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Application of CPT testing in permafrost

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ABSTRACT: This paper introduces some of the physical processes influencing the mechanical properties of permafrost and the effect of temperature change in the range 0°C to –10°C. The critical role of saline concentration in the pore fluid is described. Examples of recent CPT investigations at different permafrost sites in Russia are given to highlight the type of data that can be obtained and the interpretation for foundation engineering. Some of the investigations were completed in extremely cold conditions.

1 INTRODUCTION

The properties of frozen soil depend critically on ground temperature which impacts the performance of piled and shallow foundations in permafrost. Relatively small change in the sub-zero ground temperature of permafrost can cause significant change in the properties of the frozen soil. The mechanical properties of saline permafrost, as found in the Arctic (low lying areas, nearshore and offshore), are particularly sensitive to temperature and salinity. Indeed, saline permafrost generally contains pore fluid (with high salt concentration) at temperatures well below freezing. The mechanical behaviour of saline permafrost is a major challenge for the design of foundations for buildings, infrastructure and gas projects under development in the Arctic.

The temperature sensitivity of saline permafrost increases the challenge to recover and test undisturbed samples in the laboratory. To minimize disturbance, the sample temperature should be maintained as close to the original in situ temperature as possible. Any significant deviation in sample temperature during handling, storage or transportation may cause irreversible disturbance from thaw-refreezing. In situ testing of permafrost is highly advantageous, given the additional complexity of temperature control to obtain undisturbed samples for laboratory testing.

Thermosyphons are commonly used to extract heat from the ground that is transmitted to the atmosphere during winter, to maintain the ground at low temperature. The heat transfer mechanism works in one direction and does not introduce heat to the ground in summer. CPT can measure directly the ground properties and temperature at a controlled distance from installed thermosyphons, to monitor performance. The small hole formed by execution of the CPT may then be used to house a plastic tube containing thermistors for permanent temperature monitoring of the thermosyphons.

Piezocone tests (CPTu) with a temperature sensor provide valuable data on permafrost. The pore pressure sensor helps highlight boundaries between frozen and unfrozen layers. Other types of sensor permit measurement of resistivity for data on ice content; the presence of volatile organic materials such as methane may be measured with membrane interface (MIP) technology, all in the same test.

2 SALINE PERMAFROST

2.1 *General information*

Saline permafrost is widespread in the Arctic region along the coast, in low lying areas, nearshore and offshore. The source of salinity is the sea water. Salinity varies significantly depending on soil type, location with respect to the sea, and geological history of the soil strata. High salinity in permafrost soils was caused by the Quaternary transgression and regressions of the Polar Ocean. Cyclic temperature fluctuations inside saline permafrost, usually marine sediments, induce the formation of overcooled water brine lenses (cryopegs). Cryopegs are defined as a layer of unfrozen ground that is perennially cryotic (forming part of the permafrost), in which freezing is prevented by depression of the freezing-point due to the pore solution (Fotiev, 1999).

Saline frozen soil is a highly complex geotechnical material (Table 1). The soil behavior changes dramatically with only a small change in

Table 1. Frozen soil criteria.

Soil condition	Unfrozen	Plastic frozen	Solid frozen
Ice	Ice-free	Ice-bearing	Ice-bonded
Mechanics	Soil properties	Plastic properties	Elastic properties
Compression Index, a		a < 0.01 MPa^{-1}	a > 0.01 MPa^{-1}
Sand	>0°C	0 to −0.1°C	−0.1°C
Clay	>−0.2°C	−0.2 to −1.0°C	−1.0°C
Saline Clay*	>−1.0°C	−1.0 to −4.0°C	−4.0°C

*Saline Clay case for w = 33% Ds = 0.5% Cps = 15‰.

temperature. General soil mechanics applies when the soil temperature is above 0°C. Once the temperature is below freezing and the first crystals of ice start forming, the soil is considered as plastic frozen or ice bearing. Further reduction of temperature causes more ice crystals to form in the soil pore medium; when a critical volume of ice crystals is formed these start to bond together and the frozen soil is considered as solid frozen or ice-bonded. Russian standards (GOST 25100) provide the specific criterion named Compression Index (a) to classify plastic frozen and solid frozen soils.

Temperature boundaries between unfrozen/plastic-frozen/solid-frozen soils are determined specifically for each permafrost soil by field or laboratory testing. Several examples are provided in Table 1.

2.2 *Unfrozen water content*

The amount of unfrozen water has a controlling influence on the strength and deformation behavior of permafrost (Yershov, 1997). The amount of unfrozen water is determined by several factors, most critically temperature, salinity and mineral composition.

