In-situ Testing for Quality Assurance in Permafrost

September 15, 2015

Dr. Nikolay Volkov (Fugro Consultants, Houston, USA)
Dr. Richard Jewell (Fugro Consultants, Brussels, Belgium)

This presentation will cover the following:

- A brief introduction to **Saline Permafrost Behaviour** and the challenges for pile foundation design
- Illustrate the use of **Cone Penetration Testing** for investigation, pile design and subsequent monitoring of foundations at permafrost sites.

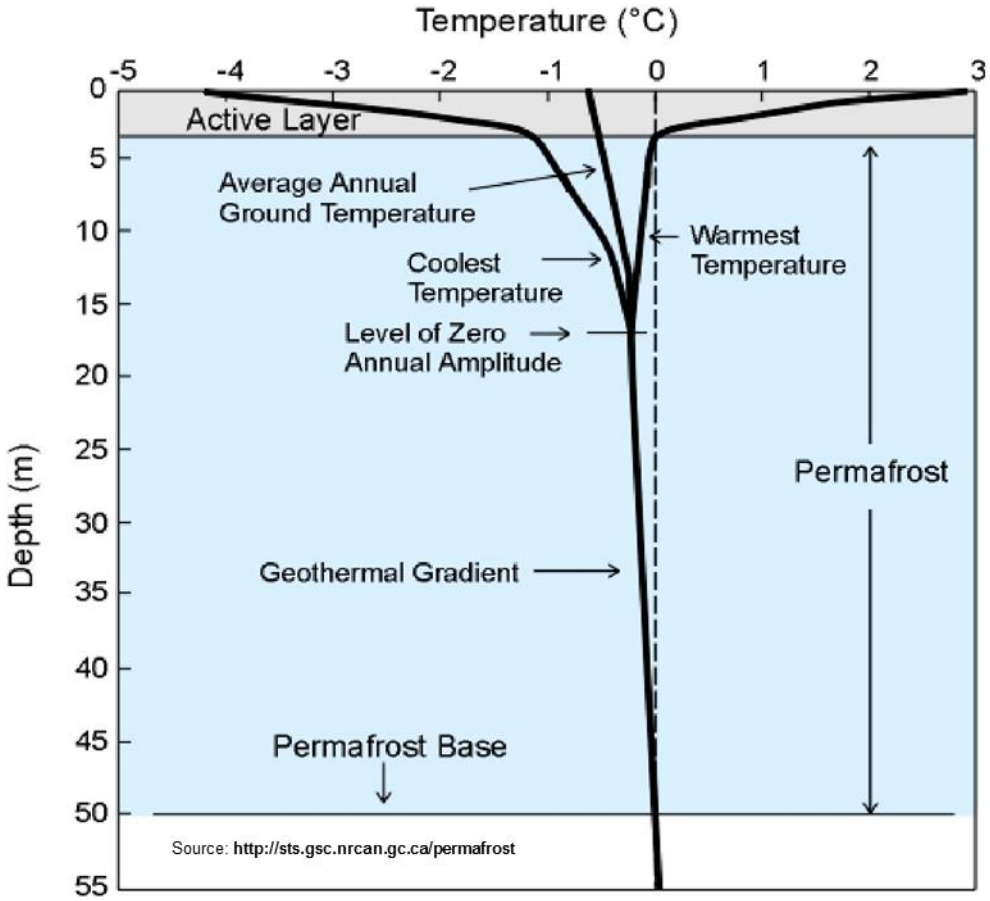
Some Permafrost Definitions

Permafrost is defined on the basis of temperature, as soil or rock that remains below 0˚ C throughout the year, and forms when the ground cools sufficiently in winter to produce a frozen layer that persists throughout the following summer.

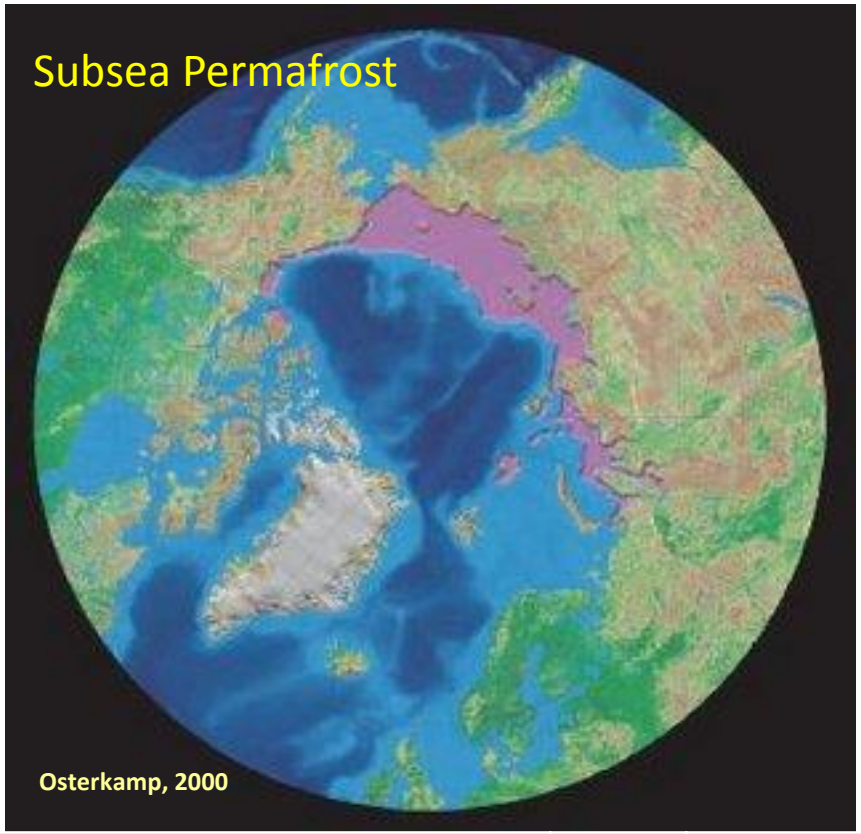
The annual range in ground temperatures is shown by the warmest and coolest temperatures occurring at depth. With increasing depth in the ground, the seasonal difference in temperature decreases. The point at which there is no discernable change in temperature is termed the "**depth of zero annual fluctuations**".

Each year a portion of the ground at the surface rises above 0ºC for part of the year. This part of the ground, termed the active layer, freezes and thaws with the changing seasons.

