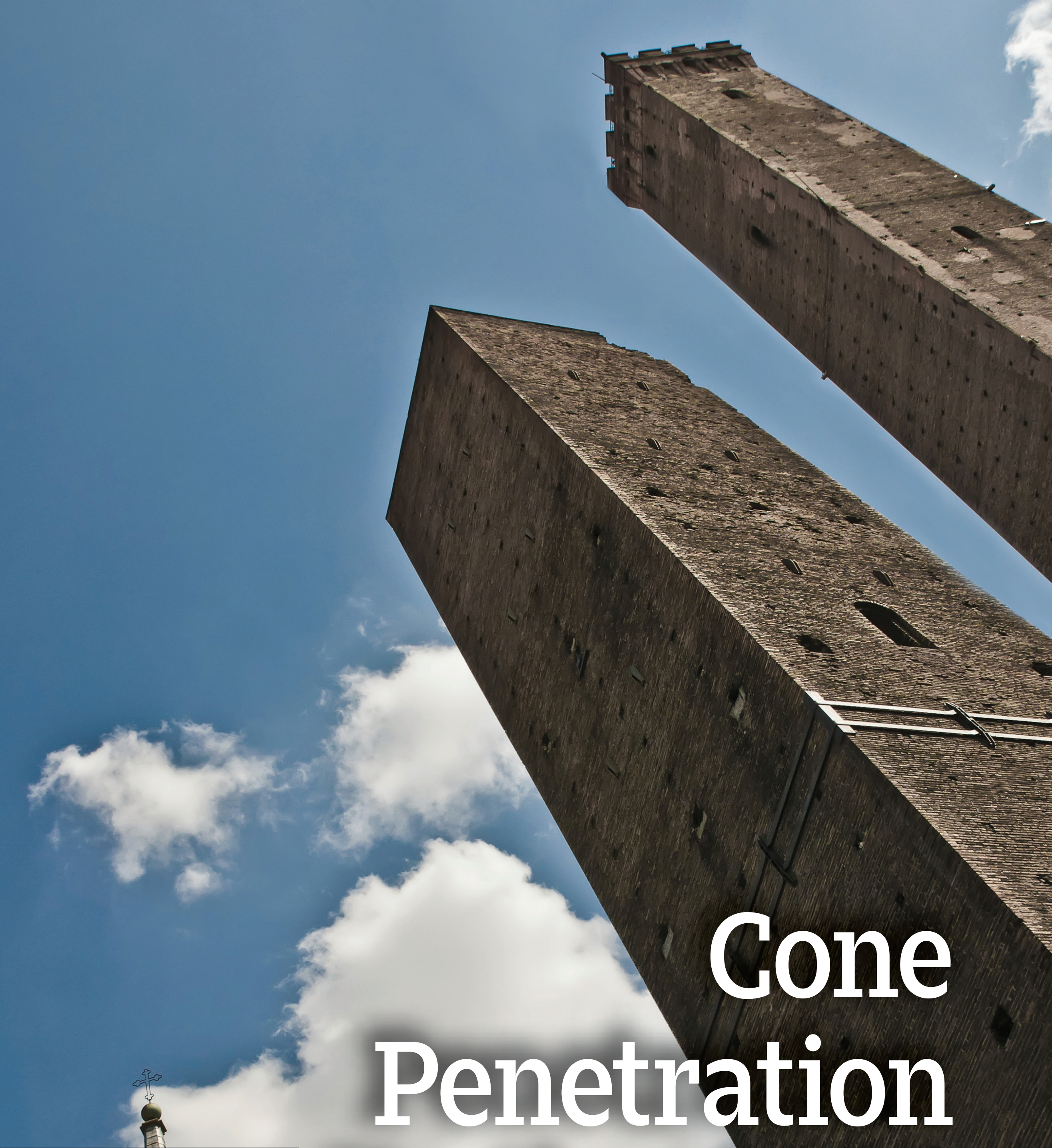

# Cone Penetration Testing 2022

CRC Press
Taylor & Francis Group

Editors
Guido Gottardi & Laura Tonni

# CONE PENETRATION TESTING 2022

This volume contains the proceedings of the 5th International Symposium on Cone Penetration Testing (CPT'22), held in Bologna, Italy, 8-10 June 2022. More than 450 authors - academics, researchers, practitioners and manufacturers – contributed to the peer-reviewed papers included in this book, which includes three keynote lectures, four invited lectures and 170 technical papers. The contributions provide a full picture of the current knowledge and major trends in CPT research and development, with respect to innovations in instrumentation, latest advances in data interpretation, and emerging fields of CPT application.

The paper topics encompass three well-established topic categories typically addressed in CPT events:
- Equipment and Procedures
- Interpretation
- Applications.

Emphasis is placed on the use of statistical approaches and innovative numerical strategies for CPT data interpretation, liquefaction studies, application of CPT to offshore engineering, comparative studies between CPT and other in-situ tests. **Cone Penetration Testing 2022** contains a wealth of information that could be useful for researchers, practitioners and all those working in the broad and dynamic field of cone penetration testing.

PROCEEDINGS OF THE 5TH INTERNATIONAL SYMPOSIUM ON CONE PENETRATION TESTING (CPT'22), 8-10 JUNE 2022, BOLOGNA, ITALY

# Cone Penetration Testing 2022

*Editors*

Guido Gottardi

*Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy*

Laura Tonni

*Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy*

CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

Cover image: photo by Claudio Turci

First published 2022
by CRC Press/Balkema
Schipholweg 107C, 2316 XC Leiden, The Netherlands
e-mail: enquiries@taylorandfrancis.com
www.routledge.com – www.taylorandfrancis.com

*CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business*



*Library of Congress Cataloging-in-Publication Data*

A catalog record has been requested for this book

ISBN: 978-1-032-31259-0 (hbk)
ISBN: 978-1-032-36228-1 (pbk)
ISBN: 978-1-003-30882-9 (ebk)
