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INFLUENCE OF THAWING CONDITIONS AND TYPE OF TESTING ON DEFORMATION CHARACTERISTICS OF THAWING SOIL

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Results are presented for laboratory studies of deformation characteristics of thawing soil for unidirectional and multidirectional thawing. Data from laboratory tests and hot plate tests were juxtaposed with the results of mathematical modeling using the Termoground program. Boundaries were established for changes to thaw and compressibility factors for different kinds of soil. Recommendations were given for the use of multidirectional thawing for laboratory determinations of soil deformation characteristics during engineering surveys.

Introduction

Soil deformation during thawing is forecast by solving two types of problems: a temperature problem and a mechanical problem. In light of the complexity of frozen soil, thawing conditions, as well as the dependence of settling due to thawing on different physical properties, forecasting deformations is a rather complex problem that requires further improvement of reliable determination of thawing soil deformation characteristics and the patterns in which they change.

Initially, tests to determine thawing soil deformation characteristics were carried out using instruments that supported unidirectional thawing, for which methods have been developed to predict settling [1, 2]. More recently, tests are ever more often carried out under conditions of multidirectional thawing. However, data for substantiating such an approach and studies to identify the influence of thawing conditions on soil deformation characteristics are all but absent [3].

An insignificant quantity of data have been collected that permit the comparison of deformation characteristics obtained under laboratory and field conditions. It should be noted that field test data were obtained under assorted test conditions. Thus, in the work of V. P. Ushkalov [4], P. D. Bondarev [5], and G. V. Porkhaev [6], tests were carried out to the thaw depth threshold, while in the work of G. I. Pakhomova [7], V. V. Dokuchaev [8], V. A. Sorokin [9, 10], Yu. G. Fedoseev [11], V. D. Ponomarev [12], A. A. Kolesov [13], A. I. Zolotar' [14], and L. N. Khrustalev [15], they were carried out to by thawing to a depth of one-half the diameter of a plate with a heated ring equal to one-third the plate diameter. A comparison of deformation characteristics data obtained under field and laboratory conditions is presented in Table 1.

Thus, it may be concluded that compressibility factors obtained under laboratory conditions may be both equal to or approximately 3 times greater than data from field tests. These values generally

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TABLE 1

Author	Region	Soil	A_c/A_s	m_c/m_s
P. D. Bondarev	Salekhard	clay	–	1.4-3.0
G. V. Porkhaev	Vorkuta	clay		1.3-1.8
V. P. Ushkalov	Zabaikal'e	clay	1.1-1.5	1.1-1.3
V. V. Dokuchaev	–	sand	5.0	–
V. D. Ponomarev	–	clay	10.0	–
L. N. Khrustalev	Vorkuta	loam	1.8-2.0	1.2-1.3
		sand	1.1-1.3	1.0-1.2
V. A. Sorokin	Vorkuta	clay	1.1-3.0	1.3-5.0
		sand	1.0-2.0	1.4-2.7
A. A. Kolesov	Western Siberia	sand	1.0-1.1	1.0-1.1
A. I. Zolotar'	Novyi Urengoi	clay	20.0	2.4
G. I. Pakhomova	Ust'-Ulim	loam	1.1-1.2	1.1-1.2

Thawing factors, determined under laboratory (A_c) and field (A_s) conditions; compressibility factors, determined under laboratory (m_c) and field (m_s) conditions.

TABLE 2

Fractional content,%								Soil name (from GOST 25100-2011)
Particle diameter, mm								
1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.01	0.01-0.005	0.005-0.001	< 0.001	
1.1	3.7	63.9	13.7	8.4	3.6	3.6	2.1	Sandy loam, heavy, powdery
0.7	1.1	11.2	24.5	30.2	12.9	10.4	9.7	Clay loam, light, powdery

TABLE 3

Soil composition	W_{tot}, unit fraction	W_{nf}, unit fraction	ρ_d, g/cm^3	W_p, unit fraction	W_L, unit fraction	t_{sf}, °C
Sandy loam	0.18	0.05	1.68	0.136	0.183	-0.1
	0.28	0.05	1.49	0.136	0.183	-0.1
Clay loam	0.3	0.1	1.43	0.2	0.295	-0.2
	0.4	0.1	1.24	0.2	0.295	-0.2

coincide for sandy soil. Thawing factors obtained under laboratory conditions are 2-20 times greater than obtained field test data values. Cryogenic makeup, moisture content, ice content, and other factors significantly influence the dispersion of deformation characteristics. It is extremely difficult to separately isolate the influence of thawing conditions.