Both the thickness of permafrost and the active layer depend on local climatic conditions, vegetation cover and soil properties as well as geothermal gradient.

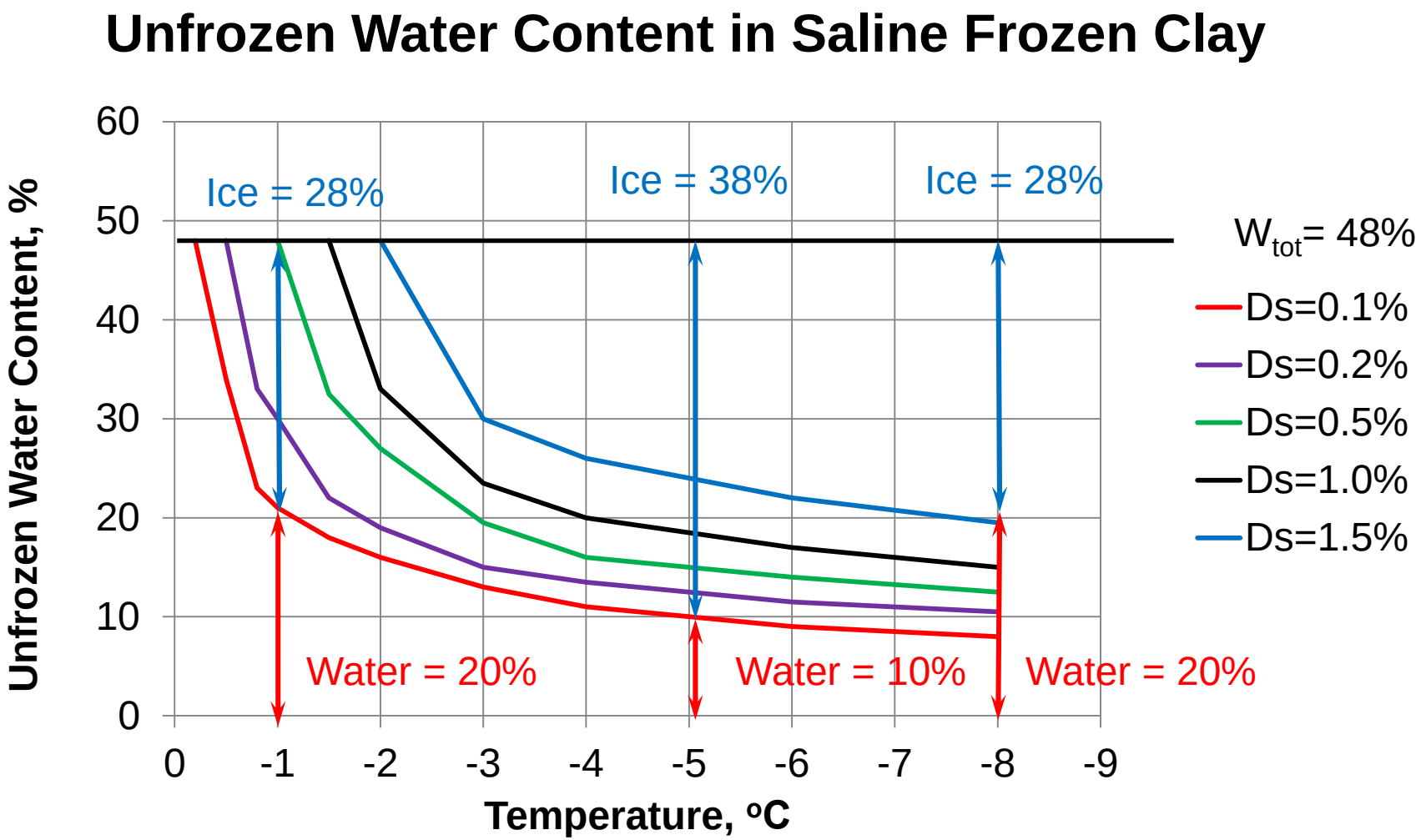


Permafrost Map / Saline Permafrost



General Term		Unfrozen	Plastic Frozen	Solid Frozen
Ice		Ice-free	Ice-bearing	Ice-bonded
Mechanics		General Soil Mechanics	Plastic properties	Elastic properties
Compression Index, a			$a < 0.01\ MPa^{-1}$	$a > 0.01\ MPa^{-1}$
Temperature	Sand	$> 0^oC$	$0 \div -0.1^oC$	$< -0.1^oC$
	Clay	$> -0.2^oC$	$-0.2 \div -1.0^oC$	$< -1.0^oC$
Salinity W=33% D_s=0.5% C_{ps}=15‰	Clay	$> -1.0^oC$	$-1.0 \div -4.0^oC$	$< -4.0^oC$

Salinity Effects – example of a clay soil with water content 48%



Pile Dimensions 20 meters deep, 0.5 m diameter

Pile Bearing Capacity Decrease due to Temperature Increase according to the Russian Standard (СНиП 2.02.04-88) and Aksenov (2001)

R_{sh} (kPa) (Design shear strength) was adopted from SNiP 2.02.04-88. See the table below with detailed calculations of Pile Bearing Capacity for the most common Soil Units (EGE – Engineering Geological Element).

Average Ds	0°C	-1°C	-2°C	-3°C	-4°C	-6°C
EGE-1 (W=25%, Ds=0.15%)	48 ton	85 ton	231 ton	361 ton	459 ton	556 ton
EGE-2 (W=25%, Ds=0.40%)	48 ton	48 ton	75 ton	140 ton	197 ton	270 ton
EGE-3 (W=23%, Ds=0.35%)	48 ton	48 ton	87 ton	176 ton	245 ton	315 ton
EGE-4 (W=24%, Ds=0.65%)	48 ton	48 ton	50 ton	58 ton	74 ton	115 ton

