Long-term strength of frozen saline soils

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Abstract. There are many experimental methods for determining the strength of frozen soils. However, the experimental period is always much shorter than the period of infrastructure facilities operation on permafrost. Hence, one of the main tasks of the frozen soils mechanics is the development of methods for prediction of long-term strength. The aim of the research is selection of equations for long-term strength prediction of frozen saline soils. The selection is carried out based on spherical template indenter test (STI) using artificial samples of two soil types (fine sand, loam) with different salinity (from 0.07% to 1.42%), water content and temperature (-2°C, -4°C,-6°C). There were 200 experimental tests. Two approaches with 10 empirical equations and time analogy method were used for long-term strength prediction. As a result, only four equations satisfied the selection criteria and can be used for the long-term strength calculations. Our studies have shown the possibility of using the time analogy method for saline frozen soils. Calculated values of equivalent cohesion for a saline-time analogy as well as for a temperature-time analogy were within confidence interval: 90% and 80% of values respectively.

1. Introduction

Long-term strength is one of the most important and poorly understood issues of soil mechanics. Freezing of water cements ground particles and increases the strength of frozen soil in comparison with thawed one. However, ice (as an ideal rheological body) causes rheological processes in frozen soils, such as creep, a decrease in strength and relaxation of stresses in time. Therefore, an important practical task is to develop reliable methods to predict long-term strength (for the 50–100 years' service life of infrastructure) using experimental data (obtained over a short period from several hours to several days).

Studies of frozen soil strength began in the 1950s under the leadership of S.S. Vyalov [1–2]. Many researchers pursued research of how various factors influence strength [1–16]. The results of those experimental and theoretical studies made it possible to get several equations of long-term strength prediction. Long-term strength depends on many factors: grain size, mineral composition, cryogenic structure, temperature, time, salinity, confining stress, load, dynamic load, relative content of organic matter, unfrozen water content, ice content. This explains the large number of solutions suggested by many authors to predict the long-term strength of frozen soils (Table 1).

Table 1. Equations for long-term strength prediction

№	Equation	Author
1	$\sigma_t = \dfrac{\beta}{\ln\dfrac{t+t^*}{B}}$	Vyalov [1]
2	$\sigma_t = \left(\dfrac{t+1}{T}\right)^{-\alpha}$	Vyalov [17]
3	$\sigma_t = \sigma_0 - \dfrac{(\sigma_0 - \sigma_\infty)\cdot t_t}{t_t + B_t}$	Zaretsky [18]
4	$\sigma_t = \sigma_\infty + \dfrac{\delta}{T}\dfrac{(\sigma_0 - \sigma_t)\cdot t}{t - t_0}$	Fish [19]
5	$\sigma_t = \dfrac{\sigma_m}{\left(\dfrac{t}{t_m}\right)^\beta}$	Roman [20]
6	$\sigma_t = \dfrac{\sigma_0}{\left(\dfrac{t}{t_0}\right)^\beta}$	Wu [21]
7	$\sigma_t = \sigma_0 \left(\dfrac{t}{t_0}\right)^J$	Konovalov [22]
8	$\sigma_t = \sigma_0 \left(\dfrac{t_0}{t}\right)^{1/\alpha}$	Fish [19]
9	$\sigma_t = \dfrac{1}{\beta}\ln\left(\dfrac{B}{t}\right)$	Zhurkov [23]
10	$\sigma_t = \sigma_i - \dfrac{T_r}{t}(\sigma_0 - \sigma_i)$	Grechishchev [24]

Notes: σ_t is strength at moment t; σ_i is strength at moment i; σ_0 is initial strength; σ_∞ is long-term strength; σ_m is strength equal to the abscissa of the pole ln t_m; t is time; t_0 is initial time; t^* is the unit time; T_r is relaxation time; t_m is time equal to 10^{-12} s; T is absolute temperature; β, B, α, T, J, δ, B_t are experimental parameters.

