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Buckling analysis of piles in solid frozen soils

V.S. Utkin, Zh.V. Kosheleva ✉, ***O.V. Yarygina***

Vologda State University, Vologda, Russian Federation

✉ *koshelevazhv@vogu35.ru*

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Abstract. The object of the research is the behavior of axial compressed piles in the foundations on continuous permafrost soils under global warming. There is a degradation of permafrost soils at present. The permafrost layer is vertically divided into two parts: 1) the top, the active layer; 2) the bottom, the frozen mass. The active layer of soil thaws in summer and freezes in winter. Frozen soil behaves as a rock in winter and as a liquid mass on some soil thickness in summer. Accordingly, the surface forces acting on the pile surface in winter time disappear in the entire melted liquid soil layer in summer time. We considered the design of a pile by the condition of the first kind buckling (form) under axial compression. We took into account the conditions when the depth of the base thawing soil increases in the upper part of the pile at the stages of operation (in the summertime of the pile operation). In addition, we considered the calculation of the pile length under the same conditions at a given load on the pile at the stage of its design. To forecast the piles operating time in pile foundations or individual piles during global warming on the Earth, an algorithm for calculating pile length at the design stage is proposed. The paper provides a numerical example of calculating the pile operational life in the solid frozen soil of the foundation in an oil pipeline support.

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1. Introduction

The object of the research is the behavior of axial compressed piles in the foundations of solid permafrost soil under the conditions of global warming on the Earth. Permafrost soils are also present in the northern regions of Russia. In the summer, there is a gradual transformation of the upper layer of permafrost into a fluid state (liquid soil). During winter periods, this layer of liquid soil remains at some increasing depth under the upper freezing layer. Therefore, it is required to develop a theory for calculating the piles bearing capacity in longitudinal bending with the time identification of buckling onset from compressive load in the operational stage. In addition, it is required to develop a method of determining the effective length of the pile at the design stage according to the same criterion of longitudinal stability at a design load.

The relevance of the study lies in the fact that the volumes of extraction, processing and use of mineral resources and energy sources are expanding in the northern regions of Russia. Pile foundations are used for the construction of buildings, gas and oil pipelines in these conditions of permafrost soils. Such pile foundations have been in operation for several decades. The development of infrastructure in the regions of the Arctic and Siberia (Russia) in the coming years was indicated by President Vladimir V. Putin in a Message on February 21, 2023. There is no information on the design of piles in the normative regulations SP 25.13330.2020 "Soil bases and foundations on permafrost soils", SP 410.1325800.2018 "Main and field pipelines for oil and gas, construction in permafrost conditions and control of works" and other sources, in the conditions noted above. All the above increases the importance of the presented article.

The design, construction and operation of foundations in areas of permafrost are very difficult tasks. The correct solution of this problem is possible only if the processes taking place in the active layer and the permafrost layer are taken into account. The active layer is the layer in which the soil freezes and thaws. If the nature of these processes is taken into account incorrectly in the design, then unacceptable deformations often occur in buildings and structures. Sometimes this fact is the reason for accidents and emergencies. Examples are the disasters during the construction of the railway to Vorkuta (Russia) and the recent failure of buildings in the city [1–14].

Permafrost is located at least 25 % of the entire land area of the globe. Huge massifs of permafrost are located in the northern part of the Eurasian continent, in the northern territories of Canada, Alaska, Greenland, on the islands of the Arctic Ocean, in Antarctica. The thickness of the frozen soil layer varies from a few tens of centimeters to a kilometer and more. For example, the largest recorded depth according to information sources is about 1500 m, and it is located in Yakutia (Russia) [11].

