Investigation Of Ways To Improve The Efficiency Of The Frozen Soils Bearing Capacity Of Boring Piles

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Abstract. The article is devoted to the investigation of the frozen soils bearing capacity of the lateral surface of ribbed piles. During the investigation we have revealed the problems of piles bearing capacity in the geocryological conditions of Yakutia on the basis of surveys of the technical condition of buildings and structures carried out for a few years from 2011-2018. A new method for calculating the damage to exploited buildings and structures is proposed. The ribbed piles offered by the authors in the course of laboratory studies showed higher bearing capacity compared with smooth lateral surface piles. Dependences of the change in the frozen soils bearing capacity on pitch and angle of the pile ribs are determined. A technique for calculating the frozen soils bearing capacity of the ribbed piles is proposed. The technological and strength properties of soil solutions for filling wells of ribbed boring piles have been studied.

1. Introduction

At present, the majority of buildings and structures in the permafrost zone are being constructed on boring piles with preservation of the frozen condition of the soils. A pile is lowered into a well drilled to a certain depth, and the space between the pile and the walls of the borehole is filled with a ground solution and maintained until freezing with the surrounding grounds. The load from the structure is transferred to the base soil through the lower end of the pile and its lateral surface. Specific forces of freezing of the lateral surface of the pile with the filler well are an order of magnitude less than the resistance of frozen soil to normal pressure. As a consequence, when the area of the working part of the pile's lateral surface exceeds the area of its lower end, the total load transmitted through it to the surrounding frozen soils is only several times greater than the total load transmitted through the lower end of the pile.

Thus, a significant drawback of widely used nowadays boring piles with a smooth lateral surface, supported by compressible frozen soils, is a low degree of use of the potential bearing capacity of frozen soil bases.

A kind of solution that fills the space between the lateral surface of the piles and the borehole walls plays a role in shaping the magnitude of the load transferred from the side surface of the boring piles to the surrounding frozen ground. Nowadays, the specific forces of freezing of ground solutions with the surface of ribbed (or similar) piles have not been sufficiently studied yet.

The need to improve the efficiency of using the potential bearing capacity of the frozen soils of boring friction piles and the need for additional study of the strength properties and technological characteristics of ground solutions determine the relevance of the studies performed.

2. Methods
Surveys of the technical condition of buildings and structures listed in this study were conducted in accordance with the current regulatory documents: GOST 31937-2011 "Buildings and structures. Rules for survey and monitoring of technical condition", RD 22-01.97 "Requirements for conducting safety assessment of operation of industrial buildings and structures of supervised industrial production facilities and objects (inspection of building structures by specialized organizations)". In 2013 Federal Service for Environmental, Technological and Nuclear Supervision issued an order No. 538 of 14 November 2013, according to which the conclusion of the industrial safety audit of buildings and structures additionally determines the remaining life (lifetime) of the building or structure. To determine the remaining exploitation period of the building or structure, you must first determine the physical wear. There are several approaches for estimating the remaining exploitation capacity of a building or structure. The main approaches currently in use were based on the Recommendations on the Evaluation of the Reliability of Buildings and Structures Based on External Characteristics (developed by TsNIIPROMZDANIY) and VSN 53-86 "Rules for Assessing the Physical Depreciation of Residential Buildings" (GOSGRAZHDANSTROY). P.I. Melnikov [1,2] identified seven geocryological regions of Yakutia. We surveyed buildings and structures in the three most populated geocryological regions: Central Yakutia, the mountain-folded Verkhoyansk-Kolyma region and the northern part of the Middle-Siberian plateau.

