Justification and selection of rational parameters of drilling piles of engineering structures (on the example of soil conditions of the Chayandinskoye oil and gas condensate field)

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Abstract. Solving the problem of rational use of building materials in the development of new fields helps to minimize ineffective consumption of applied resources. The purpose of the conducted research was to develop recommendations on the selection of rational parameters of drilling piles for engineering structures constructed on soils of the Chayandinskoye oil and gas condensate field. Bearing capacity of a base of a vertically loaded friction pile was calculated by means of existing methods. Selection of specific bearing capacity as a target parameter characterizing the efficiency of building materials and bearing capacity enabled to give a comprehensive estimate of influence of structural parameters and natural factors on bearing capacity of bored piles in a foundation soil. A complex nature of pile geometric characteristics and ground conditions’ influence on the target parameter was established during theoretical calculations. For geotechnical conditions of the Chayandinskoye oil and gas condensate field, it was established that the use of piles with a bigger diameter of 0.4-0.5 m and the length of 6 m in soils with a temperature of no more than -2.0 °C and an ice content of no more than 0.2 is rational. Practical recommendations to use the results obtained during the performed studies can reduce inefficient costs of not only material, but energy and time resources in conditions of remote industrial facilities and logistics bases.

1. Introduction
The development of new hydrocarbon fields in hard natural and climatic conditions is closely connected with installation of industrial structures taking into account geotechnical conditions. A specific feature to realize such objectives in modern economic conditions is to minimize inefficient consumption of material, energy and other resources remote from industrial facilities and logistics bases. In the implementation process of such large-scale projects as the construction of the Eastern Siberia - Pacific Ocean main oil pipeline, the Power of Siberia main gas pipeline, these tasks were repeatedly to be solved. The reasons of capital costs increase at the stage of construction of engineering structures are an extensive length of constructed facilities, a pipeline route to areas without transport and energy infrastructure.
Currently, an active development of both design and technology solutions is ongoing. That will reduce material, energy, time and other costs at the stage of preparatory work. As previously performed studies have shown, the well expansion with innovative attachments [1, 2] will provide good prospects to reduce material costs in a construction of cast-in-place piles’ foundations. The research of geometrical shapes and pile dimensions’ influence on bearing capacity of piles [3, 4], including conditions of permafrost soils [5] is under study. The possibility of more complete local mineral resources usage, which reduces dependence on supplied materials, can be achieved due to research
results of grain-size synthesis technology [6]. New design solutions with a rational usage of building materials are proposed, as well as technological methods, including those for installation of piles in permafrost soils, used on the I-st principle [7]. The study results of artificial heat-insulating additives’ effect in foundation soils will enable reduction of thermal losses for liquid hydrocarbons’ storage and transportation in Far North conditions and will prevent possible weakening of foundation soils formed by permafrost soils [8]. The research on a designed change of physical and mechanical properties of foundation soils is actively carried out [9-11].

However, it seems important to note that innovative potential of existing methods for calculation of pile foundations and their design technologies has not been fully exhausted. Obviously, their in-depth analysis will help to understand the influence of not only natural factors on bearing capacity of foundation soils, but also the influence of design parameters of building elements, their construction technologies, as well as to develop appropriate recommendations.

We suppose that understanding of regularities’ effect of certain factors on the foundation bearing capacity, combined with a wide variety of technical and technological equipment of modern construction organizations in practice will significantly expand the possibilities for rational construction of pile foundations in difficult natural climatic and geotechnical conditions.

2. Problem statement

The problem of rational use of material resources in the process of pile foundations’ construction for oil and gas industry facilities in permafrost soils’ conditions can be solved by means of integral estimate of natural and structural factors on the bearing capacity of the base of a vertically loaded friction pile.

