Recording Resolution
ENVI (Sweden)	Memocone 36 mm	Integrated Circuit (IC) semiconductor	-40 – +50°C	±1 °C	0.6 °C
Geotech (Sweden)	NOVA 36 mm	Temperature to voltage converter	-40 – +125°C	±0.5 °C	0.1 °C

temperature data (T) in conjunction with the main sounding parameters (q_c, u_2, and *fs*) and the timestamp of the recorded datapoint. Groundwater flow should e.g. primarily occur in sandy and gravely soils, where the pore pressure parameter (u_2) should show an abrupt response during sounding. If the temperature is observed to change in conjunction with such observations this might be indicative of groundwater flow, depending on how the change deviates from the expected trend. These criterions, in conjunction with other local site-specific information can be used for differentiating between groundwater flow anomalies and other potential sources of temperature anomalies in the presented datasets. However, single datapoint temperature outliers should not be given much credibility, as a thermal anomaly should persist for e.g. more than three-four consecutive recording data points during the sounding.

Project specific data

CPTU recordings that include temperature data have been collected from three different projects conducted at different sites in Norway (Figure 4); The Tiller-Flotten Norwegian Geo-Test Site (NGTS), the Onsøy NGTS site, and the ongoing Campus Ullevål construction site in Oslo. These are projects where CPTU soundings has been performed on several occasions at different times of the year, but on the same site. Project specific data is provided in Table 2. References to site specific investigations articles are provided for more detailed information of the projects, whereas the data presented here is focused around the CPTU data.

The Onsøy site is the NGTS soft clay site located in Fredrikstad municipality, that is used as a benchmark site to test various geotechnical soil investigation methods and techniques. The site is situated along rural farmland area, and the soil has been extensively mapped and characterized by others, e.g. by Gundersen et al., 2019 whom has made available a timeseries of thermistor data for comparison from this site. The soil consists mainly of clay, an 8- to 40-meter-thick deposit above bedrock. A total of eleven

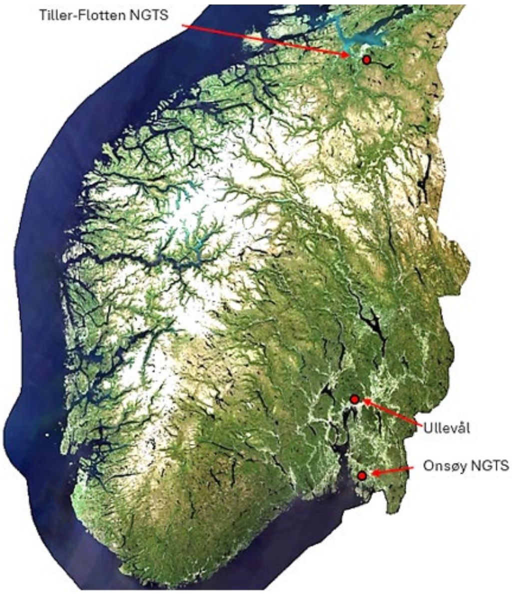


Figure 4. Overview of the project locations (source: www.norgeibilder.no).

Table 2. Overview of the project specific data. Annual air temperature is determined from the local weather stations (www.klimaservicesenter.no).

	Onsøy NGTS	Tiller-Flotten NGTS	Ullevål
Number of CPTU datasets	11	9	3
Project site terrain elevation (meters above sea level)	6	125	98
Groundwater level – determined by piezometers (meters above sea level)	5.5	124	97
Annual average air temperature (°C)	8.2	5.5	7.2
Urban or rural site	Rural	Rural	Urban

CPTUs are presented from this site, from testing in October and November 2017 and 2018 with a Geotech cone, and in February 2016 with an ENVI cone.

The Tiller-Flotten site is the NGTS quick clay site located in Trondheim municipality. The site is situated along rural farmland and forest area south of Trondheim, and the soil has been extensively mapped and characterized by others in previous work (L'Heureux et al., 2019; L'Heureux and Lunne, 2020). The soil consists of a 50-meter-thick clay deposit above bedrock. A total of nine CPTUs are presented from this site, from testing in June-, September-, and January 2017 with a Geotech cone, and in November 2018 with an ENVI cone.