To address these questions, laboratory tests were carried out to determine deformation characteristics of clay soil specimens under different thawing conditions (unidirectional and multidirectional). In parallel, the thawing process underwent mathematical modeling in the Termoground program [16], which permits the combined influence of soil temperature conditions and stress-strain state to be examined during thawing.

Investigation procedure

Experimental investigations

Experiments were carried out on clay specimens of disturbed structure, prepared from cores of marine and glacial-marine origin taken within the territory of the Taz-Yenisei Oblast at a depth of up to 5 m. The particle composition is determined using the aerometric method (Table 2).

The composition and specified physical properties are shown in Table 3 (W_{tot} is the moisture; W_{nf} is the moisture due to nonfrozen water; ρ_d is the density of the soil matrix; W_p and W_L are the moisture at the lower and upper plastic limit; and t_{sf} is the temperature of the start of soil freezing).

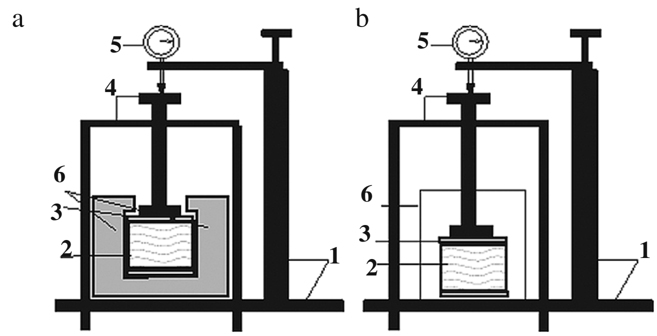

Fig. 1. Diagrams of instruments for multidirectional (a) and unidirectional (b) thawing: 1) support frame; 2) metal ring with soil; 3) perforated plate; 4) system of levers for applying load; 5) indicator; 6 a) external cylinder, 6 b) thermally nonconducting housing.

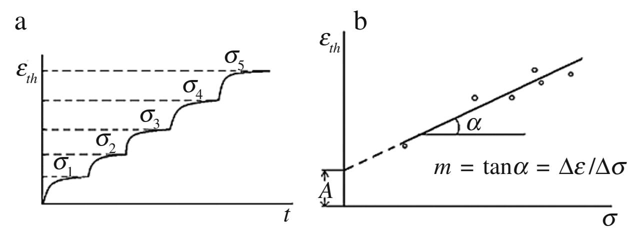

Fig. 2. Development dependencies: a) of relative settling as a function of time for each level of load; b) of stabilized settling as a function of load.

Tests were performed with threefold repetition using the standard procedure for compressive compaction of frozen soil during thawing [17] using oedometers that permit conditions for unidirectional and multidirectional thawing to be created (Fig. 1).

Unidirectional thawing tests were carried out in oedometers fabricated of Caprolon (a thermally nonconducting material, with a thermal conductivity of 0.23 W/m·K), which provided thermal insulation for specimens along their lateral surface and bottom end (the housing wall size was 3 cm) (Fig. 1, a); uninsulated compressive oedometers were used for multidirectional thawing (Fig. 1, b).

Tests to determine deformation characteristics were carried out in three phases:

I) compaction of frozen soil at a negative temperature at a load of 0.1 MPa;

II) thawing at +20°C with the same load;

III) compaction of the thawed specimen using a stepwise-increasing load. After settling has stabilized at each step, the load was increased by 0.05 MPa and held until settling had become nominally stable (0.01 mm over 12 h).

There were five load steps overall.

Obtained data (Fig. 2) was used to establish the dependence of relative settling at each load step on time (a) and of nominally stable settling on load (b), which were used to determine the thawing factor A, which is equal to the relative stabilized settling without load, and the compressibility factor m, calculated as the tangent of the inclination angle of the line to the horizontal coordinate axis.

