TCPT in permafrost: penetrometer - soil thermophysical interaction

O.N. Isaev,
NIIOSP, Moscow, Russia

I.B. Ryzhkov
BashNIIstroy, BGAU, Ufa, Russia

ABSTRACT: In order to adequately interpret CPT data, obtained in permafrost, it is important to assess the nature and specific features of penetrometer-soil thermal interaction. The paper presents results of experimental and theoretical studies of penetrometer interaction with frozen soils both during driving and stopping. Two penetrometer types were used for the experiments; one registered cone resistance and sleeve friction resistance as well as penetrometer temperature with the help of temperature sensors, located in the cone, the second one registered only penetrometer temperature with the help of temperature sensors, located in the cone (one) and along the side surface (three). The tests were conducted at constant driving rate and in creep relaxation mode ("stabilization"). A thermal model was proposed that explained the extraordinary penetrometer temperature drop effect. Comparison of penetrometer temperature curves enabled elaboration of a method for determining soil temperature in situ, based on application of penetrometer temperature stabilization coefficient.

1 INTRODUCTION

Cone Penetration Test (CPT) is widely applied for measuring geotechnical properties in unfrozen soils in geotechnical engineering.

CPT has recently been used for testing frozen soils. It has no disadvantages compared to traditional in-situ laboratory methods of engineering and geocriological investigations. In-situ geotechnical soil tests in permafrost are difficult, expensive and time-consuming. Laboratory tests have extra difficulties, such as;application of refrigerators, preserving samples integrity during long-distance transportation.

Frozen soils are mostly tested with tenso-penetrometer, equipped with an extra temperature sensor. The authors believe that such penetrometer tests should be classified as a special type of tests i.e., in international classification such tests could be called «Cone Penetration Test with Temperature Measurements» (TCPT).

TCPT can successfully be used in plastic frozen soils to evaluate soil strength and deformation characteristics, bearing capacity, settlements, pile design option feasibility and soil state evaluation (frozen or thawed). But, so far, TCPT has not been applied on a broad scale. There have been some reasons for this, such as inadequate knowledge of thermophysical aspect of TCPT application in frozen soils.

This paper describes the influence of the main technological and geological factors on thermophysical "penetrometer - frozen soil" system interaction.

2 THERMOPHYSICAL MODEL OF "PENETROMETER - FROZEN SOIL" INTERACTION

In permafrost TCPT has two phases. The first one is penetration at constant rate. The second phase is cone "stabilization" (after stop) with its freezing in the frozen soil.

To describe thermal penetrometer-frozen soil interaction a thermophysical model has been proposed, based on the following assumptions: soil is anisotropic; penetrometer is a solid piece of metal; heat is released or absorbed at the penetrometer-frozen soil interface and is proportional to their thermal conductivities.

2.1 Constant rate of penetration phase

The penetrometer initial temperature θ_{cv} is equal to in-situ soil temperature θ_s. Penetrometer-frozen soil friction generates heat, absorbed by the cone. Metal thermal conductivity is much higher than that of soil, therefore, the released heat is absorbed by the cone. Let us assume that heat flow density around the penetrometer cone is Q_{fc} and along the friction sleeve is Q_{fs}.

Cone penetration generates soil stresses, which lower ice melting point (phase transition) θ_{pt} by $\cong$ 0,075$\Delta\sigma$, where $\Delta\sigma$ (MPa) is normal stress variation on the penetrometer surface. Silty soil temperature θ_{pt} stays within –0.1 to–0.2 ^{o}C range in-situ. θ_{pt} value on penetrometer surface can be derived from q_c value. The δ thick layer around penetrometer melts ice if $\theta_s > \theta_{pt}$. This phase transition probability was evaluated by empirical "$\theta_s - q_{cv}$" dependence, obtained in plastic frozen soils. Phase transition occurs when $\theta_s \cong$ –0.1...–0.5 ^{o}C. In situ soil temperature θ_s probability is greater than phase variation probability.

Melting in phase transition layer (pt-layer) generates heat flow from penetrometer to pt-layer. Heat flow density around penetrometer cone is Q_{mc} and along friction sleeve is Q_{ms}.

