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Practical experience with cone penetration in frozen soils

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ABSTRACT: This paper summarizes recent practical experience with CPT investigations at several permafrost sites in Russia. Some of the investigations were performed in unconventional conditions such as with ice cover, in a crawl space, or from a jack-up platform. All CPT measurements used a cone equipped with a temperature sensor to confirm the subzero temperature of frozen soil. Stress relaxation tests were performed in ice-rich permafrost soils to investigate long-term soil strength in both compression and shear. Sampling of frozen soil using direct push techniques was achieved at two sites.

1 INTRODUCTION

Frozen soil has ice content and exhibits rheological behavior, meaning the stress-strain behaviour and mechanical properties change with time. The failure of frozen soil under long-term loading is important for design. The long-term soil strength (the resistance of a soil to failure in response to a long-term load application) is a key parameter in the engineering of frozen ground (Vyalov, 1986). Long-term soil strength can be considered in terms of two main components: the long-term soil strength in compression (σ_c), important for pile end bearing (q_p), and the long-term soil strength in shear (σ_f), important for pile unit side friction (f_p).

Cone penetration testing (CPT) in frozen ground provides valuable data on frozen conditions and soil properties. Both temperature and porewater pressure sensors are required for testing in permafrost (a TCPTU test). Temperature measurement is similar to pore pressure dissipation testing. Penetration is paused and the variation of temperature with time is measured to determine the asymptote. A Stress Relaxation Test (SRT) can be performed at the same time, recording the variation of cone resistance (q_c) and sleeve friction (f_s) with time, for the cone clamped in place. This provides an estimate for the long-term strength in compression (σ_c) and shear (σ_f) (Sokolov, 2020). An SRT test does not increase the time or cost, and data processing can be fully automated for results to be obtained in the field.

2 PRACTICAL EXAMPLES OF SITES WITH CPT IN FROZEN GROUND

Nine cases of TCPTU testing in the Russian Arctic from 2014 to 2021 are listed below. The sites involve a range of permafrost conditions (Figure 1):

1. 2014 – Labytnangy Civil Infrastructure
2. 2015 – Vorkuta Railroad
3. 2016 – Salekhard College
4. 2017 – Ob Gulf, Arctic LNG2
5. 2018 – Ob River, Salekhard Bridge
6. 2019 – Novy Urengoy, Civil Infrastructure
7. 2021 – Kruzenshtern Gas Field, Yamal
8. 2021 – Dikson Area, Kara Sea
9. 2021 – Norilsk river, Talnakh Bridge

The findings from this testing include:

- Frozen sand at -6°C was successfully tested with CPT equipment;
- Up to 62 m of continuous penetration through permafrost was achieved without predrilling;
- Ground ice is generally not found to be critical for cone penetration in permafrost;
- CPT refusal is generally caused by the soil density rather than ice content or soil temperature.

Four of these cases (1-4) were presented at the CPT'18 conference (Volkov et al, 2018). A description for the five sites (5-9) tested between 2018 and 2021 is given below.

2.1 *Ob river, Salekhard bridge*

TCPTU tests were performed at the Salekhard Bridge site located in the Russian Arctic, some

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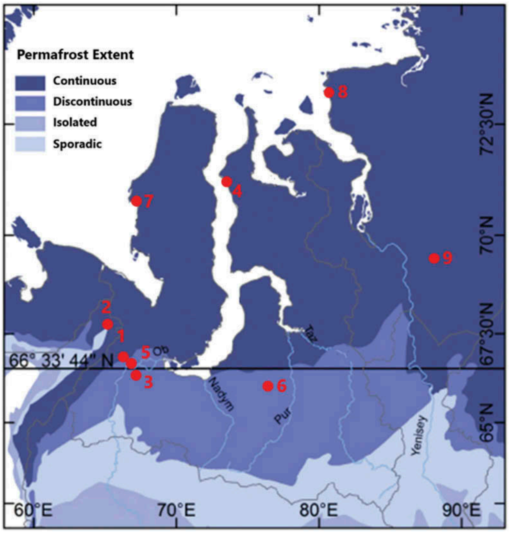

Figure 1. Permafrost sites in Siberia, Russia with CPT investigations (for numbers see description in the text).