Almost all equations were obtained for non-saline soils. Saline permafrost is widespread in sub-sea and coastal areas of the Arctic, where NaCl salts originate from marine deposits and/or seawater incursions [25–27]. Salinity affects strength [28–32]; therefore, an important task is to select the equations for predicting long-term strength of frozen saline soils.

Another way to predict long-term strength is the method of time analogies [20, 33–34]. The prediction of long-term strength is based on a regular relationship between the influence of time on the process of frozen soils destruction and the factors that determine the intensity of this process (temperature, some physical properties: salinity, ice content, organic content, etc.).

Long-term strength characteristics of frozen soil have been obtained from uniaxial and triaxial creep tests, spherical template indenter tests (STI). However, methodology may be different, even for the same test. For example, the uniaxial creep tests carry out different methods to determine the long-term strength of frozen soils: a series of samples of the same type under a constant but different load for each sample [17, 35]; under stepwise increasing loads [17; 36]; constant-stress creep [31]; the regime of relaxation [17, 37]. Another important issue in the processing of experimental data is the choice of the long-term strength criterion [16]. Spherical template indenter test has no such uncertainties. It has found wide application in the practice of research and engineering because of its simplicity and informativeness [15, 20]. STI test also allows determine the deformation modulus and viscosity [20, 38–41].

The aim of the research is to select equations for long-term strength prediction of frozen saline soils using spherical template indenter test.

2. Methods

2.1. Sample preparation

Two soil types were used to measure mechanical properties of saline frozen soils, each having a different grain size distribution: (Y) fine sand and (Z) loam. The individual soil grain size distribution curves are shown in Fig. 1.

The main parameter of saline frozen soils is salinity (i.e. salt content). Salinity is defined as the ratio of the mass of salt to the mass of absolutely dry soil and is expressed as a percentage (D_{sal}, %). The determination and classification of saline frozen soils are described in the Russian standard [42]. The basic method for salinity measurement is titration. We apply this approach to calculate salinity.

Initial (0.18 % – loam and 0.08 % – fine sand) and three additional salinities were studied throughout the test program. This range of salinities was selected to represent natural salinities found in the Arctic [25]. A salinity of 0.08 % represents a low salinity soil, whereas 1.42 % represents a high salinity soil. Temperatures for the tests varied between –2 °C and –6 °C, which reflects the range of ground temperatures on the Arctic coasts [25].

There are two water content values: saturated frozen (19 % – fine sand; 36 % – loam) and unsaturated frozen soils (9 % – fine sand; 20 % (plastic limit) – loam).
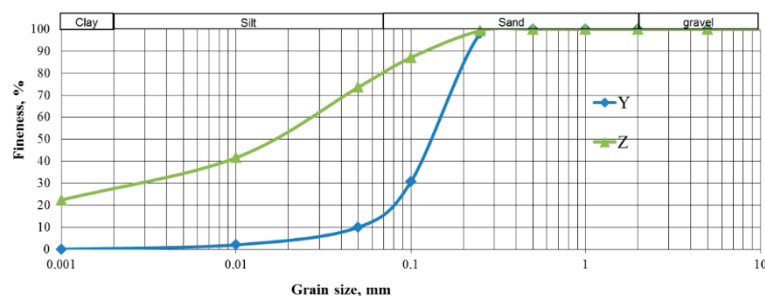

Figure 1. Grain size distribution of tested soils.

The soil was air dried prior to being mixed with water. Sand (sample Y) was sieved to eliminate any particles > 2 mm, and then submerged in a NaCl solution of the desired salinity and vibrated for 10 minutes to remove any trapped air. Soils Z were prepared by mixing each with a NaCl solution of the desired salinity until a fluid paste was obtained. Then soils were kept in the respective NaCl solution for 24 hours.

