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The effect of antifreeze reagent on seasonal frozen soils

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ABSTRACT

The design, construction, and maintenance of pile foundations are dependent on special weather conditions in Northern and Central part of Kazakhstan. The winter months in these areas are very long which starts from November to March and the air temperature usually reaches – 40-50°C. These circumstances lead to the seasonal freezing ground, special physical behavior of soil, physical properties of construction materials. The main problem of pile driving in winter is frozen ground which is difficult to excavate and driving. Moreover, the Static Load Tests for estimating the bearing capacity of pile foundations do not show accurate records in frozen soil. To solve the problems mentioned above, a special antifreeze composition has been developed and established its protective effect against soil freezing in winter. The implementation of the proposed method leads to a high productivity of driving reinforced concrete piles without the risk of their destruction. This eliminates the need for additional drilling works and more powerful and expensive rock drills, if the soil is protected from freezing. According to a special formula, the optimal mass of antifreeze is calculated, which allows protecting the soil without harming not only the soil, but also the structure of the concrete pile and the environment. During the static load test, piles driven into soil that had been covered with antifreeze has showed more accurate bearing capacity data. Scientific and experimental studies have established that antifreeze reduces the compressibility of frozen soil.

Keywords: Pile foundations, Weather conditions, Thawing effect, Risk of destruction, Temperature influence.

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1. Introduction

Choosing a suitable foundation depth and protection of piles from effects of frost is very important in areas of seasonal frost, especially where there is frost– susceptible soil. According to the study [1] driving pile on frozen soil arise harmful frost actions. The lenses of ice produce forces which lead to the displacement of all parts of the foundation. Authors of the study claim that the soil should be prevented from freezing or replaced with a frost-stable material during the pile installation and designing foundation in winter [1-4]. The research conducted by H. Vazari and Y. Han [1] has noted the significant influence of a frozen layer on the dynamic response of piles even if the frozen layer is 0.5 m. Also, the results of an article [5] have proved the impact of seasonal frozen soils on the dynamic behavior of bridges supported by pile foundations in cold regions. Authors have found the interrelation between the effects of salinity and temperature which affects the unfrozen underground water that influences on the behavior of soils. The ice crystals are formed from salt ions which during the temperature decrease they influence unfrozen soils [6] The temperature of the soil has a significant effect on the strength and behavior of piles. The studies about the variation of adfreeze bond strength on frozen materials in different temperature have been shown in studies of J. Weaver and N. Morgenstern [7], and frozen materials in saline permafrost in research of Y. Velli and A. Karpunia [8]. Moreover, author of the research [9] claims that frozen ground deforms under prolonged load and shows his lateral pile analysis on frozen soil. The results of study also have presented some notable differences between warm and frozen soils in displacement, effective stiffness, and maximum moment, shear demand during the experiment on bridge columns installed in warm and seasonally frozen soils [8; 10; 11].

Authors of a research [12] have demonstrated information about the diversity and variety of frozen soil and presented approaches on how to deal with frozen soils in designing structure by summarizing the most recent studies. The purpose of the experiment is determination the effect of antifreeze reagent on soils during the pile driving. The piles were driven in three different soils where the first pile was driven at the frozen ground, the second pile was driven into the normal ground, and the third pile was installed into the soil where antifreeze reagent was applied. The subject of this study is the role of antifreeze reagent in driving piles and testing the bearing capacity of piles in winter.

2. Materials and methods

In the geotechnical laboratory of KGS-Astana, the mechanical properties of soil were determined. The territory of the site is located in Nur-Sultan city. The geological structure at the survey site includes alluvial deposits of the Middle-Upper Quaternary age aQII-III, represented by clayey soils (loam, sandy loam, clay), sands of various sizes (fine, medium, large) and gravelly sands, as well as deposits of the Paleogene system Oligocene Pg33, represented by clayey soils. All of the above deposits are covered with a soil-vegetation layer. Mineralization of groundwater is 1975 ÷ 3765 mg / l, which characterizes them as saline. The chemical composition of the water is sulfate-chloride calcium-magnesium and calcium-magnesium-sodium, the total hardness is 19.75 ÷ 46.5 mol / dm3, the waters are very hard (Figure 1).