160 km upstream from the Ob River estuary (Figure 1, site #5). Three zones at the site of the Ob River bridge are the left bank, the right bank, and the river bed itself. The site is located in a cold region characterized by discontinuous permafrost (Figure 1). The average annual air temperature in the Salekhard area is -5.7°C. The CPT tests were performed during winter January-March 2018 when the Ob River was covered by ice. One CPT was performed to refusal on the right bank and achieved a depth 62 m (with no predrilling). The frozen state of the soil (permafrost) was confirmed by measuring temperature and collecting samples of frozen ground from the adjacent geotechnical borehole. The above is considered to be a record depth for continuous CPT penetration in permafrost.

An interesting observation was made from the CPTs on the left bank. The river formed a talik at this location (an unfrozen soil strata below or near to a river). Due to this talik, part of the soil depth penetrated was frozen and part of it not. This provided an opportunity to compare the same soil horizon in both a frozen and non-frozen state. Although it is generally known that cone resistance in frozen ground is higher compared with the same unfrozen ground, all other conditions being equal, these tests provided a direct quantitative comparison. The cone resistance in the unfrozen sand varied between 8 and 35 MPa, in the frozen sand between 12 and 54 MPa. The refusal depth was similar both in frozen and non-frozen sand and varied between 25 and 30 m.

The CPT data were interpreted to provide soil parameters and associated analysis. For pile design, impact Soil Resistance to Driving (SRD) and Blow Count analyses were completed and axial pile bearing capacity and uplift capacity were estimated, for locations characterized by both unfrozen and frozen soil conditions. The results compared favourably with subsequent full scale pile tests at the site for both static load capacity and pile drivability.

2.2 *Novy Urengoy, Civil infrastructure*

In the summer of 2019, TCPTU tests with direct push sampling were performed from a crawl space under a civil apartment complex in Novy Urengoy, Western Siberia (Figure 1, site #6).

The structure, supported by piles driven to 10 m below ground level, was experiencing gradual differential settlement due to unknown reasons. It was assumed that settlement was due to insufficient pile bearing capacity. However, the steps taken to increase pile bearing capacity did not stop the settlement. CPT testing was then applied to investigate in more detail the insitu soil conditions between and below the piles. The depth of cone penetration was 30 m, comfortably exceeding the pile length.

Frozen soil was detected at some locations at a depth 11 m (Figure 2). Distinctive peaks of high values in cone resistance and low values in sleeve friction and electric conductivity were interpreted as ice lenses. Some of these ice lenses are highlighted in Figure 2, as an example.

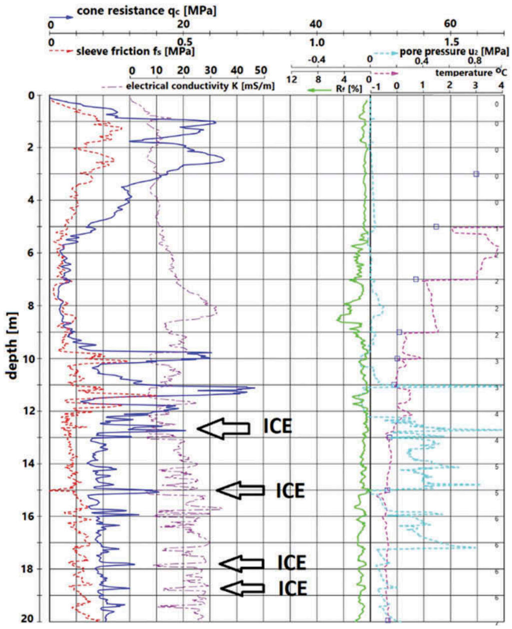

Figure 2. CPT profile in frozen soil at Novy Urengoy.