The density was set by compaction metal ring with a 7 cm diameter and 3.5 cm height. The density of each sample was determined prior to test. Salinity measurements were carried out by titration using the pore fluid extracted from the thawed samples. Water content, soil density, salinity, freezing point were determined for each test (Table 3).

Samples were subsequently frozen in a cold room at –15 °C for 24 hours to create massive cryogenic textures, to exclude the influence of the cryogenic structure on the mechanical properties. Then samples were placed in a cold room at experimental temperature for 24 hours before testing.

2.2. Spherical template indenter test

A spherical template indenter test was carried out according to Russian standard [36]. The Test program consisted of three eight-hour tests and one long-term test (prior to stabilization deformation 144–240 hours). The criteria for stabilization deformation was 0.01 mm in 24 hours.

The equivalent cohesion of frozen soil (C_{eq}) MPa is determined:

$$C_{eq} = 0.6K\frac{F}{dS_t} \tag{11}$$

where F is vertical load of spherical template indenter, d is diameter of spherical indenter, S_t is depth pressed into a sample, K is coefficient equal to 1 for long-term test.

Statistical processing of the test data was carried out according to the following algorithm. Average value C_{eqn} of the equivalent cohesion was assumed to be equal to the arithmetic mean value and was calculated from the formula

$$C_{eqn} = \frac{1}{n}\sum_{i=1}^{n} C_i, \tag{12}$$

where n is the test number; C_i are the values obtained from the results of eight-hour tests.

S is a standard deviation of the characteristic, calculated by the formula

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(C_n - C_i\right)^2}. \tag{13}$$

The coefficient of variation V of the characteristic was calculated by the formula:

$$V = \frac{S}{C_{eqn}}100. \tag{14}$$

2.3. Algorithm of calculation

The algorithm to evaluate the applicability of the long-term strength equation was as follows:

1. Data processing of eight-hour tests to obtain the parameters of the equations showed in Table 1.

2. Calculation of the long-term strength for the maximum time in the experiment and obtaining the calculated value of equivalent cohesion.

3. Calculation of confidence intervals for equivalent cohesion (based on statistical processing of eight-hour test data).

4. Comparison of the calculated values and an experimental one considering a confidence interval. The confidence interval was calculated as 3 standard deviations because the probability of deviation from the average value by more than $3S$ is very small.

5. Based on comparison, choosing the equations where the calculated values belong to the confidence interval.

6. Analysis of the relative error of equations and choosing equations with the least one.

7. Relative error between the calculated and experimental values was calculated using the formula:

$$\sigma = \frac{\left(C_{eqn} - C_{eqc}\right)}{C_{eqn}}, \tag{15}$$

where σ is the relative error, C_{eqn} is the experimental value of equivalent cohesion; C_{eqc} is the calculated value of equivalent cohesion.

Analysis of dependency on water content, soil type and salinity.

2.4. Data processing by time analogy method

Another method to predict the long-term strength is time analogy method. STI test results were processed by saline-time and temperature-time analogies.

The experimental data on the dependence of the equivalent cohesion on time for different salinity are shown in Fig. 2a.

