EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2018, vol. XXII, No. 1, pp. 46–50 **http://earthcryosphere.ru/**

RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

DOI: 10.21782/EC2541-9994-2018-1(46-50)

HOW THE TYPE OF INPUT DATA AFFECTS PROGNOSTIC TEMPERATURE CALCULATIONS FOR DESIGN IN PERMAFROST

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The design of oil and gas facilities on permafrost commonly includes several geotechnical tasks. One of them is providing operational stability of buildings and structures by project solutions based on prognostic calculations. The behavior of soils is simulated proceeding from their thermal and other physical properties. Designers and researchers most often estimate the respective parameters by calculations and use tabular data from national design standards instead of laboratory testing. We have calculated and compared several variants of input data obtained by laboratory testing and retrieved from national design standards. The results demonstrate that laboratory determination of some thermal properties of soils is indispensable for design in permafrost.

Temperature calculations, thermal properties of soils, laboratory testing, permafrost

INTRODUCTION

Design and construction of roadways, pipelines, buildings, and utility structures for the progressively increasing development of oil, gas, and mineral fields in permafrost regions requires special approaches to account for the particular engineering-geological conditions. Design envisages certain measures for temperature stabilization and geotechnical monitoring of ground proceeding from predicted changes in its thermal and other physical properties with time. Engineering solutions that provide operational stability of objects are most often based on calculations. Prognostic calculations of the thermal behavior of soils are performed using special software and input data on soil properties measurable by engineering surveys: density, natural water content, freezing point, temperature-dependent contents of unfrozen water, thermal conductivity, and bulk or specific heat capacity.

REVIEW OF NORMATIVE DOCUMENTS

Normative documents either prescribe direct measurements or allow calculations of soil parameters in different cases. Two principal working documents that guide engineering surveys in permafrost (*Regulations for Engineering Surveys in Permafrost*, Part 4 [*SP 11-105-97, 1999*] and *Basements and Foundations on Permafrost* [*SP 25.13330.2012, 2012*]) include requirements to the estimation of soil parameters. Density and natural pore water content of soils are to be measured in laboratory or in the field and are compulsory for calculations of classification parameters according to the National Standard (Working document GOST 25100-2011). Other properties used in predictions of soil temperature variations, such as freezing point, temperature-dependent contents of unfrozen pore water, thermal conductivity, and heat capacity, are often characterized with reference to tabular data.

Table 1 compares requirements in the two normative documents that regulate the determination of thermal and other physical properties of frozen ground to be used in prognostic calculations. One document [*SP 11-105-97, 1999*] considers laboratory testing separately for the pre-design, design, and operation stages and requires engineering surveys for direct measurements of parameter values to design the most important objects (classes 1 and 2). The other [*SP 25.13330.2012, 2012*] does not differentiate design stages and allows the use of predicted values for less important buildings and structures (classes 2 and 3). Thus, the two documents postulate the use of both directly measured [*SP 11-105-97, 1999*] and calculated [*SP 25.13330.2012, 2012*] parameters to design the objects of importance class 2 (hereafter calculated parameters are those from tables and formulas in the respective documents).

In addition to differentiation of design stages and importance, *SP 11-105-97* [*1999*] implies that the physical properties of soil depend on its grain size and salinity. The other document [*SP 25.13330.2012, 2012*] neglects this dependence and proceeds uniquely from the importance of objects postulating principle I (preservation of frozen ground) for important objects but giving no instructions whether measured

Table 1. **Requirements of normative documents for determination of soil physical properties**

Property	Working document	Pre-design			Surveys for					
					Design			Operation		
		Class			Class			Class		
		1	2	3	1	2	3	1	2	3
Amount of unfrozen pore water in saline soil	SP 11-105-97	+	+	+	+	+	+	+	+	+
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl
Amount of unfrozen pore water in non-saline soil	SP 11-105-97	Cl	Cl	Cl	Cl	Cl	Cl	+	+	Cl
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl
Freezing point in saline soil	SP 11-105-97	Cl	Cl	Cl	+	+	+	+	+	Cl
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl
Freezing point in non-saline soil	SP 11-105-97	Cl	Cl	Cl	+	+	+	+	+	Cl
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl
Thermal conductivity of frozen and unfrozen soils	SP 11-105-97	Cl	Cl	Cl	+	+	Cl	+	+	Cl
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl
Bulk heat capacity of frozen and unfrozen soils	SP 11-105-97	Cl	Cl	Cl	+	+	Cl	+	+	Cl
	SP 25.13330.2012	+	Cl	Cl	+	Cl	Cl	+	Cl	Cl