Pile Bearing Capacity: Sensitivity to Salinity, Temperature & Soil Type

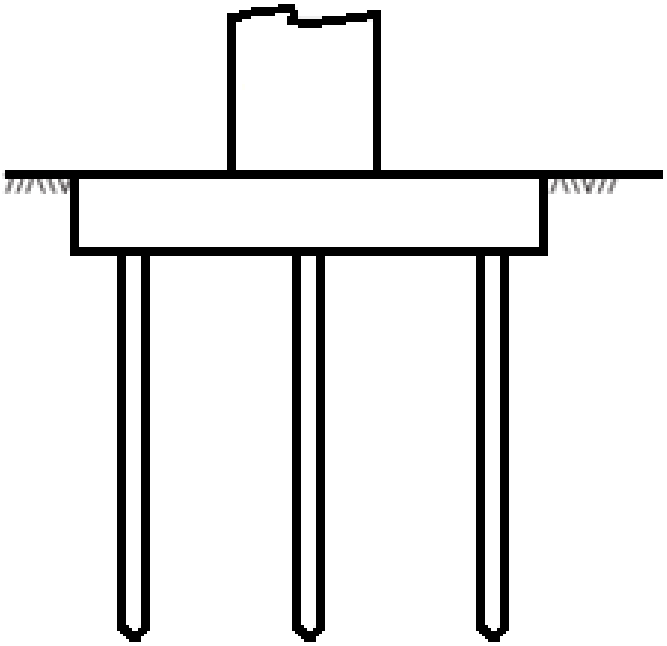
Pile Dimensions 20 meters deep, 0.5 m diameter

EGE	Ds (salinity)	0°C	-1°C	-2°C	-3°C	-4°C	-6°C
EGE-1	Min 0.10	48 ton	167 ton	298 ton	444 ton	559 ton	657 ton
	Ave 0.15	48 ton	85 ton	231 ton	361 ton	459 ton	556 ton
	Max 0.20	48 ton	51 ton	181 ton	327 ton	392 ton	490 ton
EGE-2	Min 0.20	48 ton	51 ton	181 ton	327 ton	392 ton	490 ton
	Ave 0.40	48 ton	48 ton	75 ton	140 ton	197 ton	270 ton
	Max 1.80	48 ton	48 ton	48 ton	48 ton	48 ton	48 ton
EGE-3	Min 0.20	48 ton	51 ton	181 ton	327 ton	392 ton	490 ton
	Ave 0.35	48 ton	48 ton	87 ton	176 ton	245 ton	315 ton
	Max 0.50	48 ton	48 ton	51 ton	67 ton	101 ton	182 ton
EGE-4	Min 0.50	48 ton	48 ton	51 ton	67 ton	101 ton	182 ton
	Ave 0.65	48 ton	48 ton	50 ton	58 ton	74 ton	115 ton
	Max 0.95	48 ton	48 ton	48 ton	48 ton	48 ton	48 ton