3. Theoretical studies

A complex influence of soil conditions and geometric characteristics of vertically loaded drilling piles on bearing capacity of their base was analyzed on the example of geotechnical conditions of the Chayandinskoje oil and gas condensate field (ChOGCF). ChOGCF has complex geotechnical conditions [12]. The soils of this area are mainly permafrost loams with an ice content $i$ up to 0.4, while their temperature $T_e$ is in the range of -0.5 to -2.5 °C.

Current regulations specify two principles to use permafrost foundation soils of buildings and structures. According to the I-st principle, “permafrost foundation soils are used in a frozen state maintained during the construction and entire operating period of the structure.” According to the II-nd principle “permafrost foundation soils are used in a thawed or thawing state (with a preliminary thawing to the calculated depth before the construction of the structure or with the possibility of thawing during the operation of the structure)” [13]. In the course of survey work it has been established that earthquakes as dangerous processes of endogenous nature within the ChOGCF are possible. According to the maps of general seismic zoning, the seismicity of the ChOGCF area according to GSZ-2015-A and GSZ-2015-B maps (10 and 5% probability of exceedance) is 6 points. According to the GSZ-2015-C map (1% probability of exceedance) the seismicity is 7 points. In accordance with the recommendations of current regulations, “permafrost soils should be used on the I-st principle in case of increased seismicity of the region.” [14]. Thus, according to the current regulations, “Bearing capacity of the base $F_u$, kH, of a vertically loaded friction pile or a pier foundation is calculated by the formula” [13]:

$$F_u = \gamma_t \cdot \gamma_c \cdot \left( R \cdot A + \sum_{i=1}^{n} \left( R_{af,i} \cdot A_{af,i} \right) \right),$$

where $\gamma_t$ is a temperature factor that takes into account changes in a soil temperature; $\gamma_c$ is a base interaction factor; $R$ is a calculated resistance of frozen soil under a pile lower end or under a pier foundation base, kPa. $A$ is an area of pier foundation base or an area of pile bearing on a soil, m²; $R_{af,i}$ is a calculated resistance of a frozen soil or a soil solution to a shift on a side surface of pile freezing or a pier foundation within the $i$-th layer of soil, kPa. $A_{af,i}$ is a freezing surface area of the $i$-th layer of soil.
with a pile’s side surface, and for the pier foundation $A_{gfi}$ is a freezing surface area of soil with a lower foundation step $m^2$; $n$ is a number of permafrost soil layers defined during calculation. Since the territory is characterized by complex geological conditions, it might be possible to calculate several options of soil conditions with different soil temperature $T_e$ and its ice content $i$. As a target parameter characterizing the efficient use of building materials for a pile installation, it is proposed to choose specific bearing capacity $\Phi$, determined by the following dependence

$$\Phi = \frac{F_u}{V},$$

(2)

where $V$ is a volume of a vertically loaded friction drilling pile (referred to as a pile), $m^3$. The following initial conditions and assumptions were adopted in performing theoretical studies:

- pile diameters were assumed to be 0.1, 0.2, 0.25, 0.3, 0.35, 0.4 and 0.5 m, with their lengths ranging from 3 to 12 m;
- permafrost soils of the base were homogeneous in composition and were represented by nonsaline loams, the soil temperature in depth was constant, the soil ice content did not exceed 0.4;
- calculated values of strength characteristics of permafrost soils were taken according to reference tables [13];
- nondimensional temperature factor $\gamma_t$, taking into account changes in the temperature of foundations’ soils due to random changes in temperature of the outside air, was assumed to be equal to one $\gamma_t=1$;
- nondimensional base interaction factor $\gamma_c$ was assumed to be equal to one $\gamma_c=1$.

Calculations’ results of specific bearing capacity $\Phi$ of the pile depending on average (equivalent) soil temperature $T_e$ for various values of a pile’s diameter and length are represented graphically in Figure 1. The ice content of soil in calculations was accepted as $i<0.2$. 