Note. + is measured, Cl is calculated.
The colors [pink] and [green] denote, respectively, different and identical requirements to the way of parameter determination.

or calculated parameter values should be used for principle II. The two documents disagree about this point in more than 40 % of cases (Table 1) and agree only about laboratory testing for detailed design of most important (class 1) buildings and structures, as well as pre-design and detailed design calculations for importance class 3. In all other cases, one document requires laboratory measurements while the other allows calculated values and vice versa. Note that the specifications for engineering-geological surveys are compiled with reference to both documents.

In the presence of this controversy, most soil users choose to save time and money for engineering surveys and are satisfied with predicted parameter values. The calculations are commonly performed according to Supplement B [*SP 25.13330.2012, 2012*] which contains a number of assumptions being, to a large extent, a synthesis of theoretical and empirical data gained for years of experience. For instance, the freezing point is assumed to depend on soil type and salinity (with constant values assigned to each type of non-saline soil) but not on water content, despite numerous publications on the influence of soil moisture on freezing temperatures [*Votyakov, 1952; Saveliev, 1971; Shevelev, 1979; Ershov, 2004; Aleksyutina and Motenko, 2017*]. The grain size is neglected as well, and the same parameter values are suggested for gravelly and silty sand. Meanwhile, permafrost soils (including sands) contain greater percentages of silt and clay particles because of frost weathering [*Aleksyutina and Motenko, 2017*] and, hence, larger amounts of bound pore water. Thus more pore water remains unfrozen, which depresses the freezing point, i.e., the thermal properties of soils change [*Ershov, 2001, 2004; Cheverev, 2004*].

The amount of unfrozen pore water at different temperatures is estimated (point B.6 in [*SP 25.13330.2012, 2012*]) on the basis of soil salinity and plasticity index. This assumption leads to 0 % of unfrozen pore water in all non-saline sands (including silty varieties) and in some silt varieties, which is not true [*Votyakov, 1952; Ershov, 2001; Aleksyutina and Motenko, 2017*].

Thermal properties of soil are determined using Table B.8 from [*SP 25.13330.2012, 2012*]. The working document is advantageous over the Building Norms and Regulations of 1988 due to additional requirements as to the thermal properties of saline soils which actually have multiple controls (particle size, moisture content, dry-weight density, salinity, etc.) [*Ershov, 1984*] hardly allowable in all combinations. Therefore, Table B.8 in [*SP 25.13330.2012, 2012*] summarizes data for several soil types distinguished according to classification factors. For instance, it considers jointly sands of different size fractions and salinities and gives same parameter values for low-salinity sands of certain water contents and densities. However, the actual difference in these values may exceed 10 % for natural sands of salinities 0.05 and 0.14 %, other things being equal, and may be still greater if the sands differ in grain size (e.g., for gravelly and silty sands).

Thus, the design thermal properties are often based on input data of originally low quality which may lead to significant errors in the predictions that are used for reference in decision making about construction strategies, as well as about approaches to thermal stabilization of soils and engineering protection of buildings and structures.

INPUT DATA FOR MODELING

The results of prognostic calculations presented below are based on measured thermal parameters of soils and on their tabular values according to *SP 25.13330.2012* [*2012*], for medium-grained sand and clay silt. The calculations were performed for three cases: (1) parameter values all measured; (2) heat capacity and thermal conductivity assumed according to tabulated data from *SP 25.13330.2012* [*2012*] and amount of unfrozen pore water measured; (3) amount of unfrozen pore water, heat capacity and thermal conductivity assumed according to *SP 25.13330.2012* [*2012*]. The properties of soils used in the calculations are listed in Tables 2–4.

The experimental data were obtained at the certified laboratory of *AO Fundamentproekt*. The freezing point was measured on a certified instrument *IRS-1* to an accuracy of ±0.05 °C. The thermal properties of soil were determined by needle probing on a *Decagon KD2-Pro* thermal properties analyzer, to an accuracy of ±2.5–5.0 % for thermal conductivity and ±5 % for specific heat [*ASTM D5334-14, 2014*]. The content of unfrozen pore water was measured by a contact method [*Ershov, 2004*], with a difference between two parallel measurements of no more than 0.1 % at the soil moisture 0 to 2 % and no more than 0.3 % at moisture above 5 %. The temperature of samples was maintained constant, to ±0.1 °C. Note that the reliability of the results depends on the certification and regular calibration of instruments.