DOI: 10.1201/9781003308829

*Cone Penetration Testing 2022 – Gottardi & Tonni (eds)*


# Comparison of frozen soil strength characteristics by cone penetration and triaxial compression testing

Daniil Lagosha
*Lomonosov Moscow State University, Russian Federation*

Ivan Sokolov & N.G. Volkov
*Fugro, Russian Federation*

ABSTRACT: The paper provides comparison of field and laboratory tests of permafrost soil. Electrical resistivity and temperature piezocone penetration tests (RTCPTu) were carried out in the area of sporadic distribution of permafrost. RTCPTu detected islands of permafrost at depth more than 10 meters. Based on this information, undisturbed samples of warm permafrost soils with massive cryogenic structure and thick ice lenses (up to 10 cm) were collected using CPT equipment with a direct push soil sampler (MOSTAP) mounted instead of cone. The samples were kept in frozen condition and transported to the soil lab, where physical properties and triaxial compression tests were carried out. The CPT results included the characteristics of long-term frozen soil strength such as $\sigma_c$ – the long-term cone resistance and $\sigma_n$ – the net long-term cone resistance. The results of triaxial tests provided the characteristics of peak strength: $\sigma_1$ – the maximum vertical stress and $\sigma_1$-$\sigma_3$ – deviator stress at failure. The frozen soil samples were cleared from ice lenses since it is not possible to test them with thick ice lenses. The results of CPT and triaxial testing showed fairly similar values, when the cone measured resistance in frozen soil with massive cryogenic structure. When the cone was located near ice lenses, the net long-term cone resistance appeared to be much lower compared to deviator stress. This observation is in line with conventional theory on physics of ice which states that ice has near-zero long-term strength. The obtained results clearly show the value and advantage of CPT in permafrost (in-situ testing) compared with triaxial compression testing (laboratory). The properties of frozen soil in-situ may significantly differ from properties of frozen soil in a sample. This must be considered for designing civil structures on permafrost.