Figure 1. Preparation of materials for scientific and experimental work: cutting the soil for testing

According to the total content of easily and moderately soluble salts, the soils that make up the survey area are non-saline. Based on the field description of the soils and the results of laboratory tests, the soils were divided into engineering-geological elements (IGE) in the stratigraphic sequence of their occurrence. The following are the elements of the soil:

– IGE-1. Topsoil – tQIV;
– IGE-2. Loam – aQII-III;

– IGE-3. Sandy loam – aQII-III;
– IGE-4. Clay – aQII-III;
– IGE-5. Fine sand – aQII-III;
– IGE-6. Sand of medium size – aQII-III;
– IGE-7. Coarse sand – aQII-III;
– IGE-8. Gravelly sand – aQII-III;
– IGE-9. Clay – Pg33.

Laboratory driving piles was conducted in three different boxes. The boxes were made from wood with dimensions of 150 (length) x 70mm (width) x 250 mm (height). The first box was filled up with soil and the second box was filled up with soil with antifreeze reagent on surface. These two boxes were put into the freezer for seven days where the temperature was -30°C. The third box was filled up with soil and kept for seven days at room temperature. The model piles were made from plastic and printed by 3D Printer. The size of piles was 10x10 mm (thickness) x 150 mm (length). The mass of each pile is 12 mg. The density of the plastic is 1.38 g/cm3. Piles were modeled from the piles with sizes 40x40 (thickness) and 600 m (length) in a ratio 1:40 (Figure 2) [5].

Figure 2. The model piles made of plastic

Method of calculation of antifreeze reagent consumption was as follows. Antifreeze reagents in Kazakhstan are usually used on roads in dealing with winter slipperiness and they are applied according to the norms of established method. It is important to determine how much antifreeze reagent should be used in order to prevent soil freezing in winter time as it affects not only soil but also environment, structure of the pile, and foundation. The calculation of the chemical reagents consumption on roads to thaw the snow and ice was considered in the work of Doctor of Technical Sciences. A. Kiyalbayev [13] and a PhD A. Sarsembayeva [14]. Authors note that the mass of the reagents can be determined by the density and thickness of the snow-ice, and melting capacity of the reagent. Based on that formula, it has been calculated the mass of antifreeze reagent for the sandy loam layer as the reagent is applied on top of the soil. In order to plot a Gibbs diagram at the university's laboratory, it has been identified the different concentration of antifreeze reagent in different temperature. The mixture of water and reagent in ratio 1:30 was in a liquid state until the -50°C, below that temperature the water in soil has started to crystallize and formed ice and salt formation. The most expressive characteristic of the salt-water system is given in Gibbs diagram below (Figure 3).