The predictions were made for 30 years, which is an average life time of the infrastructure for oil and gas production and transportation. The initial ground temperature was assumed to be –1 °C throughout the modeling depth (40 m). The boundary conditions were of order III on the top of the modeling domain and of order II, with zero heat flux, on its base and sides.

The assumed climate parameters were averaged over the period from 1990 to 2015 as reported from the Igarka weather station (at www.Atlas-Yakutia.ru). The modeling aimed at comparing the temperature fields that influence the stability of engineering structures for oil and gas production, and the ground surface within the sites was assumed to be free from vegetation. The climate parameters used in the calculations and the respective boundary conditions are given in Tables 5 and 6.

The modeling was run using the *Geoheat3d* software [*Computer Program No. 2017610461, 2017*] cer-

Table 2. **Physical properties of soils**

Soil type	λ_f	λ_{uf}	C_f	C_{uf}	ρ_d, kg/m^3	W_{tot}	W_p	T_{fp}^*, °C
	W/(m·K)		kJ/(m^3·K)			u.f.		
According to laboratory measurements (case 1)								
Sand	3.06	1.73	1627	2260	1582	0.232	–	–0.4
Clay silt	1.99	1.60	2100	2570	1720	0.206	0.164	–0.4
According to SP 25.13330.2012 [2012] (cases 2, 3)								
Sand	2.99	2.59	1933	2728	measured	measured	–	measured
Clay silt	1.76	1.49	2421	3057	measured	measured	measured	measured

N o t e: *measured* means laboratory data; other values are according to *SP 25.13330.2012* [*2012*].
* T_{fp} in *SP 25.13330.2012* [*2012*] is denoted as T_{bf} (beginngin of freezing).

Table 3. **Soil moisture due to unfrozen pore water in sand**

Cases 1, 2*		Case 3**	
T, °C	W_w, %	*T*, °C	W_w, %
–0.4	23.2	–0.4	23.2
–0.5	11.0	–0.5	0.0
–0.6	6.5	–0.6	0.0
–0.7	3.5	–0.7	0.0
–0.8	2.0	–0.8	0.0
–1.4	0.7	–1.4	0.0
–2.2	0.6	–2.2	0.0
–15.0	0.5	–15.0	0.0
–30.0	0.1	–30.0	0.0

* According to laboratory measurements.
** According to *SP 25.13330.2012* [*2012*].

Table 4. **Soil moisture due to unfrozen pore water in clay silt**

Cases 1, 2*		Case 3**	
T, °C	W_w, %	*T*, °C	W_w, %
–0.4	20.6	–0.4	20.60
–0.5	18.8	–0.5	10.66
–0.6	17.3	–1.0	9.51
–0.8	14.0	–2.0	8.20
–1.1	10.0	–3.0	7.54
–1.4	7.6	–4.0	7.22
–2.0	5.0	–8.0	6.72
–15.0	3.1	–15.0	6.23
–30.0	2.0	–30.0	5.20

* According to laboratory measurements.
** According to *SP 25.13330.2012* [*2012*].

Table 5. **Climate parameters**

Month	Air temperature, °C	Snow depth, m	Snow density, t/m³	Wind speed, m/s
I	−27.7	0.71	0.46	3.6
II	−25.2	0.82	0.53	3.3
III	−16.8	0.87	0.56	3.6
IV	−9.2	0.78	0.52	3.7
V	−0.6	0.19	0.24	3.8
VI	10.6	–	–	3.6
VII	15.7	–	–	3.3
VIII	12.0	–	–	3.1
IX	4.9	0.05	0.19	3.4
X	−6.3	0.23	0.25	3.8
XI	−20.3	0.45	0.33	3.3
XII	−25.1	0.58	0.39	3.7

Table 6. **Air temperature (T) and heat transfer coefficient (α) at the top of modeling domain**

Month	T, °C	α, W/(m²·K)
I	−27.7	0.56
II	−25.2	0.55
III	−16.8	0.55
IV	−9.2	0.57
V	−0.6	1.08
VI	10.6	21.05
VII	15.7	18.93
VIII	12.0	18.03
IX	4.9	13.23
X	−6.3	0.95
XI	−20.3	0.64
XII	−25.1	0.59

tified for calculations of freezing-thawing cycles and temperature dynamics in built-over and open soils.