An example of temperature dependence of unfrozen water content on salinity (Ds) in frozen clay is shown in Figure 1 (Yershov, 1997). The total water content is 48% when the clay temperature is above 0°C. Cooling the clay causes some portion of pore water to freeze gradually as the temperature decreases. Thus at −1°C the total water content is shared between ice content (28%) and unfrozen water content (20%). Further cooling down to −5°C increases ice content to 38% and decreases unfrozen water content to 10%.

The influence of salinity is also highlighted, Figure 1. The amount of unfrozen water increases as salinity increases under otherwise equal conditions, including total water content. For instance, the proportion of ice and unfrozen water 28% and 20% occurs at −1°C for the saline frozen clay Ds = 0.1% but at −8°C for the saline clay Ds = 1.5%.

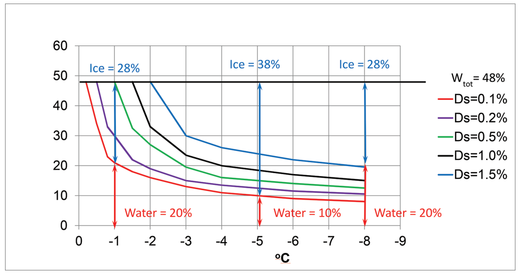

Figure 1. Unfrozen water content in frozen saline clay as a function of salinity (Ds) and temperature (Yershov, 1997).

Table 2. Preliminary design values for shear strength of adfreezing for saline frozen soils (clays).

Soil salinity, D_{sal},%	Design values for shear resistance R_{af}, kPa				
	−1°C	−2°C	−3°C	−4°C	−6°C
0.05	100	150	200	250	300
0.10	75	130	180	230	290
0.20	40	95	150	210	270
0.30	25	60	110	170	245
0.50	10	30	60	100	150

*SP 25.13330.2012 (former SNiP 2.02.04-88) provides these numbers for estimation purposes.

This impact of salinity influences the mechanical properties of the clay in a similar way.

2.3 *Mechanical properties and pile bearing capacity*

Mechanical properties of saline frozen soils depend strongly on temperature and salinity due to the unfrozen water content. For example, parameters for the shear resistance due to adfreezing, R_{af}, for saline frozen soils as a function of temperature and salinity are shown in Table 2. These parameters are from the Russian Standard "Soil bases and foundations on permafrost soils" (SP 25.13330.2012), taken from Table B.9 at page 66.

These parameters illustrate the dramatic effect of temperature and salinity on the mechanical properties of saline frozen soils. Changing temperature by 5°C, from −6°C to −1°C, would decrease soil shear resistance by 3 times for relatively pure water (D_s = 0.05%) or 15 times for more saline soil (D_s = 0.50%). An increase in soil salinity (perhaps misjudged by site investigation) from D_s = 0.05% to D_s = 0.50% would decrease soil shear resistance by a factor 2 (at −6°C) to10 (at −1°C).

Similar changes in magnitude due to salinity are observed for other mechanical properties of soil including deformation modulus.

3 EXAMPLES OF CPT TESTING IN PERMAFROST

3.1 *Salekhard and Labytnangy*

In 2014, Fugro performed geotechnical investigation of permafrost at several sites located in Salekhard and Labytnangy, Western Siberia, Russia. Permafrost was detected at 22 locations with the CPT temperature sensor. There was no refusal due to cone resistance and no "pre-drilling" was needed to conduct the tests; all predetermined depths for testing were achieved and the maximum depth was 34 m. The soil temperature was between 0°C and –1.2°C and the average cone resistance between 8 and 40 MPa, depending on the soil type.

3.2 *Vorkuta railway*

In 2015 Fugro performed a pilot project for Russian Railway to diagnose the condition of a railway embankment, located on permafrost near Vorkuta city, Russia (Sokolov et al. 2016). The CPT was performed directly from a railway flat-car within a 3 hours period. Total penetration was reached at a depth of 12 m. Two soil layers were identified, which correlated to the borehole data obtained several years previously, and the mechanical properties were estimated for each layer according to SP 25.13330.2012; E_f = 42 MPa (deformation modulus) and C_{eq} = 480 kPa (equivalent cohesion) for the first soil layer, and E_f = 22 MPa and C_{eq} = 84 kPa for the second soil layer. CPT results showed permafrost between 4 m and 12 m depth. Six detailed measurements of temperature with thermal equilibration (analogy with pore water pressure measurement) were performed that showed subzero values between –0.1°C and –0.7°C.