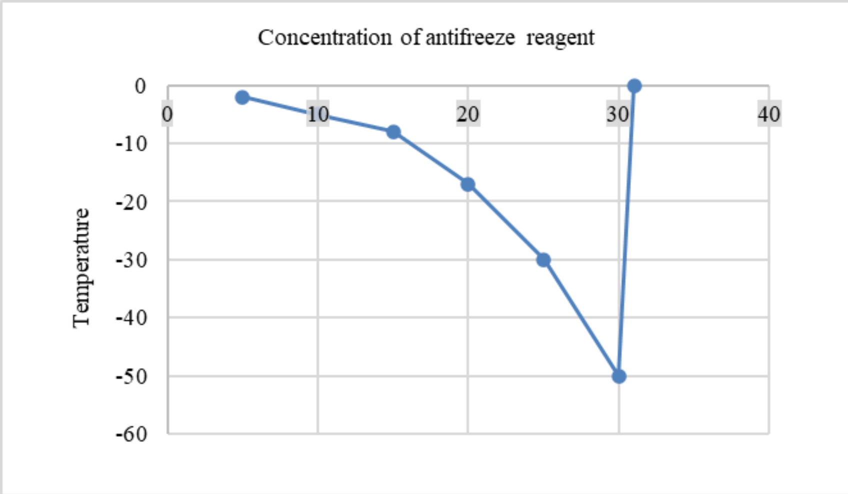

Figure 3. Gibbs diagram for antifreeze reagent

Before building the foundation of the structure, the top soil of construction site usually is subject to removing [15-33]. Consequently, the antifreeze reagent is spread on the second layer, which in this case, it is sandy loam. From the geological investigation, all the characteristics of this layer are known [34-56]. Sandy loam edQIII-IV – characterized by the following indicators of physical and mechanical properties given in Table 1.

Table 1. Physical and mechanical properties of sandy loam

No.	The name of indicators	unit of measurements	Limit values		Average (normative) values
			min	max	
1	Natural humidity	%	6.25	8.0	6.74
2	Humidity in the yield strength	%	15.5	18.0	17.0
3	Moisture at rolling limit	%	13.5	15.2	14.4
4	Plasticity number	%	1.2	4.0	2.5
5	Consistency		0.28	0.81	0.60
6	Soil density	g/cm^3	1.60	2.01	1.79
7	Density of soil particles	g/cm^3	2.35	2.80	2.59
8	Porosity coefficient	share units	0.385	0.686	0.542
9	Moisture degree	share units	0.256	0.440	0.326
10	Specific adhesion	kPa	39.6	47	44.5
11	Angle of internal friction	degree	24.2	27.0	26.4
12	Deformation modulus (compression at natural moisture)	MPa	34.5	42	39.8

According to the SNiP 23-01-99 the average temperature of coldest five days in Nur-Sultan city is -37°C. Normative frozen ground depth is 205 cm according to SP RK 2.04-01-2017. The amount of antifreeze reagent was also calculated and was taken for this temperature. Considering the prevention of the frozen ground, it is enough to protect the first 10 centimeters of the surface of the soil [57-74]. The equation for the determination of antifreeze reagent for 1m^3 of soil surface will be:

$$\rho = 1.79\ g/cm^3, \tag{1}$$

$$M_w = 0.37\ g/cm^3, \tag{2}$$

where: ρ=density of the soil; $C_{anti.r}$=concentration of antifreeze reagent; M_w=mass of water in soil; $m_{anti.r.}$=mass of antifreeze reagent. In 1m^{3}of soil, there is 37 kg of water.

$$m_{anti.r.} = \frac{C_{anti.r.} * M_{water}}{100\% - C}, \tag{3}$$

where: $C_{anti.r} = 25\%$ at the temperature $- 30°C$:

$$m_{anti.r.} = \frac{25\% * 37 \text{ kg}}{100\% - 25\%} = 12.3 \text{ kg}. \tag{4}$$

Locally for each pile with the size of 40x40, the mass of antifreeze reagent will be as follows:

$$0.4 * 0.4 = 0.16 \text{ m}^2, \tag{5}$$

$$12.3 \text{ kg} * 0.16 \text{ m}^2 = 1.79 \text{ kg}. \tag{6}$$

3. Results and discussion

The first box with antifreeze reagent has been kept and monitored for 15 days at the freezing camera. The soil was soft, so the antifreeze reagent prevented the whole soil in the box from freezing. The plastic pile was easily driven by the hummer in 13 hits. The results can be seen at the Figure 4.