RESULTS

Figures 1 and 2 show temperature fields of sand and clay silt soils calculated for the latest summer of the 30th year (each for three cases of input data). The freezing point (T_{fp}) is the difference $T - T_{fp}$; depths are in meters; shades of yellow mark zones of unfrozen soils.

The calculations demonstrate how the way of estimating thermal properties may affect the predicted temperature variations and the final result. The thaw depth in sand was 3.7 m when estimated with all parameters measured directly but was much greater in two other cases: 8.4 m with thermal parameters assumed according to *SP 25.13330.2012* [*2012*] and amount of unfrozen pore water measured and 8.8 m with all parameters assumed according to *SP 25.13330.2012* [*2012*]. For clay silt, on the contrary, a larger thaw depth was inferred from measured input data while tabulated data led to a smaller value (2.9 m and 2.5 m, respectively). Thus, the temperature predictions for sand with reference to *SP 25.13330.2012* [*2012*] would incur quite costly but unreasonable ground stabilization measures, which are far more expensive than pre-design experimental measurements. Construction on clay silt may face unpredicted hazard (which hopefully would be detected on time) and require special engineering solutions to prevent and mitigate the related defects during construction and operation.

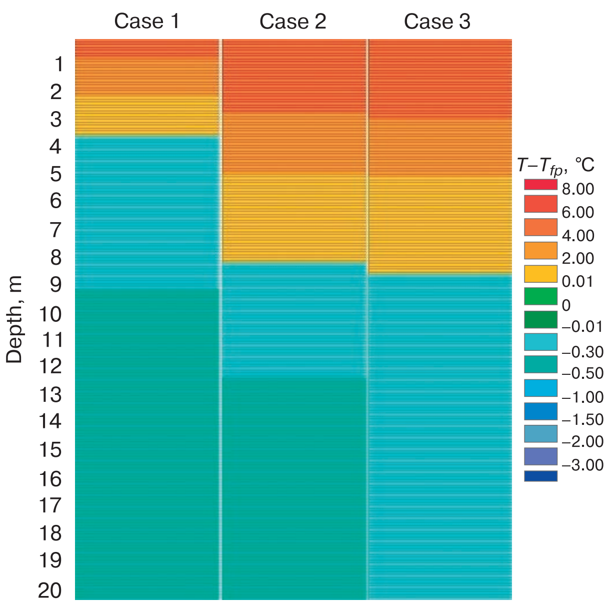

Fig. 1. Temperature fields of sand soil: end of summer, 30th year of calculations.

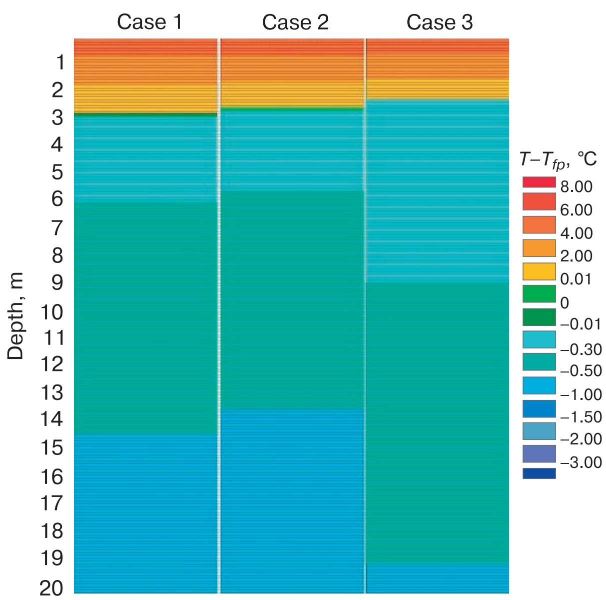

Fig. 2. Temperature fields of clay silt soil: end of summer, 30th year of calculations.