## 1 INTRODUCTION

Conventional geotechnical drilling and sampling of permafrost is a challenging problem due its vulnerability. Frozen soils with high ice content at a temperature near freezing point may be easily disturbed due to frictional heating, drilling fluid, ice brittleness and other factors. CPT on permafrost is a maturing technology which has been successfully applied recently. A great benefit would be to use CPT equipment together with direct push soil sampling which is commonly used for non-frozen soils. This combination of CPT and frozen soil sampling was successfully tested in the city of Novy Urengoy, West Siberia, Russia in 2019.

The site is located in Novy Urengoy, Russia. The soils of the site were investigated on a depth of more than 25 m using field and laboratory tests. Retrospectively the site is located in the northern part of the West Siberian plain in the river basin, where accumulation of lake-alluvial sediments took place. The surface relief is flat due to urban construction. Site soils are represented by clays (from sandy to silty) and sands, rarely peat. In some areas, there are permafrost soils from a depth of 9-15 meters.

The roof of permafrost soils is marked at different depths under the structures on this site. Moreover, there is the complete absence of frozen rocks on some parts of the site. So, there are uneven settlements of structures, which lead to theirs deformation and formation of cracks in them, causing the emergency condition of structures.

The site was located in the basements of two residential buildings (Figures 1, 2). The height of the basements is less than 2 meters. There are many continuous sewer and heating pipes inside, complicating the tests. Thus, site conditions did not permit the using of a heavy vehicle-based cone penetration unit or other commonly used field methods using large-sized equipment.

DOI: 10.1201/9781003308829-69

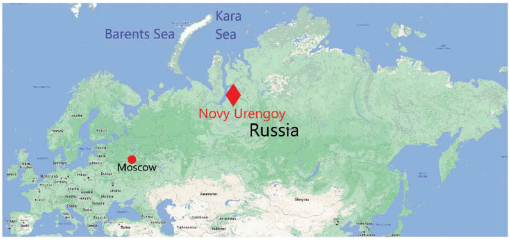


Figure 1. Map location area – Novy Urengoy, Russia.

Figure 2. Site view.

## 2 FIELD TESTS OF PERMAFROST - CPT

### 2.1 *CPT performing*

To perform cone penetration tests (CPT) with measuring of conductivity, temperature and pore pressure RTCPTu, a special small-sized unit with a nominal penetration force of 150 kN was used (Figure 3).

CPT was carried out in two modes: continuous (a constant rate-controlled penetration) and "with stabilization" of the cone (similar to "dissipation" test but rods are kept clamped). The second mode when $q_c$ is measured is also called stress relaxation test, which carried out in a frost layer of the soil to investigate the relaxation behaviour of permafrost.

The stress relaxation test allows to obtain the soil strength parameters similar to those of the continuous type test, but instead of the values of first type test, stabilized second type test values of the cone and at the friction sleeve resistance ($q_{cs}$, MPa and $f_{ss}$, MPa) are obtained. Based on the results of the stress relaxation test, it is calculated the long-term strength of the soil under the cone ($\sigma_c$, MPa) and on the friction sleeve ($\sigma_s$, MPa). In moving of a cone, the soil is loaded by a value more than the instantaneous strength. When a cone stops moving, it is fixed and the stress relaxation is recorded. The values are recorded until the readout parameters stabilize.

Correlation of the listed parameters for frozen soils is as follows:

- for the cone resistance: $q_{cv} > q_{cs} > \sigma_c$ is always observed, and $q_{cv} = q_{cs}$ (0 sec) at the same CPT point and at the same depth;

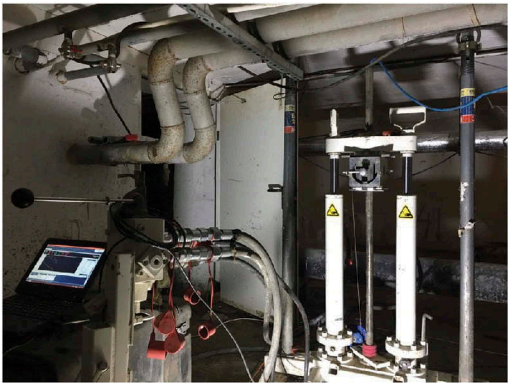

Figure 3. Map location area – Novy Urengoy, Russia.