	> 200 ton
	200 - 300 ton
	< 300 ton

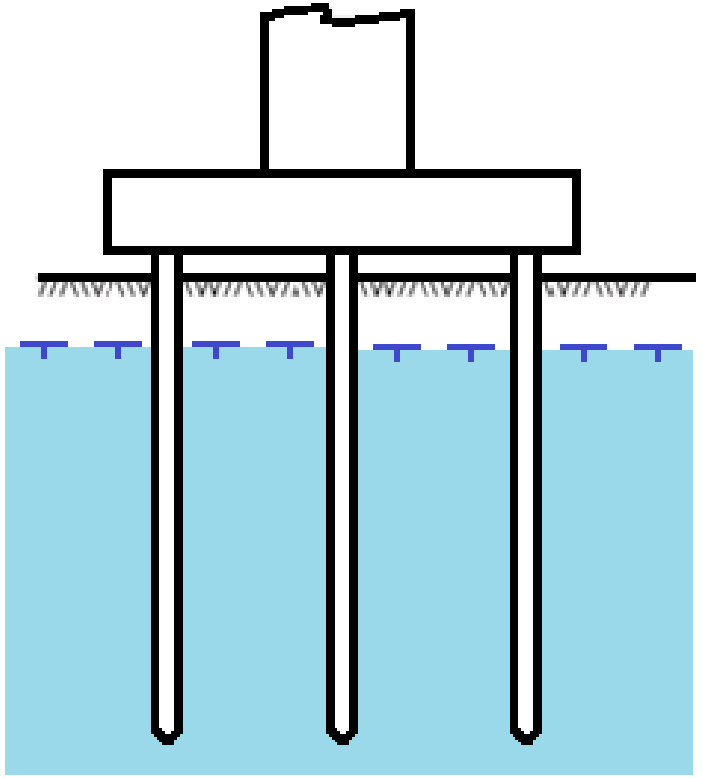
Pile Foundation

Non Permafrost



Pile Bearing Capacity assumed to be constant during the life of the foundation

Permafrost

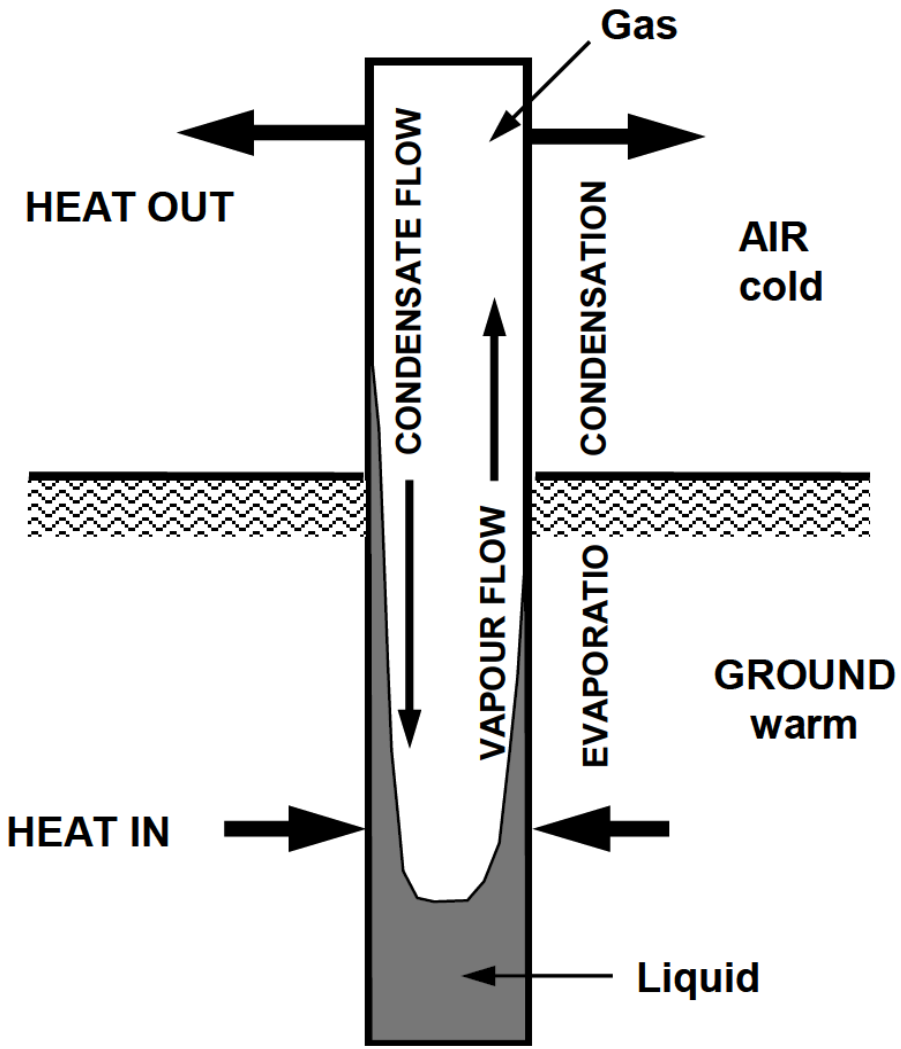


Pile Bearing Capacity may change with time if so does soil temperature

Piles and Permafrost (1)

Piles	Pros	Cons
Reinforced Concrete Piles	• high production, • easy to install, • long track record	• dimension limitation: depth 10-12 m and area 0.09 m^2, • requires predrilling • require special production facilities
Steel Pipe Piles	• high production, various dimensions, • easy to install, • long track record	• dimension limitation: depth 10-12 m • may require predrilling, • backfill (unfrozen/dry)
Auger Cast In Place Piles	• bigger diameter and greater depth 20 m or more • in-situ installation	• concrete curing causes heat emission, melting frozen soil

Thermosyphon Principle



Thermosyphon Design based on heat pipe concept

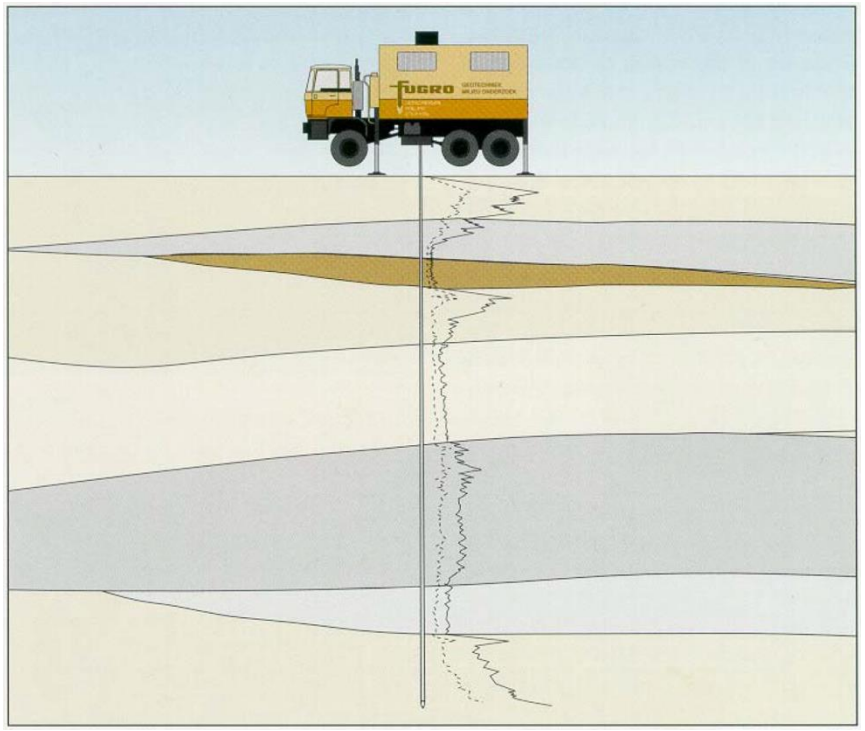
Piles and Permafrost (2)

Non Permafrost	Permafrost
Homogeneous	Heterogeneous
Pile Load MUST NOT EXCEED Pile Bearing Capacity	
Pile Bearing Capacity, stays constant during the operation period	Pile Bearing Capacity may change within a short period of time, it depends on soil temperature
Pile Bearing Capacity remains constant at +20^{o}C and +1^{o}C	Pile Bearing Capacity loses up to 90% of its initial magnitude when frozen becomes non-frozen
	Pile Bearing Capacity of saline permafrost loses up to 50% of its initial magnitude when permfrost soil temperature increases by 1^{o}C
Geotechnical monitoring	Geotechnical Monitoring + Temperature Monitoring