A direct push probe was then used to collect samples of the frozen soil, using a regular MOSTAP sampler with 35 mm inner diameter (Robertson, 2014). The collected samples confirmed the presence of frozen soil with ice lenses of thickness up to 10 cm (Figure 3). The frozen soil was tested in the laboratory and was found to have a high density that would not compress significantly due to thawing (Table 1). Rather, the thickness of ice lenses were such that significant differential settlement would be expected from gradually melting ground ice.

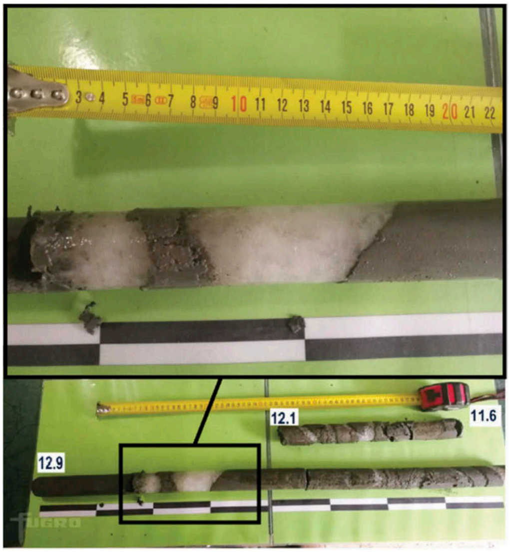

Figure 3. Frozen soil samples with ice lenses collected by direct push sampler mounted on CPT press at Novy Urengoy.

Table 1. Physical and strength properties of the tested soil.

	Value		
Parameter	Min	max	average
Depth, m	10.5	15.0	-
Soil temperature (T), °C	-0.3	-0.11	-0.20 (8)*
Freezing temperature, °C	-0.15	-0.06	-0.11 (8)
Particle density (ρ_s), g/cm^3	2.60	2.69	2.66 (10)
Density (ρ), g/cm^3	1.98	2.17	2.07 (10)
Dry density (ρ_d), g/cm^3	1.60	1.89	1.75 (10)
Porosity (n), %	29	40	34 (9)
Void ratio (e)	0.42	0.67	0.52 (9)
Water content (W), %	15	24	18 (10)
Liquid limit (W_L), %	20	28	24 (10)
Plastic limit (W_p), %	13	17	15 (10)
Plasticity index (I_p), %	7	11	9 (10)
Liquidity index (I_L)	0.24	0.59	0.39 (10)
Cone resistance (q_c), MPa	4.22	13.52	7.31 (10)
Long-term compression strength (σ_c) MPa	0.08	1.89	0.91 (10)

* (8) – number of tests.

Based on these findings, engineering measures were taken to minimize the heat flow from the building to the ground, including thermal insulation of the basement. A cooling system comprising two-phase thermosyphons was installed to a depth 10 m to cut down any residual heat flow. The geodetic monitoring of the structure since has shown that the differential settlement ceased and the structure has been stable since the cooling system was put into operation.

2.3 *Kruzenshtern gas field*

Twelve TCPTU tests were performed in the period January-February 2021 on the Sharapov Shar gulf of the Kara Sea (Figure 1, site #7). Ten of the tests reached the designed penetration depth in the range 44 m to 54 m. Early refusal of two other tests were at depths 27 m and 35 m.

The depth of water in the gulf varies between 1 and 4 m. It was unknown if the permafrost would be continuous or discontinuous at the site, and the field investigation was to characterize the ground conditions and presence of permafrost. Only one test encountered permafrost from 9 m depth with a temperature between -0.35 and -1.58°C (Figure 4).

Several peaks of high values in cone resistance and low values in sleeve friction were observed. They were not as clear as the ones at the Novy Urengoy site. However, they were interpreted as ice lenses and some of them are indicated on Figure 4.

