Effective modes of driving piles into seasonally frozen Soil

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Abstract. The disadvantage of this method is the additional costs of using drilling machines and disposal of soil, which also leads to an increase in labor costs and a decrease in work productivity. It is necessary to place an additional set of drilling equipment, an excavator and vehicles for soil removal at the construction site. The authors proposed a technology, when the piles are driven into the leader wells to the depth of the frozen soil to solve this problem. The wells are arranged by means of a thermal vibrolider, installed on the head of a pile driver, on its adjacent face with a pile hammer and moved along it with the help of guides under the cable transmission action. Thermovibrolider is made in the form of a cylindrical hollow rod with a tip, where a vibrating submer is installed. A heating coil is installed in the tip, and there are ribs along its lateral surface, used for cutting soil and breaking its solidity, but also for transferring additional heat to it, which leads to intensification of thawing processes. The presented technological solution makes it possible to increase the efficiency and reliability of the driving piles process into such soil by eliminating of pile shafts destruction during their immersion through the frozen layer, as well as reducing the values of the piles deviations in the planned position.

1. Introduction
Frozen soil is characterized by the properties of increased resistance due to free liquid freezing in it, immersing prefabricated pile elements of various manufacture, both from reinforced concrete and steel. It is known that the "instantaneous" strength of such soil is tens and even hundreds of times higher than for soil in a thawed state during pile driving. In clayey soils, this state begins at temperatures ranging from -0.5 to -5.0 °C degrees. Their shafts are destroyed due to an increase in the number of hammer blows under such conditions and with a frozen layer thickness of up to 2–3 m, driving piles in traditional modes. This problem is partially solved by increasing the strength characteristics of the pile material by increasing the concrete class to B30-B35 or by transverse piles’ reinforcement. However, this increases the cost of making piles by 30%. As experience shows, even if it is possible to immerse the pile, punching the specified soil thickness, then, the processes of the pile displacement in the planned position and its lateral sliding along the frozen soil crust during immersion with the highest strength characteristics, takes place. This leads to the piles displacements in the planned position up to 20-30 sm. Thus, the geometric centers of the piles do not coincide with the supporting structures’ axes of the walls or columns, which require either the immersion of duplicate elements or an increase in the grillages reinforcement for the perception of super-design bending moments.
In order to find optimal solutions to this problem, the authors carried out a search and analysis of literary sources.

The studies of the numerical modeling of screw piles’ design parameters, immersing in frozen soil, are presented in the works of Wang, T., Tai, B., Zang, C., Zhang, Z. (2017). The selection method of pile parameters is shown, taking into account the soil mass characteristics [1]. Screw piles have a limited bearing capacity, therefore, they are not rational to use in the construction of multi-storey buildings and structures.

In the research work of Aksenov, V.I., Gevorkin, S.G. (2007) the geometric dimensions of frozen soil local thawing zone, driving prefabricated piles, are substantiated. The work does not show how the resistance of such soil changes when the piles are immersed by various methods [2].

Gu, Q., Yang, Z., Peng, Y. (2016) presented the results of loading reinforced concrete piles immersed in frozen soil under the action of horizontal loads, including seismic effects. It is shown that the obtained results agree with sufficient accuracy with the data of mathematical modeling [3]. At the same time, issues of quality assurance of such piles during their immersion were not considered in the work.

The article of Liu, J., Wang, T., Tai, B., Lv, P. (2020) presents the results of pile foundations deformations during the soil frost heaving. A list of measures is given to reduce the swelling negative effect, when single piles are driven into the ground. At the same time, the technological parameters of pile driving have not been studied [4].

In the work of Gilev, N.G., Zenkov, E.V., Poverenniy, U.S., Dubrov, A.D., Kuzmin, D.A., Melentev, A.S., Pavlov, V.A., Berdnikov, N.N. (2019) a methodology for finding optimal and solutions for pile foundations during the construction of oil and gas production facilities on permafrost soils is presented [8]. The article discusses the technique of the technical and economic options comparison for constructing pile foundations while maintaining the base soil in a frozen state during the construction process. The method substantiation for constructing pile foundations with soil thermal stabilization systems (STS) is presented. The issues of additional costs for driving piles into frozen ground have not been studied in the article.

Zhussupbekov, A., Shin, E.C., Shakhmov, Z., Tleulenova, G. (2018) studies of the effect of various characteristics of frozen soil on the bearing capacity and settlement of the pile foundation were carried out. A brief report on laboratory tests for static load on model prefabricated reinforced concrete piles (cross section 4 × 4 cm and length 60 cm) in seasonally frozen soils is presented. The depth of the frozen soil was 10 cm, the temperature was -5 °C, -10 °C, +20 °C [9].