- for the friction sleeve resistance: can be $f_{sv} \approx \approx< f_{ss}$ and $f_{sv} > f_{ss}$, but $f_{sv}$ and $f_{ss}$ are always more than $\sigma_s$.

Cone penetration tests in velocity mode were executed at 2 cm/s for maximum depths up to 30 m, including tests in cone stabilization mode. They were performed to a depth of 25 m below the ground surface. Temperature and stress relaxation measurements were mostly made at the depth of permafrost spreading: from 7-9 m to 25 m with intervals of 1 m at 9-11 m and 2-5 m at 11-25 m. Frozen soil temperature measurements confirmed the presence of frozen soils at the site. The tests were carried out in July-August 2019. Measured temperatures in the frozen soils ranged from -0.9 to -0.1°C.

### 2.2 *MOSTAP soil sampling*

Soil sampling was performed with a MOSTAP direct push soil sampler (Robertson, 2014) from the CPT unit. A total of 13 soil sampling points were executed on the site. Sampling was carried out very close to the CPT points, at a distance of 1-2 m, for reliable correlation of the results of testing and sampling and minimal influence of soil variability factor. In total, 146 samples were taken, of which 110 of them were unfrozen and 36 of them were frozen (Figure 4). It is worth to emphasize that the sampling of frozen soils using the MOSTAP technology was carried out for the first time.

In this paper, frozen clay was considered as the object of researching. It was chosen due to the fact that it was the cause of uneven sedimentation at the site. It was also of scientific interest to research the strength characteristics of the frozen soil areas with thick ice lenses.

Considering frozen soil layer was investigated well by both sampling and cone penetration testing. The temperature of the investigated soil varies from -0.3 to -0.11°C. It is deposited from a depth of 10 m. Sampling was carried out at a depth of

10-15 m. 11 samples were taken. Within this layer, 16 points of CPT were executed in the velocity mode and 45 stress relaxation tests in the stabilization mode of the cone. Out of this number of tests, values for analysis were selected from 8 points. All the CPT points with stress relaxation tests were located very close to the frozen soil sampling points - at a distance of 1-2 m.


Figure 4. Part of investigated frozen soil, sampled by MOSTAP.

## 3 LABORATORY TESTS OF PERMAFROST – TRIAXIAL COMPRESSION TESTING

### 3.1 *Specimens preparing*

Various characteristics of the composition and properties of investigated soils were determined in the field laboratory. According to their results, the soil can be characterized as frozen clay from silty to sandy, with ice from well-bonded, no excess ice to thick ice inclusions, non-saline, from very stiff to soft.

To determine the strength characteristics of the investigated soil by triaxial test, specimens were made of selected samples of frozen clay. Soil samples with a massive cryogenic structure were tested in a triaxial compression apparatus to ensure that the homogeneity condition of the specimen was met.

Specimen preparation for the test was carried out in a special room with the maintenance of negative temperature (cryogenic chamber). The specimens cut from the frozen samples had a cylinder shape with a height (h) to diameter (d) ratio of 2:1 (70 mm: 35 mm) (Figure 5).

### 3.2 *Performing tests and theirs results*

The chamber and the counter-pressure system of the triaxial apparatus chamber supplying the fluid to the stamps, and the holes in the stamps were filled with a special liquid with a negative freezing temperature by raising the pressure in the counter-pressure system with complete displacement of air bubbles. The triaxial tests were executed in the consolidated-undrained mode without pore pressure measurements. The investigated soil was in the frozen state, so it was not possible to measure pore pressure.

