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PROPERTIES OF FROZEN GROUND AND ICE

TANGENTIAL FROST HEAVING FORCES OF CLAY AND SANDY SOILS ACTING ALONG THE METAL SURFACE

A.G. Alekseev[1,2,*]

[1] *Gersevanov Research Institute of Bases and Underground Structures,*
Vtoraya Institutskaya ul. 6, Moscow, 109428 Russia
[2] *Moscow State University of Civil Engineering,*
Yaroslavskoye sh. 26, Moscow, 129337 Russia

**Corresponding author; e-mail: adr-alekseev@yandex.ru*

The results of experimental studies of the tangential frost heaving forces of clay and sandy soils in laboratory conditions on three installations with different single-plane shear rates at constant normal load are presented. The installations made it possible to perform conditionally instantaneous shift, long-term tests with the application of a stepwise shifting load and a shift at a constant speed. As a result of complex studies, the dependences of shear resistance or equivalent tangential forces of frost heaving of sand and loam on water content (from 10 to 28%) and temperature (from 0 to –10°C) on the metal surface have been established. An increase in soil water content and a decrease in soil temperature leads to an increase in the resistance to soil shear. The shear resistance of sand is up to two times higher than similar values for loam under identical shear conditions, temperature and water content. An increase in soil moisture leads to an increase in the contact area of soil particles through ice layers with a metal foundation and to an increase in the bonds between the particles as a result of an increase in the volume of ice. It is established that the resistance to conditionally instantaneous shear is up to three times higher than the values of extremely long-term shear resistance and shear at a constant speed under similar thermal humidity conditions.

Keywords: *tangential forces, frost heaving forces, frozen soil, resistance to the shift, foundation surface, laboratory studies.*

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INTRODUCTION

When building foundations in heaving soils below the depth of seasonal freezing, frost heaving forces act on the foundation along its lateral surface. Under the action of frost heaving, the foundations are deformed: they move upwards and, according to some observations, the displacement reaches 15 cm or more, and the magnitude of the tangential heaving forces exceeds 200 kN [*Safronov, 1985; Ivanin et al., 2020; Shulyatiev, 2020*]. Deformation of structures under the action of tangential forces of frost heaving leads to significant costs for the restoration of damaged structures. Therefore, the assessment of the magnitude of the tangential forces of frost heaving is an important scientific and practical task.

The tangential forces of frost heaving were quite actively studied in the Soviet Union [*Dalmatov, 1957; Dubnov, 1967; Peretrukhin, 1967; Orlov et al., 1977*]. Laboratory studies by B.I. Dalmatov [*1957*] and then Yu.D. Dubnov [*1967*] made it possible to establish the following regularity: the value of stable freezing forces is close to the value of tangential forces of frost heaving of soils. As a design characteristic, the steady value of freezing resistance under certain permafrost-soil conditions should be taken [*Dubnov, 1967*]. The experiments of Yu.D. Dubnov showed that a consistent increase or decrease in the speed of soil movement according to the foundation model does not change the value of stable freezing resistance, provided that the speed of soil movement differs by no more than ten times. A change in the speed of soil movement by 50–100 times has a significant effect, which changes the stable freezing resistance by 40–50%. Under natural conditions, there are no sharp changes in the speed of soil movement along the foundation, so the effect of speed when measuring stable freezing resistance under laboratory conditions can be ignored. To reduce the experiment time, the recommended rate of soil movement along the foundation material is 10–20 mm/day.

Similar time dependences of the tangential frost heaving forces and heaving deformation are found in foreign works (for example, [*Penner, 1974*]).

Due to the complexity of the field method of studying frost heaving of soils, it has not found wide application in construction practice and is used exclusively for scientific purposes [*Safronov, 1985;*

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Ivanin et al., 2020; Shulyatyev, 2020], although the only Russian regulatory document [*GOST 27217-2012, 2013*] was developed specifically for field studies of the tangential forces of soil heaving. Foreign regulatory documents [*ASTM D 5918-063, 2006; BS 812-124:2009, 2009; Eurocode 7, 2013*] also do not contain requirements for determining the shear forces of soil heaving and methods for their determination.