In the article of Tretyakova, O.V., Yushkov, B.S. (2017) the design of a bored cone pile for the foundations of transport tunnels on frozen clay soils of the Urals and Siberia are proposed. [10]. According to the authors’ research, such solutions are ineffective for the purposes of civil engineering.

Studies of the pile’s vibration penetration parameters are given in Mayrberger, T., Braun, K., Scott, W.N., Cologgi, J. (2013). The authors have developed vibration equipment moving along the mast of the drilling rig. Small diameter steel piles were immersed and then tested with static loads while monitoring the temperature field measurement in frozen soil. The effectiveness of the vibration equipment use in comparison with shock methods has been established. [11]. In another publication of Mayrberger, T., Braun, K., Scott, W.N., Cologgi, J. (2012), the authors present the results of driving steel piles into pre-drilled wells within the filling such wells with sand and water pouring [12].

In the article of Verstova V.V. (2012) the methods of driving piles and sheet piles with their vibrational deepening into the ground using various vibrotechnical means are substantiated [13]. Examples of the application of such techniques, working in frozen soils are not shown. It should be noted that the vibration method of driving reinforced concrete piles, installing a vibrator on the pile head leads to its deformations. Therefore, this method is mainly effective for driving steel piles.

Duan, Z., Wu, Y., Yan, P. (2012) present the results of substantiating the comparative efficiency of different modes of drilling piles in frozen soils [14]. It is shown that the modes of hydraulic soil extraction during well drilling are effective for the conditions of seasonally frozen soils in western Chi-
A method for the selection of drilling fluid parameters is presented, which allows minimizing the development of wellbore deformation processes.

New type of prefabricated piles proposed by Li, N., Xu, B. (2008). The authors solved the problem of piles reliable operation in the ground under the periodic cycles of freezing and thawing [15]. This is solved by arranging depressions and cavities along the surface of the pile filled with porous materials. According to the authors, such a solution will allow achieving a decrease in the gradient of temperature fluctuations in the soil. Such a decision will lead to a significant increase in costs for the manufacture of piles in the factory. It will also be difficult to ensure the quality of the backfill when it is immersed in the ground, using traditional methods.

It follows that the drilling method, when the piles are driven into previously drilled leader wells, which diameter is 1-2 sm less than the smallest cross-section of the pile, taking into account the presented analysis. Self-propelled drilling rigs equipped with augers are mainly used for drilling.

The disadvantage of this method is the additional costs for the use of drilling machines and soil disposal, which also leads to an increase in labor costs and a decrease in productivity. In addition, it is not always possible to place an additional set of drilling equipment, an excavator and a vehicle port for soil removal in the presence of cramped conditions at a construction site.

An alternative method is known with preliminary thawing of frozen soil within the immersion depth of the piles. On the territory of Russia, the method of driving piles into wells, arranged in a combined method with a steam thermal vibrolider, was actively used. The drilling rig consists of a GR-15-30 pipelayer, a PL-2A or V-401 vibratory pile driver, a thermal vibrator and a guide. Additionally, a steam generator and a power plant are introduced, which are moved by means of a tractor. The steam thermal vibrolider thaws frozen soil to the required depth with economical steam consumption and rapid freezing of piles. The maximum penetration rate is 8-40 m/h for this method [16].

The disadvantage of this method is the need for additional space to accommodate a drilling rig and a mobile container, containing a steam generator and a power plant, moved by a tractor. In addition, the use of steam generators is currently irrelevant, unproductive, such equipment is not serially produced, which calls into question its mass use [17]. Thus, this method is ineffective according to the criterion of using modern machines and equipment for work in freezing temperatures.

Thus, a practically important conclusion follows about the need for research in this area.

2. Materials and Methods

The authors proposed a new technological solution in order to ensure the effectiveness of the driving piles method into seasonally frozen soil. Previously, in the places where the piles are immersed, leader wells are arranged to the depth of the frozen soil. The wells are arranged by means of a thermal vibrolider mounted on the head of the pile driver, on its adjacent face with a pile hammer and moved along it with the help of guides with a cable transmission.