According to the eight-hour tests data, a curve C_{eq} – ln (t) is drawn (time in seconds). All curves are similar. Therefore, the construction of the generalized "base" curve is conducted graphically, same as for thermoreologically simple bodies. The time shifts between each pair of neighboring C_{eq} – ln (t) curves are determined and their mean value is found. Then the experimental points are transferred to the adjacent graph (Fig. 2b). Values with minimal salinity are transferred to the graph without changing the coordinates. The experimental points are shifted by Δ1-2; the points of the third curve are shifted by the sum of the time shifts between curves 1-2 and 2-3: etc. As a result of this construction, we obtain a generalized curve for a long-term equivalent cohesion for the conditions of the highest salinity Fig. 2b.
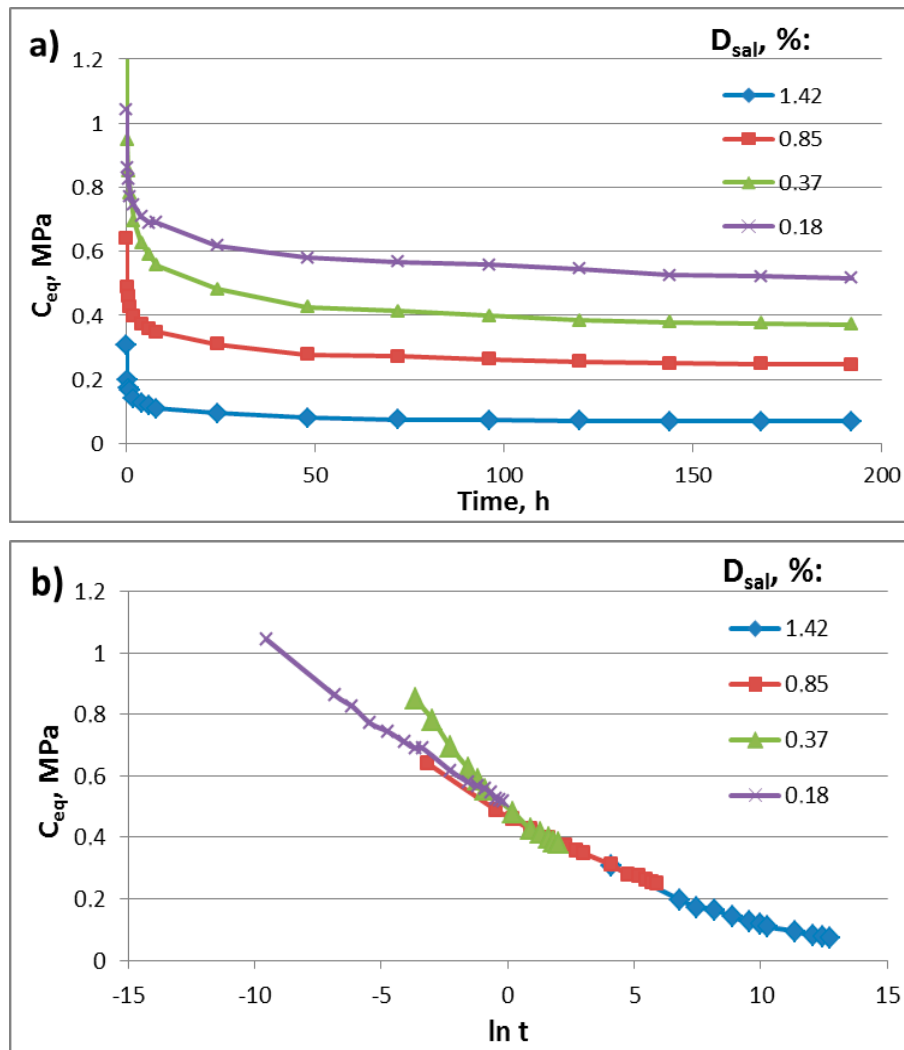

Figure 2. Test results (loam, water content = 20 %, T = –6 °C) (a) equivalent cohesion versus time for different salinity and (b) generalized curve for a long-term equivalent cohesion.

Next, we determine the dependence ln (Δ) versus $D_{sal(n)} - D_{sal(n-1)}$ and the equation, which allow to calculate the shift value for any salinity. The experimental data processing showed that the generalized curves are well approximated by equation:

$$C_{eqc} = Ae^{B\ln(t)}, \tag{16}$$

where C_{eqc} is the calculated value of equivalent cohesion; A and B are parameters that depend on the type of soil, temperature, loading mode; t is time in seconds. The values of parameters A and B are determined based on computer-analyses.

Comparison of experimental and calculated values showed good convergence of results for loam (Table 2). The same approach was used for the method of temperature-time analogy. But instead of salinity, the dependence of the equivalent cohesion on temperature was considered.

Table 2. Experimental and calculated values equivalent cohesion for loam (W = 20 %, T = –6 °C).