In this case to determine the strength of the soil in full stresses, it was measured by the peak of the stress deviator. The specimen is broken by applying a vertical loading with the pressure in the chamber

Figure 5. Example of a test soil specimen in cross-section and longitudinal section.

previously reached and the drainage blocked. Kinematic test mode was used: vertical loading is applied with a given constant rate of deformation of the specimen. The rate of specimen loading was 0.02 mm/minute.

Soil temperature during triaxial tests is -1°C. This is the highest subzero temperature that can be maintained in the apparatus to keep specimens in frozen state. In the natural soil conditions, their temperature is close to the freezing start temperature and to zero - from -0.3 to -0.1°C, which is technically extremely difficult to assign in the device today. The tests lasted from 11 to 21 hours. The consolidation time of the samples was 4 hours. The confining stress in the triaxial device was within 280-300 kPa.

Of the executed five tests, it can be highlighted two "paired" tests, i.e. performed on specimens taken from one sampling point and one depth interval, and one "unpaired" test. Therefore, all specimens were aged for 1 day and tested under identical consolidation and loading conditions, so the "paired" tests could be compared to each other.

Figures 6 and 7 show the results of triaxial tests. Specimens No. 2-5 exhibited a brittle behaviour, specimen No. 1 exhibited a ductile behaviour (Figure 7). “Paired” specimens No. 1 and No. 2, No. 3 and No. 4 showed quite close peak strength to each other: 697 and 679 kPa; 989 and 935 kPa, respectively. The results are repeatable and confirm the validity of the testing procedure.

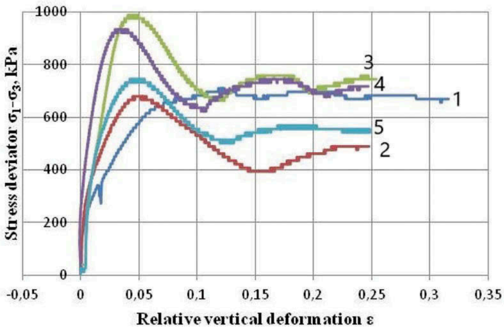


Figure 6. The graph of deviator stress dependence on vertical axial deformation.

It should be noted that fracturing time of specimens No. 1 and No. 2 was quite close - 15 and 13 hours, respectively. At the same time, specimens No. 3 and No. 4 had two times more different fracturing times - 7 and 16 hours. However, in both cases the values of stress peak deviator in “paired” specimens are quite close.

The vertical stresses $\sigma_1$ and deviators at fracture of specimens $\sigma_1$ - $\sigma_3$ obviously have the same patterns. The values of $\sigma_1$ and $\sigma_1$ - $\sigma_3$ range from 0.96 to 1.28 MPa and from 0.68 to 0.94 MPa, respectively.

Figure 7. A frozen soil sample after the triaxial test and its failure character.

## 4 COMPARISON CPT AND TRIAXIAL TESTS RESULTS

### 4.1 *Mechanism of tests*

The triaxial tests simulated natural soil conditions similar to the stress relaxation tests performed by cone penetration testing.

The mechanism of these tests is quite similar. In the triaxial compression device, the stamp transmits vertical stress to the specimen, and the fluid filling the chamber space makes all-round pressure on the specimen, allowing the stress-strain state of the tested soil in the natural conditions to be remake as much as possible (Figure 8b).

When executing the stress relaxation test by CPT, the cone is penetrated directly into the soil to the depth of the investigation, stopping at that depth. As a result, the soil mass makes all-round compression of the investigated soil layer from all sides, and the cone, similarly to the stamp in the triaxial apparatus, assigns vertical stress at a constant rate of deformation. In addition, CPT is sensitive to transient zones of the soil mass (changes in soil type) and soil variability, such as ice lenses, due to the influence zone of the cone (Figure 8a).