3.3 *Thermosyphon monitoring at Salekhard College*

CPT testing was applied in December, 2016 to diagnose the condition of piled foundations at the Salekhard College, Western Siberia, Russia. The frozen soil under Salekhard College was maintained by thermosyphons that were exposed in the crawl space below the building. CPT tests were completed from within the crawl space to measure cone resistance q_c [MPa], sleeve friction f_s [kPa] and temperature T [°C] at several locations relative to the thermosyphons and piles. Data was obtained both within the zone of influence of the thermosyphons and at sufficient distance from thermosyphons and piles to provide "baseline" measurements. Based on this data: 1) the cooling effect of the thermosyphons was directly measured (soil temperature decrease), 2) the pile bearing capacity could be estimated, and 3) pile capacity compared at different locations beneath the building (Volkov et al. 2017).

As a result of this investigation, it was determined that all the soils in the foundation are in a frozen state and that there is no permafrost thawing to a depth of 8 m, as had been implied by a previous investigation using conventional methods. The measured temperature values in the reference CPT locations were between –0.4°C to –1.3°C. Based on the code calculation, the bearing capacity of a single driven pile 300 mm × 300 mm and 8 m long is about 53 tons without taking into account the active layer; this significantly exceeds the design load of 20 tons. The thermosyphons had a cooling effect on the frozen soil. During the first winter season the soil temperature decreased by –0.5°C to –0.8°C (to –1.0°C to –2.1°C absolute values), resulting in an increased pile bearing capacity up to 77 tons, 42% higher than the reference pile capacity in the natural ground.

3.4 *Ob Bay*

Fugro performed geotechnical site investigation in 2017 on the Gydan peninsula near Ob Bay, Western Siberia, Russia. The soil conditions on the site were characterized by continuous permafrost with solid frozen sand at a mean annual ground temperature about –6°C. Such soil conditions are often stated to be unsuited for CPT investigation. Since there was no published data to substantiate that belief, Fugro performed a CPT trial to confirm applicability of the method in such soil conditions. The cone used for this test included sensors for temperature, pore pressure and electrical conductivity. The result of the CPT test is shown in Figure 2.

The cone resistance values for the 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.

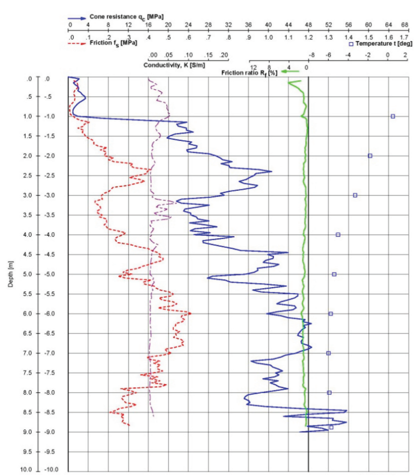

Figure 2. CPT profile in frozen sand at Ob Bay.

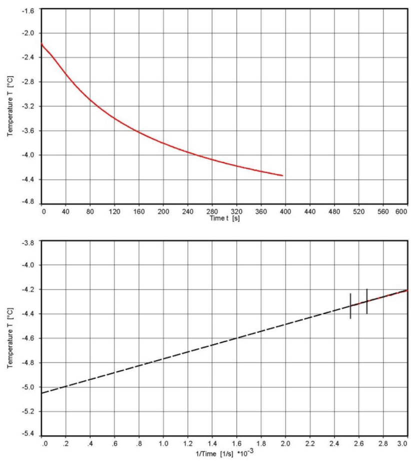

Figure 3. CPT temperature measurement at 4 m in frozen sand.

The electrical conductivity (resistivity) was also measured and the values varied between 0.0023 S/m (440 Ohm*m) and 0.0705 S/m (14 Ohm*m). It should be noted that between 3.0 m and 3.7 m the electrical conductivity is relatively high which is likely due to an increase in salinity. The average electrical conductivity equals 0.03 S/m (electrical resistivity 45 Ohm*m) in this depth interval. This is high (low) compared with the electrical conductivity for sand situated below 0.0037 to 0.0093 S/m (273 to 120 Ohm*m). This presumed increase in salinity corresponds with a marked reduction in cone resistance for the sand compared with the sand below; q_c = 22 to 28 MPa in the (presumed) saline sand interval and q_c = 36 to 48 MPa in the (presumed) non-saline sand interval below. All these correlations correspond qualitatively with the ratios of recommended values in SP 25.13330.2012 (Table 2).

An example of temperature measurement in frozen sand is provided in Figure 3. The time spent for temperature measurement is about 400 seconds. Other temperature measurements in this test were between 300 and 600 seconds. The accuracy of temperature measurement is 0.05°C. The resolution of the temperature sensor is 0.001°C.