The magnitude and nature of the transfer of the load to the frozen soils of the base of ribbed piles were investigated on pile models in frozen sands at the Underground Laboratory of the Permafrost Institute SB RAS at a constant temperature of -3 ° C. The tests were carried out according to the method of step loading of piles, given in GOST 5686-2012 "Soils. Methods of field tests with piles" and used by I.N. Votyakov [3] during the testing of pile models. Models of piles were frozen in round pipes 325 mm in diameter with a wall thickness of 8 mm (Fig. 1). A smooth reinforcing bar with a diameter of 12 mm was welded to the pipe, on which a system of rods with three degrees of freedom was mounted to fix the indicator. Studies of the bearing capacity of helical piles made by domestic and foreign authors [4, 5, 6, 7, 8] showed that the geometric characteristics of pile ribs are adopted depending on the ratio of the diameter of the ribs to the magnitude of pitches (distance between ribs). Therefore, we have made models of piles with a small relative height, capable of withstanding loads from the lever presses, which are equipped with an underground laboratory. The cross-section of the models of piles is taken as round, with a diameter of 60 mm. The total length of the piles is 150 mm, the height of the ribbed part is 95 mm. Models with a constant pitch equal to \( l = d/3 \) and with an angle of inclination of the ribs 40 °, 45 °, 50 °, 55 ° and 60 ° are made to study the influence of the geometrical parameters of the ribs on the value of the transferred load in frozen soils (\( l \) is the length of the pile, \( d \) is the diameter of the pile). The other part of the piles was made with a constant angle of inclination of the edges equal to 45 °, and the pitch of the ribs equal to \( l = d/6; l = d/4; l = d/3 \) and \( l = 5d/12 \).

Fig.1. Pile model test installation

Investigations of the technological characteristics of ground solutions included studies of the temperature and duration of freezing of ground solutions, which were carried out according to the method of investigation of similar characteristics of soils. The possibility of applying this technique to
the soil was shown by Savvina A.E [9]. Freezing of solutions was carried out in a laboratory freezer “Liebherr mediline” with a minimum freezing temperature of -45 °C. Samples of solutions were frozen at -20 °C in 300 ml vessels. The freezing point was determined as the most stable, following a temperature jump from the supercooling temperature [10]. The freezing time of ground solutions was determined at a constant temperature of -3 °C. Samples of test solutions were poured into 300 ml vessels. Investigations were carried out for the main five types of solutions: calcareous-sandy with a lime content of 34%, calcareous-soil with a lime content of 34%, calcareous-soil with 25% lime, cement-sand and cement-soil.

Strength characteristics of ground solutions: resistance to shear along the surfaces of freezing with soil and pile material, determination of bearing capacity of the ribbed piles base using various types of ground solutions.

3. Results

Based on the survey results, it was revealed that the methods for estimating the physical tear and wear of a building are more applicable to estimating the value of a real estate object when calculating the volume of repair and restoration measures, but not for the purposes of a technical condition survey. When building on permafrost soils, the foundations are of the critical importance, therefore, the total physical tear and wear (or damage) of the building (or structure) should be taken as the largest of the values obtained for the base-foundation system and for the overground part of the building (or structure). On the basis of these data, we propose the following formula for the expert evaluation of the damage to an exploited building or structure:

\[ e = e^*, \text{ if } e' > e^* \]

\[ e = e', \text{ if } e^* > e' \]

where \( e' \) – damage to the overground structures of a building or structure, \( e^* \) - damage of the base-foundation system.

Then

\[ e' = \frac{\sum_{i=1}^{n} \alpha_i E_i}{\sum_{i=1}^{n} \alpha_i} \]

\[ e^* = \frac{\sum_{i=1}^{n} \alpha_i E_i^*}{\sum_{i=1}^{n} \alpha_i} \]

where \( e'_i \) - the maximum amount of damage of certain types of overground structures, \( e^*_i \) – maximum amount of damage of certain types of the base-foundation system, \( a_i \) - coefficients of significance of certain types of structures.

According to this technique, an expert assessment of the damage to buildings and structures was carried out. By results of calculations the following relations: if \( e = 0 \), if \( e = 0-0,2 \) technical condition of building or structure is assessed according to GOST 31937-2011 as "workable", if \( e = 0,2-0,6 \) – «limited able», if \( e = 0,6-1,0 \) – «emergency».

The distribution of buildings and structures by geocryological areas, which are presented in Fig. 2, is obtained. The abscissa shows the distribution of objects for damage, the ordinates - the number of objects surveyed.