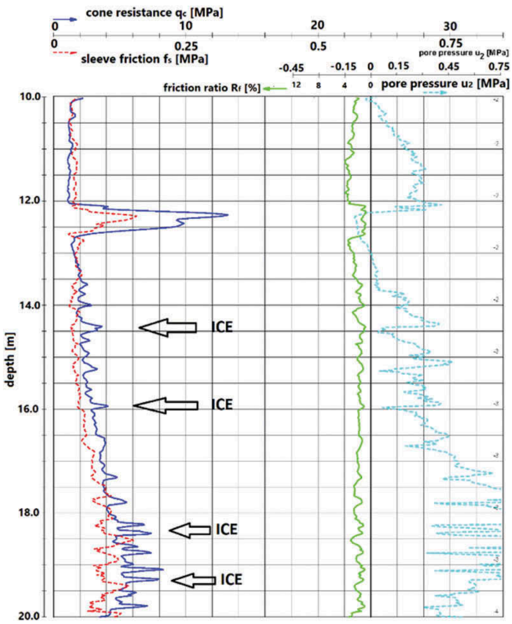

Figure 4. CPT profile in frozen soil at Sharapov Shar, Yamal peninsula.

To confirm the presence of permafrost, direct push sampling was applied close to the CPT test location. The sampler was a regular RANGER with an inner diameter 45 mm. The collected samples confirmed the presence of frozen soil (Figure 5). The cryogenic structure is massive with rare ice layers.

Figure 5. Frozen soil samples with ice lenses collected by direct push sampler mounted on a CPT press at Sharapov Shar.

2.4 *Dikson area, Kara sea*

TCPTU tests were performed in the summer 2021 from a jackup platform nearshore in the area of Dikson, Kara Sea (Figure 1, site #8). Permafrost was not detected although in several locations the clay soil was found to have a temperature in the range 0 to 1°C. The clay was not frozen because of the salinity of the pore water. Conventionally, the measurement of ground temperature nearshore is problematic. To use conventional thermistors, these must be installed in a dry borehole and then monitored with time. In comparison, the TCPTU test is not complex and has a relatively low cost and required time for testing. In addition to the temperature data, a TCPTU test provides valuable data on the variability of temperature and mechanical properties with depth.

2.5 *Norilsk river, Talnakh bridge*

Cone penetration tests with temperature measurements (TCPTU) were performed on the right bank of the Norilsk river, located above the Arctic circle, 15 km from Talnakh city (Figure 1, site #9). The site is located in a cold region characterized by continuous permafrost, with an average annual air temperature in the Norilsk area of -9.6°C. However, the testing revealed a talik at the site formed due to the thermal impact of the Norilsk river.

The TCPTU tests detected ice rich permafrost at the site over a depth range 10 m to 30 m (Figure 6). The ice rich permafrost was confirmed by geotechnical borehole drilling. The volumetric ice content (I_{tot}) was measured in soil laboratory. The volumetric ice content is the ratio of the volume of ice in a sample to the volume of the whole sample, expressed as a fraction (Everdingen, 2005).

The measured temperature of the ice-rich permafrost varied between -0.1 and -0.6 °C. The top layer of permafrost (10 m to 18 m) comprised clay with organic matter, a stratified cryostructure with high ice content $0.40<I_{tot}<0.60$. When thawed, the water content was W_{tot}=110% and density ρ=1.36 g/cm^3. The layer below (18m to 30 m) comprised clay with organic matter, a stratified cryostructure and high ice content $0.60<I_{tot}<0.90$ (Figure 7). When thawed, the water content was W_{tot}=263% and density ρ=1.12 g/cm^3.