In 2016, with the participation of the author, a standard was developed for the laboratory determination of the specific shear forces of frost heaving [*GOST R 56726-2015, 2016*]. The document took into account the only method for determining the tangential forces of frost heaving of soils under laboratory conditions [*Guidelines..., 1973*], which was not widely used due to the complexity of the design of the experimental setup.

The purpose of this study is to optimize the determination of the integral tangential heaving force, taking into account the thermal and moisture regimes of freezing heaving soils. The experiments were carried out by three methods using different soil shear rates on a metal foundation (conditionally instantaneous tests, long-term tests, and tests at a constant rate) for sandy and clayey soils. The results obtained can be used in engineering-geological surveys and calculation of foundations on heaving soils.

METHOD FOR DETERMINING THE TANGENTIAL FORCES OF FROST HEAVING OF SOILS UNDER LABORATORY CONDITIONS

The experiments were carried out by three laboratory methods: (1) conditionally instantaneous tests, (2) long-term tests with the application of a stepped load, and (3) shear at a constant speed. The experimental setup made it possible to set loads both in the normal and tangential directions with respect to the sample under study, so that a single-plane shear was ensured.

The normal stress of 0.1 MPa was applied for all installations. The studies were carried out for two types of soil: loam and sand, the characteristics of which are presented in the table. The moisture content was set equal to 10, 20, and 28% for loam soil and to 10, 15, and 20% for sandy soil. The studies were carried out for a metal plate made of steel grade 09G2S. The experiment was performed in triplicate.

Method for studying the conditionally instantaneous shear resistance along the freezing surface. Tests to determine the value of the conditionally instantaneous shear resistance along the freezing surface were carried out on a VSV-25 device, the scheme of which and the methodology of work followed [*Guidelines..., 1973*]. A soil sample in a metal ring was installed in the upper part of the shear carriage, and a foundation sample in the form of a metal plate was located in the lower cage.

The soil sample was installed in the device and loaded with a given normal load using a dynamometer. A continuously and uniformly increasing shear load was applied to the foundation sample quickly (more than 100 mm/day), but without impact. The duration of the test was 20–30 s. The experiment ended when the metal plate was torn off the ground or when the soil sample moved without further increase in load. The value of conditionally instantaneous resistance soil shear along the freezing surface was determined as the quotient of the breaking force divided by the area of the sample. The test temperature was set at 0, –1, –2, –4, –6 and –10°C.

Method for studying the ultimate long-term shear resistance. Tests to determine the value of the maximum long-term shear resistance along the contact of the freezing soil surface and the metal surface were carried out according to the method described in [*GOST 12248-2010, 2012*], in shear devices. A foundation sample was installed in the lower part of the shear carriage of the device; a metal ring was built into the upper part of the device body, into which the soil under study was placed.

A carriage with a foundation sample and a frozen soil sample was placed in the device, after which a dynamometer was installed, with which the normal load was maintained during the test, as well as a displacement sensor, then a shear load was applied stepwise.

Table 1. **Physical characteristics of soils in the study of shear forces of frost heaving**

Soil type*	Particle content (%) of different size (mm)							C_u	W_g	ρ_s	W_L/W_{sat}	W_p	I_p	I_{om}
	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.002	<0.002							
	$A_{0.5}$	$A_{0.25}$	$A_{0.1}$	$A_{0.05}$	$A_{0.01}$	$A_{0.002}$	A_0							
Silty sand (heterogeneous)	1.3	7.4	53.4	28.2	2.6	4.8	2.3	3.21	0.6	2.60	–/17.0	–	–	0.7
Clayey silt loam	0.8	2.7	15.2	17.7	28.7	20.4	14.5	–	2.4	2.61	30.8/–	18.7	12.1	2.4

Note: C_u is the degree of grain composition inhomogeneity; W_g is hygroscopic moisture, %; ρ_s is the density of soil particles, g/cm^3; W_L/W_{sat} is the ratio of moisture at the yield point to the total moisture capacity, %; W_p is the moisture content at plastic (rolling) limit, %; I_p is the plasticity number; and I_{om} is the relative content of organic matter, %.

