Soil Mechanics and Foundation Engineering, Vol. 47, No. 5, 2010

EXPERIMENTAL INVESTIGATIONS

STRENGTH OF SOILS FROZEN TO PIPELINE MATERIALS

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UDC 624.139:621.643

Test results are presented for various types of soils subject to shear when frozen to the surface of materials used for the construction of oil and gas pipelines. The role of various factors in the formation of the cryogenic structure of the surface of freezing, and its effect on the development of adhesion between soils and materials is indicated.

Study of the shear strength of soils frozen to the surface of various materials is one of the most critical problems of frozen-soil mechanics. This is associated with industrial and economic exploitation of northern and northeastern regions of the country. In laying-out routes for oil and gas pipelines, it is necessary to determine the strength of soils frozen to the pipeline materials.

Shear tests of soils along the freezing surface were conducted on upper-Pleistocene-Holocene soils of various origin, which were extracted from holes on the Ural and Yamal coastlines of the Baydaratskaya Gulf, and also from a natural rock outcrop in the region of the Yamburg gas-condensate field GCF). The grain-size distribution of the soils is presented in Table 1, and their physico-mechanical characteristics in Table 2.

A device PRS built by the Scientific-Research Institute of Foundations and Underground Structures, which had been developed by A. V. Sadovskii and S. E. Gorodetskii, was used for the tests. The device possesses convenient components, is recommended by many researchers [1-3 and others], and corresponds to GOST 24586-90 [4]. Metallic forms, which ensure uniform freezing of the soil on all sides were employed to freeze the soils to the materials. The form consists of an effective ring with an area of 40 cm^2 and height of 3.5 cm, a cylindrical disk with an area of 40 cm^2 and thickness of 1.5 cm, which is fabricated from steel and concrete, and screwed-on external yokes, Steel, concrete, and the film that covers gas pipelines and had been glued onto the steel disks were used as materials frozen to the soils.

The studies were conducted with disturbed soil specimens in conformity with [4]. The predried and pulverized soil was moistened by distilled water to its corresponding in-situ moisture content, allowed to stand in a hermetically sealed container for one day, and then placed in the form. The internal surface of the effective ring of the form was preliminarily lubricated with a commercial grease to prevent its freezing to the soil. To reduce redistribution of moisture, the specimen was placed for 4 h in a refrigerated chamber at 0°C, and uniformly frozen for 5-6 h at minus 20°C, and then allowed to stand for one day in the refrigerated temperature at 0.1-0.2°C, and removed from the form and tested in the shearing device.

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 5, pp. 25-28, September-October, 2010.
0038-0741/10/4705-0197

TABLE 1

Soil and sampling location	Age and origin of soil	Grain-size distribution (%) of soil particles, 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. Peaty clayey loam (Baydaratskaya Gulf, Yamal)	*m,am*IV	0.3	2.5	87.7	5.8	1.5	0.8	1.2	0.2
2. Silty sand (Baydaratskaya Gulf, Yamal)	*lb*III-IV	1.0	1.3	70.0	27.2	0.5	–	–	–
3. Fine-grain sand (Baydaratskaya Gulf, Ural)	*m*IV	0.5	5.0	71.6	18.6	36.1	0.6	0.2	0.4
4. Sandy loam (Yamburg GCF)	*la*III-IV	–	–	2.0	75.0	11.0	–	4.0	8.0

TABLE 2

Number of soil (see Table 1)	Density ρ, g/cm^3	Moisture content W, %	Particle density ρ_s, g/cm^3	Plasticity limit, %		Plasticity index	Peat content, %	Salinity, %	Freezing point, °C
				lower	upper				
1	1.65	55	2.36	43.1	24.0	19.1	0.16	3.28	-4.5
2	1.93	23	–	–	–		–	0.05	-0.1
3	1.86	22	–	–	–		–	0.17	-0.6
4	1.93	23	2.67	26.9	21.0	5.9	–	–	-0.15

The conditionally instantaneous τ_{fs} and ultimate long-term freezing τ_∞ strengths were determined both with and without a normal load of 0.1 MPa for each type of material and temperature.

The value of τ_{fs} was determined by uniformly increasing the shear load to failure (complete separation) over a period of 20-30 sec.

