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Evaluation of the strength parameters of clay loams during freezing–thawing cycles

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ABSTRACT: Destructuring settlements due to frost heave during the structures' exploitation are often not taken into account at the designing stage, although they are indirectly related to the bearing capacity of the soils. The objective of this research was analyzing the effect of the number of freezing–thawing cycles on the strength characteristics of soils. Tests of the clay loams with void ratio $e = 0.55$ and with various initial parameters (initial moisture content, and the number of freezing–thawing cycles) was carried out. According to the experimental results, the cohesion largely depends on the above parameters which might lead to its decrease by up to 5 or 6 times. The internal friction angle demonstrated an indefinite behavior during the freeze-thaw cycles, which is confirmed by a literature review. Changes in strength parameters of the soil during freezing–thawing cycles can lead to significantly decreasing of the soil bearing capacity. A program based on the least-squares method was used to calculate the approximation coefficients of the dependence describing the changes in strength characteristics from the abovementioned parameters. Changes in strength characteristics must be taken into account when designing structures, as they can lead to additional settlement or even subsidence of the foundations.

1 INTRODUCTION

Many scientists around the world have observed changes in soil moisture and density during freeze–thaw cycles and, accordingly, a change in bearing capacity, directly related to engineering characteristics (Wang et al. 2010, Sarsembayeva & Zhussupbekov 2021, Qi et al. 2008). Options for addressing these impacts were investigated by (Yarbaşı et al. 2007, Kalkan 2009, Ghazavi & Roustaie 2010). Russian scientists from the Soviet era, including M.N. Goldstein, A.M. Pchelintsev, E.P. Shusherina, and N.A. Tsytovich (Goldstein 1948,

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Pchelintsev 1964, Tsytovich 1973, Shusherina et al. 1970), have studied the influence of the number of freezing–thawing cycles on the mechanical properties of soils and contributed to the development of methods for strengthening base soils subject to freezing (Medvedev 2007, Kiselev 1985).

A significant part of the conducted experiment deals with road construction in areas with seasonally frozen soils, as well as problems associated with freezing–thawing of the roadway and its subgrade, such as settlement, frost heaving, and slope sliding (Ling et al., 2009; Li et al., 2016; Tebaldi et al., 2016).

Destructuring settlement and heave settlement during the exploitation of buildings and structures are not taken into account in most construction design standards, although they are indirectly related to the strength characteristics of the soil. According to (Magushev et al. 2011), the vertical deformation of foundations on a natural base is determined as the sum of four components (Equation 1): calculated settlement, elastic settlement, destructuring settlement, and heave settlement.

$$\boldsymbol{S} = \boldsymbol{S}_{\boldsymbol{comp}} + \boldsymbol{S}_{\boldsymbol{elast}} + \boldsymbol{S}_{\boldsymbol{destr}} + \boldsymbol{S}_{\boldsymbol{heave}'} \quad (1)$$

where $\boldsymbol{S}_{\boldsymbol{comp}}$ is the calculated value of the final settlement, according to regulations, which is a consequence of repacking of particles under a load, leading to soil compaction, within the compressible thickness.

$\boldsymbol{S}_{\boldsymbol{elast}}$ is settlement associated with the unloading of the excavation and the subsequent construction of the foundation and backfilling with soil.

$\boldsymbol{S}_{\boldsymbol{destr}}$ is settlement associated with destructuring of soil, for example, under the influence of heavy machinery, frost exposure, water saturation, unfavorable weather conditions, etc.

$\boldsymbol{S}_{\boldsymbol{heave}}$ is heave settlement associated with the accumulation of shear strains in the soil leading to the squeezing out of the soil from under the base of the foundation.

Destructuring settlement $S_{\mathrm{d}estr}$ and heave settlement S_{heave} are not taken into account by domestic standards (SP 22.13330.2016) and are indirectly related to the strength characteristics of soil. The change to these characteristics caused by freezing–thawing is studied in this paper.

Many geotechnical scientists have paid great attention to studying the changes caused by freezing in the cohesion and the angle of internal friction of the soil as these are the main strength characteristics. It is generally accepted that with an increase in the number of freezing–thawing cycles, cohesion decreases, but the stabilized value of cohesion after several freezing–thawing cycles remains controversial (Chang et al. 2014, Wang et al. 2005, Wang et al. 2018, Yu 2007, Liu et al. 2016, Zhang et al. 2015). However, some results show that cohesion increases or defies the obvious law when exposed to freezing–thawing (Fang et al. 2012). Studies of changes in the angle of internal friction of soil are rather contradictory: according to some studies (Wang et al. 2010, Wang et al. 2005, Yu 2007, Fang 2012), the angle of internal friction increases; according to other studies (Chang et al. 2014), it decreases or remains constant (Zhang 2015, Su et al. 2008, Dong et al. 2010). Some studies note the inconsistent nature of the change in the angle of internal friction during freezing–thawing (Wang et al. 2005, Lui et al. 2016, Wang 2012). One way or another, the obtained scientific results are difficult to apply in engineering practice unambiguously. In 2018, Wang et al. were the first to propose a mathematical equation using correction factors for calculating the shear strength of soil during freezing–thawing, which had never been considered before (Wang et al. 2018). However, the dependence is only for clays with a moisture content of 18.5%.