The Campus Ullevål construction site in Oslo is situated in the urban city district of Ullevål. The property has been extensively mapped and characterized for dimensioning of the foundation to the new NGI office building that is currently being constructed (see e.g. Gjengedal and Bjørnarå, 2024; Løyland et al., 2024). The soil consists mainly of clay, up to 40-meter-thick deposit above bedrock. A total of three CPTUs are presented from this site, from testing in July and August 2021 with a Geotech cone. These CPTUs were conducted 1 to 5 meters distance from the basement/foundation of a then existing office building, which was later demolished. The old building was originally completed in 1966.

Results and discussion

The CPTU sounding data from Onsøy NGTS is presented in Figure 5 and 6. In Figure 5 the temperature from all eleven CPTU soundings are rendered with an interpretational aid box showing guideline trends for the expected seasonal variations at the various times of drilling in February, October and November. The available thermistor data from Gundersen et al.

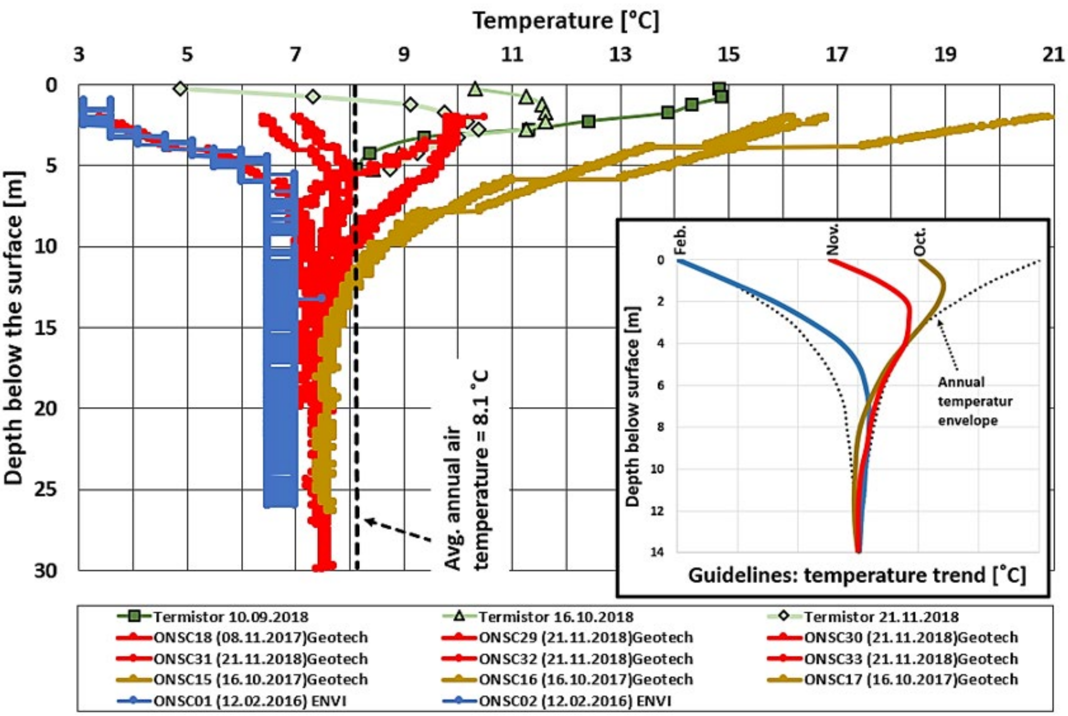
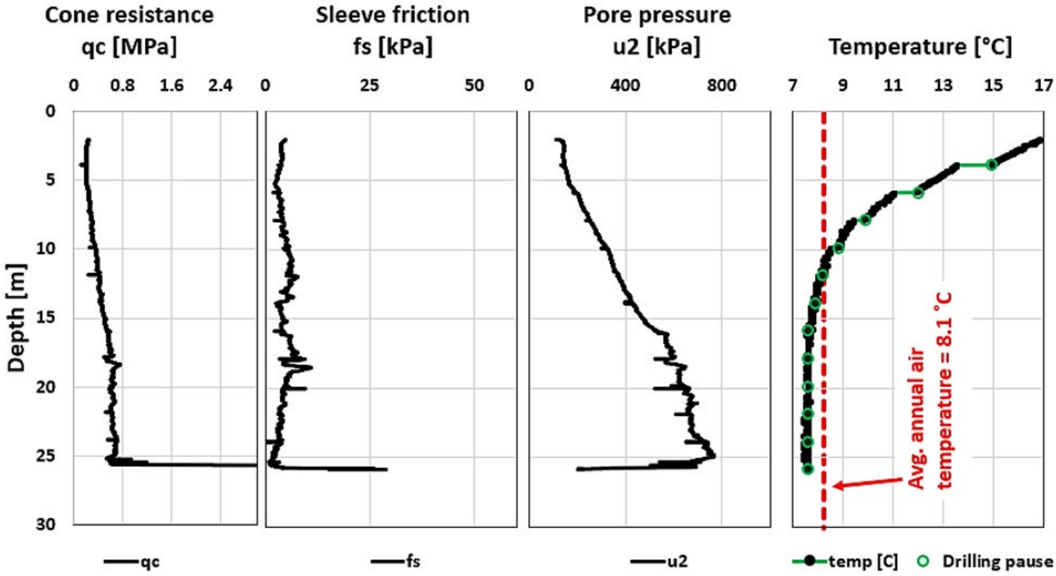