Penetrometer cone (or friction sleeve) is heated when phase transition heat flow density Q_{mc} (Q_{ms}) is less than friction heat flow density Q_{fc} (Q_{fs}). And if penetrometer (or friction sleeve) cools down it occurs vice versa. Predominance of one of these processes depends on geological and technological features. Evidently, there is a certain critical pt-layer thickness δ_c (δ_s) when $Q_{mc} = Q_{fc}$ ($Q_{ms} = Q_{fs}$).

It is more probable that when penetrometer starts moving, Q_m and Q_f are not equal. This gives rise to temperature gradient between penetrometer and frozen soil and heat flow between them that lowers temperature gradient. Heat transfer flow density is

$$Q_t = - \lambda \, grad \, \theta \quad (1)$$

where λ is convective heat transfer coefficient, $grad \, \theta$ is temperature gradient.

After a certain time period penetrometer temperature reaches equilibrium state i.e., $\theta_{cv} = \theta_{cb}$ with

$$Q_t = |Q_m - Q_f| \quad (2)$$

2.2 Penetrometer "stabilization" state

When driving ends the temperature gradient is $|\theta_{cb} - \theta_s|$ that levels penetrometer temperature θ_{cs} to in-situ soil temperature θ_s. To describe this process the well-known equation for cooling (or heating) of a solid in a medium at constant temperature can be used

$$(\theta_{cs} - \theta_s)/(\theta_{cb} - \theta_s) = exp(-2i\alpha t_s / \rho c d_s) \quad (3)$$

where θ_{cs} is penetrometer temperature at moment t_s after penetration stop; ρ and c are soil density and specific heat; i is dimensionless parameter, $i \approx 3$ for cone, $i \approx 2$ for friction sleeve; d_s is penetrometer diameter.

Based on equation (3) with "$t_s - \theta_{cs}$" curve involved it is possible to calculate in-situ soil temperature θ_s. Evidently, equation (3) is better for unfrozen soil and for frozen soil with no pt-layer.

Heat interaction, when pt-layer is formed around penetrometer, is the most complicated case. After penetration stops in the process of "stabilization", compression stress reduces around the penetrometer and freezes pt-layer that generates heat flow from pt-layer to the penetrometer. Notably, during the first three seconds cone resistance q_{cs} lowers by 20 to 40 %. Hence, this heat flow duration should be short.

3. EXPERIMENTAL STUDY OF "PENETROMETER – FROZEN SOIL" THERMOPHYSICAL INTERACTION

3.1 Equipment and procedure

The tests were staged in Vorkuta, Labytnangy on plastic frozen soil, typical for the regional geology. The soils were frozen silty and clayey with l5 to20% gravel inclusions. In-situ soil temperature was from 0 to -1^{o}C , but sometimes as low as -2 ^{o}C. The permafrost soils were tested with the help of mobile unit S-832M in penetrometer "stabilization" mode. The maximum testing depth was 20 m.

In the course of investigations the measuring apparatus AISG-1M was improved. It included thermometrical strain gauge penetrometer (TCPT-penetrometer) for measuring soil resistance to cone penetration and sleeve friction as well as the temperature of the penetrometer cone (see Fig. 1).

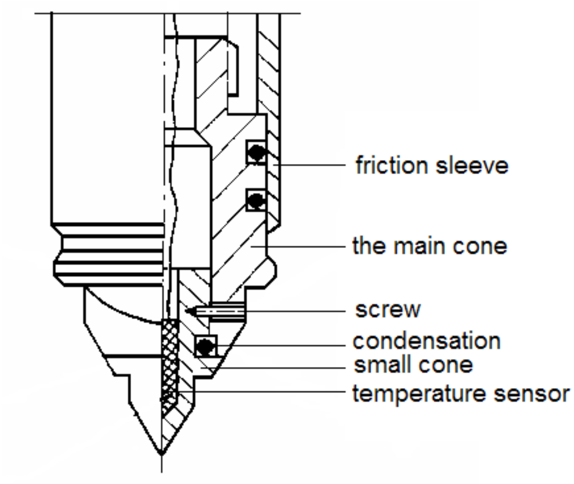

Figure 1. Design of TCPT-penetrometer cone.