Mathematical modeling

A two-step solution was carried out using Termoground, of: 1) the temperature problem, the result of which determined the temperature patterns during a fixed period of time, and 2) the mechanical problem, with an analysis of soil settling during thawing and compaction.

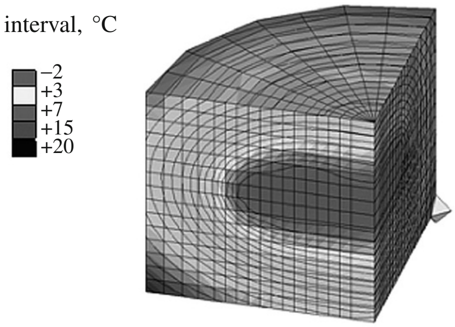

Fig. 3. Fragment of the scheme for analyzing the temperature problem for multidirectional thawing.

Freeze-thaw processes in the Termoground program module are described with a thermal conductivity equation, with due regard for ground water phase transformations in the negative temperature interval for non-steady-state temperature conditions in a three-dimensional soil space [18].

Settling of thawing soil was modeled in the program using the dependency proposed by M. F. Kiselev [19]:

$$d\varepsilon_{th} = \frac{W - W_P - K_d I_P}{\rho_w / \rho_s + W_{tot}}, \tag{1}$$

where I_P is the index of plasticity; ρ_w is the density of water, ρ_s is the density of soil particles; K_d is a compaction factor that depends on particle size in clay soil and compaction pressure during thawing.

$$K_d = aI_P^{-b} + c, \tag{2}$$

where a, b, and c are empirical factors that depend on pressure.

Relation (1) is applicable at pressures 0.05-0.6 MPa and does not consider soil cryogenic texture singularities. Analysis was carried out for modeled specimens having massive cryogenic texture at a load of 0.1 MPa.

An axially symmetric scheme was adopted to solve the temperature problem of soil thawing under laboratory conditions, represented by one-fourth of a cylinder having a 35.5 mm radius and a height of 35 mm and consisting of 2000 finite elements.

The properties of the initial soils are shown in Tables 1 and 2. The thermophysical characteristics required for the analysis were taken from code specification SP 25.13330.2012.

The impact of temperature on soil was specified using a special "quadrilateral heat exchange" element. Use of this element leads to more accurate results when solving small-scale problems [20]. "Quadrilateral heat exchange" is a type III boundary condition. The element parameters are temperature and heat transfer coefficient. The initial specimen temperature was taken to be −2°C. At each step of the solution, the model was exposed to a constant temperature of +20°C. The heat transfer coefficient was taken to be 9 W/(m^2·°C), the thawing process for a two-hour time interval was divided into 96 segments (each minute, for the first 1.5 hr of the solution, and every 5 minutes thereafter).

Type III boundary conditions were specified in the upper portion along the plane of interaction between the metal plate and the soil for unidirectional thawing conditions and in the upper and lower portions and along the walls for multidirectional thawing; in all other cases, type II conditions with zero heat flow were specified (Fig. 3).

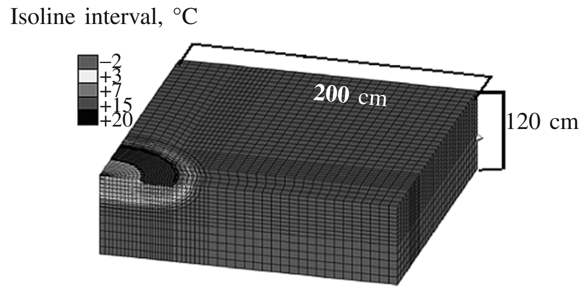

Fig. 4. Fragment of the scheme for analyzing the temperature problem under the plate.