Some Applications of CPT Testing in Permafrost

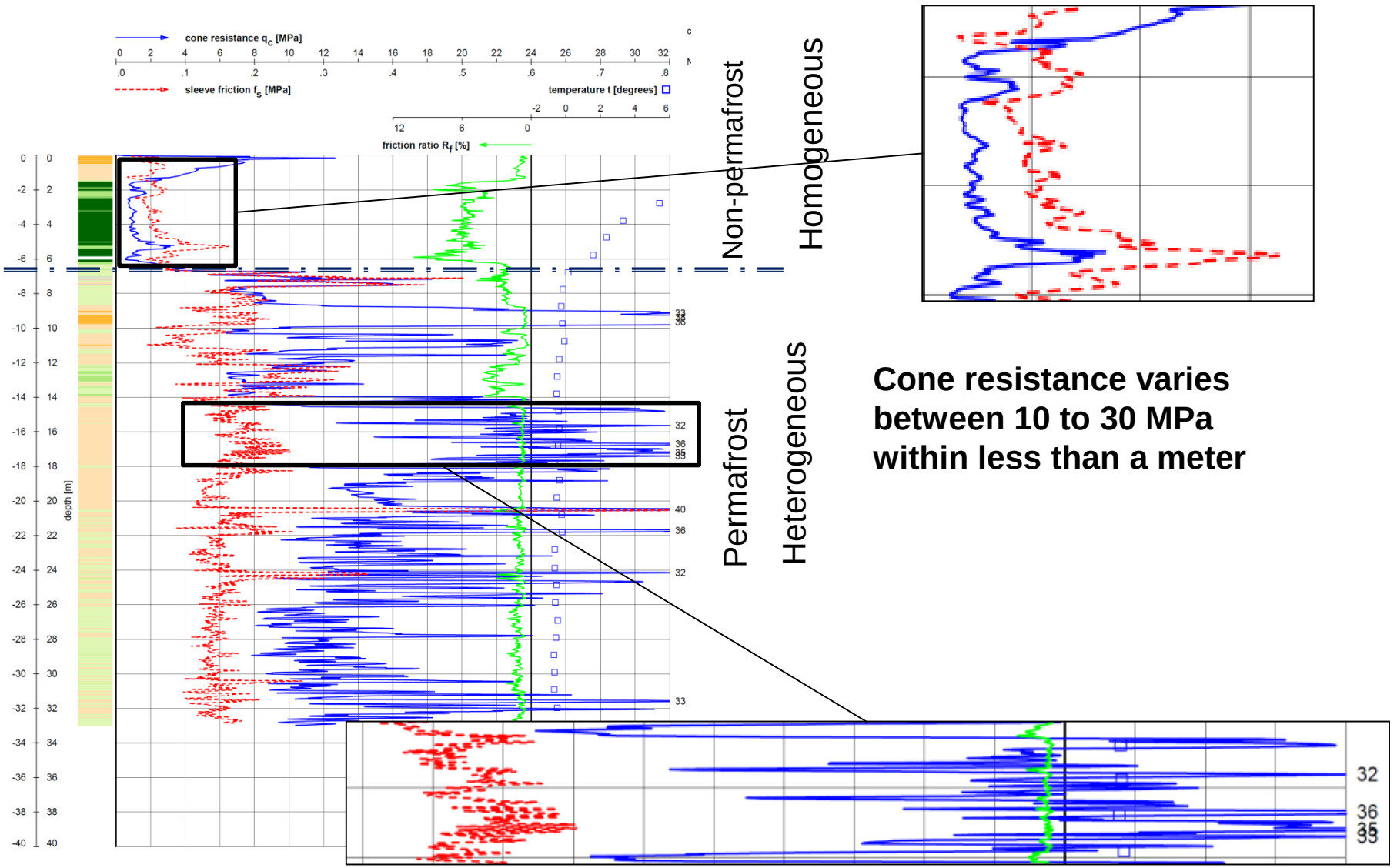
Application of CPT:

1) Immediate Temperature Measurement
2) Soil Strength Profile Measurement
3) Pile Bearing Capacity Evaluation
4) Temperature Monitoring Installation
5) Thermosyphon Operation Check-up
6) Maintenance of Pile Foundations during the Life of the Project (Geomonitoring).
7) *Measurement of ice content **
8) *Measurement of soil conductivity allowing determination of salinity **

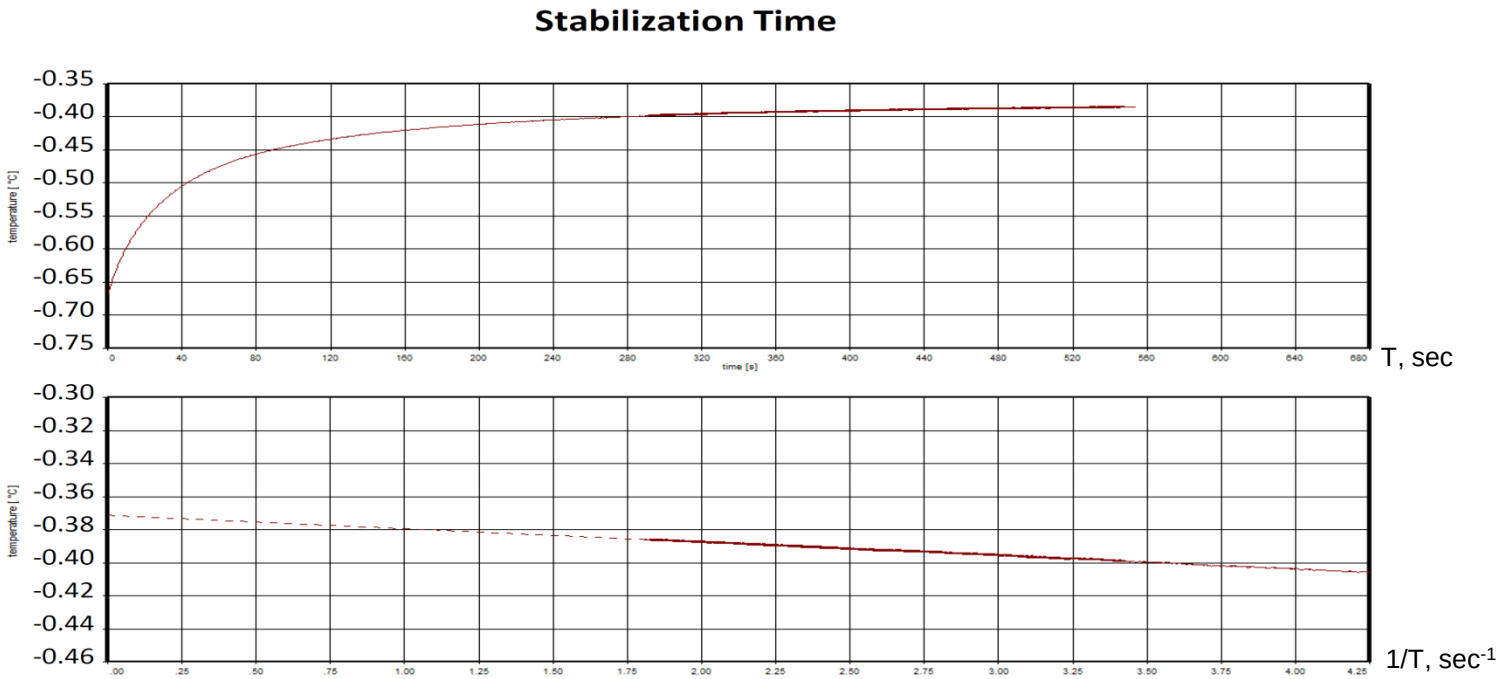


** sensors in use but not yet used in permafrost*

Heterogeneous Response in Permafrost



Temperature Measurement



<u>Thermal equilibrium time and temperature measurement</u>:

- Direct temperature measurement is done at a certain depth with any spacing between single measurements.
- Temperature stabilization of cone tip is controlled by CPT operator in real-time mode in accordance with SP 25.13330.2012.
- Average time for temperature stabilization completion in frozen soil is 10 minutes.