Brief historical reference: BashNIIstroy firstly proposed TCPT in 1981 within the framework of Gosstroy dedicated program OC.031. In 1983 TCPT-penetrometer was tested in permafrost (Vorkuta) and a concept of soil in-situ temperature measurement during "stabilization" phase was proposed.

Also a simple thermo-penetrometer (T-penetrometer) was developed (see Fig. 2). It had standard size. One temperature sensor was built-in the cone, and the other three temperature sensors were installed on the shaft lateral surface.

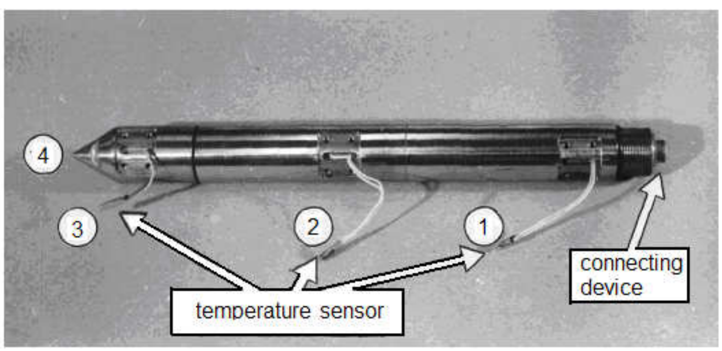

Figure 2. Thermo-penetrometer.

Penetrometer "stabilization" test procedure included four stages:

- penetrometer driving at 0.5 m/min rate;
- penetrometer "stabilization" at certain depth, coinciding with termination of hydraulic fluid feeding into hydraulic jacks that resulted in soil resistances deterioration and penetrometer freezing in frozen soil;

- penetrometer redriving to 0.1 m depth after freezing;
- disconnection of the shaft hydraulic clamp, raising the clamp and adjusting the rod to new level.

Parallel to penetration tests soil temperature was measured in thermo-metrical boreholes.

3.2 Results of experimental investigations

The impact of technological and geocryological factors on penetrometer thermophysical interaction with frozen soil was investigated.

Constant rate of penetration phase. The data and obtained results in frozen soils in constant rate of penetration tests indicated that the penetrometer temperature can rise and decrease (see Fig. 4). The rate of penetrometer cooling and heating ($\theta_{cv} - \theta_{cs}$) varied within –0.3 to +1.1 ^oC range. It was registered that the penetrometer cooled down ($\theta_{cv} < \theta_{cs}$) mainly within in-situ soil temperature θ_s range from –0.15 to –0.5 ^oC. At lower soil temperatures the penetrometer temperature increased ($\theta_{cv} > \theta_{cs}$). The lower was the in-situ soil temperature the greater was the heating rate. Penetrometer tip and side surface temperature rose at about the same rate. In thawed soils penetrometer heating rate ($\theta_{cv} > \theta_{cs}$) varied roughly linearly versus cone penetration resistance (see Fig. 3). When cone penetration resistance q_{cv} changed from 0.1 to 14 MPa the heating rate varied within +0.1 to +8.5 ^oC range.

Penetrometer "stabilization" phase. Penetrometer temperature "stabilization" "$t_s - \theta_{cs}$" curves had complicated character. It was especially so within in-situ soil temperature –0.1 to –0.7 ^oC range, where inflection points were observed on the curves. Such points appeared within initial 5 minutes of "stabilization". This is why it was impossible to determine in situ frozen soil with the help of equation (3).

