Cone Penetration Testing 2022 – Gottardi & Tonni (eds)
© 2022 the Author(s), ISBN 978-1-032-31259-0

Long-term strength determination of frozen soils by CPT

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

ABSTRACT: Frozen soils show rheological behavior which results in changing mechanical properties in time under applied load. It is highly complicated to determine the long-term strength of a frozen soil. Rheological behavior of frozen soils appears in creep or stress relaxation. This paper presents a new method to measure long-term strength of frozen soils using CPT equipment named Stress Relaxation Test (SRT). Conventional tests are focused on the creep behavior by creating constant loads and measuring strains. The SRT is based on stress relaxation approach by creating constant deformations and measuring stress by a cone. Cone resistance (q_c) would give compression long-term strength, as for sleeve friction (f_s) – shear long-term strength. SRT long-term strength results can be applied directly to pile bearing capacity estimation. A comparison between such estimation and results from a full scale static pile load test is provided in the paper.

1 INTRODUCTION

1.1 *Frozen soil rheological behavior*

The frozen soil shows a rheological behavior under an excess load from structures. In order to describe the degree of rheological behavior, the long-term strength is used which is the resistance of a soil to failure in response to a long-term load application (Tsytovich, 1975). In other words, long-term soil strength corresponds to a stress at and below which no failure takes place within practically observable period of load application. Long-term strength of frozen soils is 5 to 15 times less than instantaneous strength, or resistance to rapid destruction. The key long-term strength characteristics of frozen soil are long-term compressive strength and long-term shear strength over the freezing surface (Sayles, 1968).

There are two ways to evaluate long-term soil strength. The first way is to measure deformation under applied constant load which are high enough to induce non-attenuating creep which results in failure with time or, in another words “deformation vs time”. When several tests are conducted with various loads, the curve “load vs time of failure” is plotted. An asymptote of the curve is interpreted as the ultimate long-term strength.

The second way is to measure the excess stress caused by applied constant deformation. The definition of stress relaxation is given by Vyalov (Vyalov, 1986). It is a process of decrease in stress over time, which is necessary to maintain constant deformation. Stress relaxation happens due to redistribution of elastic and plastic deformations in time. The relaxation period is one of the most important rheological parameters of frozen soils. It is important to highlight that relaxation period is much shorter (by several orders) compared to after-effect period. This is the main advantage of the proposed new method.

1.2 *S. Vyalov’s logarithmic equation application for frozen soil behavior*

The strength of frozen soils decreases over time as a result of the absence of a long-term strength limit for ice, which is a permanent and important component of frozen soil. An accelerated method of testing soils for long-term strength, using a “dynamometric” apparatus shortening the test period was invented by Vyalov. The design of the apparatus provides the application of the load to a soil sample through a dynamometer with fixation of its position and recording of decreasing stress value on it. The logarithmic relaxation equation is used to process the obtained data.

Logarithmic equation of long-term strength:

$$\tau = \frac{\beta}{\ln \frac{t_p+1}{T}} \quad (1)$$

where τ — measured cone resistance or sleeve friction in MPa; t_p— measurement time, s; β, T – the parameters are temperature and strain rate dependent (Vyalov, 1986).

DOI: 10.1201/9781003308829-27

2 CPT APPLICATION FOR LONG-TERM STRENGTH EVALUATION

2.1 *CPT in Stress Relaxation Test (SRT) mode*

The principle scheme of the dynamometric method is implemented in the Stress Relaxation Test (SRT) of frozen soil by CPT with stabilization. When the cone is deployed on a test depth, the load is kept applied to the soil, exceeding the value of its instantaneous strength, but when the cone penetration is paused like for a dissipation test, the cone is kept loaded (the rods are clamped) and the stress relaxation is recorded. For each individual SRT, a single value of long-term strength of frozen soil is obtained. To be more specific, for data obtained using a cone resistance sensor is the long-term compressive strength of the frozen soil, and for data obtained using a sleeve friction sensor, it is the value of the long-term shear strength. A result of the measurement is the values of the long-term strength of frozen soil were obtained at each depth of the cone SRT deployment.