D_{sal}	Experimental values			Calculated values		
	t, h	C_{eqn}, MPa	A	B	C_{eqc}, MPa	
0.18	192	0.52	2.6	–0.127	0.47	
0.37	192	0.37	1.9	–0.127	0.34	
0.85	192	0.25	1.16	–0.127	0.21	
1.42	192	0.07	0.46	–0.127	0.08	

3. Results and Discussion

The results of the experiments showed that an increase in salinity led to a decrease in equivalent cohesion for all tested soils. As a result, it was found that the coefficient of variation does not exceed 15 %, and its average value is 7–9 % (Table 3).

Table 3. Results of experimental research.

Soil	Test No.	W, %	ρ, g/sm^3	T_{bf}, °C	D_{sal}, %	T = –2 C		T = –4 C		T = –6 C	
						C_{eqn}, MPa	V, %	C_{eqn}, MPa	V, %	C_{eqn}, MPa	V, %
Y	1	9	1.88	–0.34	0.08	0.36	5	0.59	13	0.70	13
	2	9	1.89	–0.64	0.16	0.20	6	0.27	9	0.39	12
	3	9	1.88	–1.28	0.38	0.02	9	0.07	2	0.18	9
	4	9	1.87	–3.90	0.76	–	–	0.04	6	0.11	5
	5	19	1.86	–0.35	0.08	0.38	8	0.80	11	0.85	9
	6	19	1.87	–0.56	0.16	0.22	12	0.53	14	0.65	15
	7	19	1.86	–1.05	0.30	0.09	14	0.17	9	0.31	6
	8	19	1.86	–3.71	0.66	–	–	0.07	13	0.15	8
Z	9	20	1.88	–0.45	0.18	0.33	9	0.42	12	0.63	11
	10	20	1.89	–0.98	0.37	0.23	6	0.39	14	0.51	13
	11	20	1.87	–1.96	0.85	0.07	11	0.24	6	0.34	12
	12	20	1.88	–3.69	1.42	–	–	0.04	12	0.12	12
	13	36	1.67	–0.39	0.18	0.47	8	0.53	13	0.61	10
	14	36	1.67	–0.88	0.35	0.43	10	0.50	13	0.58	14
	15	36	1.66	–1.85	0.78	0.19	11	0.26	13	0.48	12
	16	36	1.67	–3.44	1.33	–	–	0.08	13	0.17	10

Initially, all the data were processed and the parameters of the 10 equations (Table 1) were obtained. As a result, only four equations (1), (2), (5), (7) were selected, where calculated values of the equivalent cohesion were in the confidence interval (95 % of the calculated values). 80 % of the deviations in the calculated values of saline frozen soils strength were obtained for other formulas at a temperature of –2 °C. Frozen soils are multicomponent systems and salinity affects the content of ice, unfrozen water and mechanical properties, especially in an area of intense phase transitions.