The purpose of this research is to analyze and to study the mathematical dependence of changes in the strength characteristics of clayey soils with different void ratios and initial moisture content due to freezing–thawing cycles.

2 MATERIALS AND METHODS

The southern area of the Tyumen region of the Russian Federation contains -clayey soils which are considered as frost-susceptible soils, resulting in severe frost heave during the winter time.

Remolded clay loam samples with the particle density 2.70 g/cm3 were compacted in accordance with the Russian State Standard GOST 30416–2012 "Soils. Laboratory testing. General" (GOST 30416-2012). The samples were compacted in four layers, with the required density and moisture content. The specimens were prepared as cylinders in metal rings of 71.5 mm in diameter and 35 mm in height. Physical characteristics of the soils are presented in Table 1.

Table 1. Physical characteristics of the soil.

No.	Designation	Indicator	Unit	Value
1	ρ_s	Density of soil particles	g/cm3	2.70
2	w_P	Plastic limit	-	0.15
3	w_L	Liquid limit	-	0.27
4	I_p	Plasticity index	-	12.1
5	e	Soil void ratio	-	0.55
6	W	Initial moisture content	%	16.5/19.5

In the experiment, two paired samples were considered for testing with varied initial settings (Table 1). Tests were conducted on loam with void ratio e = 0.55 and two different initial moisture contents (W = 16.5% and W =19.5%).

The samples were frozen at a temperature of −20 °C and thawed at 20 °C, with the freezing time and thawing time each being 12 h. The specimens were covered with sleeves during the freeze–thaw cycling to prevent the evaporation of water. The all-round freezing method with constant temperature was applied for the freeze–thaw cycle test in a closed system without a water supply. The samples were placed in metal rings without normal stress. The samples experienced different numbers of freeze-thaw cycles of 0, 1, 3, 5, 10 (Table 2).

The experiment set matrix is presented in Table 2.

Table 2. Experiment set.

Experiment No.	Void ratio, e	Moisture content W, %	Number of freeze-thaw cycles, Nc
1	0.55	16.5	0
2	0.55	16.5	1
3	0.55	16.5	3
4	0.55	16.5	5
5	0.55	16.5	10
6	0.55	19.5	0
7	0.55	19.5	1
8	0.55	19.5	3
9	0.55	19.5	5
10	0.55	19.5	10

The engineering properties of soil samples after freeze–thaw cycles were determined using a direct shear apparatus, according to GOST 12248–2010 "Soils. Laboratory methods for determining the strength and strain characteristics" (GOST 12248-2010). Four shear tests were conducted with normal stresses 100, 150, 200, and 300 kPa. After conducting experiments under each set of conditions and processing the results of the direct shear test, the data were analyzed to determine the influence of each of the studied factors (Lawson & Erjavec 2017).

3 RESULTS AND DISCUSSIONS

The results of the direct shear test for each experimental sample set are presented in Table 3.

Figure 1 shows that the angle of internal friction increases dramatically up to two times during the first freeze-thaw cycle. Further freezing-thawing up to three cycles can lead to a decrease in the angle of internal friction to the initial value or lower. In general, the character of the freeze-thaw curve is not constant. After ten freeze-thaw cycles, the characteristic either remains equal to the initial value (W=16.5%) or exceeds it by 1.5 times (W=19.5%).