* According to [*GOST 25100-2011, 2013*].

The load at the first stage of the test was set taking into account temperature conditions and type of soil according to Table 6.2 [*GOST 12248-2010, 2012*]; the increment of the tangential load was set taking into account Table 6.3 [*GOST 12248-2010, 2012*]. Each load step was maintained until conditional stabilization of the deformation. The strain increment not exceeding 0.01 mm per 12 h was taken as conditional strain stabilization. The next load stage was applied to the specimen after strain stabilization was achieved at the previous stage. If no stabilization of the deformation was observed at the next stage of loading, the load was maintained until the development of deformation at a constant rate during two successive 12-hour intervals.

The test was terminated if a constant strain rate was set for at least two steps of the shear load, or if strains developed at an increasing rate. The limiting long-term value of shear resistance along the freezing surface with the foundation material was determined as the highest shear stress at which the sample deformation was stabilized at a given normal stress. The test temperature was 0, –1, –2, –6, –10°C.

The processing of experimental data was carried out according to the creep ε–t curves (ε, mm; t, h) and the relationship between shear stress and total strain at the moment of stabilization $\ln t$–$\ln \varepsilon$ in logarithmic coordinates according to [*GOST 12248-2010, 2012*].

Method for studying shear resistance at constant speed. Studies of shear at a constant rate or specific shear forces of frost heaving were carried out in an experimental setup that provided shear along a fixed plane with a constant speed of movement of a foundation sample over a soil sample in the range of 5–20 mm/day [*Cheverev, Alekseev, 2016*].

The installation had a carriage with a holder for a soil sample in the upper part and a foundation sample in the lower part. A normal load was applied to the soil sample, and a shear load at a constant speed was applied to the foundation sample. The soil shear resistance was measured with a force sensor with an accuracy of 0.01 MPa, the movement of the sample in time was measured with a displacement sensor with an accuracy of 0.01 mm.

Stable shear resistance in the experiment was recorded at the moment when the maximum displacement of the foundation material sample relative to the soil sample reached at least 10 mm. The experiments were carried out at five temperatures: 0, –1, –2, –4, and –6°C. At temperatures of –1, –2, –4°C, a constant carriage movement speed of 0.42 mm/h (10 mm/day) was set; at a temperature of –6°C, the carriage movement speed was set to 0.21 mm/h (5 mm/day), as the speed of 10 mm/day at this temperature could not be ensured because of the failure of the samples.

Procedure for preparing soil samples for shear testing. The soil and foundation samples for all test facilities were identical, so sample preparation was carried out in the same way. The soil was placed in a metal ring of 71.5 mm in diameter and 35 mm in height.

The studied soil at room temperature was laid into the ring by layer-by-layer compaction and then combined with the foundation sample. After preparing and testing of the soil sample, the bulk density and moisture content of the soil were monitored. The samples of the soil and foundation were placed in a freezer with a low subzero temperature (–26°C) for freezing and formation of a massive cryostructure. After freezing, the soil and foundation samples were transferred to a freezer, where the test temperature was maintained for the experiment. Before testing, soil and foundation samples were kept in a freezer at a given temperature for at least 12 h.

PATTERNS OF DEVELOPMENT OF TANGENTIAL FORCES OF FROST HEAVING OF SOILS

Studies carried out by three laboratory methods with different shear load application rates made it possible to identify patterns in the development of tangential heaving forces or stable shear resistance in dependence on temperature and moisture content for sandy and clayey soils along the freezing interphase with a metal surface.