Practical Application of CPT in Permafrost (1)

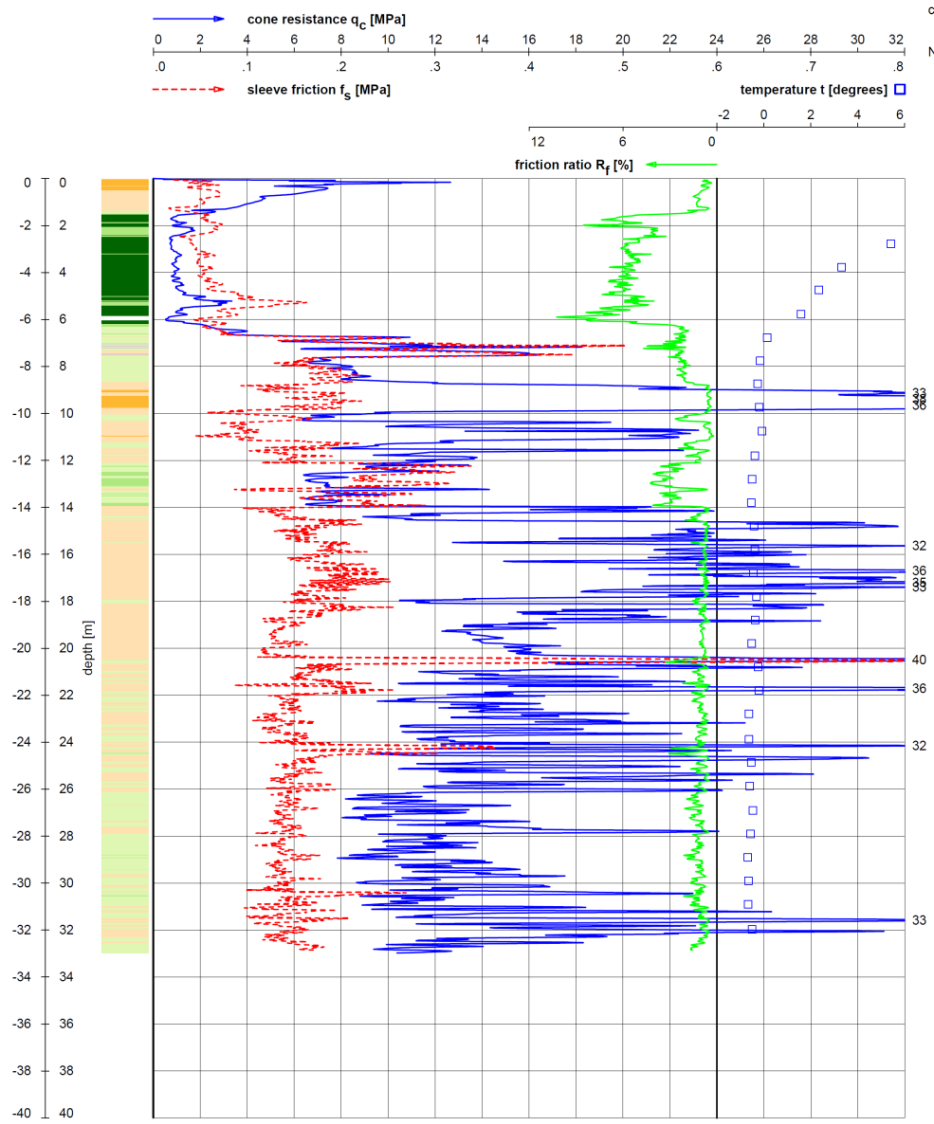
Temperature Measurement:

1. Immediate temperature profile measured within 1 day

2. Temperature measurement accuracy
   a) Generic Requirement +/-0.1°C
   b) Actual Accuracy 0.01°C
   c) Sensor Resolution 0.001°C

3. Direct temperature measurement, not an interpretation of geophysical data.

4. Permanent temperature monitoring easily installed in CPT hole after test.



Practical Application of CPT in Permafrost (2)

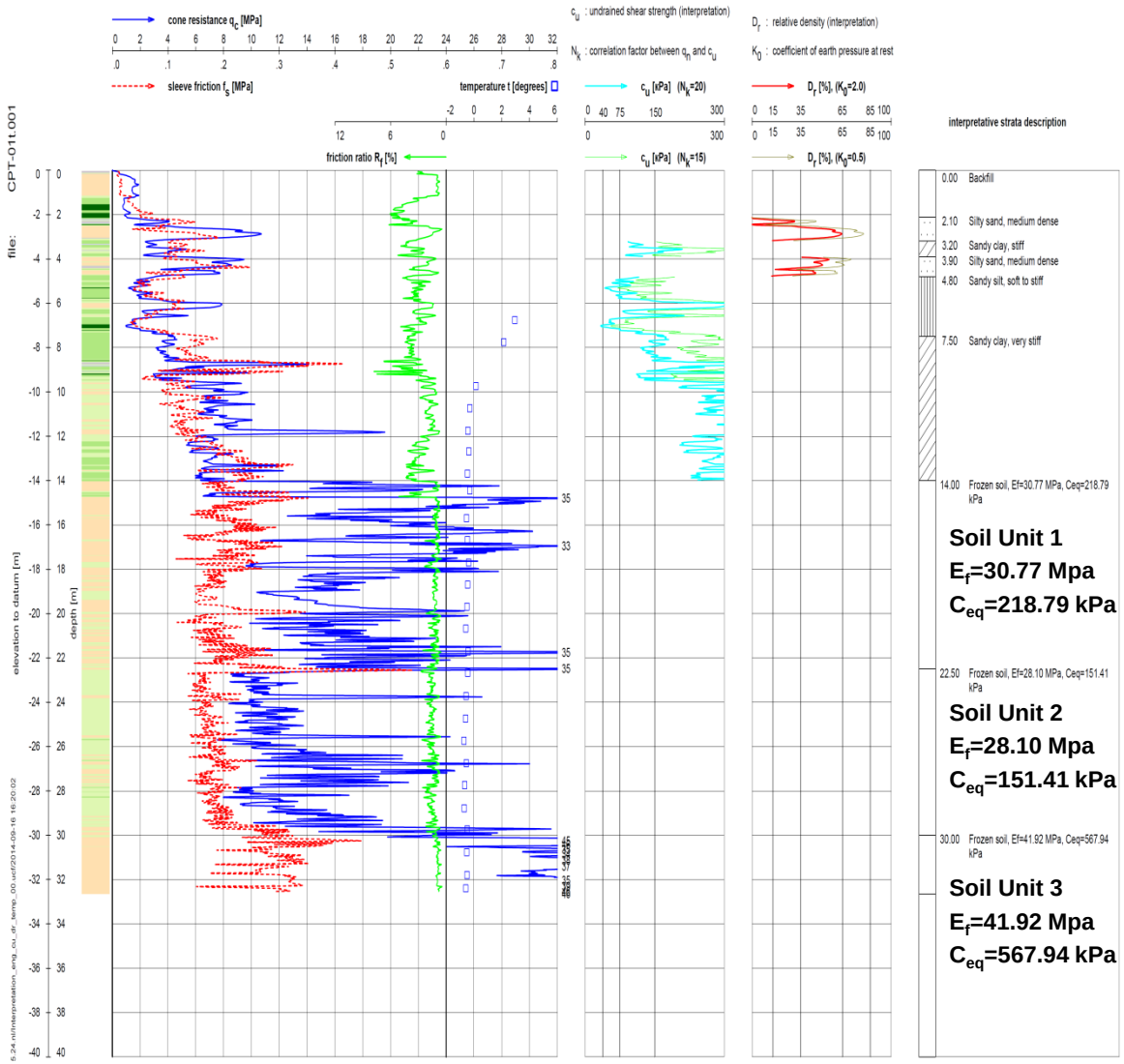
Soil Capacity Assessment:

