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Cone penetration testing of permafrost soils

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Abstract

Cone penetration testing (CPT) has great potential for geotechnical engineering in permafrost. Cone resistance q_c [MPa] and sleeve friction f_s [kPa] are measured in basic tests, and pore pressure u_2 [MPa] is measured in CPTu tests. Geotechnical engineering in permafrost requires additional data such as temperature t [°C], electrical conductivity σ [S/m], as well as pore pressure u_2 [MPa]. Interpretation of the measured CPT data allows long-term soil strength and ad-freezing shear resistance to be estimated, key parameters for foundation engineering in permafrost.

Keywords: CPT, permafrost, pile bearing capacity, long-term soil strength, electrical conductivity, temperature.

Introduction

Fugro has performed several projects using CPT technology for geotechnical site investigation in permafrost since 2014. These projects include:

- Several sites located in Salekhard and Labytnangy, Western Siberia, Russia, in 2014. Permafrost was detected at 22 locations from the CPT temperature data. The maximum penetration depth was 34 m.
- A pilot project in 2015 for Russian Railway to diagnose the condition of a railway embankment, located on permafrost near Vorkuta city, Russia (Sokolov et al., 2016).
- Salekhard College, Western Siberia, Russia in 2016 to diagnose the condition of piled foundations and the performance of thermosyphons (Volkov et al., 2017);
- On the Gydan peninsula (near Ob Bay), Western Siberia, Russia in 2017, where the soil conditions were characterized by continuous permafrost with solid frozen sand at a mean annual ground temperature around -6°C (Figure 1).

It was widely thought that permafrost conditions were not suited to CPT investigation. However, through the above projects, Fugro has demonstrated that the method is well suited in even the most challenging permafrost soil conditions and provides highly valuable data.

The measured in-situ data provides much detail on permafrost soil properties, obtained simply and economically; with different sensors providing rich data.

Figure 1. Fugro CPT truck on the Arctic coastline at Ob Bay on the Gydan Peninsula

Measured Field Data

Cone resistance and sleeve friction

An example of a CPT profile measured at the Gydan peninsula is shown on **Figure 2**. The cone resistance values for the frozen sand varied between 20 MPa and 55 MPa. The sleeve friction ranged between 100 kPa and 600 kPa. Such numbers are high and correspond to very dense sand. The active layer is clearly detected at 1 m below the ground surface; this is confirmed by cone resistance values between 1 MPa and 4 MPa, and a measured ground temperature 0°C at this depth.

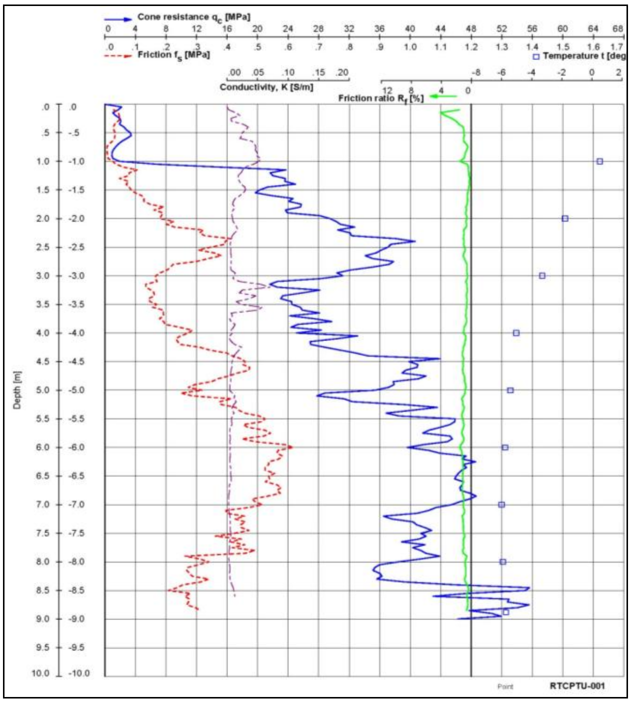

Figure 2. CPT data in non-saline frozen sand at the Gydan peninsula

Temperature

Soil temperature is a critical parameter for permafrost behavior and material properties. Measuring temperature in frozen soils by CPT has many advantages: 1) Only a very short measuring time is required; as a rule, based on Fugro experience with more than 100 measurements, a duration of 10 minutes is enough to stabilize the thermal regime and measure the in-situ soil temperature. 2) The accuracy of temperature measurement is ±0.01°C and hence very precise for permafrost studies; a typical accuracy requirement is ±0.1°C. 3) CPT provides direct measurement of soil temperature at any depth. Fugro often measures temperature at increments 1 m. However, the increments could be 5 cm or 5 m, there are no restrictions. After completion of a test, a casing can be installed into the CPT hole to provide access for continuous temperature monitoring at critical locations.

Electrical conductivity

Electrical conductivity (EC) is sensitive to ice content that reduces conductivity significantly, almost to zero. The continuous EC profile was used to discriminate soil layers, Figure 2. In addition, electrical conductivity allows soil salinity to be estimated, another critical factor for the mechanical properties of frozen soils. Electrical conductivity results obtained by CPT testing can also be applied as part of geophysics surveys, such as electrical tomography, to provide the reference 1D profile for 2D or 3D models.

Pore pressure

Pore pressure measurements also provide valuable data. The soil permeability can be estimated from dissipation tests; in the case of frozen soils, the permeability may be compared with published results (Nixon, 1991). In addition, continuous pore pressure measurements clearly identify boundaries between frozen and non-frozen soils.

CPT Data Interpretation

CPT results can be used to estimate the key mechanical characteristics in geotechnical engineering, such as deformation modulus E_f (MPa), equivalent cohesion C_{eq} (kPa) and pile bearing capacity of frozen soils according to the Appendix L of the Russian standard (SP 25.13330.2012).

Fugro has developed a new technique that processes CPT data to evaluate long-term soil strength and ad-freezing shear strength. This paper will show comparisons between:

1) Recommended values for pile tip resistance in non-saline frozen soils provided in the Russian Standard (SP 25.13330.2012) and stabilized cone resistance values measured by CPT.

2) Measured soil friction and ad-freezing shear resistance and recommended values R_{af} of pile side friction from Russian Standard (SP 25.13330.2012).

Such comparisons show good correlations between the CPT test results and recommended values in the Standards. The temperature dependence of long-term soil strength and ad-freezing shear strength shows similar trends to that found from the conventional theory for frozen soil mechanics.

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