The cone becomes heated due to friction between the cone surface area and the ground during cone penetration. In frozen sand the heat is absorbed by the surrounding media and the resulting temperature change is not as large as is in non-frozen soils. The tremendous advantage of CPT testing in permafrost soils, compared to non-frozen soils, is that the time required for temperature measurement is significantly shorter. While it would take several hours to stabilize cone temperature equal to that of the surrounding non-frozen soil where q_c = 20 to 40 MPa, in frozen soil with similar cone resistance values it takes about 10 minutes to complete temperature measurement.

The CPT data from Ob Bay (Figure 2) shows the depth of the active layer as about 1 m. This is shown by the temperature measurement at 1 m equal to 0°C. The cone resistance q_c also jumps significantly from 1 MPa to 24 MPa at this depth.

The minimum measured soil temperature was −6.0°C at 7 m depth. Below this depth the soil temperature starts gradually to increase reaching −5.7°C at a depth 9 m. It should be noted that the observed pattern of temperature variation with depth fully corresponds with the theoretical insights into the temperature regime of permafrost in the layer of annual temperature fluctuation.

4 GEOTECHNICAL MONITORING

4.1 *Existing practice*

Geotechnical monitoring of structures built on permafrost is very important. As described earlier, permafrost is very sensitive to temperature and salinity change, and these may be induced by climate change and man-made impact. There is a strong need for monitoring technology to provide sufficient data on frozen soil conditions below a structure.

The majority of structures on permafrost are built on piled foundations. An illustrative analysis for the condition of pile foundations is given below.

The frozen soil condition in relation to pile foundations can be classified in four stages (see Table 3).

1. Normal condition of frozen soil is when the designed pile bearing capacity corresponds (equals) to the actual pile bearing, and exceeds the load transferred to the pile. The soil tem-

Table 3. Frozen soil condition classification with reference to pile load and pile bearing capacity.

Foundation condition	Description
1. Normal	No visible problem detected Pile Load Actual PBC ≈ Design PBC Soil Temperature ≤ Design Value
2. Weakened	No visible problem detected Pile Load ≤ Actual PBC ≤ Design PBC Soil Temperature > Design Value
3. Poor	Visible deformations/displacements of pile are detected. Actual PBC ≤ Pile Load Soil Temperature > Design Value
4. Critical	Critical deformations/displacements of pile are observed. Actual PBC ≪ Pile Load Soil Temperature > Design Value

perature regime corresponds to that assumed in design, which is usually equal to the natural ground temperature "as it was" before the construction started, or colder (if thermosyphons are applied). Based on general practice, it is assumed that if the temperature of frozen soil is maintained at a certain level, no problems caused by permafrost should be faced.
2. Weakened condition is when due to an increase of the soil temperature, or other reason, the frozen soil becomes weaker. Actual pile bearing capacity is then less than designed, but it still exceeds the load transferred to the piles.
3. Poor condition is when the weakening of frozen soil continued and reached the point when the actual pile bearing capacity is close to the pile load. At this stage the pile load starts to redistribute between the piles which are typically installed in pile groups. The load on a weak pile equals its actual pile bearing capacity and the rest of load transfers to a neighboring pile. This redistribution of load prevents the structure from failure. However, minor deformation and damage may occur and be visible.
4. Critical condition is when the weakening of frozen soil reaches the point when actual pile bearing capacity is less than the load applied to the pile. In this case, settlement of the structure occurs and significant deformation and damage causes the operation of the supported structure to be suspended and often complete closure of the structure follows.

Based on the classification in Table 3, measures and solutions for engineering protection of a structure and foundation can be identified as follows:

Normal condition—no additional engineering measures for protection are required.

Weakened condition usually requires low-cost measures and solutions, which are aimed at indirectly improving the soil foundation, but not the structure itself, such as:

- application of thermal insulation,
- readjustment of existing thermosyphon operation,
- control on surface water flow,
- change of snow removal procedures,
- finding and fixing water leaks from surrounding civil infrastructure.

Poor condition requires high-cost measures and solutions, aimed at directly improving the soil foundation and support for the structure, such as:

- application of additional thermosyphons,
- reinforcement of the structure by installation of anchors, reinforcement supports, etc,
- reinforcement of foundation framework,
- installation of additional piles.

Critical condition—no engineering measures for protection are considered. Complete shutdown of a structure is enforced. Engineering design of the structure demolition is required.

4.2 *Existing methods for geotechnical monitoring on permafrost*

Current geotechnical monitoring methods for structures located on permafrost can be classified into three groups: 1) geodetic, 2) structural and 3) temperature.