Dependence of the conditionally instantaneous shear resistance along the freezing surface on the temperature and moisture regimes of soils. A decrease in the temperature of sandy soil from 0 to –10°C leads to an increase in conditionally instantaneous shear resistance from 0.04 to 1.21 MPa at the moisture content of 10%, from 0.07 to 2.01 MPa at the moisture content of 15%, and from 0.09 to 2.58 MPa at the moisture content of 20% (Fig. 1).

For loam, lowering the test temperature from 0 to –10°C led to an increase in shear resistance from 0.07 to 1.14 MPa at the moisture content of 10%, from 0.10 to 1.39 MPa at the moisture content of 20%, and from 0.18 to 1.65 MPa at the moisture content of 28% (Fig. 2). The dependence of the shear resistance on the moisture content was clearly manifested: with an increase in the moisture content, the shear resistance also increased within the considered temperature range.

The resistance to conditionally instantaneous shear of sand at the studied temperatures was significantly higher than that of loam.

The temperature of the soil is decisive in the formation of the freezing interphase between the wet soil and the foundation structure. At high soil temperatures (to –1°C), the shear resistance is low (<0.5 MPa) for both loam and sand; a further decrease in temperature leads to an almost linear increase in shear resistance.

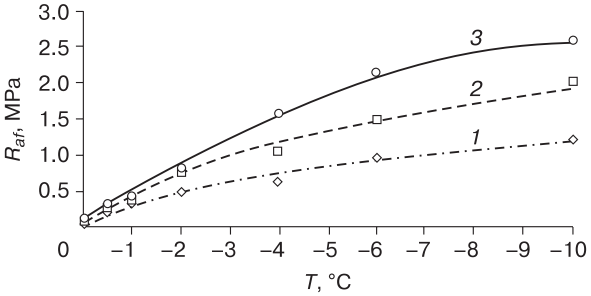

Fig. 1. Dependence of conditionally instantaneous shear strength (R_{af}) of frozen sand on test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 15\%$; (*3*) $W = 20\%$.

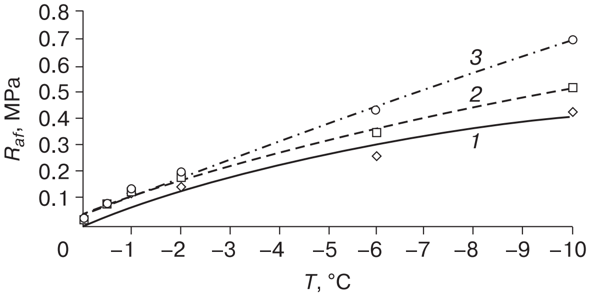

Fig. 3. Dependence of the ultimate long-term shear resistance (R_{af}) of frozen sand on a metal surface on the test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 15\%$; (*3*) $W = 20\%$.

Dependence of the maximum long-term shear resistance on the temperature and moisture regime of soils. The ultimate long-term shear resistance increases with an increase in the moisture content of the soil sample and a decrease in the test temperature from 0 to −10°C increased both for sand and loam. For sandy soil, it increased from 0.02 to 0.42 MPa at the moisture content of 10%, from 0.02 to 0.52 MPa at the moisture content of 15% and from 0.03 to 0.70 MPa at the moisture content of 20% (Fig. 3). For loam, it increased from 0.01 to 0.33 MPa at 10% moisture, from 0.02 to 0.37 MPa at 20% moisture, and from 0.03 to 0.49 MPa at 28% moisture (Fig. 4). The values of the ultimate long-term shear resistance for sand were significantly higher than for loam: at the moisture content of 10%, the difference was 0.05–0.09 MPa; at the moisture content of 20%, the difference was 0.05–0.33 MPa.

In the zone of high temperatures (0 to −1°C), a more intensive increase in the value of the maximum long-term shear resistance was noted than at low temperatures (−1 to −10°C), which is explained by the transition of soil from a thawed state to a frozen state and an increase in shear resistance not only due to the adhesion of the soil to the foundation but also due to the freezing of these materials. The ultimate long-term shear resistance of both clay and sandy soils depends on the temperature and moisture regime and increases with decreasing temperature and increasing soil moisture content.