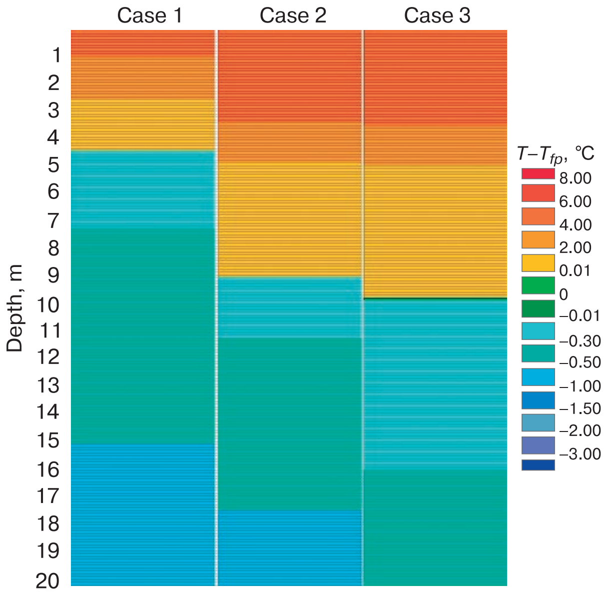

Fig. 3. Temperature fields of a fill pad: end of summer, 30th year of calculations.

Production and utility structures at oil and gas fields are often built on fill pads lying over muddy soils. Therefore, calculations were also performed for such a site, for the three types of input data (Fig. 3), with a fill pad thickness of 3 m. The starting conditions were same as reported above.

The thaw depth predicted with reference to fill pad properties according to *SP 25.13330.2012* [*2012*] reaches 9.8 m (Fig. 3), which contradicts principle I of using soils as foundation and requires special thermal stabilization measures. However, they are actually unnecessary, because experimental input data give a twice shallower thaw depth of 4.5 m. Thus, the client may save on engineering surveys but incur much greater costs on protection and stabilization of soils.

CONCLUSIONS

1. Specifications for engineering surveys commonly require the use of both *SP 11-105-97* [*1999*] and *SP 25.13330.2012* [*2012*] National Standards, but the two working documents disagree about the way of input data determination for design purposes, which is misleading for design and survey companies and their clients, as well as for experts.

2. The disagreement between results based on experimentally measured and tabulated input data is greater for sand than for clay silt, because the respective parameter values are especially strongly generalized in *SP 25.13330.2012* [*2012*].

3. Thermal conductivity, specific heat, and amount of unfrozen pore water, the key parameters that control the dynamics of processes in soils, should be measured directly for design and construction on permafrost. At the time being, there are no normative documents that would regulate prognostic calculations and prescribe direct determination of the soil thermal properties. Thus, clients should demand direct measurements of the respective parameters in specifications for engineering surveys; otherwise, low-quality predictions will require additional capital and operational costs, including costs for improving the stability of objects.

References

Aleksyutina, D.M., Motenko, R.G., 2017. The composition, structure, and properties of frozen and thawed deposits on the Baidaratskaya Bay coast, Kara Sea. Earth's Cryosphere (Kriosfera Zemli) XXI (1), 11–22.

ASTM D5334-14, 2014. Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure. West Conshohocken, USA, 53 pp.

Cheverev, V.G., 2004. The Nature of Cryogenic Properties of Soils. Nauchnyi Mir, Moscow, 234 pp. (in Russian)

Computer Program No. 2017610461, 2017. Certificate of Registration. Federal Agency for Intellectual Property of the Russian Federation. (in Russian)

Ershov, E.D. (Ed.), 1984. Thermal Properties of Rocks. Moscow University Press, Moscow, 204 pp. (in Russian)

Ershov, E.D. (Ed.), 2001. Fundamentals of Geocryology. Book 4. Dynamic Geocryology. Moscow University Press, Moscow, 688 pp. (in Russian)

Ershov, E.D. (Ed.), 2004. Methods for Geocryological Studies. Moscow University Press, Moscow, 507 pp. (in Russian)

Saveliev, B.A., 1971. Physics, Chemistry, and Structure of Natural Ice and Permafrost. Moscow University Press, Moscow, 505 pp. (in Russian)

Shevelev, A.S., 1979. Mechanical Properties of Permafrost. Stroyizdat, Moscow, 129 pp. (in Russian)

SP 11-105-97, 1999. Engineering-Geological Surveys for Construction. Part IV. Regulations for Works in Permafrost. Gosstroi RF, Moscow, 54 pp. (in Russian)

SP 25.13330.2012, 2012. Basements and Foundations on Permafrost. Ministry of Regional Development of the Russian Federation, Moscow, 109 pp.

Votyakov, I.N., 1952. On the method for estimation of water phase composition in frozen soils of natural structure, in: Permafrost Studies in Yakutia. Izd. AN SSSR, Moscow, Issue 3, pp. 72–87. (in Russian)

Received March 4, 2017