An example of SRT relaxation curve provided below on Figure 1.

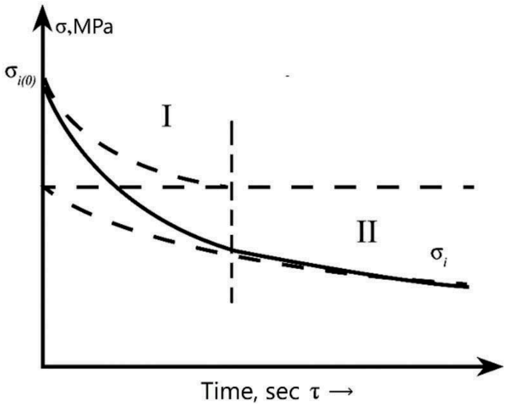

Figure 1. Stress relaxation curve.

During the stress relaxation test, an increase in plastic deformation occurs due to a decrease in the part of elastic deformation keeping the constant value of the total deformation. The proportion change causes the stress relaxation. To evaluate the value of the long-term strength of the soil, the SRT should be performed until a certain point of stress reduction in the sensor, which presents in the stage II of the relaxation curve, Figure 1. In stage I of the relaxation curve, the cone freezes into the soil after penetration pause starts. At this stage besides relaxation some creep happens and contributes some inconsistency to the measured curve. Then the stage II starts when creep contribution is negligible and the curve starts to follow the equation (1) (Sokolov, 2020).

2.2 *SRT data processing*

To process the SRT results, measurements of stress relaxation at each cone deployment depth are taken into account and processed using the long-term strength equation (1), reduced to the form y = kx+b.

$$\frac{1}{\sigma} = \frac{1}{\beta} \cdot \ln(t_p + 1) - \frac{1}{\beta} \cdot \ln T \qquad (2)$$

where $y = \frac{1}{\sigma}; x = \cdot \ln(t_p + 1); k = \frac{1}{\beta}; b = -\frac{1}{\beta} \cdot \ln T$

Figure 2 illustrates processing linearized cone resistance data for a SRT. The value of the reliability of the linear approximation of the data in this case is 0.997.

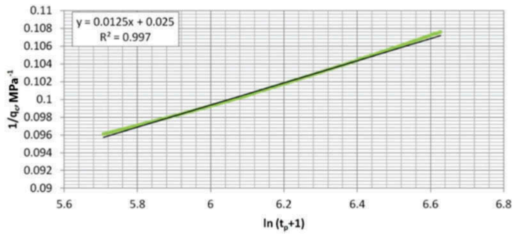

Figure 2. Example of SRT data linearization.

Based on the obtained coefficients k = 0.0125 and b = 0.025, the coefficients β = 80, T = 0.139 and the equation of long-term compressive strength is defined:

$$\sigma_c(t) = \frac{80}{\ln \frac{t_p+1}{0.139}} \qquad (3)$$

where σ_c — interpreted as the compressive long-term strength of the soil.

Equation (3) allows to calculate a long-term strength value for any period of time. For instance, for 10 days σ_c = 5.1 MPa and for 100 years σ_c = 3.4 MPa.

Similarly, based on the sleeve friction sensor data, the obtained value is interpreted as the shear long-term strength of frozen soil.

It is important to set the frame of applicability of Equation (2). The stress relaxation measurements under the tip of the cone were obtained. Successful completion of the test is reached upon condition of the stage II of the relaxation curve is met. The same situation was observed for the sleeve friction sensor. It is assumed that, on the stage I, the cone freezes into the ground, and only after that rheological behavior can be clearly observed on the data, which represents in data curves (q_c and f_s) following the Equation (2).

The field data quality assessment is required to check the applicability of the field data, i.e. if the stage 2 was reached during the test. The field data acquisition software was developed with continuous analysis array of the obtained data using Equation (2). After the stress relaxation test starts, Equation (2) is applied for an interval of the relaxation curve. In the example on Figure 3a, an interval of 100 seconds is used for calculation. The data of 600-700 seconds interval has automatically processed to calculate β, T factors (Figure 3b).