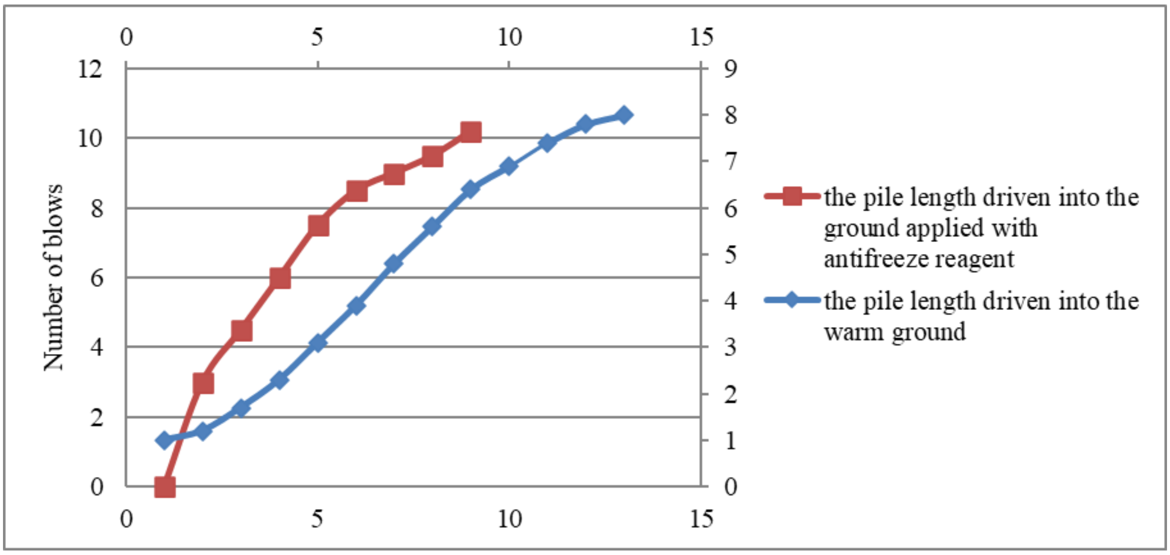

Figure 4. Depth of model pile (cm)