There is a degradation of permafrost soils at present. It is caused by global warming and anthropogenic influences (heat loss of buildings, waterlogging and flooding of areas, errors in the construction and maintenance of urban infrastructure, salinization of soils). As a result, there is a reduction in the area of permafrost soils, an increase in their temperature and a deepening of the active layer of soil. All the above leads to decrease of soil bearing capacity and loss of stability of buildings and structures with possible catastrophic and other consequences. One such disaster occurred in Norilsk (Russia) at CHP-3 in May 2020. A massive diesel fuel leakage and subsequent catastrophic contamination of nearby rivers and lakes occurred due to sagging foundations and oil tank supports. In the Taimyr Telegraph online publication, Mikhail Korolev, deputy director of the Institute of Applied Mechanics of the Russian Academy of Sciences, head of the geomechanics laboratory and head of the applied geomechanics department at National Research Moscow State University of Civil Engineering, noted that the permafrost area is rapidly shrinking, the depth of seasonal thawing and freezing is changing, the temperature of frozen ground has risen from –6 °C to –2.5 °C, and temperature changes of even one degree often lead to a 50 percent loss in bearing capacity of piles [15].

More than 300 buildings in Yakutsk (Russia) have been seriously damaged due to subsidence of frozen soil in the last 30 years according to the studies given in [16–23]. In 1992, the percentage of damaged buildings was 10 % in Norilsk (Russia), 22 % in Tiksi (Russia), 35 % in Dudinka (Russia), 50 % in Pevek (Russia) and Amderma (Russia), 55 % in Magadan (Russia), 60 % in Chita (Russia) and 80 % in Vorkuta (Russia). Unfortunately, by 1999, the number of structures damaged due to uneven foundation subsidence increased in Norilsk by 42 %, in Yakutsk by 61 %, and in Amderma by 90 % compared to the previous decade. The Taimyr Telegraph online publication notes that in 2009 in Norilsk a quarter of the housing stock is under special control for the condition of soils and supporting structures, and every year one or two houses are declared uninhabitable due to foundation deformation [15].

The need to develop the method for calculating piles under the above-described conditions is due to the lack of calculation methods in the normative regulations SP 25.13330.2020 "Soil bases and foundations on permafrost soils" and in other documents. In addition, the reason for the study is the presence of areas with solid frozen soils in the Russian Federation and the inevitable global warming of the Earth.

The purpose of the research is to develop methods for calculating the safe operating time of piles in the foundations of existing buildings and the length of piles in pile foundations during the design phase under conditions of global warming on Earth. The piles are under axial compression conditions in solid-frozen soil bases. The criterion of pile stability (form) under longitudinal bending is considered.

2. Methods

Permafrost in Russia occupies large areas in the European territory and especially in Siberia. The permafrost layer is vertically divided into two parts: 1) the top, the active layer; 2) the bottom, the frozen mass. The active layer of soil thaws in summer and freezes in winter. The thickness of this layer varies in Russia and varies from a fraction of a meter up to four or more meters [24]. It is possible to say that the thickness of thawing layer of soil can reach significant dimensions after 50–100 years of building exploitation in permafrost conditions, according to existing forecasts. The thickness of the layer is not known in advance. Thus, in order to avoid accidents, it is necessary to study and develop preventive measures nowadays. For example, it is necessary to measure the thickness of thawed ground at different time intervals. Then extrapolate the thickness limit to the planned lifetime of the pile from the data obtained. The pile length and its bending stability must be taken into account. It is also necessary to determine the pile length in the design phase with regard to the pile's service life.

There are two types of active layer of soil: merging and nonmerging. In the first case, the active layer freezes completely in winter and joins the permafrost. In the second case, a layer of thawed ground (suprapermafrost groundwater) remains between the upper permafrost layer and the permafrost strata in winter time. In the second case, in summer time, the top soil layer thaws and a common active thawed layer is formed with the suprapermafrost groundwater. This layer affects the lower frozen ground, partially transforming it into a fluid state. Over time, with global warming on Earth, the active thawing layer increases. For example, as noted above, it reaches considerable depth in some areas of Russia. Thus, the active layer contains groundwater, which is deposited (located) on the permafrost soil. In the permafrost state, soils are divided into rocky, semi-frozen and dispersed soils. The temperature gradient ranges from –36 °C in winter to +34 °C in summer [24].