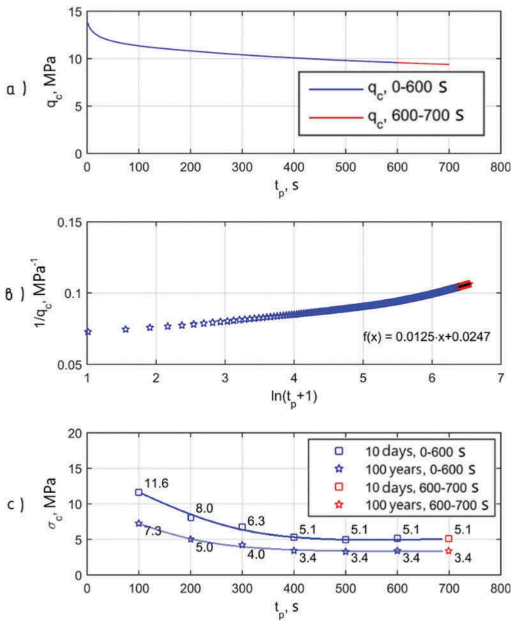

Figure 3. Field iteration processing of the SRT data.

Next, the equation of the long-term strength is derived, as shown above for the formula (3), and the soil long-term strength (σ) is calculated for lifetime period t_p = 100 years in seconds. Figure 3c shows values for 100 years (red asterisk), also shows values for 10 days (red square) at the end part of the relaxation curve 600-700 seconds.

This algorithm can be applied to calculate the long-term strength for any part of the collected data. Six previous iterations were performed correspondingly for the sections of the curve for the 1-100 seconds (the First iteration), for the 100-200 seconds (the Second iteration), etc. and displayed in blue, respectively (Figure 3c). Figure 3c shows that, the calculated long-term soil strength values are consistent started from period 400 seconds, and they are equal to 3.4 MPa for lifetime period t_p = 100 years and 5.1 MPa for the lifetime period t_p = 10 days.

Figure 3a shows slow decreasing of the stress value in the sensor, we suggest that the stress relaxation curve had to reach the stage II starting from 400 second of the test, and follows Equation (3).

Figure 3 illustrates just 7 iterations of the field QA approach, but the data acquisition software adds a new long-term soil strength value every new record of the stress in the sensor (Sokolov, 2020).

3 FIELD DATA APPLICATION

3.1 *Pile bearing capacity calculation*

The pile bearing capacity (PBC) calculation is based on the long-term soil strength data. The calculation is based on a similar conventional approach, the sequential summation of the values of end bearing and side friction. The difference is that the developed calculation does not use any empirical factors. The calculation is made according to the formula:

$$F_{ui} = \sigma_c \cdot A + \sum \sigma_s \cdot A_{af,i} \tag{4}$$

where σ_c – average compression long-term soil strength; A — pile area; σ_s — average shear long-term soil strength; $A_{af,i}$ — unit side area of the pile.

The calculation is performed for the recorded values of σ_c and σ_s for each measurement of stress relaxation test. The test-time interval t_p is set as 10 days, in the case of a full-scale pile test under a static load, and the life-time interval t_p is 100 years to evaluate the ultimate long-term pile bearing capacity.

Construction site nearby Salekhard was selected to confirm the SRT based results and PBC calculation in frozen soils. On this site, full-scale static pile load tests (SPLT) were carried out. SRT was performed near the tested pile within 2 meter distance (Volkov et al, 2019).

SPLT was conducted in accordance with GOST 5686-2012. The load was applied in 10 steps, each step lasted 1 day and was equal 5 or 10 tons. The last step lasted for 24 hours was F_H = 55 tons, the next step F_H = 60 tons caused pile failure. GOST 20522-2012 provides equation (5) to calculation the ultimate long-term pile bearing capacity:

$$F_H^H = 0.65 \cdot F_H \tag{5}$$

where F_H^H – ultimate long-term pile bearing capacity; F_H – step load at which the pile failure occurred.