To obtain τ_∞, we tested frozen soil specimens under stepwise-increasing loads to failure [4].

Results of the testing of frozen soils placed in shear along the surface of freezing with the various materials are presented in Table 3, from which it is apparent that for a drop in temperature of from −1 to −3°C, and from −3 to −10°C, the τ_{fs} and τ_∞ values for the various soils and materials increased by 50-70%. This suggests that an increase in freezing strength occurs with decreasing temperature in the region of rapid phase transitions, and is associated with a pronounced reduction in the content of unfrozen water in the soils. As the temperature continues to drop, a less robust increase in freezing strength is associated primarily with an increase in the strength of the ice-cemented bonds.

The freezing strength also depends on the type of soil. At the same temperature, the τ_{fs} and τ_∞ values for the clayey loam frozen to various materials is lower than those for the sands. Here, the freezing strength of the sandy loam is higher than that of the sands; this is explained by the different salinities of the soils.

Analysis of the influence exerted by the type of material frozen to the soils on the freezing strength indicates that the τ_{fs} and τ_∞ values increase in the order film-steel-concrete for all soils and temperatures investigated. The roughness of the surface and water receptivity of the materials increase in this same order. As indicated in [5-12], therefore, the freezing strength is largely determined by the roughness of the surface, depending on the type of material. This is associated with the fact that the overall area of the shearing surface, and the role played by the strength of the frozen soil in shear increases with increasing roughness.

The effect of the normal load on the freezing strength was determined on the sand (Yamal) and sandy loam (Yamburg GCF), which were frozen to the steel and film at −3°C. The tests were conducted both with and without the 0.1-MPa load. Moreover, the sandy-loam specimens frozen to the steel and film at −1°C were tested without the normal load; this made it possible to evaluate the effect of adhesion and friction on the development of freezing strength.

TABLE 3

Soil	Moisture content of specimens W, %	Specimen density ρ, g/cm^3	Temperature t, °C	Normal load σ, MPa	Material	Average strength, MPa	
						τ_{fs}	τ_∞
Sand (Ural)	22/22	1.85/1.86	-3	0.1	steel	0.38	0.075
	21/21	1.85/1.85			concrete	0.45	0.10
	21/22	1.86/1.86			film	0.25	0.05
	21/22	1.86/1.86	-10	0.1	steel	0.82	0.23
	22/22	1.86/1.86			concrete	1.05	0.30
	22/22	1.85/1.85			film	0.42	0.10
Sand (Yamal Peninsula)	23/23	1.94/1.94	-3	0.1	steel	0.41	0.075
	23/23	1.93/1.94			concrete	0.49	0.10
	23/23	1.94/1.94			film	0.30	0.05
	23/23	1.93/1.93		0	steel	0.21	0.025
	23/23	1.93/1.93			film	0.16	0.04
	22/22	1.94/1.93	-10	0.1	steel	1.10	0.60
	22/22	1.93/1.93			concrete	1.24	0.60
	23/23	1.93/1.94			film	0.68	0.25
Sandy loam (Yamburg)	23/23	1.94/1.94	-1	0	steel	0.30	0.019
	23/23	1.94/1.94			film	0.21	0.034
	23/23	1.93/1.93	-3	0.1	steel	0.57	0.200
	23/23	1.93/1.93			film	0.41	0.113
	22/24	1.92/1.90		0	steel	0.42	0.067
	23/23	1.90/1.93			film	0.35	0.069
Clayey loam (Yamal Peninsula)	55/55	1.65/1.65	-10	0.1	steel	0.21	0.053
	55/55	1.65/1.65			concrete	0.25	0.050
	55/55	1.65/1.65			film	0.18	0.018

Note. The values of W and ρ to the left of the line correspond to the conditional-instantaneous τ_{fs}, and those to the right of the line to the limiting long-term τ_∞ freezing strengths.

At −3°C and under the normal load of 0.1 MPa, τ_{fs} and τ_∞ were 33 and 27%, and 28 and 43% higher, respectively, for the sand and sandy loam frozen to the steel than for the same soils frozen to the film.