Figure 5. CPTU temperature data from Onsøy NGTS. The thermistor data is reproduced from the data of Gundersen et al. (2019). The annual air temperature is determined from the local weather station SN3190 and SN17000 (www.klimaservicesenter.no).



(2019) are also included for comparison. As shown in the figure, the general shape of the CPTU data mimic the expected trends for each month, but with a significantly larger span in the upper sections of the profiles compared to the thermistor data and the guidelines indicated in the bottom right corner. There are even significant differences for CPTUs that are conducted on the same day. The deviation is perhaps most notable for the October soundings where there occurs significant deviation in the first 10 meters of the profile for all three soundings.

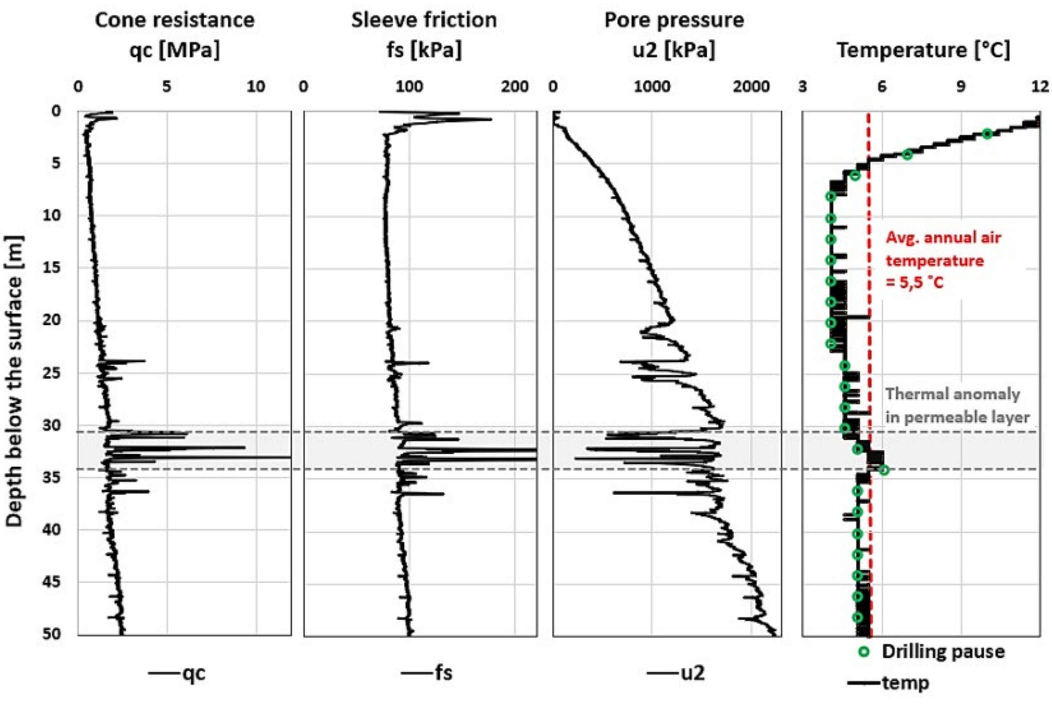
This is most likely due to the fact that the CPTU probes were not stored at the same temperatures before drilling, nor allowed to acclimatize to the soil temperature before sounding. If the CPTU cone is pushed into the soil with an unacclimatized temperature the deviation will need time to adjust. Due to the 20 mm/s penetration rate during the sounding, there will be a specified timeframe for the temperature sensor to adjust to the surrounding soil. The deviation becomes apparent when the driller needs to extend the drill rod, which typically occurs every 1 or 2 meters. This causes the cone to be stationary within the soil for a few minutes at a time. Within this timeframe the cone temperature converges towards the surrounding soil temperature, and this causes the datapoints within this section of the graph to display a markedly shift in the same depth location. The larger the temperature difference, the larger the shift in the graph. As the probe attains the in-situ temperature the shifts gradually disappear as the cone temperature acclimatized with the soil temperature. The cone tends to be almost fully acclimatized within 3 – 4 rod extensions (Figure 6).