The thermal vibrolider is installed on pile driver mast, which implements pile driving, on its adjacent face with a pile hammer (Figure 1). Thermovibrolider is made in the form of a cylindrical hollow rod with a tip on one side and a rigidly connected flange on the opposite side, where a vibrating submer is installed. An adapter is located between the tip and the rod, which is rigidly fixed to the rod, and the connection with the tip is detachable. The tip of the thermovibrolider has a conical shape, in the central cavity with a heat-resistant insulator and a screw groove on the outer surface that contains a heating coil, made of wire with high resistivity. The spiral is supplied with power by means of a cable, passed through the central hole of the thermovibrolider. A heat-resistant elastic gasket is installed between insulator and adapter to prevent axial movement of the insulator. Radially directed ribs are rigidly fixed on the outer surface of the tip with internal longitudinal channels. Transverse radially located holes are made in the tip walls. The ribs serve to cut the soil mass and break its solidity, but also to transfer additional heat to it, which leads to the intensification of thawing processes. Channels and holes are required for intensive heat transfer through the walls of the tip and fins by reducing the volume of heated steel elements. The cross-section of the thermovibrolider tip can be cylindrical or multifaceted, for example square. The dimensions and number of ribs are set depending on the tip size and
the pile immersed in the ground (traditionally used dimensions are 300x300, 350x350 and 400x400 mm).

**Figure 1.** Cross-section of a pile driver with a thermovibrolider installed on its mast: 1 - pile driver mast; 2 - pile hammer; 3 - thermovibrolider; 4 – pil.
Figure 2. Thermovibrolider cross section: 1 - hollow cylindrical bar; 2 - conical tip; 3 - flange; 4 - adapter; 5 - heat-resistant insulator; 6 - heating coil; 7 - electric cable; 8 - heat-resistant elastic gasket; 9.10 - appropriately directed ribs with internal longitudinal channels; 11 - transverse radial holes.

3. Results
The authors developed a technology for driving piles into seasonally frozen soil, which makes it possible to implement the presented set of mechanization.

Previously, in the places where the piles are immersed, leader wells are arranged to the depth of the frozen soil. Before the start of the thermal vibrolider immersion, its tip together with the ribs is covered with a cover made of heat-insulating material, and the heating coil is connected to the electrical network. The heat, generated by the coil, heats the walls, fins and tip of the tip. After reaching the required degree of heating, the cover is removed and the thermovibrolider is immersed. The dive is carried out with the spiral turned on. In this case, the heat released by it is added to the heat arising from the friction of the tip against the ground, and causes it to thaw in the near-wall zone and under the tip. The size of the thawing zone depends on the released amount by the spiral and is determined by the amount of energy consumed and thermophysical properties of the developed soil. After the thermovibrolider is immersed to the required depth, equal to frozen layer thickness (up to $2–3\,\text{m}$), the thermovibrolider is removed, and to increase the thawing zone, the extraction can be performed with the spiral turned on. Thus, in the frozen soil, a well is formed with a thawed zone of soil and destroyed solidity of the walls, providing a decrease in soil resistance with further immersion of the pile. The pile is driven into the formed borehole immediately, ensuring that the borehole walls do not freeze up and
the thawed soil swells in it after removing thermal vibrator. Pile driving is performed under standard conditions typical for immersion at positive temperatures.

In order to calculate the duration of thawing and the unit costs of electricity, thawing the soil with a thermal vibroller, you should use the methodology, described in the recommendations of the Gersenov SRIBP (1982). Defrosting time in hours \( t \) is calculated by the formula:

\[
t = 1.59 R^2 \sqrt{\frac{\sigma \omega}{(a^2 P)}},
\]

where \( R \) – radius of thawing can be taken equal to the value of the pile side section plus 5 m; \( \sigma \) - latent heat of ice-water phase transition, equal to 0.093 kWh / kg; \( \omega \) – ice content in frozen ground, kg / m³; \( a \) – thermal diffusivity of thawed soil, m² / h; \( P \) – specific power of the heating element, kW / m.

The thermal diffusivity value of the soil is calculated by the formula:

\[
a = \frac{\lambda}{c},
\]

where \( \lambda \) – thermal conductivity of thawed soil, kcal / m × t × °C; \( c \) - volumetric thermal conductivity of thawed soil, kcal / m³ × °C.