Relative error distribution for different temperatures was calculated for the four selected formulas (Fig. 3). Test number in the Fig. 3 and 4 corresponds to "Test No." in Table 3.
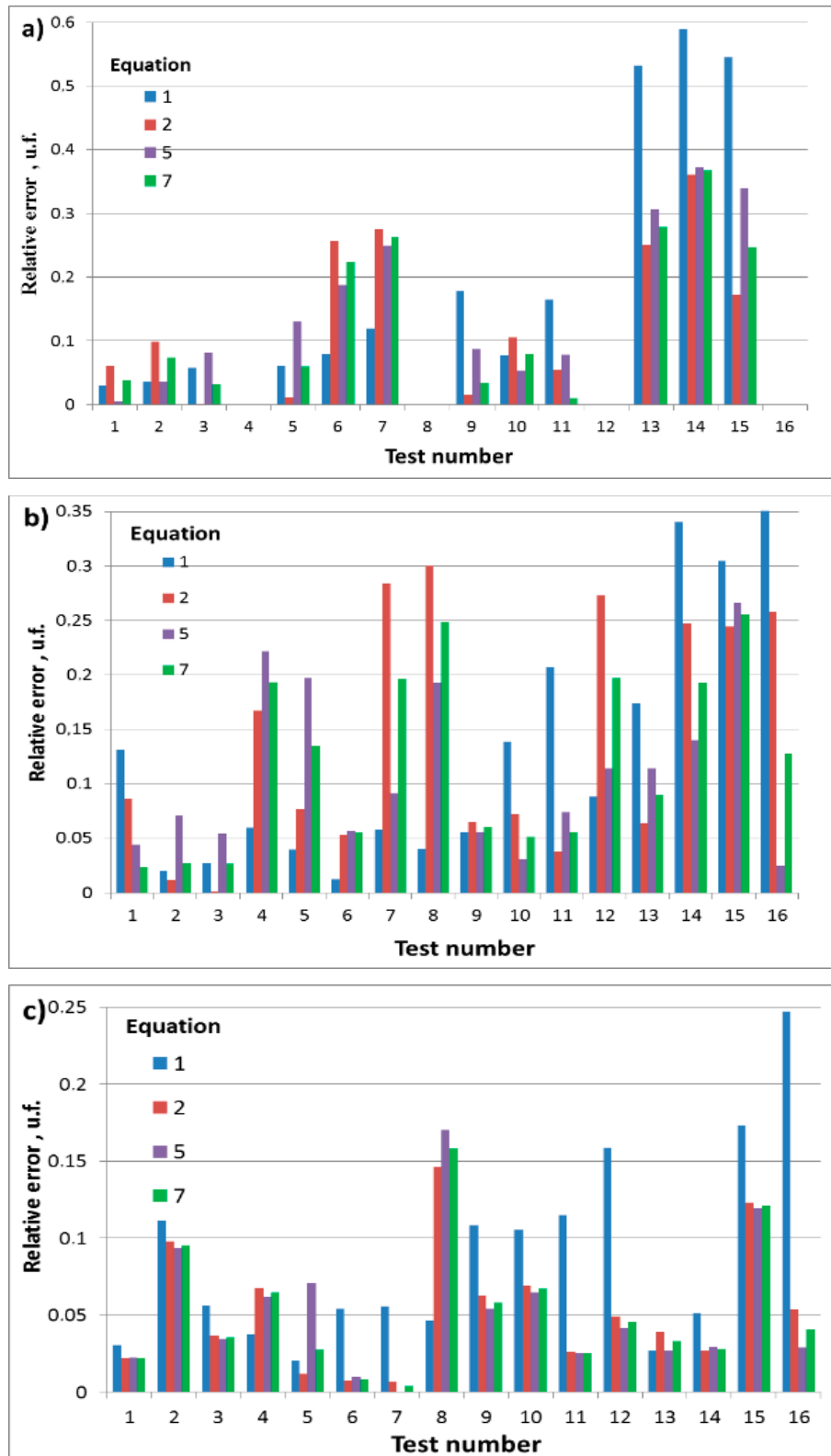

Figure 3. Histograms of distribution of relative errors for different soil types at different temperatures: a) –2 °C, b) –4 °C, c) –6 °C.

The next step was to select the minimum value of the relative error and the most accurate equation. As a result, for fine sand, the data are best approximated by equation (1). For loam, at a temperature of –2 °C, the best is the equation (2), and at temperatures –4 °C and –6 °C – the equation (5). For sandy soils, the relative error is less than in loam, which is associated with a different content of unfrozen water that significantly affects the strength properties.