At greater depth (>10 meters) the temperature incrementally trends towards a stable temperature of 7.5 ˚ C for the nine Geotech soundings, slightly lower than the local annual average air temperature of 8.1˚ C. The ENVI cone data has a poorer sampling accuracy, which might explain the slightly colder temperature of 7.0 ˚ C, and the much poorer sampling resolution is visualized in the plot by the much more jagged trendlines.

In Figure 6 the temperature data for the ONSC17 sounding is presented together with the conventional CPTU data (q_c, f_s and u_2). The low values and smooth shape of the qc and fs parameters indicated clay as the dominant soil type in most of the profile, and the reduction of q_c and f_s from 18 meters depth indicate softer clay in the bottom section. There are no observable temperature anomalies at depths greater than 10 meters in the ONSC17 sounding, and the figure serves nicely to show how a CPTU profile should look like where groundwater flow does not occur.

The CPTU sounding data from Tiller-Flotten NGTS is presented in Figure 7 and 8 and include a particular deep CPTU sounding that does contain an anomaly at depth. In Figure 7 the temperature data of this sounding (TILC18) is presented together with the conventional CPTU data (q_c, f_s and u_2). The relatively low values and smooth shape of the qc and fs parameters indicated soft clay as the dominant soil type in most of the profile. However, the rough scatter that occurs at 30-34 meters depth, with increased friction and cone resistance simultaneously with a markedly reduction in pore pressure (u_2), indicates coarser material in this section of the profile. It can also be observed that there occurs a slight anomaly in the temperature data in this section, where a minor increase in temperature also is indicative of coarser soils, most likely sand or gravel material.

However, the cause of this anomaly is not clear, and it is not detected by the other CPTUs since they are not drilled to this depth (Figure 8). The relatively poor data resolution of the ENVI cone does not provide a clear indication on what occurs when the cone is stationary within the zone. If the temperature anomaly occurs due to frictional heat generated from sounding in the coarse material, one would expect the temperature to cool down again when the driller pauses to change the drill rod at 32 meters dept, but this seemingly does not occur. This might therefore suggest that there is a flow of water within this coarse layer and that the groundwater enters at this point in the soil with a slightly higher temperature than the soil temperature above and below.



In Figure 8 the temperature data from all nine CPTU soundings are rendered with the interpretational aid box showing guideline trends for the expected seasonal variations at the various times of drilling in January, June, September and November. The general shape of the CPTU data mimic the expected trends for each month, with the exception of one CPTU in January and one CPTU in November. However, most of the trends have a significantly larger span in the upper sections of the profiles compared to the guidelines. This is also here most likely because the CPTU probes were not stored at the same temperatures before drilling, nor allowed to acclimatize to the soil temperature before sounding, perhaps most clearly seen in the January CPTU sounding with a large gap at 2 meters depth.

In the Campus Ullevål project, there are also observed temperature anomalies in the sounding data, particularly in two of the three CPTUs. The CPTU sounding data from Campus Ullevål site is presented in Figure 9 and 10. In Figure 9 the temperature data from three CPTU soundings are rendered with the interpretational aid box showing guideline trends for the expected seasonal variations in July and August. The available thermistor data from Gjengedal and Bjørnarå (2024) are also included for comparison and display the whole year of 2024, three years later, where temperature measurements are conducted in thermistor sensor IN2 installed about 15 meters from the N19 CPTU sounding.