![Graphs showing specific bearing capacity $\Phi$ for different pile diameters and lengths.](attachment:image.png)
Figure 1. Effect of average (equivalent) soil temperature $T_e$ on specific bearing capacity $\Phi$ of piles of various diameter and length ($i < 0.2$).

Calculations’ results of specific bearing capacity $\Phi$ of a pile depending on average (equivalent) soil temperature $T_e$ for various values of the pile’s diameter and length are shown graphically in Figure 2. The soil ice content in calculations was accepted as $0.2 \leq i < 0.4$.

Figure 2. Influence of average (equivalent) soil temperature $T_e$ on specific bearing capacity $\Phi$ of piles with a various diameter and length ($0.2 \leq i < 0.4$).

The results of calculations of specific bearing capacity $\Phi$ of the pile depending on its length for various values of its diameter are presented graphically in Figure 3. The average (equivalent) soil temperature $T_e$ in calculations assumed to be equal to -0.5 °C and -2.5 °C. The ice content in calculations was accepted as $i < 0.2$. 

Figure 3. Influence of pile length on its specific bearing capacity \( \Phi \) for various values of pile diameter and average (equivalent) soil temperature \( T_e \) \((i < 0.2)\).

The results of calculations of specific bearing capacity \( \Phi \) of piles with a length of \( l = 3 \) m and \( l = 12 \) m depending on their diameters for soil ice content \( i < 0.2 \) and \( 0.2 \leq i < 0.4 \) are shown graphically in Figure 4. The average (equivalent) soil temperature \( T_e \) in calculations was equal to -0.5 °C and -2.5 °C.

![Figure 4](image-url)

Figure 4. Influence of pile diameter on its specific bearing capacity \( \Phi \) for various pile lengths and soil ice content.

4. Study results

Performed theoretical studies clarify the degree of influence of both geometric characteristics of the pile, such as its diameter and length, and natural factors, such as soil temperature and its ice content on the bearing properties of a pile base.

As graphic data show (see Figures 1 and 2), an increase of a pile diameter always results in the increase of pile’s specific bearing capacity \( \Phi \). Thus for example, a pile diameter increase from 0.1 m to 0.5 m with the length \( l = 3 \) m, the average (equivalent) soil temperature \( T_e = -0.5 \) °C and ice content \( i < 0.2 \) results in the increase in specific bearing capacity \( \Phi \) from 2650 kN/m\(^3\) to 18250 kN/m\(^3\) or by 6.88 times. For similar soil conditions, but with a longer pile length \( l = 12 \) m, there is an increase in specific bearing capacity \( \Phi \) from 2474 kN/m\(^3\) to 13854 kN/m\(^3\) or by 5.6 times.

In the course of theoretical studies, it was found that an increase in a pile length with other conditions being equal, leads to a decrease in its specific bearing capacity \( \Phi \), mostly for piles with a larger diameter (Figure 3). For example, an increase in a pile length from \( l = 3 \) m to \( l = 12 \) m with a pile’s diameter of 0.1 m and average (equivalent) soil temperature \( T_e = -0.5 \) °C and ice content \( i < 0.2 \) results in a decrease in its specific bearing capacity \( \Phi \) from 2650 kN/m\(^3\) to 2474 kN/m\(^3\) or by 1.07 times. For a pile with 0.5 m diameter, under similar calculation conditions, there is a decrease in the specific bearing capacity \( \Phi \) from 18250 kN/m\(^3\) to 13854 kN/m\(^3\) or by 1.32 times.