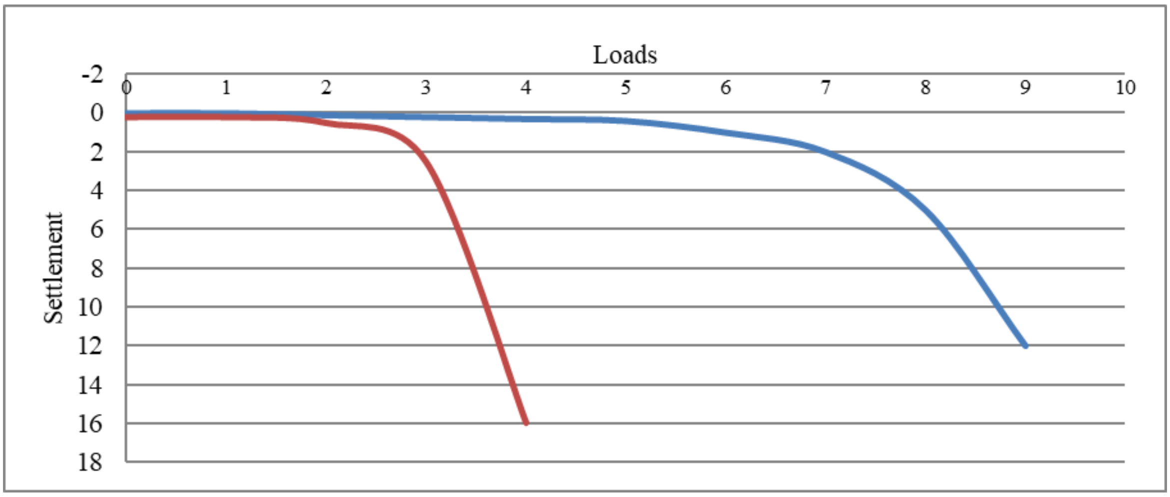

Figure 5. The results of static load test

Moreover, the piles were tested for static load test in the freezer camera under different load conditions and in constant loads (increasing in steps) (Figure 5). The ruler was used to measure the settlements of the pile. As for loads, the dumbbells were used with different weights of 1 kg, 2 kg, 4 kg, 5 kg, 6 kg, and 8 kg. The pile has started to settle from 4 kg for 0.1 mm, and at the 8 kg it was totally went into the soil. The second box which was kept at the room temperature +18°C has also been tested for static load test. The pile was fully driven in 8 hits by a hummer [75-97]. The third box which was put to freezer without an antifreeze reagent was fully frozen. The pile could not be driven after 100 hits and even after boring it for 5 cm. The head of the plastic pile was damaged by a lot of hits. The soil was thick [10]. At the construction site, the method of doing experiment a little different as the soil ground was already frozen and covered by snow. The outdoor temperature was -25°C. The antifreeze reagent was put locally in places of two piles (Figure 6). The aim of this experiment is to see the effect of antifreeze reagent whether it thaws the already frozen soil. After putting the reagent, the places of piles were constantly monitored. At the first day of experiment, it has been noticed that the snow on the surface of the soil was fully melted (Figure 7). At the third day, the depth of thawing soil reached 3 cm (Figure 8).

Figure 6. An antifreeze reagent on frozen ground

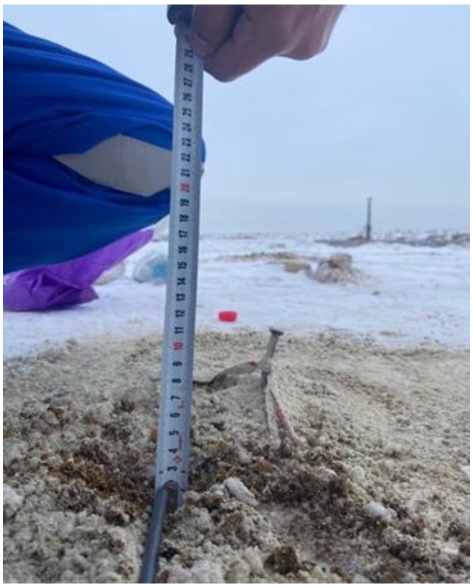

Figure 7. Measuring the thawed depth first day

Figure 8. Measuring the thawed depth third day

After 14 days the depth of thawed soil was 10 cm. Outdoor temperature was -27°C in day time, and -30°C at night. The soil ground on surface was soft and wet. It has been decided to drive one of the piles without boring in these places as there were some thawing results. Number of hits on already drilled places was 198, while on thawed ground this number was 200. The number of hits in two different methods was similar which proves the effectiveness of using antifreeze reagent even in frozen ground [98-117].

The piles have been tested for bearing capacity. These tests were carried out according to the requirements of GOST 5686-2012 "Soils. Field test methods with piles" [118]. The load on the pile was created using a 100-ton hydraulic jack "Enerpred DU100P150" with a pumping station "Enerpac P462", abutting against a test and loading stand, weighing 120.0 tons. The load was recorded with a pressure gauge up to 1000 atm (kgf / cm2) of the MA100VU100 type with a graduation rate of 20 atm (kgf / cm2) and a digital dynamometer of the "Load Cell" type connected to the SLT2 monitoring system. The settlement of each pile was measured by two 6PAO deflection meters with a scale division of 0.01 mm, and also by four digital electronic displacement transducers of the type 027DG1, 027DG2, 027DG3, 027DG4 working in conjunction with SLT2. The piles were tested with static stepwise increasing loads, the first five steps of 120 kN (80 atm), then 60 kN (40 atm) and were brought to a maximum load of 840 kN (for piles No. 62), and for piles No. 66 up to a maximum load of 960 kN. With the maximum applied load on pile No. 62 equal to 840 kN, on pile No. 66 equal to 960 kN, the displacements of the piles were 48.01 mm, 40.14 mm, respectively (Figures 9, 10).