Compared to the guidelines in the box, the general shape of the CPTU data mimic the expected shapes also for this project, but the trends are tilted towards higher temperatures for the whole profile lengths and are not shown to stabilize towards depth, but rather gradually approach the local annual air temperature. These CPTUs are drilled a few meters from the foundation of the old NGI headquarters and this trend is relatively similar to the data

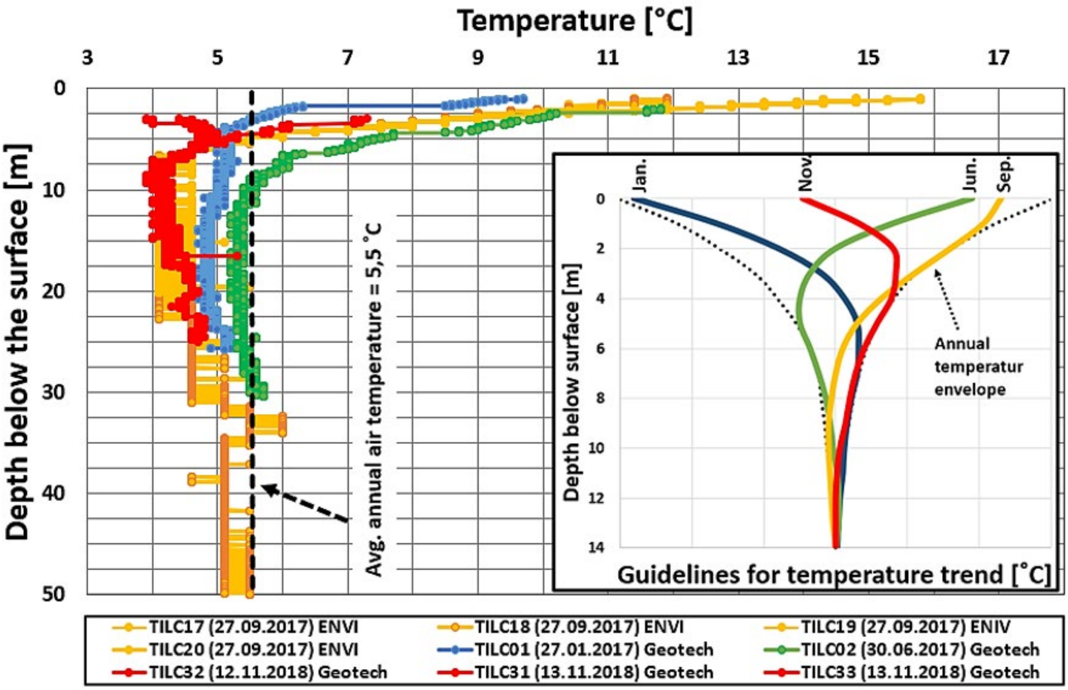


Figure 8. CPTU temperature data from Tiller-Flotten NGTS. The annual air temperature is determined from the local weather station SN68262 (www.klimaservicesenter.no).

presented by Libel et al. (2011) for energy well boreholes drilled in urbane environments. The temperature might therefore be affected by the thermal influence of the old NGI building.

The CPTU trends are also seen to have a significantly larger span in the upper sections of the profiles compared to the guidelines. This is also here most likely because the CPTU probes were not stored at the same temperatures before drilling, nor perhaps, allowed to acclimatize to the soil temperature before sounding. However, when compared to the temperatures measured by Gjengedal and Bjørnarå (2024), a series of measurements conducted three years later, there is an apparent shift in the annual temperature envelope for the year of 2024 compared to the typical envelope for rural areas described by Kurylyk et al. (2015) (the guideline box). The shapes of the CPTU data do in fact closely mimic the local measurements of Gjengedal and Bjørnarå (2024), which suggests that local soil and urban effects might explain the deviations.