The strength τ_{fs} of the sand frozen to the steel at −3°C was greater by 24% than the sand frozen to the film, while τ_∞ of the sand frozen to the film was 37% higher than the sand frozen to the steel. For the sandy loam, however, the strength (adhesion) τ_{fs} when frozen to the steel was 17% higher than that when frozen to the film, while τ_∞ was 3% higher when frozen to the film than when frozen to the steel. At −1°C, τ_{fs} of the sandy loam frozen to the steel was 30% greater than when frozen to the film, while τ_∞ was greater by 44% when frozen to the film than when frozen to the steel.

Under the normal load, therefore, the strengths τ_{fs} and τ_∞ of the sand and sandy loam frozen to the steel were higher than when frozen to the film. With no normal load, their τ_{fs} values were higher when frozen to the steel than when frozen to the film, while their τ_∞ values were greater when frozen to the film than to the steel at both temperatures.

The latter fact is illogical, since the film is a material that is less water-receptive than steel. This is most likely explained by characteristic features of the formation of the cryogenic structure of the contact between the frozen soils and materials.

Microscopic observations indicated that a continuous interlayer of ice with a thickness of approximately 0.05 mm is formed over the freezing area where the frozen sand and sandy loam come in

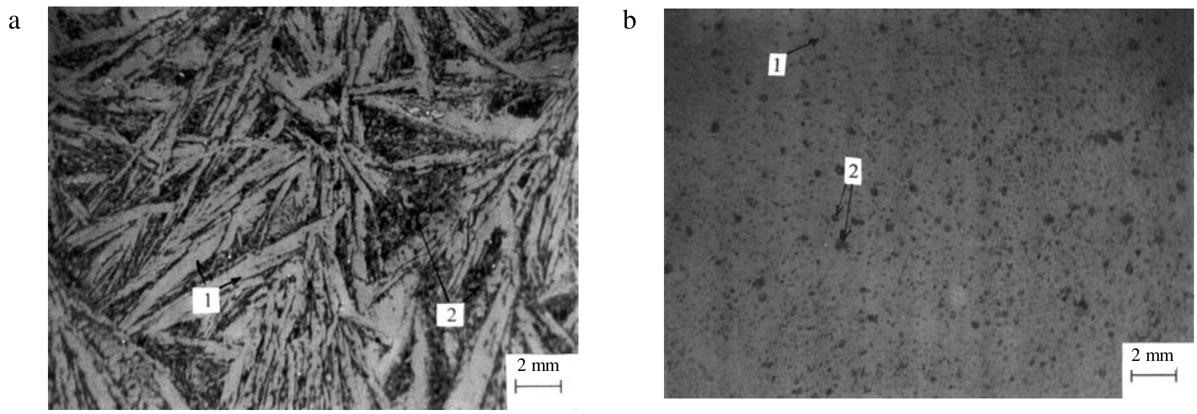

Fig. 1. Cryogenic structure of surface where sand (Yamal) is frozen to film (a) and steel (b): 1) ice; 2) soil.

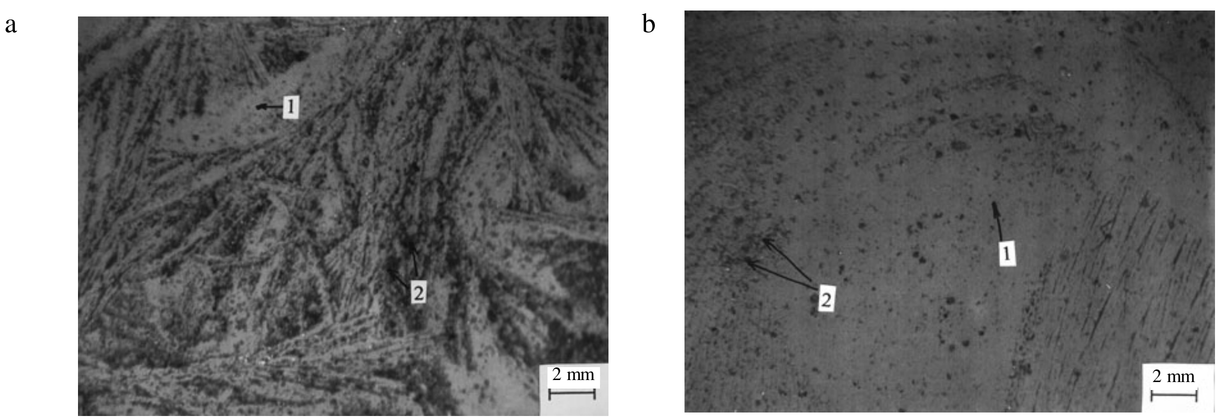

Fig. 2. Cryogenic structure of surface where sand (Yamburg) is frozen to film (a) and steel (b): 1) ice; 2) soil.