A stepwise increase in the shear load during testing can be used when assessing the magnitude of the tangential frost heaving forces for conditions of uniform freezing of the soil and an increase in the external load on the shear area. However, the obtained value does not fully reflect the desired value of the specific tangential force of frost heaving, which is characterized by the sliding friction resistance of frozen soil over the freezing surface. In tests to determine the maximum long-term shear resistance, the value is estimated at which the displacement deformations of the foundation are stabilized, i.e., sliding friction does not occur. Long-term tests precede the stage of frozen soil sliding on the foundation surface. The objective value of the specific tangential forces of frost heaving should be determined under the condition that frozen soil moves along the foundation at a speed that characterizes the resistance of sliding friction. To estimate the desired value, the next series of tests was carried out at a given constant speed of soil movement along the contact with the foundation.

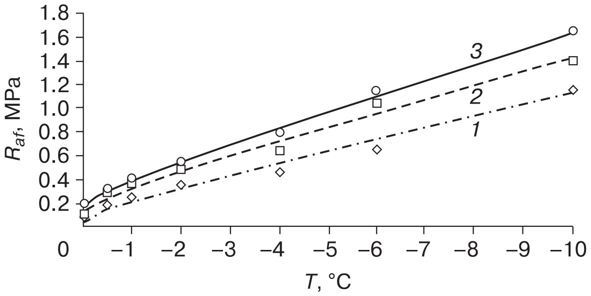

Fig. 2. Dependence of conditionally instantaneous shear strength (R_{af}) of frozen loam on test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 20\%$; (*3*) $W = 28\%$.

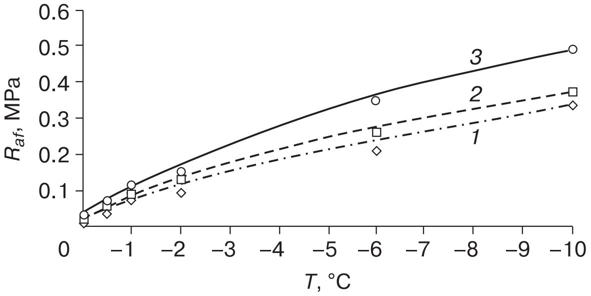

Fig. 4. Dependence of the ultimate long-term shear resistance (R_{af}) of frozen loam on a metal surface on the test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 20\%$; (*3*) $W = 28\%$.

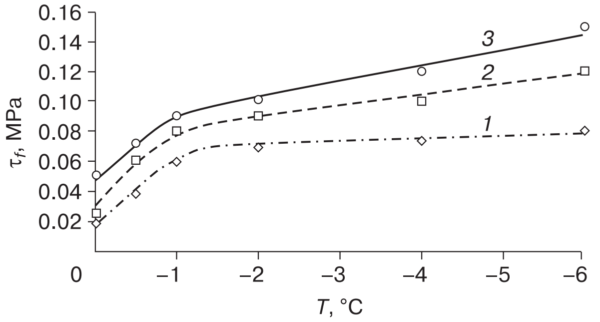

Fig. 5. Dependence of the specific tangential heaving forces (τ_f) of frozen sand on a metal surface on the test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 15\%$; (*3*) $W = 20\%$.

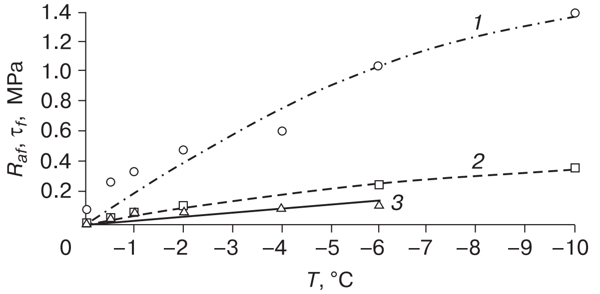

Fig. 7. Dependence of shear resistance (R_{af}) and specific tangential heaving forces (τ_f) on temperature for loam with the moisture content of 20%:

(*1*) method 1, conditionally instantaneous shear resistance; (*2*) method 2, extremely long shear resistance; (*3*) method 3, shear at a constant speed τ_f.