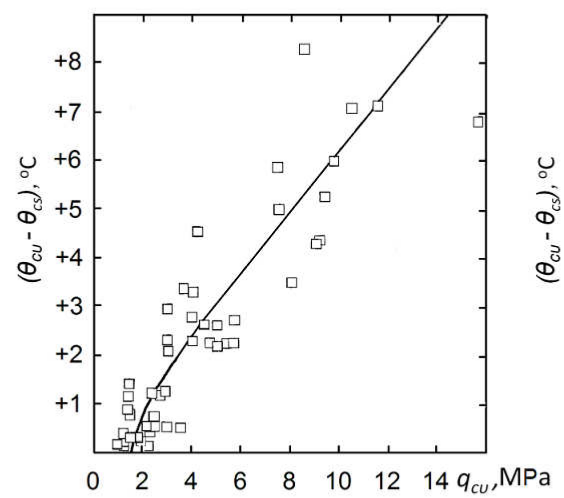

Fig. 3. Dependence of penetrometer cone heating rate on thawed soil resistance

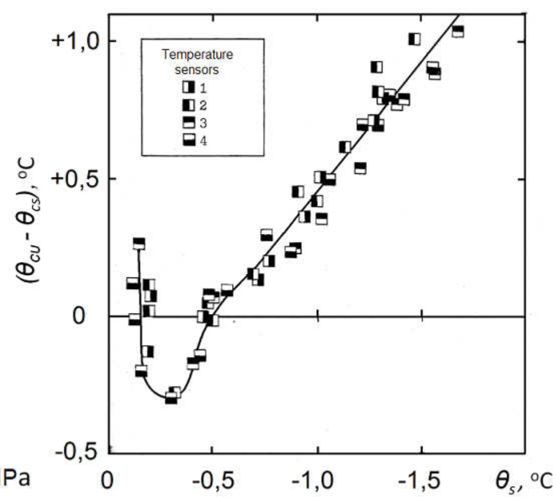

Fig. 4. Thermo-penetrometer temperature variation rate versus frozen soil temperature

Usually, penetrometer temperature reached in-situ soil temperature θ_s in 10 to 20 minutes. The temperature curves were compared with borehole thermometry data. The 0.01 ^{o}C/min reduction rate criterion was established via the comparison. Mean square root error was 0.07 ^{o}C.

4 RECOMMENDATINS FOR USING TCPT– PENETROMETER

TCPT-penetrometer data, compared with borehole thermo-metrical data, enabled reduction of cost, labor and time of in-situ soil temperature measurements.

Large volume of temperature data at different locations and depths could be measured efficiently on site. The obtained data were digitized on PC to plot 2D temperature profiles and isotherms. 3D profile with isotherm surfaces was also obtained.

TCPT is an efficient quick-look technique to investigate and monitor soil beds in the period of construction for timely project design updating. TCPT is a very useful tool for monitoring the thawing of frozen soil beds prior to and in the course of construction period. It allows monitoring of thawed zone boundary variations and soil consolidation rate (by measuring cone resistances) under its own weight.

In emergencies TCPT-penetrometer could be a unique tool for quick-look monitoring of soil temperature profiles. It is especially so, as borehole thermometry needs certain time for temperature to level up after drilling.

The penetrometer can be applied in Arctic regions for hydraulically filled islands and drilling platforms. Its application for investigation and monitoring of cryogenic processes is very promising.

Practical permafrost engineering needs on-line data of soil condition (frozen or thawed). It is also important to obtain data on soil salinity and the content of vegetation impurities. The techniques, developed by the authors, enables monitoring of soil condition by measuring soil resistances to cone penetration.

5 CONCLUSION

This paper shows that thermophysical interaction between penetrometer and frozen soil yields important effects due to ice presence in frozen soil. e.g. penetrometer could be cooled while being driven into frozen soil. This phenomenon was quantified with the help of a thermophysical model. These effects should be taken into consideration when using CPT data for evaluating geotechnical properties of soils, needed in permafrost engineering practice. TCPT enables efficient and cost-effective soil temperature monitoring in situ during “stabilization” period.

REFERENCES

Heat and mass exchange. Heat engineering experiment: Guide book/Ametistov E.V. et al. Moscow, Energoizdat, 1982, 512 p.

Volkov F.E., Isaev O.N. Application of C-832M units for monitoring and evaluation of temperature variations in permafrost. Abstr. All-Union Conf. “Geocryological forecast in construction and area development”.- Vorkuta, 1985. – C, 224-226 pp.

Ladanyi, B., “Determination of geotechnical parameters of frozen soils by means of the Cone Penetration Test”, Proceedings of the 2nd European Symposium on Penetration Testing, Amsterdam, Vol. 1, 1982, pp. 671- 678.

Isaev O.N., Shvarev V.V., Konstantinov A.V., Tichomirov C.M., Sadovsky A.V. Advancement of cone penetration testing for investigating geotechnical properties of frozen soils // Proc. of the Int. Symp. on Cone Penetration Testing, CPT’95 Linköping, Sweden, October 4-5, 1995, vol. 2, pp. 179-186.