contact with the steel at −3°C (Figs. 1, a and 2, a). There is no continuous ice interlayer at the contact between the frozen soils and the less water-receptive surface of the film. The ice, which occupies approximately 50% of the freezing area, is made up of fan-shape fragments (see Figs. 1, b and 2, a). The frozen soil comes in contact with the film between the ice formations.

Studies [5-12] and others are devoted to investigation of the influence exerted by a contact interlayer of ice on freezing strength. According to data gleaned from [5, 6, 8, 11], maximum strength is confined to the continuous ice interlayer during rapid loading. If for any reasons, no ice separation occurs at the soil-material contact during freezing, or is local in nature, the freezing strength of the specimens will be lower. At the same time, a continuous contact interlayer will lower the freezing strength under a long-term shearing load due to the plastic properties of the ice [6, 10].

Thus, the various correspondence of the conventional-instantaneous and limiting long-term adhesion of the frozen soils to the steel and film is associated with the different cryogenic structure of the freezing surface when the soils are frozen to the steel and film. Under a normal load, differences in friction at the contact between the frozen soils and materials play a predominant role in the development of freezing strength.

The study was conducted with the support of Grant No. 08-05-92220 from the Russian Fund for Fundamental Research.

REFERENCES

1. *Laboratory Methods of Frozen-Soil Investigation* [in Russian], edited by E D. Ershov, Izdatel'stvo Moskovskogo Gosudarstvennogo Universiteta, Moscow (1985).
2. G. P. Mazurov, *Physico-Mechanical Properties of Frozen Soils* [in Russian], Stroiizdat, Leningrad (1975).
3. B. A. Savel'ev, *Methods of Frozen-Soil and Ice Investigation* [in Russian], Nedra, Moscow (1985).
4. *GOST 24586-90. Soils. Methods for Laboratory Determination of Strength and Deformability Characteristics of Frozen Soils* [in Russian].
5. A. V. Sadovskii, "Determination of the strength of soil frozen to concrete by the plane-shear method," *Tr. Nauchno-Issled. Inst. Osn.*, No. 3, 70-79 (1967).
6. A. V. Sadovskii, *Strength of soils frozen to foundation materials, Materials Presented at the Second International Conference on Geocryology* [in Russian], No. 7, Yakutsk (1973), pp. 210-214.
7 . I. B. Sevel'ev, Bond strength in frozen soils as a function of contact-ice structure and unfrozen water, Author's abstract of dissertation for Candidate of Technical Sciences, Moscow (1974).
8. G. L. Prazdnikova, "Formation of the contact zone between a soil and foundation surface," *Tr. Nauchno-Issled. Inst. Osn. Podzem. Sooruzh.*, No. 64, 115-124 (1974).
9. G. L. Prazdnikova, "Investigation of the contact zone of freezing between a soil and the surface a foundation," *Tr. Nauchno-Issled. Inst. Osn. Podzem. Sooruzh.*, No. 77, 138-143 (1982).
10. M. S. Vorob'ev, "Factors responsible for the shear strength of soils frozen to the lateral surface of a pile," *Tr. Polyar. Nauchno-Issled. Inst. Stroit.*, 24, 24-31 (1973).
11. S. S. Volokhov, "Effect of the surface roughness of foundation materials on their strength when frozen to soil under various conditions," *Geoekol. Inzh. Geol. Gidrogeol. Geokriol.*, No. 3, 76-81 (1993).
12. S. S. Volokhov, "Role of the contact zone between frozen soils and foundations in the development of freezing strength," *Osn., Fundam. Mekh. Gruntov*, No. 4, 26-30 (1997).