Dependence of the specific tangential forces of frost heaving on the temperature and moisture regimes of soils. The specific shear forces of frost heaving of the soil were estimated from the value of the stable shear resistance of the frozen soil sample relative to the model of a metal foundation moving at a constant speed.

With a decrease in the temperature of the experiment from 0 to –6°C, the values of the specific tangential heaving forces for the studied soils increased. For sandy soil, the tangential forces increased from 0.02 to 0.08 MPa at the moisture content of 10%, from 0.03 to 0.12 MPa at the moisture content of 15%, and from 0.05 to 0.15 MPa at the moisture content of 20% (Fig. 5). For loam, the specific tangential frost heaving forces increased from 0.01 to 0.12 MPa at the moisture content of 10%, from 0.02 to 0.13 MPa at the moisture content of 20%, and from 0.04 to 0.14 MPa at the moisture content of 28% (Fig. 6).

Freezing of the soil with the foundation is due to the appearance of ice-cement bonds formed as a result of freezing of water at the contact of the soil and the foundation. At high temperatures during experiments, when not all the pore water is frozen, the resistance to the shear consisted of freezing forces and adhesion forces of soil particles with the foundation material through water films; at zero temperatures, of the adhesion forces of soil particles with the foundation.

The freezing forces of sandy soil and foundations are higher than those for loamy soils because sandy soils do not have a double electrical layer around sand particles, unlike loamy soils. In addition, the size of sand particles is much larger than that of clay particles, which leads to an increase in cohesive forces.

With a decrease in soil temperature, the amount of unfrozen water decreases, and the area of freezing of soil particles with the foundation increases.

An increase in the moisture content and, accordingly, the degree of filling of soil pores with water in the sample leads to an increase in the contact area of soil particles through ice layers with the foundation and an increase in the number of bonds between particles due to an increase in the volume of ice. This circumstance leads to a general increase in the shear resistance forces of wetter soils.

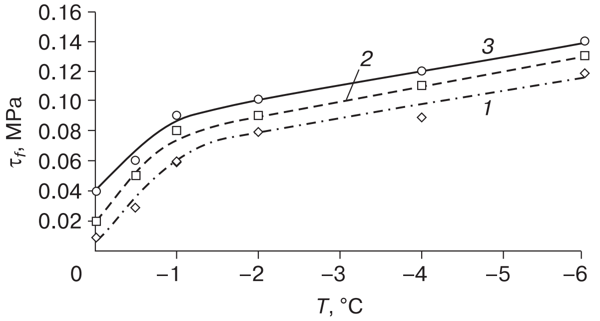

Fig. 6. Dependence of the specific tangential heaving forces (τ_f) of frozen loam on a metal surface on the test temperature and initial moisture content:

(*1*) $W = 10\%$; (*2*) $W = 20\%$; (*3*) $W = 28\%$.

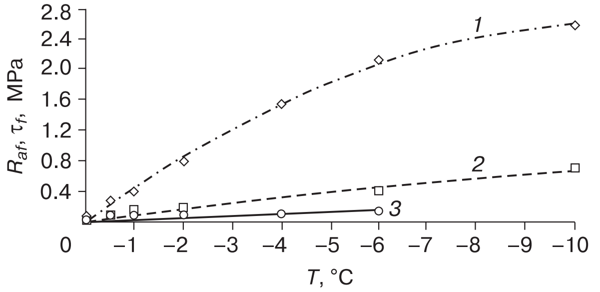

Fig. 8. Dependence of shear resistance (R_{af}) and specific tangential heaving forces (τ_f) on temperature for sand with the moisture content of 20%:

(*1*) method 1; (*2*) method 2; (*3*) method 3.