1. Sleeve Friction and Cone Resistance

2. Estimation of mechanical properties of frozen soils according to Russian Standard SP 25.13330.2012 Deformation Modulus E_f (MPa) and Equivalent Cohesion C_{eq} (kPa).

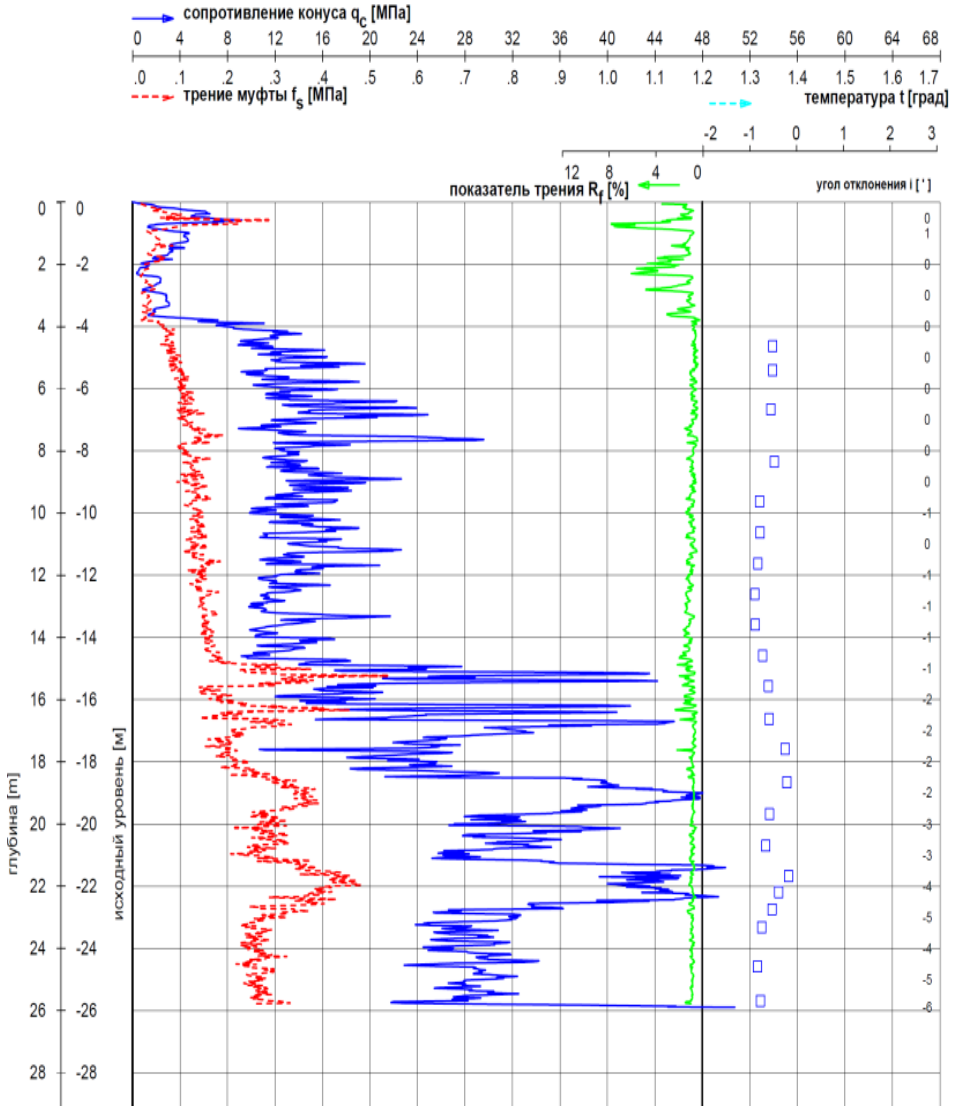
3. Pile Bearing Capacity according to SP 25.13330.2012.

4. Detection of soil units (EGU/GTU - Engineering Geological Unit, Geotechnical Unit).



Example of CPT Interpretation for Pile Bearing Capacity

TCPT-01 СП 25.13330.2012			
Глубина от поверхности, м	Лобовое Rc*A, кН	Боковое Rafc,i*Aaf,i кН	Общее Fui, кН
4.0	288	51	339
5.0	317	73	390
6.0	341	102	443
7.0	346	140	487
8.0	337	188	525
9.0	336	233	570
10.0	333	282	615
11.0	330	332	662
12.0	309	388	697
13.0	313	445	758
14.0	353	507	860
15.0	423	594	1017
16.0	463	729	1192
17.0	466	865	1331
18.0	516	958	1474
19.0	565	1126	1691
20.0	506	1318	1823
21.0	564	1468	2032
22.0	558	1720	2279
23.0	480	1942	2421
24.0	481	2075	2556
25.0	493	2217	2709