Most damaged buildings and structures operated according to the I principle are built on hanging piles with a smooth lateral surface established by drilling technology, which indicates their low reliability in changing geocryological conditions, aggravated by tendencies to an increase in soil temperature and the degree of their salinity. This fact makes it necessary to introduce new constructive solutions for piles, which make it possible to increase the efficiency of using the load-carrying capacity of frozen base soils.
In my opinion, the most rational way for increasing the efficiency of using the load-bearing capacity of frozen base soils is boring piles with an uneven lateral surface. The effectiveness of this type of piles has been proved by many Russian and foreign scientists [1, 11, 12, 13, 14, 15]. There is a patent Kuzmin G P, Zhang RV, Remizov VA [16], in which a pile foundation with a ribbed lateral surface is presented, and recommendations for calculating the pile base bearing capacity are proposed. In this case, it is assumed that the soil or ground solution under the pile ribs works for compression, which is much more effective than the work of the soil or ground solution to shear along the surface of the frost with the foundation material.

To determine the base bearing capacity of ribbed piles on the basis of scientific and normative literature [17, 18, 19, 20, 21], we proposed the formula:

$$F_u = \gamma_t \gamma_c \left( RA + \sum R_{sh,i} A_{sh,i} + \sum R_{rib,i} A_{rib,i} \cos \alpha \right)$$

where $\gamma_t$ – temperature coefficient, taking into account the change in the temperature of the soils due to random changes in the outdoor temperature; $\gamma_c$ - base condition factor; $R$ – design resistance of the frozen soil under the lower end of the pile; $A$ – area of the lower end of the pile on the soil; $R_{sh,i}$ - design resistance of the frozen ground to the $i$-th layer shear; $A_{sh,i}$ – the shear surface area of the $i$-th layer; $R_{rib,i}$ – design pressure on the frozen soil under the lower edge of the $i$-th rib; $A_{rib,i}$ – support surface of the lower edge of the $i$-th edge; $\alpha$ – angle of ribs.

During the experiments, the frozen soil under the lower end of the pile was excluded from operation. Therefore, when calculating the bearing capacity of the base of the pile models, the work of the ground under the lower end of the pile was not taken into account. The experimental and calculated values of the bearing capacity of the pile models from the pitch of the ribs are shown in Fig.3.

The results of the experiments showed that with an increase in the pitch between the ribs with a constant value of the angle of inclination of the lower faces equal to 45°, the bearing capacity along the lateral surface of the experimental piles decreases (Fig.3, a). To my opinion, this was caused by a decrease in the total area of the lower edges of the ribs. The same regularity is observed for the calculated values of the bearing capacity with an increase in the relative value of the pitch of the ribs from $d / 6$ to $5d / 12$ of the diameter of the pile (25 mm), and increases at pitch $d / 2$, although at pitch $5d / 12$ and $d / 2$ (25 and 30 mm) of the area were the same. This is due to the fact that in these cases, the same soil mass is subjected to compression work, but the shear resistance of the soil acts in a certain zone near the lower edges of the ribs, as evidenced by the data given for screw piles, when the work of the soil is shifted at a pitch of blades greater than $1/3$ of the diameter of the blades is not taken into account.

Therefore, with a pitch not less than $d / 2$ (1/2 of the diameter of the pile), the work of the soil must not be taken into account for shear. The calculated values are also larger than those experienced at a pitch of 10 mm (1/6 of the diameter of the pile), which is explained by the fact that in this case, the normal stresses of adjacent ribs are superimposed, although not so much, at a pitch equal to 15 mm (1/4 of the pile diameter). Therefore, the proposed formula is fully applicable only for the pitch of the
ribs 1/4-5/12 pile diameter (15-25 mm) - in these cases there is no strong superposition of compressive stresses from adjacent ribs and, at the same time, the shearing strength of intercostal soil.