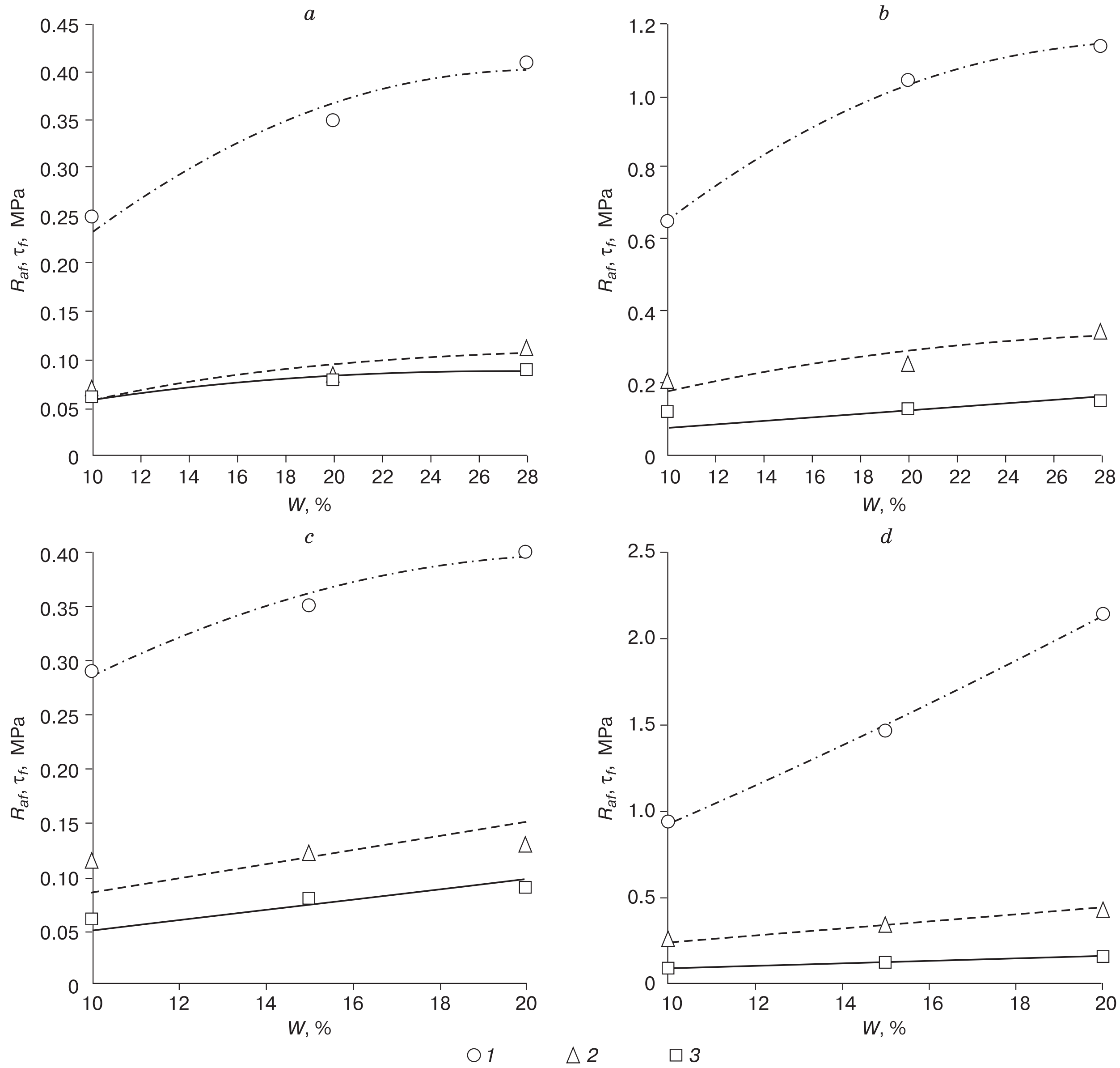

Fig. 9. Dependence of shear resistance (R_{af}) and specific tangential heaving forces (τ_f) on the moisture content (*W*):

a – loam, *T* = –1°C; *b* – loam, *T* = –6°C; *c* – sand, *T* = –1°C; *d* – sand, *T* = –6°C; (*1*) method 1; (*2*) method 2; (*3*) method 3.