For all calculated cases, it was found that a soil temperature decrease always leads to an increase in the specific bearing capacity of a pile (Figures 1 and 2). For example, a decrease in soil temperature from -0.5 °C to -2.5 °C and ice content \( i < 0.2 \) for a pile length \( l = 3 \) m and 0.1 m diameter, results in an increase in specific bearing capacity \( \Phi \) from 2650 kN/m\(^3\) to 7600 kN/m\(^3\) or by 2.87 times. There is an increase in specific bearing capacity \( \Phi \) from 18250 kN/m\(^3\) to 46000 kN/m\(^3\) or by 2.52 times for a pile’s diameter of 0.5 m. Under similar soil conditions, for a pile with \( l = 12 \) m and 0.1 m diameter, specific bearing capacity \( \Phi \) increases from 2474 kN/m\(^3\) to 7318 kN/m\(^3\) or by 2.96 times, and for a pile with 0.5 m diameter, specific bearing capacity \( \Phi \) increases from 13854 kN/m\(^3\) to 38938 kN/m\(^3\) or by 2.81 times.

As theoretical studies have shown, alteration in a soil ice content has little effect on specific bearing capacity \( \Phi \) of a pile, but this effect is stronger for shorter piles (Figure 4). Thus, for a pile \( l = 3 \) m and 0.1 m diameter, installed in a soil with temperature -0.5 °C and ice content \( i < 0.2 \), its specific bearing capacity \( \Phi \) is 2650 kN/m\(^3\). An increase in ice content to 0.4, with other calculation parameters being...
equal, leads to $\Phi$ decrease to $2567\ \text{kN/m}^3$ or by 1.03 times. For a pile of 0.5 m diameter, its bearing capacity decreases by 1.13 times - from $18250\ \text{kN/m}^3$ to $16167\ \text{kN/m}^3$. In its turn, for a pile with $l = 12\ \text{m}$ and 0.1 m diameter, installed in a soil with the temperature -0.5 °C and ice content $i < 0.2$, its specific bearing capacity $\Phi$ is 2474 $\text{kN/m}^3$. The increase in ice content to 0.4, with other calculation parameters being equal, results in a decrease of $\Phi$ to 2448 $\text{kN/m}^3$ by 1.01 times. For a pile with 0.5 m diameter, its specific bearing capacity decreases by 1.05 times i.e. from $13854\ \text{kN/m}^3$ to $13188\ \text{kN/m}^3$.

5. Conclusions

A rational use of building materials with the achievement of goal in construction operations that is providing reliability and required bearing capacity of a pile is of interest in practice of foundation construction.

The analysis of existing calculation methods of bearing capacity of bases, formed by permafrost soils for vertically loaded friction piles and technologies of their installment, from a view point of complex influence of structural parameters and natural factors on a rational use of building materials allows development of recommendations for efficient engineering solutions in specific geotechnical and natural-climatic conditions.

The effect of piles’ geometry as well as physical and mechanical properties of frozen soil on specific bearing capacity $\Phi$ was established conducting theoretical studies with a target parameter that takes into account the efficiency of using materials in installation of piles:

1) if a pile diameter increases from 0.1 to 0.5 m, the specific bearing capacity increases in the range from 5.60 to 6.88 times;

2) when a pile length increases from 3 to 12 m, the specific bearing capacity decreases in the range from 1.07 to 1.32 times

3) if a soil temperature decreases from -0.5 °C to -2.5 °C, the specific bearing capacity of piles increases in the range from 2.52 to 2.96 times;

4) a change in ice content from 0.2 to 0.4 brings to a decrease of specific bearing capacity of piles in the range from 1.01 to 1.05 times.

According to the results of studies performed in geotechnical conditions of the Chayandinskoye oil and gas condensate field, it was found that rational parameters are:

- usage of piles with increased diameter of 0.4-0.5 m and no longer than 6 m;
- installation of piles at lower temperatures not higher than -2.0 °C and with ice content of no more than 0.2.

It should be noted that the increase of piles length leads to a decrease in the efficiency of applied pile materials. A discovered significant influence of the soil temperature on the efficiency of pile materials can serve as a serious argument in favor of more active use of seasonal cooling devices in the construction of pile foundations in permafrost soils. Practical recommendations to use the results obtained during the studies will reduce inefficient costs, of not only material, but also energy and time resources in conditions of remote industrial facilities and logistics bases.

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