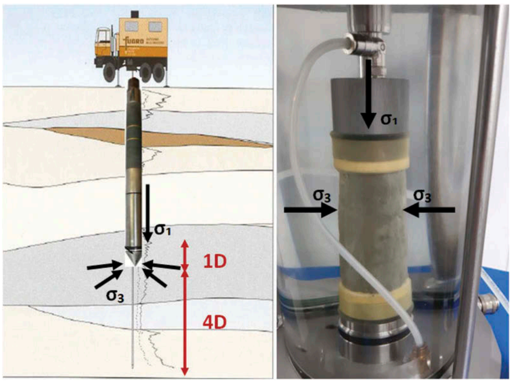


Figure 8. Mechanism of the main stresses in the test method of: a) CPT and zone of influence of the cone; b) triaxial compression.

The principle of the major stresses in both test methods is similar, but it is necessary to consider factors that will reflect the difference between the results obtained by them. These factors are:

- ground temperature;
- geometric shape of the stamp/cone;
- soil variability;
- stress-strain state of the soil.

As a result of the performed tests and their processing the following strength characteristics were obtained:

- by CPT method:
- ● cone resistance $q_c$;
- ● long-term cone resistance $\sigma_c$;
- ● net long-term cone resistance $\sigma_n$;

- by triaxial compression method:
- ● vertical stress at specimen failure $\sigma_1$;
- ● stress deviator at specimen failure (peak soil strength) $\sigma_1$ - $\sigma_3$.

The cone resistance of the soil $q_c$ in this paper is taken equal to the corrected cone resistance values

$$q_t = q_c - (1 - a)u_2 \quad (1)$$

where a - base area coefficient of the cone,
$u_2$ - pore pressure (Lunne et al., 1997),
i.e. pore pressure in frozen soils is not considered. Consequently, $q_t = q_c$.

From the values of $q_c$ obtained from direct measurements, it was obtained the values of the long-term cone resistance $\sigma_c$. For this purpose, it was used the method of calculating this parameter based on the dynamometric method of Vyalov (1986).

This method of measuring stress relaxation helps in evaluating the long-term strength of the soils which serve as the basement of the structure. Processing application of stress relaxation curves obtained in the field tests with the help of the described equation makes it possible to obtain values of long-term strength of soil at a given depth. The validity of application of this equation is confirmed by researches of Vyalov (1986), Volkov and Sokolov (2018; 2019; 2020).

## 4.2 *Comparison of the results*

Based on the obtained values of the long-term cone resistance $\sigma_c$, the values of the net long-term cone resistance of the soil $\sigma_n$ were obtained by:

$$\sigma_n = \sigma_c - \sigma_{vo} \quad (2)$$

where $\sigma_{vo}$ - overburden stress (Lunne et al., 1997).

To compare the results of the strength characteristics investigation of the investigated soil, the values of $\sigma_c$ and $\sigma_1$ and as well $\sigma_n$ and $\sigma_1 - \sigma_3$ were taken and their dependence on the depth of the investigation was plotted (Figures 9, 10).

As a result of the analysis it should be paid attention to the following:

1. The pattern of $\sigma_1$ and $\sigma_1$ - $\sigma_3$ values growth with depth is clearly traced, similar to the pattern of the long-term cone resistance of the soil.
2. The values of $\sigma_c$ obtained at the depth of investigated soils vary from 0.25 to 1.15 MPa. It should be noted the increase of long-term cone resistance of the soil with increasing the depth of investigation.

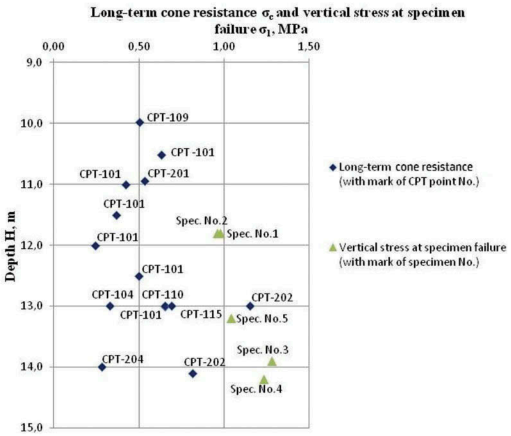


Figure 9. The graph of long-term cone resistance and vertical stress at triaxial test failure of specimen dependence on depth.