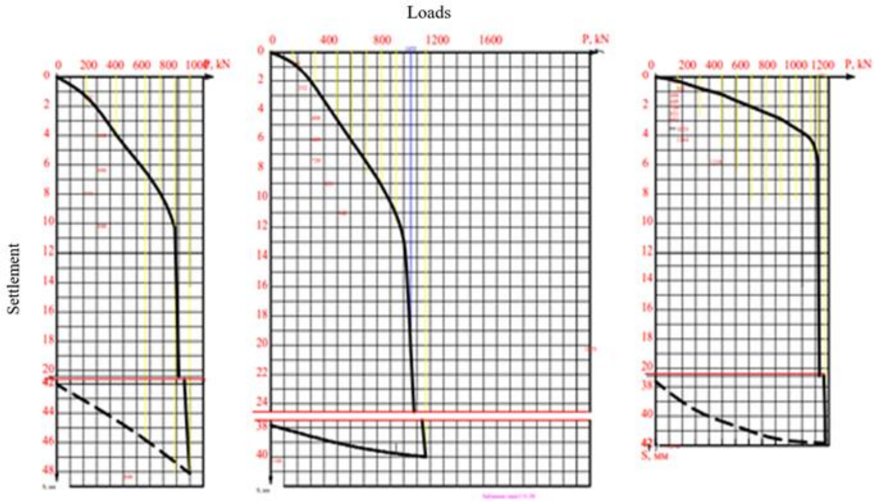

Figure 9. Results of Static Load Test: settlement of pile No. 62

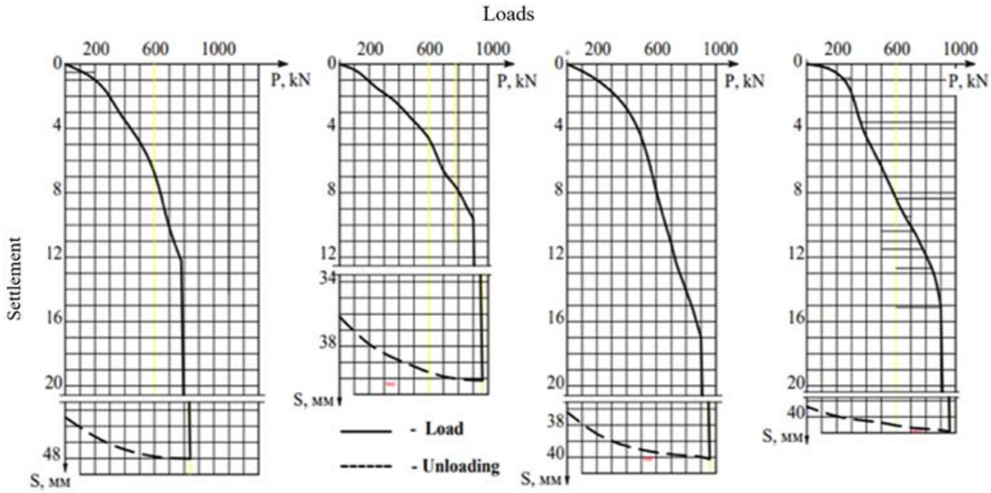

Figure 10. Results of Static Load Test: settlement of pile No. 66

Each pile was unloaded in double steps with observation of each unloading step for at least 15 minutes. After complete unloading (to zero), observation of the elastic displacements of the pile was carried out for 60 minutes, with the movement of the piles being recorded every 15 minutes. The bearing capacity of the piles, according to the results of their static load tests at the above construction site, were: 780 kN and 900 kN.

4. Conclusions

1. It has been identified the protecting effect of antifreeze reagent from soil freezing in winter.
2. Implementation of the proposed method leads to the high productivity driving of reinforced concrete piles without the risk of their destruction.
3. Moreover, there is no need on additional drilling works and more powerful and expensive hammers for driving piles if the soil has been protected from freezing.
4. The given formula of calculating the mass of antifreeze reagent can protect the soil without harming not only the soil but also the structure of concrete pile and environment.
5. The comparison of two model box tests has been proved the effectiveness of antifreeze reagent which eases the penetration of piles into the ground in winter time.
6. The thawing effect of antifreeze reagent on already frozen soils has been found out during the experiment.
7. It has been possible to test the piles for static load test in winter time as there was thawing effect from the used reagent.
8. During the static load test, piles that are driven into the soil where the antifreeze reagent was applied have shown more accurate bearing capacity data.
9. It has been identified that the antifreeze reagent decreases the compressibility of frozen soil.

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