The analysis of the equations applicability showed a high dependence on the temperature of the tests. Thus, the maximum values of the relative error are observed (up to 40 %) at a temperature of –2 °C, and at a temperature of –6 °C the relative error does not exceed 15 %. As the temperature decreases, the strength increases. This is caused by the reduction in the layer's thickness of unfrozen water and the increase in the ice cementations of soil particles. In addition, we can note an increase in the relative error with increasing salinity at temperatures –2 °C and –4 °C. The unfrozen water content, the thickness of the water films, and, probably, the number of the initial structural defects depend on salinity. This leads to large variations in strength values with increasing salinity.

An increase in the relative error is also obtained with increasing water content, especially at a temperature of –2 °C. Probably, the increase of water content may lead to redistribution of stresses on weak saline pore ice [10].

The long-term equivalent cohesion was calculated according to the time analogies method. As a result, 90 % of the calculated values of the equivalent cohesion for the saline time analogy and 80 % for the temperature time analogy are within the confidence interval. Fig. 4 shows the relative error values for different soil types. The distribution of errors is quite chaotic in this case.
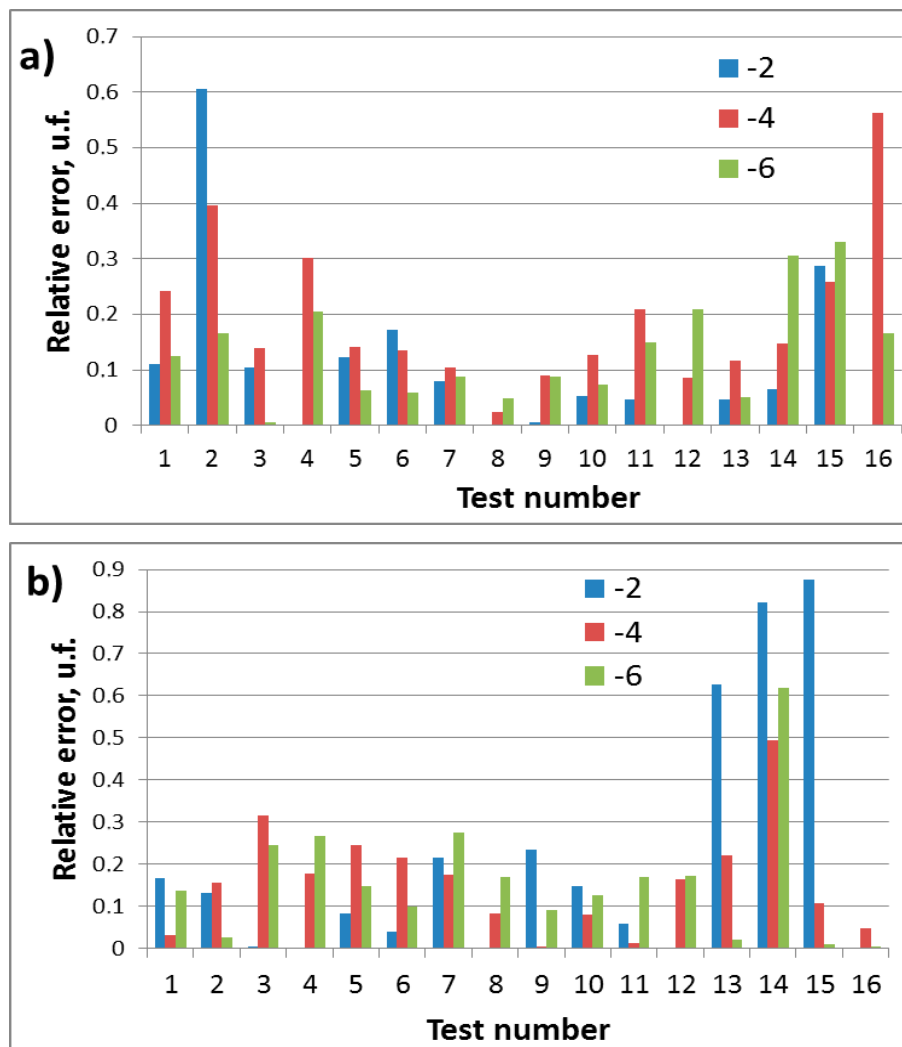

Figure 4. Histograms of distribution of relative errors for different soil types at different temperatures (°C) with: a) saline time analogy b) temperature time analogy.