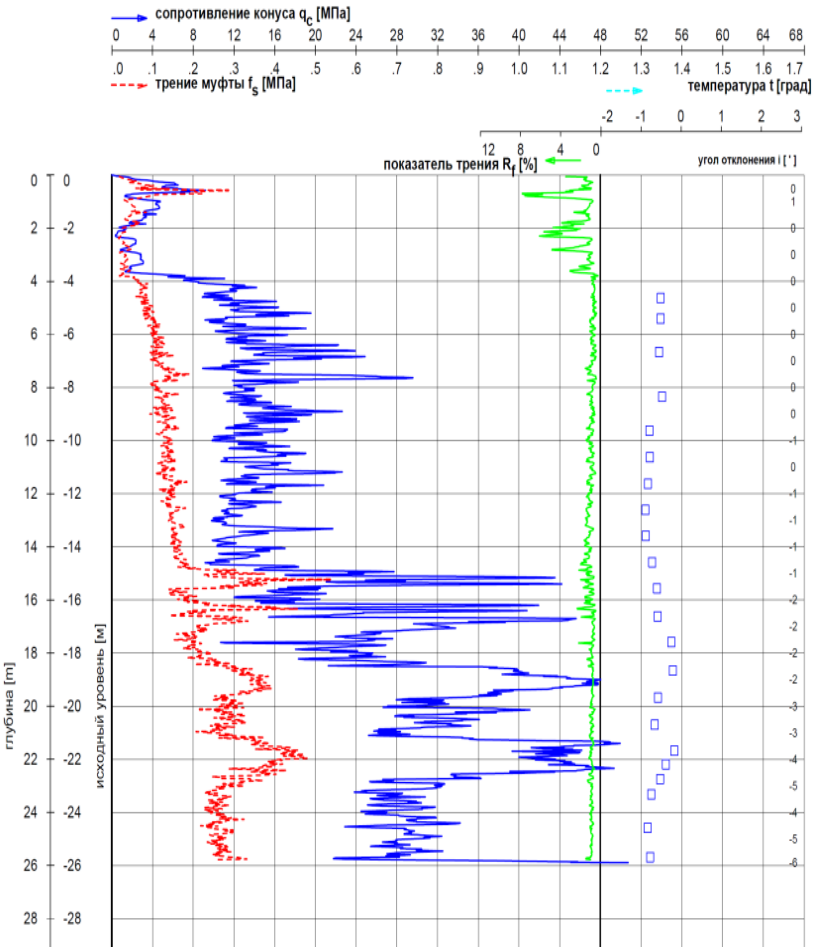


Application of CPT for Thermosyphon Operation Check-up

Geomonitoring Methods and Pile Conditions

Pile Condition	Description Pile Bearing Capacity (PBC) Soil Temperature	3D Laser Scanning, Total Station, HydroLevel	Strain Gauges, Load Cells	CPT	Temperature Monitoring
1. Normal	No visible problem detected Pile Load < Actual PBC ≈ Design PBC Soil Temperature ≤ Design Value	Zero displacement	Full Transmitted Load from Structure, which correlates with Design Value	Measured Pile Bearing Capacity value is equal or above the design value.	Measured temperature essentially stays constant.
2. Weakened	No visible problem detected Pile Load ≤ Actual PBC ≤ Design PBC Soil Temperature > Design Value			Measured Pile Bearing Capacity value is less than the critical design value. The difference is not significant.	Measured temperature is higher than the initial and design.
3. Poor	Visible deformations/displacements of pile are detected. Actual PBC ≤ Pile Load Soil Temperature > Design Value	Low displacement	Non-Uniformly Transmitted Load from Structure, which correlates with Actual Pile Bearing Capacity	Measured Pile Bearing Capacity value is less than the design value, but higher than the critical design value.	
4. Critical	Critical deformations/displacements of pile are observed. Actual PBC << Pile Load Soil Temperature > Design Value	High displacement		Measured Pile Bearing Capacity value is significantly less than the critical design value.	

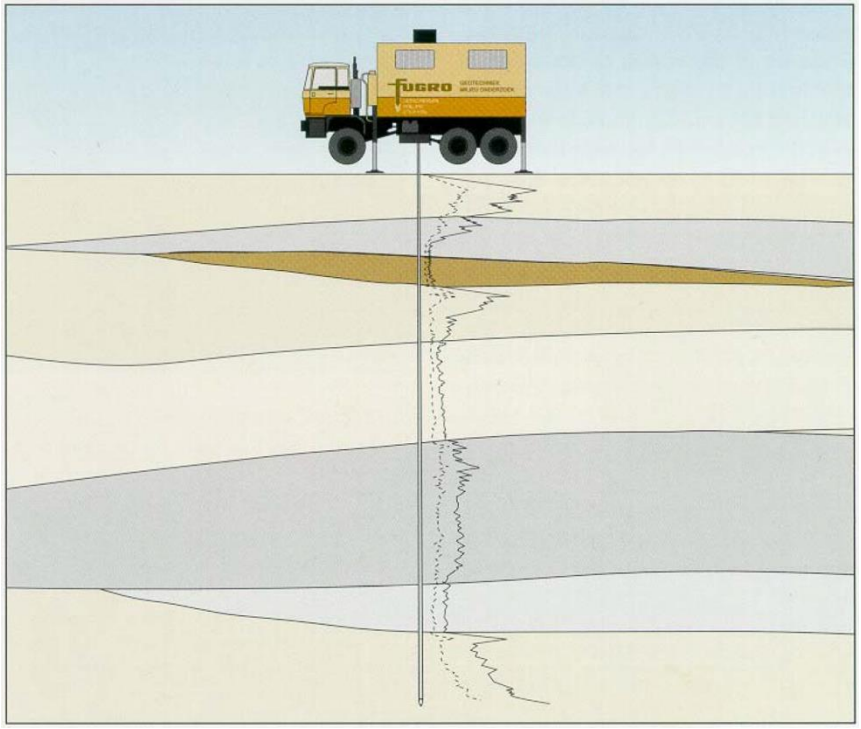
Some Illustrations from CPT Field Survey Work in Summer



Some Illustrations from CPT Field Survey Work in Difficult Conditions

Application of CPT:

1) Immediate Temperature Measurement
2) Soil Strength Profile Measurement
3) Pile Bearing Capacity Evaluation
4) Temperature Monitoring Installation
5) Thermosyphon Operation Check-up
6) Maintenance of Pile Foundations during the Life of the Project (“Geomonitoring”).
7) *Measurement of ice content **
8) *Measurement of soil conductivity allowing determination of salinity **



** sensors exist but not yet used in permafrost*

Thank you for your attention.

Please do not hesitate to ask any questions or clarifications.

nvolkov@fugro.com
r.jewell@fugro.com