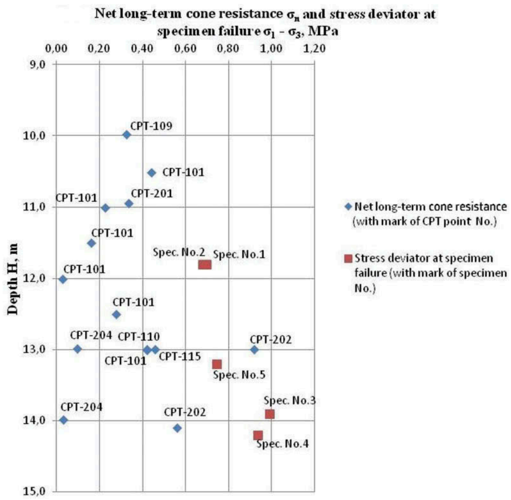


Figure 10. The graph of net long-term cone resistance and stress deviator at triaxial test failure of specimen dependence on depth.

3. The values of $\sigma_n$ change from 30 to 920 kPa. A higher net long-term cone resistance with increasing depth is also noted.
4. Minimum values of $\sigma_n$ (30 kPa) are close to zero. This indicates the presence of ice lenses in the zone of cone influence. Such frozen soils are characterized by low bearing capacity during long-term loading application.
5. The maximum values of $\sigma_n$ (0.56-0.92 MPa) and $\sigma_c$ (0.82-1.15 MPa) obtained by CPT correlate well with stress deviators (0.7-1.0 MPa) and vertical stress (0.96-1.3 MPa) in failure of specimens tested by triaxial compression. These values were observed in frozen soils with massive cryogenic

structure, which was confirmed by sampling. In addition, frozen soil samples were tested in the triaxial apparatus with exactly this cryogenic structure to meet the condition of sample homogeneity.

6. The temperature of the triaxial tests is -1℃. This is the highest subzero temperature that can be maintained for high-temperature frozen specimens in triaxial testing. In the natural soil conditions, their temperature is close to the freezing start temperature and to zero - from -0.3 to -0.1℃, which is technically extremely difficult to create in the device today. As it is known, when the temperature of frozen soil decreases, its strength increases. Perhaps that is why the values of the results of triaxial tests are correlated with the maximum values of CPT.

Thus, the results of cone penetration and triaxial testing show fairly similar results in the case of a massive cryogenic structure of soil. Determining the strength in frozen soil with lensed cryogenic structure is currently a important question. There is not yet a consistent method for such determination. In this case, CPT revealed that in frozen high-temperature ice-rich clays, the long-term strength over time when the load is applied will tend to small values, close to zero.

## REFERENCES


Lunne T., Robertson P.K., Powell J.J. 1997. Cone penetration testing in geotechnical practice. Publishing house of the Spon Press, London and New York.

Robertson, P.K., and Cabal, K.L. 2014. Guide to Cone Penetration Testing for Geotechnical Engineering, 6th Edition, Signal Hill, California: Gregg Drilling & Testing, Inc.

Sokolov I. 2020. Determination method for strength properties of frozen soils by cone penetration testing. PhD Thesis – Moscow State University, Moscow (in Russian).

Volkov, N., Sokolov, I. & Jewell, R. 2018. CPT Testing in Permafrost. Proceedings 4th International Symposium on Cone Penetration Testing / N. Volkov [and etc.] // – CPT'18. – Netherlands, Delft – 2018. – pp. 1258–1268.

Volkov N.G., Sokolov I.S., 2019. Estimation of pile bearing capacity in permafrost based on stress relaxation measured by cone penetration testing. Geotechnics, Vol. XI, No. 1, pp. 68–78.

Vyalov, S.S. 1986. Rheological Fundamentals of Soil Mechanics, Volume 36, 1st Edition. Publisher: Elsevier.