Basically, the researchers performed long-term strength calculations for only one equation. Many equations were developed in the 60s and 80s for non-saline soils. Comparison of several equations was practically not carried out. The article Zhang [15] describes the comparison of three equations (1, 5, 6) for non-saline soil (Shaanxi-Fuping loess) based on the data spherical template indenter test. The calculation

results of equation (1) were larger, than the other equations (5, 6). Therefore, the author suggested using equations (5, 6).The prediction of long-term strength for frozen non-saline and saline soils was carried out for Bolshezemelnaya tundra determined by uniaxial compression and spherical template indenter test [13]. Only four equations (1, 2, 3 and 5 Table 1) were used to predict long-term strength. Based on a comparison of the experimental and calculated values of long-term strength and an assessment of the reliability of the predictive equations, the following conclusions were obtained:

- Logarithmic equation (1) and Exponential equation (5) are acceptable for all types of soils.
- Exponential equation (2) yields good results for non-saline and slightly saline soils.
- Fractional-linear equation (3) yields satisfactory results for non-saline soils.

The same results were obtained for our saline frozen soil, the equations (1) and (5) showed better convergence. There are two hypotheses about long-term strength. According to the first one, long-term strength decreases indefinitely, and long-term strength tends to zero. According to the second one, long-term strength decreases to a limited extent and the long-term strength takes on a finite value. Equations (1) and (5) refer to the first case, which was developed based on the kinetic theory of body destruction [43].

The possibility of predicting long-term strength by the time analogy method was confirmed for other types of soils under various test methods [20, 33]. The methods of time-based analogies are very prospective to predict the long-term strength of frozen soils. These methods allow to obtain values of long-term strength for the entire range of factors that reduce strength (temperature, salinity, stress). The same series of experiments makes it possible to not only obtains the values of the long-term strength for a period comparable to the service life of structures, but also to determine the regularities of temperature, salinity influence on the strength of frozen soils. Our studies have shown the possibility of using time analogy method for saline frozen soils.

Sayles [3] carried out a complex research of the long-term strength of frozen soils. The strength decreased for 1000 hours from 25 % to 5 % compared with the instantaneous value. The general character of the dependence how the strength of frozen soils depends on time is the same [44]. There are many methods for determining the strength of frozen soils: shear, triaxial and uniaxial creep test, tension test, spherical template indenter test. Curves of long-term strength in different tests are identical, as shown by Vyalov [44]. They are similar for all types of tests and differ only in numerical values. If the absolute values of strength for different types of loading are different, their relative values, equal to the ratio of strength at a given instant of time to instantaneous strength, are practically the same. This testifies of the unified physical nature of the destruction process and independence of this process from the type of stress state. Thus, the obtained regularities and equations for predicting the long-term strength of frozen saline soils can also be used in other types of tests.

4. Conclusions

The analysis of all the considered equations of long-term strength (1-10 Table 1) allows us to draw following conclusions. Only four equations (1), (2), (5), (7) were selected, where calculated values of the equivalent cohesion were in the confidence interval (95 % of the calculated values). The data are best approximated by equation (1) for fine sand, equation (2) at a temperature of –2 °C and equation (5) at temperatures –4 and –6 °C for loam.

Time analogy method is very promising for the prediction of long-term strength of frozen soils. This method helps to predict the strength with temperature and salinity change. Using of equations does not allow this. 90 % of the calculated values of equivalent cohesion for a saline-time analogy and 80 % for a temperature-time analogy were within the confidence interval when calculating the long-term strength.

Thus, geotechnics can use the proposed formulas to predict long-term strength of frozen saline soils, which will increase the accuracy of calculations. Neglecting changes in strength with time may lead to accidents of infrastructure.

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