When the soil is moistened, first of all, strongly bound water is formed, then loosely bound and finally free. At the moisture content of 10%, the main part of the water is in a bound state, which ensures a high content of unfrozen water in clay soil at a negative temperature. Thus, with a decrease in soil moisture, the amount of ice in the soil is significantly reduced, and, consequently, the freezing area and shear resistance decrease.

Studies have shown a similar dependence of shear resistance on temperature for all three test methods: with a decrease in soil temperature from 0 to –10°C, an increase in shear resistance takes place (Figs. 7, 8). An increase in shear resistance is also observed with an increase in the soil moisture content. Sandy soils are characterized by higher values of shear resistance than loam (Fig. 9). An increase in the moisture content of sand leads to an increase in the adhesion of sand particles (which are much larger than clay particles) and the foundation sample.

With a conditionally instantaneous shear, the shear resistance value significantly (by more than three times) exceeds the shear resistance values obtained during tests in other installations. The value of long-term shear resistance is slightly higher than the value obtained when shearing at a constant speed.

The magnitude of shear resistance or tangential heaving forces determined by methods 2 and 3 are identical in direction, but differ in magnitude by 10–40%. The shear resistance values obtained by method 2 (ultimate long shear) exceed the values obtained by method 3. The shear resistance values obtained by conventionally instantaneous shear (method 1) are significantly higher (up to five times) than the values obtained by methods 2 and 3.

The conducted studies have shown that the most reliable value of the specific tangential frost heaving forces, corresponding to the sliding friction resistance of frozen soil over the foundation material, can be determined in the installation ensuring soil shear along the foundation with a constant speed.

Determination of the specific shear forces of frost heaving by the shear method at a constant speed is typical for most cases of soil heaving during freezing near the foundation, when there is an integral increase in the depth of freezing and, as a result, in the pressure of frost heaving.

However, there are special cases, when a sharp freezing of the soil and a rapid deformation of the soil and foundation as a result of heaving are possible, especially when the freezing soil layer is in cramped conditions. These circumstances can arise with a sharp decrease in air temperature and with artificial freezing of the soil. In such cases, when the heaving pressure, which is largely characterized by the forces of crystallization of pore water during freezing, increases at a significant rate (>100 mm/day), it is recommended to determine the magnitude of the tangential frost heaving forces by conditionally instantaneous tests.

CONCLUSIONS

1. Three laboratory methods for estimating the magnitude of shear resistance equivalent to the tangential frost heaving force were selected: conditionally instantaneous tests, long-term tests with a stepped load, and shear at a constant speed.

2. Based on the results of comprehensive studies, the dependences of the shear resistance of sandy and loamy soils on the moisture content (from 10 to 28%) and temperature (from 0 to –10°C) were established: with an increase in soil moisture and a decrease in temperature, an increase in soil shear resistance occurs. The shear resistance of sandy soils is twice as high as that of loamy soils. The forces of sandy soil freezing with the foundation are higher than those of loamy soil because sandy soil does not have a double electrical layer, and the size of sand particles is much larger than the size of clay particles. With a decrease in temperature, the amount of unfrozen water decreases and the area of freezing of soil particles with the foundation increases.

3. An increase in the moisture content and the degree of filling of soil pores with water in the sample leads to an increase in the contact area of soil particles through ice layers with the foundation; in addition, with an increase in the moisture content and in the volume of ice, the number of bonds between particles increases.

4. It was determined that the resistance to conditionally instantaneous shear (speed more than 100 mm/day) is up to three times higher than the values of specific long-term shear resistance and specific shear forces of frost heaving.

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