TABLE 4

Soil type	Number of Specimens	Mean Value		Variation Factor V, unit fraction	
		W_{tot}, unit fraction	ρ, g/cm^3	W_{tot}, unit fraction	ρ, g/cm^3
Sandy loam	12	0.18	1.98	0.01	0.01
	12	0.28	1.91	0.02	0.01
Clay loam	12	0.30	1.86	0.02	0.01
	12	0.40	1.74	0.02	0.01

After the temperature problem has been solved, stress effects on soil through the plate were modeled without a radial deformation capability, as is the case for compression. The plate pressure on the soil was specified as constant and equal to 0.1 MPa over the entire time interval.

The process of testing frozen soil using a hot plate was modeled to forecast the deformation characteristics [21]. The design setup has dimensions of 200×200 cm in plan view, with a soil layer thickness of 120 cm (Fig. 4). The figure shows one-fourth of a round plate, the radius of which is 40 cm (5,000 cm^2 total area). The plate circles a heating ring 25 cm wide (about 1/3 the plate diameter). The thawing temperature is +20°C.

After attaining the thawing depth of 40 cm (1/2 the plate diameter), nominal heating of the soil model was terminated and settling was analyzed. Temperature readings from the previous step, determined at 15 minute intervals, were used at each step of the analysis.

Results

Experimental investigations. Deformation characteristics were determined for soil specimens with specified initial density and moisture values; these same characteristics were used for modeling as well. Statistical data processing for both unidirectional and multidirectional thawing was carried out for 24 specimens of sandy loam and clay loam (Table 4).

Clearly, the specimen moisture variation factor did not exceed 2%; the density factor did not exceed 1%. The results of statistical processing of experimental data are shown in Table 5. Mean values were calculated for the thawing factor A, compressibility factor m, and variation factor V obtained under different thawing conditions, as well as of the variation factor calculated during a general evaluation of both unidirectional and multidirectional thawing (Table 5).

From the experimental investigation, it was determined that the thawing factor A is greater for multidirectional thawing than for unidirectional thawing. The maximum difference between the values was 12% for sandy loam and 23% for clay loam. At the same time, the thawing variation factor for both thawing conditions did not exceed 7%.

TABLE 5

W_{tot}, unit fraction	Unidirectional thawing		Multidirectional thawing		Mean value for both thawing conditions	
	A, unit fraction/m, MPa^{-1}	V, unit fraction	A, unit fraction/m, MPa^{-1}	V, unit fraction	A, unit fraction/m, MPa^{-1}	V, unit fraction
sandy loam						
0.16	0.137/0.091	0.056/0.062	0.148/0.082	0.033/0.042	0.142/0.087	0.059/0.076
0.28	0.194/0.102	0.026/0.093	0.204/0.095	0.036/0.058	0.199/0.099	0.041/0.079
clay loam						
0.3	0.123/0.111	0.073/0.061	0.133/0.093	0.052/0.136	0.128/0.102	0.068/0.128
0.4	0.224/0.123	0.029/0.061	0.244/0.107	0.062/0.057	0.234/0.115	0.065/0.092

TABLE 6

Soil type	W_{tot}, unit fraction	Thawing conditions	Relative deformation for stress of		Deformation characteristics	
			0.1 MPa	0.3 MPa	A, unit fraction	m, MPa^{-1}
Sandy loam	0.18	1	0.028	0.043	0.020	0.076
	0.18	2	0.028	0.043	0.020	0.076
	0.28	1	0.107	0.159	0.081	0.260
	0.28	2	0.114	0.171	0.086	0.286
Clay loam	0.3	1	0.077	0.100	0.066	0.114
	0.3	2	0.084	0.109	0.071	0.124
	0.4	1	0.144	0.202	0.115	0.290
	0.4	2	0.169	0.231	0.137	0.311

The compressibility factor m, per the test data, is greater for unidirectional thawing than for multidirectional thawing. The maximum difference between the values was 18% for sandy loam and 26% for clay loam. The variation factor m for both thawing conditions did not exceed 13%, i.e., data sampling may be said to be sufficiently uniform.

Deformation characteristic values satisfy the three-sigma rule (if the random value is distributed normally, then the absolute value of its deviation from the mathematical expectation does not exceed three times the mean-square deviation), so that we may use the criteria for comparing mathematical expectations and dispersions of both thawing methods (unidirectional and multidirectional). Deformation characteristic dispersions were compared on the basis of a Fisher distribution (for a test significance $a = 0.05$). Calculated values turned out to be less than the table values, and consequently, deformation characteristic dispersions for different thawing conditions are equal.