The geodetic group includes various methods such as 3D Laser Scanning, Total Station Theodolite, HydroLevel, etc. All these methods measure distances, angles, coordinates, etc. of reference points on a structure in a certain period of time. Comparison of positions of the reference points provides information on whether the structure has been displaced or not and by how much. These methods only detect the deformation of a structure, which happens when a structure foundation is in Poor or Critical condition. The geodetic methods are not capable to predict whether deformation may occur or not, i.e. are not applicable for Normal or Weakened condition, as zero displacement is detected.

The structural group includes methods which use strain gauges and/or load cells, installed in structural elements for geotechnical purpose inside piles or near the contact between pile head and the structure itself. The strain gauges provide the strain which the pile is experiencing. Load cells provide the load transferred from structure to pile. Analysis of stress-strain behavior of the structure and distribution of loads on piles allows identification of critical strains or pile-load redistribution, which correlates to Poor and Critical conditions of the soil foundation. However, as for the geodetic approach, these methods are not capable to identify Normal or Weakened condition or to predict future deformation before it occurs.

The temperature monitoring methods are usually limited to temperature monitoring wells installed near piles and/or thermosyphons. This method is the most widespread for monitoring foundations in permafrost. Temperature monitoring detects the temperature regime of foundation soils. If the soil temperature stays within design values, the condition of the soil foundation is assumed to be good. If the temperature rises, then based on subjective opinions of experts, special engineering measures and solutions are developed. It should be noted, that usually no additional investigation is performed and often wrong/inappropriate measures are applied, sometimes causing harmful side effects and needless expense. If no engineering measures are applied, then the soil foundation may reach the critical condition causing loss of the structure. Temperature monitoring is necessary for geotechnical monitoring, however, it is not enough to diagnose the soil foundation condition and develop proper solutions for engineering protection.

4.3 *CPT application for geotechnical monitoring*

A new standard STO 36554501-049-2016 was released by Russian design institute NIIOSP in 2016. The standard rules and guides CPT application on permafrost to monitor, diagnose and control soil foundations. For saline permafrost it is suggested to use CPT equipment that measures the following parameters in one push:

- q_c [MPa] – cone resistance, or soil resistivity under the cone tip
- f_s [kPa] – sleeve friction, or soil resistivity along the cone sleeve
- T [°C] – soil temperature
- u_2 [kPa] – pore pressure
- K [S/m] – electrical conductivity of soil.

Based on the data obtained by the cone, the following parameters can be calculated:

- Pile Bearing Capacity (PBC) estimated according to STO 36554501-049-2016,
- Soil temperature as a direct measurement,
- Soil salinity estimated from electrical conductivity, and
- Deformation modulus and soil strength calculated according to STO 36554501-049-2016.

For geotechnical monitoring purposes, CPT testing should be performed at the same key locations periodically (annually or every three/five years) depending on the site conditions. The results of CPT from one location should be compared to the corresponding results measured previously to evaluate the trend in parameters and foundation properties (PBC, Temperature and Salinity). If one parameter is gradually changing, then the trend should be analyzed and engineering measures considered.

An example of PBC analysis is provided in Table 4 where based on the relation between the interpreted PBC, Pile Load (PL) and designed PBC, the permafrost foundation condition can be derived.

Table 4. CPT monitoring.

Foundation condition	CPT
1. Normal	Measured PBC is equal or greater than the design PBC.
2. Weakened	Measured PBC is less than the design PBC, but higher than the design PL. The difference is not significant.
3. Poor	Measured PBC is less than the design PBC and equals the design PL.
4. Critical	Measured PBC is less than the design PL.

The CPT technology is the only method today, which can detect permafrost soil foundation degradation at an early stage. This degradation may be caused by a rise in either temperature and/or salinity in frozen soils. Other methods are not capable to determine when soil foundation start weakening. Also the data from CPT testing can forecast when and under which conditions the poor condition may occur, since it measures not only soil temperature, but also salinity and mechanical properties of the permafrost soils, together with the interpreted PBC.

Application of CPT technology can solve the problem of geotechnical monitoring for foundations in permafrost.

5 CONCLUSIONS

Several big infrastructure projects have been developed in recent years in the Arctic region, where saline permafrost is widespread. Permafrost degradation is a significant challenge for Arctic infrastructure which may be impacted by climate change or more direct man-made causes. Even a small increase in ground temperature and/or salinity of saline frozen soil can significantly decrease the mechanical properties of the soil and hence the bearing capacity of piles. The CPT is a powerful method to monitor and diagnose the condition of soil foundations on permafrost. Correct knowledge of soil foundation conditions permits properly designed engineering solutions and remedial measures to be derived, avoiding high costs or loss of monitored structures.

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