For both CPTU N15 and N19, a temperature anomaly at about 15- and 14-meters depth is observed, respectively (Figure 9). The same deviation is observable in the IN2 thermistor data of Gjengedal and Bjørnarå (2024). The temperature increases significantly in this section of the sounding profile, particularly for the N15 sounding. The temperature data of the N15 sounding is presented together with the conventional CPTU data (q_c, f_s and u_2) in Figure 10. The low values and relatively smooth shape of the q_c and f_s parameters along much of the profiles indicated clay as the dominant soil type in most of the profile. However, there are numerous rough scatters along the profile, which suggest that there are thin layers of coarser material in between the clay. The particular

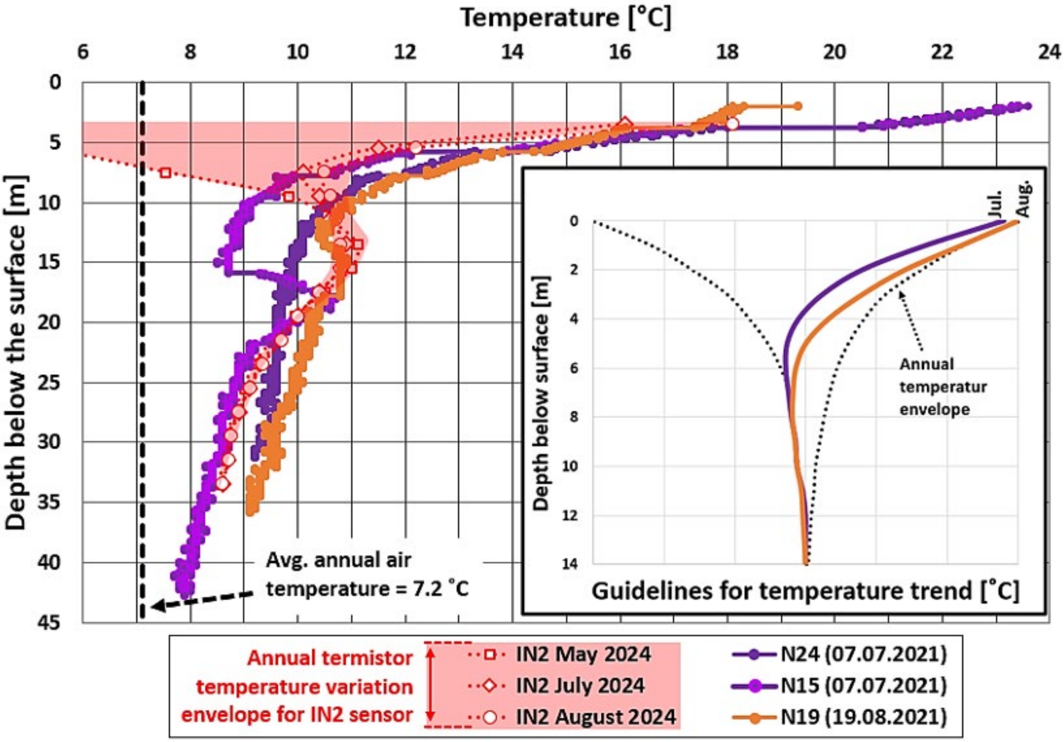


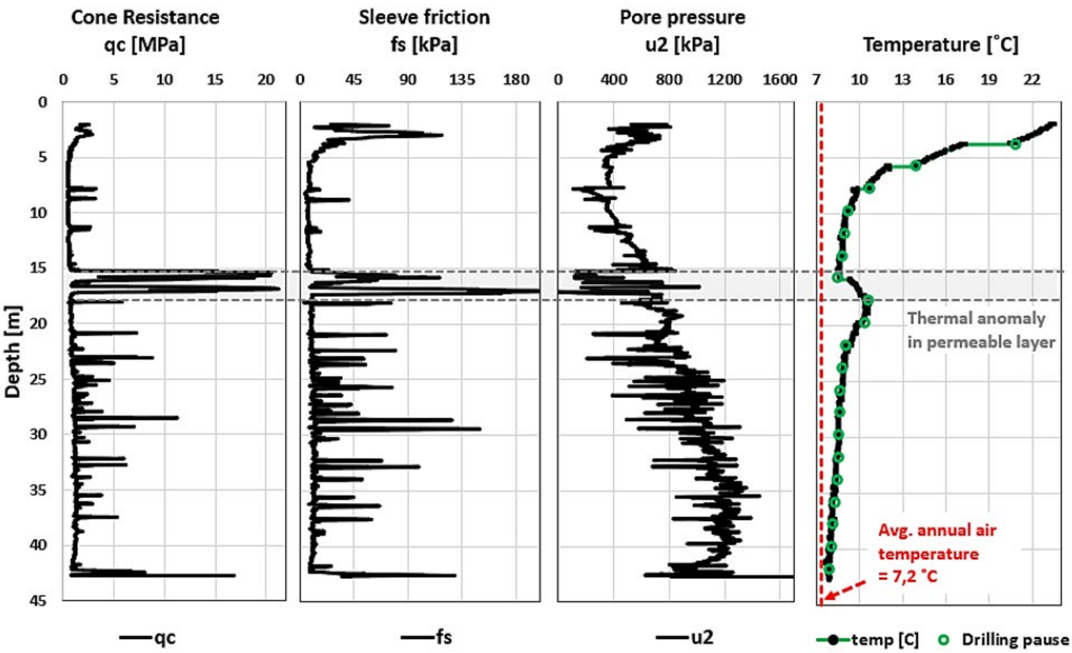
Figure 9. CPTU temperature data from Campus Ullevål performed with Geotech Nova cone. The thermistor data is reproduced from the data of Gjengedal and Bjørnarå (2024). The annual air temperature is determined from the local weather station SN18700 (www.klimaservicesenter.no).

increase in q_c and f_s that occurs at 15 to 17 meters depth, corresponding with a markedly drop in the pore pressure (u_2), suggests that there is a sand or gravel layer here. The markedly increase in temperature emphasize this as well.

The cause of this anomaly is here quite clearly due to other phenomenon than frictional heat. If the temperature anomaly occurs due to frictional heat one would expect the temperature to cool down when the driller pauses to change the drill rod at 15.8 meters dept, but in this case the opposite occurs. A markedly temperature increase actually happen as the cone is stationary for some few minutes (Figure 10). The elevated temperature persists also during the next pause and drill rod change at 17.8 meters depth and only starts to decline when the cone is pushed further into the clay below. This therefore suggest that there is a flow of water within this coarse layer and that the groundwater enters at this point in the soil with a markedly higher temperature than the soil temperature above and below. The persistence of the thermal anomaly in the IN2 temperature data for the whole year of 2024 (Figure 9) also confirms that this anomaly is a stable and with annual continuation, suggesting that the phenomena causing this anomaly is a consistent event, as groundwater flow should be.