When the angle of the edges of the edges was changed from 45 to 55 degrees with their pitch \( \frac{d}{3} \) (20 mm), the design load capacity decreased from 873 to 794 kg, and the experimental load increased from 1000 to 1400 kg (Fig.3, b). An increase in the experimental value of the bearing capacity when the angle of inclination of the edges of the edges varies from 45 to 55 degrees is the result of a reduction in the application of stresses from neighboring ribs. Further increase in the angle of inclination of the edges of the edges led to a decrease in the bearing capacity, which is due to the fact that the vertical component of the transmitted load on the ground is thereby reduced. In this case, the intercostal soil shift occurs after the occurrence of the limiting state of the soil under the lower edges of the ribs. That is, with the angle of inclination of the ribs tending to 90 °, the soil works, as in the case of a smooth pile, and the strength will depend on the resistance of the soil to the shearing along the surface of the frost with the pile.

![Graphs of the dependence of the bearing capacity on the geometrical parameters of the ribs: a. When changing the pitch of the ribs; b. When changing the angle of inclination of the lower edges of the ribs](image)

**Fig.3.** Graphs of the dependence of the bearing capacity on the geometrical parameters of the ribs:
- a. When changing the pitch of the ribs;
- b. When changing the angle of inclination of the lower edges of the ribs

![Results of regression analysis of the dependence of the bearing capacity on the geometric parameters of the ribs: a. When changing the pitch of the ribs; b. When changing the angle of inclination of the lower edges of the ribs](image)

**Fig.4.** Results of regression analysis of the dependence of the bearing capacity on the geometric parameters of the ribs:
- a. When changing the pitch of the ribs;
- b. When changing the angle of inclination of the lower edges of the ribs

The proposed method for calculating the base of ribbed piles as a whole is applicable for estimating the bearing capacity with a rib spacing of 1/3-5/12 of the diameter of the piles (20-25 mm for our case) and with an angle of inclination of the edges of the edges of 45-60 degrees.

Regression analysis showed that the dependence of the load-bearing capacity on the change in the pitch of the ribs can be described by the exponential law (Fig.4, a), and the dependence of the bearing capacity on the angle of inclination of the ribs by the cubic function (Fig.4, b).
Studies of the freezing temperature of ground solutions showed that the temperature, which is closest to 0 °C, is about -0.1 °C, has a calcareous-soil solution with lime content of 25% (Fig.5.). The lowest freezing point, close to -0.4 °C, has a cement-sandy solution. With respect to the duration of freezing, all solutions differ little (40-46 hours) and only the calc-soil solution has a freezing time of 61 hours.

![Fig.5. The results of measuring the freezing temperature of ground solutions](image)

Investigation of the strengths of the freezing of ground solutions with soil and foundation material on shear devices showed that the resistance to shear along the freezing surface of ground solutions based on cement and drill cuttings is on average 31% higher than on the surface of the freezing surface with the foundation material. Shear resistance of ground solutions based on lime on the surface of freezing with soil and concrete is approximately the same.

Tests of models of ribbed boring piles in various ground solutions showed that the bearing capacity of models of ribbed piles with a ground solution based on drill cuttings and sand differ slightly (an average of 8% more).

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**Conclusion**

1. Surveys of the technical condition of buildings and structures in the geocryological conditions of Yakutia have revealed the low reliability of smooth boring piles with changing geocryological conditions. Therefore, it is necessary to introduce new constructive schemes for piles, which make it possible to increase the efficiency of the use of the base bearing capacity. The proposed method assessing the damage to buildings and structures has confirmed its applicability for the inspection of the technical condition of buildings and structures under various geocryological conditions.

2. Experimental studies of models of ribbed piles in frozen sands on static pressing loads proved that an increase of the angle of inclination of the ribs to certain values is the result of reduction in the application of stresses from adjacent ribs. Experimental values of the bearing capacity with increasing pitch are reduced, which is associated with decrease in the total area of the lower edges of the ribs. The soil resistance to shear acts in a certain zone near the ribs, is confirmed by differences in the calculated and experimental values of the bearing capacity.

3. Investigations of technological, strength characteristics of ground solutions and testing of ribbed pile models, established by drilling technology in various ground solutions, showed that ground solutions based on drill cuttings (sandy loam) with the addition of 25% lime can be used for pouring in wells for piling drilling technology.

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