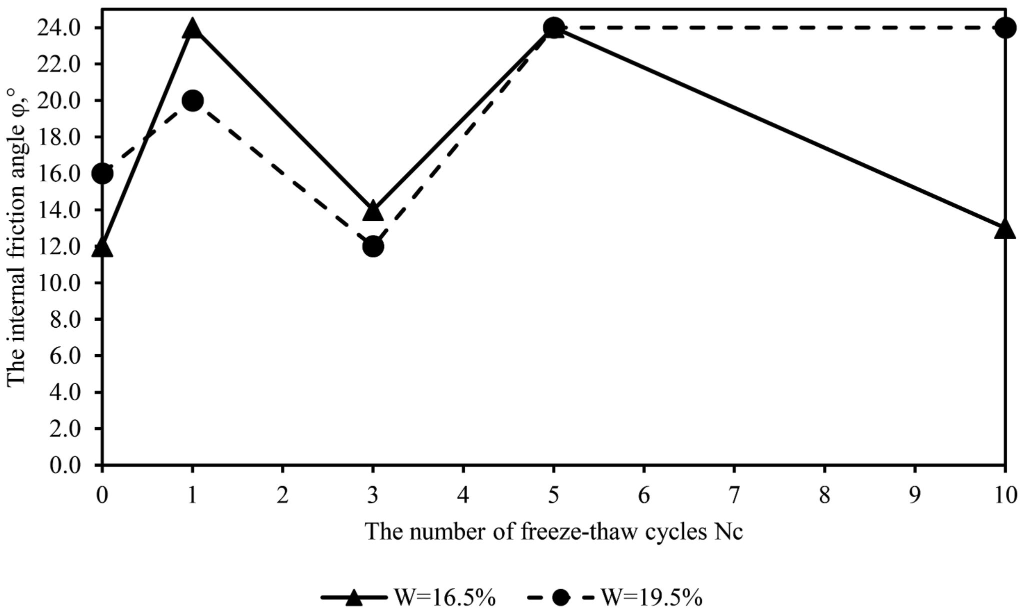

Figure 1. Dependence of the internal friction angle of the soil with e=0.55 from the number of freeze-thaw cycles.

Table 3. Direct shear test results.

Experiment No.	Void ratio, *e*	Moisture content *W*, %	Number of freeze-thaw cycles, N_c	Internal friction angle *φ*,°	Cohesion, kPa
1	0.55	16.5	0	12	39
2	0.55	16.5	1	24	22
3	0.55	16.5	3	14	41
4	0.55	16.5	5	24	6
5	0.55	16.5	10	13	28
6	0.55	19.5	0	12	39
7	0.55	19.5	1	24	22
8	0.55	19.5	3	14	41
9	0.55	19.5	5	24	6
10	0.55	19.5	10	13	28

The study have shown that the first freeze-thaw cycle leads to a decrease in the cohesion up to 44% (Figure 2). Further freezing-thawing leads to restoration of the initial value of the cohesion. However, the cohesion decreases up to 6 times after five or ten cycles of freezing-thawing.

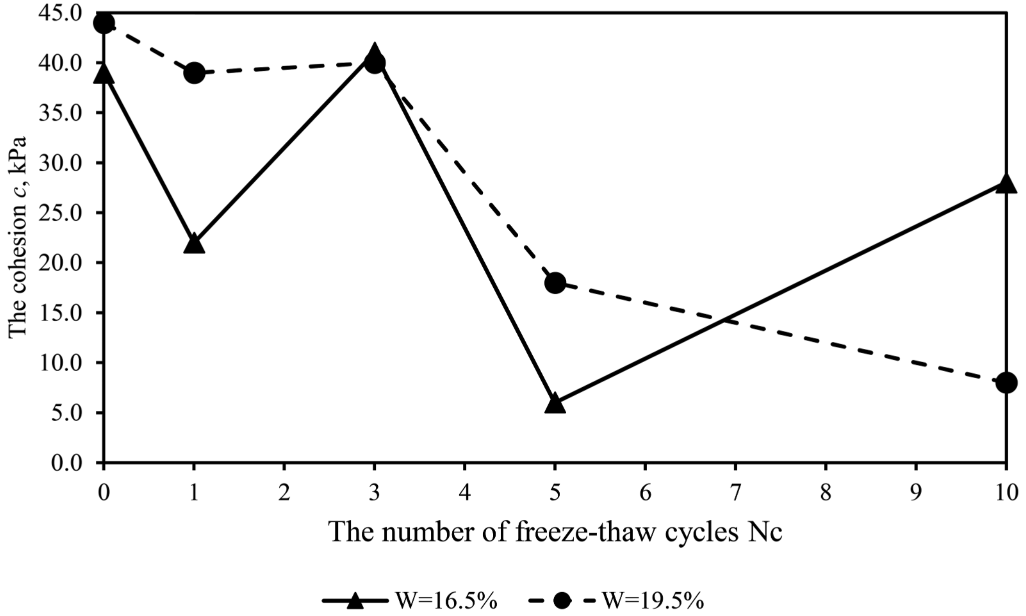

Figure 2. Dependence of the cohesion of the soil with e=0.55 from the number of freeze-thaw cycles.

4 CONCLUSIONS

In this work, a paired experiments were conducted in order to analyze the influence of the number of freezing–thawing cycles on the engineering characteristics of soil, such as angle of internal friction and cohesion. According to the results of the study, the following outcomes were highlighted:

The angle of internal friction increases dramatically up to two times during the first freeze-thaw cycle. Further freezing-thawing up to three cycles can lead to a decrease in the angle of internal friction to the initial value or lower. In general, the character of the freeze-thaw curve is not constant. After ten freeze-thaw cycles, the characteristic either remains equal to the initial value (W=16.5%) or exceeds it by 1.5 times (W=19.5%).

The first freeze-thaw cycle leads to a decrease in the cohesion up to 44%. Further freezing-thawing leads to restoration of the initial value of the cohesion. However, the cohesion decreases up to 6 times after five or ten cycles of freezing-thawing.

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