However, to confirm the hypotheses that such thermal anomalies, as presented in Figure 7, 8 and 9, actually represents groundwater flow phenomena, one would rely on supplementary information with more specific hydrogeological site investigative techniques to evaluate the groundwater flow regime on the Tiller-Flotten NGTS and Campus Ullevål site. Further work should therefore include the evaluation of piezometer data and other site investigations performed at the presented project sites.

That being said, it is evident that the information obtained from evaluating the temperature data in conjunction to the standard CPTU parameters will improve the soil and data interpretation process and highlight yet another perspective on the soil conditions on site. In this respect, the presented data from these three projects, in conjunction with the presented



interpretational methodology, might be found useful for the industry as a means to evaluate CPTU temperature data also in other projects.

Conclusion

CPTU data from three different geotechnical sites have been presented, showing three different scenarios in terms of temperature responses in soil. In two of the projects there has been detected temperature anomalies in conjunction with the occurrence of coarser soil layers within clay dominated strata. The trend of the temperature data in these anomalies, particularly towards depth greater than 10 meters, are not explainable by more commonly known causes, such as frictionally generated heat or faulty storage conditions of the cone before sounding. It is thus hypothesised that these anomalies are indicative of the occurrence of groundwater flow within these permeable layers.

The use of the temperature data from CPTU sounding thus show promise as a tool that can enable the detection of permeable zones in the soil where there might be flowing groundwater. In this case the CPTU temperature data is a useful tool that can help geotechnical engineers improve the soil and data interpretation process, and in this way the CPTU temperature data can help to reduce uncertainty in new construction projects, perhaps particularly those that want to employ energy geostructures. The much-needed temperature data required in energy geostructures projects can be acquired in conjunction with the conventional CPTU site investigations that are used for soil characterisation today, at no additional costs.

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