Comparison of PBC calculation results based on SRT with the results on SPLT in frozen ground provided in the Table 1.

The bearing capacity of a driven pile with length of 10.6 m in frozen soil with a time interval of 10 days is about 66 tons (663 kN), and the pile failure occurred at load step of 60 tons. The SRT value differs by 10% from SPLT value. These are very close results. In turn, the calculated SPLT value for 100

Table 1. Comparison of PBC calculation results based on SRT and SPLT.

Time period	10 days SRT	SPLT	100 years SRT	SPLT
End bearing	446*	—	292	—
Side friction	217	—	117	—
Ultimate	663	550-600	409	357-390

* All values are in kN.

years is equal to 39 tons and the calculated SRT value is about 41 tons (409 kN). The obtained results for 100 years correlate to each other relatively good as well.

3.2 *Long-term strength for various soils*

The results of σ_c and σ_s measurements were collected from the various sites in Russia where permafrost ground was encountered (Sokolov, 2020). The results were classified with different soil types and averaged to a single value. This allowed to compare them with the recommended values which are commonly used to verify the design values, in particular, R – pile unit end bearing, R_{af} – pile unit side friction (Aksenov, 2001). The comparison of the values is presented in Table 2.

Table 2. Comparison between long-term soil strength measured by SRT (σ_c and σ_s) and recommended values for pile unit end bearing (R) and pile unit side friction (R_{af}).

Soil type	Ice content	σ_c kPa	R kPa	σ_s kPa	R_{af} kPa
Lean clay	None	2430	900-1100	69	40-100
	Low	1335	800-950	35	40-100
	Medium	707	400-550	19	40-60
	Rich	517	400-550	21	40-60
Silty clay	None	2228	750-1050	114	40-60
	Low	2179	850-1050	53	40-60
Silty sand	Low	1963	1000-1800	23	50-130
Fine sand	Low	4584	1000-1700	63	50-80
Medium sand	Low	6977	1500	171	50

The results clearly show the influence of the ice content. In lean clay and silty clay σ_c and σ_s decrease if the ice content increases, so as the recommended R and R_{af}. This tendency is confirmed by theoretical studies of the ice content influence on the mechanical properties of the frozen soils.

The influence of the grain size if other conditions being equal, can also be observed for silty, fine and medium sands. An increase of coarse particles gives more resistance to both compression and shear.

4 CONCLUSIONS

Stress Relaxation Test (SRT) of frozen soil by CPT with stabilization was developed based on an accelerated laboratory method of testing soils for long-term strength, using a principle of the “dynamometric” apparatus invented by Vyalov. The logarithmic relaxation equation is used to process the field data.

SRT provides individual values of the long-term strength for frozen ground at a certain depth. Data obtained using a cone resistance sensor is interpreted as long-term compressive strength of the frozen soil (σ_c), and data from sleeve friction sensor – the long-term shear strength (σ_s).

The results on σ_c and σ_s are applicable for calculation of pile bearing capacity in the frozen soil without empirical factors.

The results of σ_c and σ_s on the various sites showed consistency and good relation with the recommended values for pile unit end bearing and pile unit side friction.

REFERENCES

Aksenov, V. I. 2001. Recommendations for determine the frozen soils strength with a marine type of salinization. FGUP PNIIIS, Moscow. – 42 pages (in Russian).

Sayles, F.H. 1968. Creep of frozen sands, United States Army Corps of Engineers CRREL.

Sokolov I. 2020. Determination method for strength properties of frozen soils by cone penetration testing. PhD Thesis – Moscow State University, Moscow, 2020 – 149 pages (in Russian).

Tsytovich, N. A. 1975. The Mechanics of Frozen Ground, New York, McGraw-Hill, 448 p. ISBN-10: 0070654107

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, http://dx.doi.org/10.25296/2221-5514-2019-11-1-68-78.

Vyalov, S.S. 1986. Rheological Fundamentals of Soil Mechanics, Volume 36, 1st Edition. Publisher: Elsevier. ISBN: 0444600566. 564 pages.