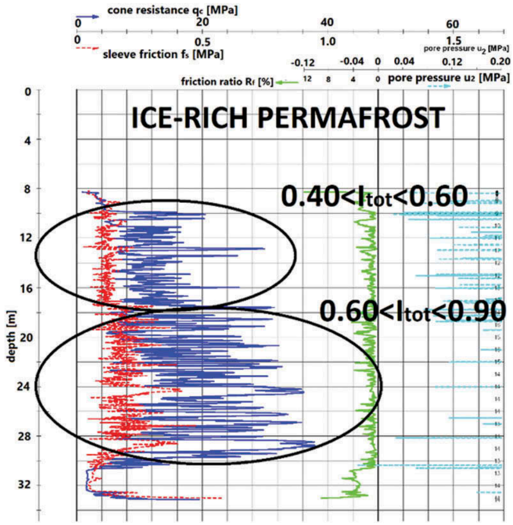

Figure 6. CPT profile in ice-rich permafrost near Norilsk.

Figure 7. Ice-rich permafrost samples collected near Norilsk.

3 STRESS RELAXATION TEST

3.1 *Rheological behavior*

Rheological behavior is inherent for frozen soils. The degree of rheological behavior depends on the physical properties of the frozen soil (ice content, water content, cryogenic structure, etc.). Rheological behavior is characterized by two interrelated parameters: creep and long-term strength (Vyalov, 1986). Long-term soil strength corresponds to a stress level below which no failure takes place within a practically observable period of load application. A stress in excess of the long-term strength results in failure after a certain time. In this paper we consider "practically observable period of load application" as 100 years. If the time period is different, for instance, 50 years, the term is described as the "long-term strength for 50 years".

There are two approaches to evaluate long-term strength (Figure 8). The most common is to measure deformation under an applied constant load to describe creep, i.e. deformation change with time. The second approach measures the stress caused by a constant applied deformation to describe stress relaxation, i.e. stress change with time. The second approach is considered in this paper.

Relaxation	Creep
Stress vs time	Deformation vs time
Constant deformation	Constant stress
Relaxation period << Period of after-effect	

Figure 8. Correlation between Creep and Relaxation in the Rheological testings.

Stress relaxation is the decrease of stress with time in response to constant deformation applied to the soil. Relaxation of stress results from a redistribution of elastic and plastic deformation. All physical bodies possess both elastic and viscous properties. However, the material behavior depends on the correlation between the period of load application (i.e. the observation period) and the relaxation period. If the observation period is shorter than the relaxation period, a body behaves as a Hookean solid. In the alternative case, it behaves like a Newtonian fluid.

The Relaxation period varies significantly for different materials. For instance, limestone 10^{11} sec (thousands of years), glass 10^{10} sec (hundreds of years), ice 10^{2} sec (hundreds of seconds), water 10^{-11} sec. In the case of water, for instance, when acted on by a force lasting less than 10^{-11} sec it behaves elastically. Rocks experience load over periods of geological time and may develop viscous flow, which can be observed in folding. Ice behaves like an elastic body, failing in its brittle form if struck (or loaded) rapidly, a force applied for less than 10^{2} sec (Vyalov, 1986). A long-term load causes ice to flow as a viscous material, as occurs in glaciers. Similar behavior, i.e. brittle failure under a rapid load application and viscous flow due to a long-term load, can be observed in frozen soils.

It is important that the relaxation period does not equal the period of after-effect. The process of relaxation occurs much faster than the process of creep, i.e. relaxation period significantly shorter than period of after-effect, which differs by several orders (10^{n}). This fact provides a key advantage for the second approach to evaluate the long-term strength which is based on stress relaxation measurements versus the first approach based on creep measurements.

3.2 *Stress relaxation test procedure (SRT)*

Relaxation test approach for soils was first proposed by Vyalov in 1986. It was called an "accelerated method of testing soils for long-term strength, using a dynamometric apparatus". The method description said "if an initial stress is given which is close to the hypothetically instantaneous strength (as determined in advance), the finite value of stress will approach the ultimate long-term strength". The stress should be measured in time.

The stress relaxation curve should then be processed by a fitting method to determine the empirical coefficients for the following equation:

$$\sigma_c = \frac{\beta}{\ln\left(\frac{t_p+1}{T}\right)} \tag{1}$$

where σ_c = long-term soil strength; t_p = measured time; and β, T are empirical coefficients.