Mean characteristics obtained using both methods were compared using Student's t distribution for two independent samples for equal dispersions. The t criterion data turned out to be less than the critical value, which suggests that the two methods for determining deformation characteristics are of equal significance.

Mathematical modeling. Settling was modeled for unidirectional (1) and multidirectional (2) thawing. The results of analysis are presented in Table 6, where it is evident that modeled settling is 5%-20% greater for multidirectional thawing than it is for unidirectional thawing. The greatest difference is typical for clay loam. For sandy loam with 0.18 moisture, thawing conditions have practically no impact on settling. This is related to the impact of the creation of a stress state in the soil during thawing, upon which the parameter K_d in equation (1) depends.

For multidirectional thawing, the soil's frozen kernel is a stress concentrator (stresses about the kernel exceed the stresses at the surface of the device walls by a factor of 3), which results in greater compaction in the center, as well as a redistribution of moisture. Thus, after multidirectional thawing, there is less moisture in the center of the specimen than at the lateral surface. This effect has been recorded both experimentally, while studying the distribution of moisture inside of soil after thawing and

TABLE 7

Soil type	W_{tot}, unit fraction	Deformation characteristics, calculated for:			
		laboratory conditions		field conditions	
		A, unit fraction	m, MPa^{-1}	A, unit fraction	m, MPa^{-1}
Sandy loam	0.18	0.020	0.076	0.018	0.075
	0.28	0.081	0.26	0.048	0.150
Clay loam	0.3	0.066	0.114	0.063	0.075
	0.4	0.115	0.29	0.091	0.213

compaction under conditions of compression. Thus, modeling of thawing processes confirmed that thawing conditions affect soil settling during thawing.

Data from studies by G. M. Pakhomova [7] and V. P. Ushakov [4] were used to compare settling of thawing soil in response to a heat plate under field and calculated using the Termoground program.

Experimental settling obtained for both field and laboratory conditions was 1.5-3 times higher than what was calculated by the program. This is related to relation (1) not taking account of the impact of cryogenic structure and of various physicomechanical processes that occur during thawing. However, the obtained analytical settling permits a qualitative assessment of the way in which deformation characteristics change under various thawing conditions and types of testing.

A comparison of deformation characteristics, obtained from modeling data for laboratory compression and field tests under unidirectional thawing conditions, is shown in Table 7, from which it follows that the thawing factor consistently increases with the increase of moisture during compression testing. Thawing and compressibility factors for sandy loam with 0.18 moisture turned out to be near in value. An increase in moisture in both sandy loam and clay loam causes an increase in deformation characteristics by 30%-50%.

Conclusions

Based on completed experimental and theoretical investigations, as well as the result of mathematical modeling, we may draw the following conclusions:

1. The value of factor *A* under conditions of multidirectional thawing is greater than the value for unidirectional thawing. Conversely, the value of factor *m* is greater for unidirectional thawing. This is related to the influence of the stressed state that is created in soil during thawing. Statistical processing of experimental data shows that the mean values and dispersions obtained for deformation characteristics for different thawing conditions are identical, which allows us to conclude that both procedures for determining deformation characteristics may be used during the initial engineering survey phase.

2. The results of mathematical modeling using the Termoground program allow a qualitative assessment of the influence of thaw and compaction conditions on settling of thawing soil. Settling is 5%-20% greater for multidirectional thawing under compressive conditions. For multidirectional thawing of soil, the frozen kernel is a stress concentrator, which results in greater compaction of the specimen in the center, as well as a redistribution of moisture. This effect has been recorded both experimentally, while studying the distribution of soil moisture after thawing and compaction under conditions of compression.

3. Design deformation characteristics for compression tests are 5%-20% greater than data values from field testing using hot plates, which is caused by a difference in the process of stress formation in soil during thawing and compaction. Thus, the redistribution of stresses arising in soil during testing is one of the factors that significantly influence deformation characteristics, alongside cryogenic structure, moisture content, ice content, etc.

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