The power of the electric heating element is determined by specific power of heating element and its length is determined by the formula:

\[
P = \frac{(\sigma \times \omega \times R^2)}{(0.39 \times a \times S^2)},
\]

where \( S \) – area of the thawed zone. If we take into account that thawing is performed locally within the immersed element, then expression (3) can be written as:

\[
P = \frac{(\sigma \times \omega \times R^2)}{(0.39 \times a \times \pi)},
\]

Specific electricity consumption (kWh / m³) is determined by the formula:

\[
W = P \times t \times (h + 1) / (\pi R^2),
\]

where \( h \), \( m \) - length of the electric heater, determined depending on the frozen layer depth.

Equations (1) - (5) make it possible to determine the duration of thawing and the costs, immersing a thermal vibroller within the frozen soil layer. It should be noted that the value of the leader's immersion time will be less than the value, determined by formula (1) due to its immersion in vibration mode.

Thus, the specific consumption of electricity should be determined, taking into account the experimental driving of piles at various modes of driving the thermal vibroller. This will allow you to select the optimal immersion mode at minimal cost and acceptable indicators of the pile immersion duration, taking into account their immersion within the frozen soil layer.

4. Discussion

The set of technological operations, indicated in the main part of the article, achieves an increase in the efficiency of the buildings pile foundations construction from prefabricated driven piles, immersed at negative temperatures in seasonally frozen soil by reducing costs, constructing foundations by eliminating the destruction of pile shafts when they are immersed through the frozen layer, and also reducing the values of piles deviations in the planned position, to allow increasing the speed of drilling in frozen soils.

This makes it possible to increase the efficiency and reliability of the driving piles process into such soil by eliminating the pile shafts destruction when they are immersed through the frozen layer, as well as reducing the values of the piles deviations in the planned position, to allow increasing the speed of drilling wells in frozen soils.

In addition, with an increase in the hammer weight, it is possible to drive piles without using leader holes. In this case, guide holes are arranged in the soil by means of a thermal vibrolider that form a rigid conductor in frozen soil, which makes it possible to exclude the displacement of the pile in the planned position that are observed without the use of additional measures. This makes it possible to
exclude additional costs for the construction of grillages in the form of its increasing in reinforcement, the device of monolithic broadenings, etc.

New solution makes it possible to exclude the presence of a drilling rig at the construction site and the disposal of drilled soil in contrast to the preliminary loosening of the soil with augers. In contrast to the methods of soil preliminary heating, additional costs for electrode or steam heating of the soil are excluded, which significantly increases the terms of work. The advantages of the proposed solution include its efficiency due to the combined effect of vibration and heating processes on the frozen soil. These processes are implemented in one working body - a thermal vibroller, which, in turn, can be installed on a pile driver.

5. Conclusions
The research results of issues, related to the immersion of prefabricated piles in frozen soil, which is characterized by the properties of increased resistance due to free liquid freezing, immersing pile elements are presented in the article by the author.

As a result, their destruction or displacement occurs in the planned position from the design position when the piles are immersed. Analysis of scientific publications and work experience has shown that the problem of reducing the frozen soil resistance is solved by loosening it with augers or preliminary heating with electrodes, steam, etc.

Such methods have disadvantages in the form of additional costs for the drilling machines operation and disposal of soil, which also leads to an increase in labor costs and a decrease in work productivity. Methods for preheating the soil are not very effective due to the increase in the time required for heating the soil. At the same time, subsidence of the soil surface, etc. is possible with significant areas of the heating section.

In this regard, the authors have developed a technology for driving piles into frozen soil, which includes preliminary drilling of wells with a thermal vibrator in places where piles are driven. It is installed on a pile driver mast, on its adjacent face with a pile hammer and moved along it under the cable transmission. Thermovibrolider is a barbell with a tip attached to a vibrator. Moreover, the tip is equipped with cutting ribs, a heating coil is installed inside of them, it is connected to the electrical network.

Its deepening is ensured by reducing the lateral resistance forces of the soil under vibration and heat, generated by the spiral heating the leader walls, during the operation of the thermal vibrolider. When piles are immersed in the formed wells, the destruction of their pile shafts is excluded when they are immersed through the frozen layer, as well as the decrease in the values of the piles deviations in the planned position to allow increasing the drilling speed in frozen soils.

The methodology for calculating the duration and unit consumption of electricity during thawing of soil with a thermal vibrolider is presented.

The authors see the subject development in the experimental study implementation to determine the parameters of the thermal vibrolider operation. At the first stage, it is necessary to carry out a laboratory stand, which will allow establishing the optimal parameters of its operation in the form of warming up the frozen soil and vibration impact. Thus, it is necessary to establish the optimal parameters of the well construction in the ground according to the criterion of minimum energy consumption costs.

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