Once the empirical coefficients are determined the long-term strength for a given period of time, for instance 100 years, may be calculated.

The proposed laboratory method was not practically useful at the time due to the low quality of measurement equipment and impossibility to determine the instantaneous strength in advance. Because of these limitations, a pure relaxation test on frozen soils is not common practice.

However, the accelerated method approach can be applied for the conditions when performing in-situ a CPT temperature dissipation test (or pore pressure dissipation test). The only requirement is that the dissipation is performed with the rods clamped (to ensure not movement). In such a case, the deformation is kept constant and the stress relaxation can be measured by the cone (q_c) and sleeve friction (f_s) sensors.

The Stress Relaxation Test (SRT) is described in detail by Sokolov (2020). A key step in the processing was to apply the fitting curve method not for the entire curve, but for the curve starting at some point. This is the point that separates two parts of the curve: the first part corresponds to the relaxation-creep stage while the second part to the relaxation stage. Once this separating point is determined it is possible to back calculate the empirical coefficients β and T for equation (1) and thereby calculate the long-term strength in compression and shear.

3.3 *Results*

SRT results from site #5 (Figure 1) were verified by comparing with the results of a static pile load test (Volkov, 2019, Sokolov, 2020). The common practice calculates the pile unit end bearing, q_p, from the calculated equivalent average cone resistance, q_{ca}, multiplied by an end bearing coefficient, k_c (Robertson, 2014). This approach did not work well for frozen soils because ice contributes significantly to the cone penetration resistance, but little to the long-term soil strength. Thus in case of ice rich permafrost, the end bearing coefficient, k_c, may be very low compared to common values for non-frozen soils. For instance, based on the numbers provided in Table 2, k_c (which is correlated to the relation between σ_c/q_c), varies from 0.017 to 0.086 and is quite low compared to k_c for non-frozen soils 0.2 to 0.5 (Robertson, 2014).

Table 2. CPT measured and SRT evaluated results.

Depth, m	T, °C	q_c MPa	σ_c MPa	f_s kPa	σ_s kPa
17.4	-0.41	8.96	-	153	67
20.6	-0.53	15.34	0.48	115	51
23.3	-0.49	13.65	0.48	209	23
27.6	-0.21	22.06	0.43	146	15
31.7	-0.09	1.28	0.42	75	15
32.0	+0.09	1.12	-	48	-
14.8	-0.27	15.28	0.48	114	29
17.7	-0.30	7.08	0.60	187	-
20.6	-0.21	18.27	0.49	255	16
23.5	-0.15	27.95	0.73	231	12
26.4	-0.11	31.92	0.55	294	7
30.0	-0.10	1.68	-	70	39
30.7	+0.13	2.05	-	60	-

4 CONCLUSIONS

Practical application of CPT in frozen ground has been illustrated for nine different sites with various degrees of permafrost. The CPT is able to penetrate frozen soils, including frozen sands, ice-rich soils and ice lenses. This application of CPT testing could be significantly enlarged for the current geotechnical activities in the Arctic.

Cone penetration testing provides a lot of data which can be obtained in one push performed within one working day. Perhaps most significant is that a CPT used with a temperature sensor is capable to detect frozen soils by measuring the soil temperature directly. The pore water pressure sensor provides very useful complementary data. For reference, this test has been called by the acronym TCPTU.

In addition, by using a Stress Relaxation Test (SRT) it is possible to estimate the long-term soil strength in both compression (σ_c) and shear (σ_s). The long-term strength results on one of the sites were confirmed by comparison with a static pile load test. The results on σ_c and σ_s derived for other sites also show consistency with the recommended values for pile unit end bearing and pile unit side friction.

Ice content in frozen soil plays a major role and influences strongly key parameters such as long-term strength. TCPTU testing shows great applicability for ice-rich frozen soils both to detect ice and evaluate long-term soil strength in compression and shear. Push sampling methods using the CPT equipment can recover samples for laboratory testing.

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