The proposed article deals with the behavior and calculation of piles under a building or structure according to their bearing capacity in solid frozen soils. Frozen soil behaves as a rock in winter and as a liquid mass on some soil thickness in summer. Accordingly, the surface forces acting on the pile surface in winter time disappear in the entire melted liquid soil layer in summer time. In this case, the pile load is completely transferred to the underlying frozen soil layer. Although soils of the rock class (type) occupy a minor place in Russia, they are of interest in construction practice during the design, construction and operation phases of buildings and structures. This is due to the complete absence of information about the operation and calculation of piles in the SP 25.13330.2020 "Soil bases and foundations on permafrost soils" and in other existing and previously existing normative regulations.

It is known [25] that the bearing capacity for a long rod of a constant specified length in compression is limited by the value of critical force, and for a rod with a constant specified load is limited by the value of its critical length. These criteria will be used in the proposed compression pile calculations in permafrost conditions of frozen ground at the base of foundations. Individual calculation examples will be demonstrated.

The pile design peculiarity in solid frozen soils is that the pile bearing capacity under compressive load can be additionally limited by the buckling (form) of the pile. This occurs when the thawed soil layer thickness reaches the critical pile length according to the condition of its stability with its ends restrained in the foundation pile cap and in the underlying frozen soil, as shown in Fig. 1. This does not correspond to the design diagram of SP 25.13330.2020 "Soil bases and foundations on permafrost soils" shown in Fig. 2 for thawed soil with the friction forces on pile surface $R_{af} A_{af}$ given in equation (1) below.

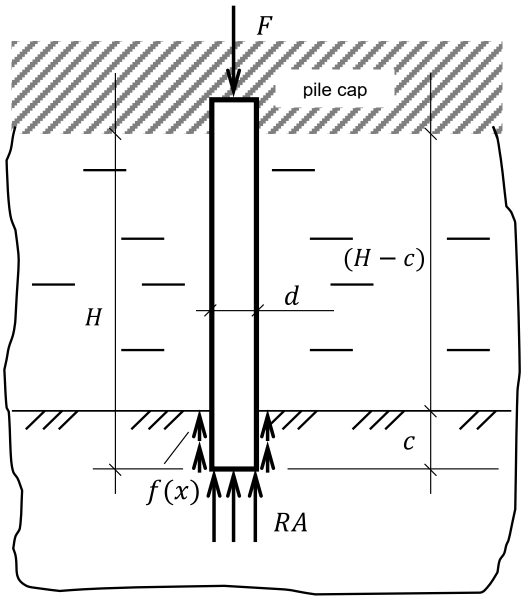

Figure 1. Design diagram of a pile in solid-frozen soil at permissible thawing depth, d – cross-sectional diameter of the pile (borehole).

The limit design diagram of a pile with the top part restrained in the foundation pile cap and the bottom part restrained in the frozen soil at length c is shown in Fig. 1. The value of length c must be at least 0.5 m according to SP 410.1325800.2018 "Main and field pipelines for oil and gas. Construction in permafrost conditions and control of works".

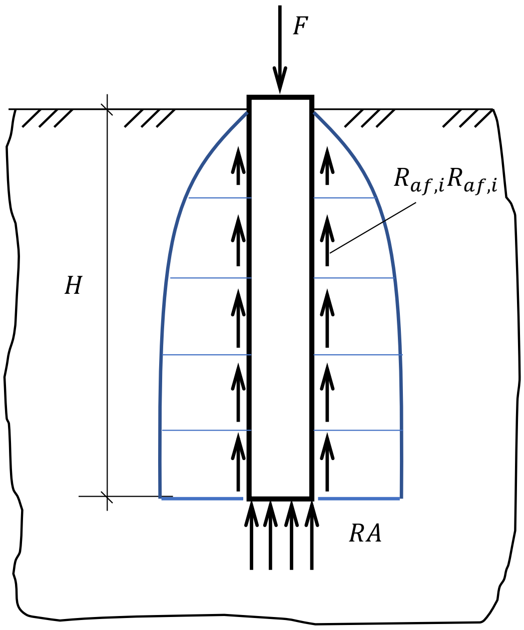

Figure 2. Design diagram of the limit state of a pile under load according to SP 25.13330.2020.

The information from the SP 25.13330.2020 is given in Fig. 2 as a design diagram of a pile in axial compression in permafrost soil bases. The soils go into a fluid state during thawing but retain the effect on the pile surface in the form of friction forces $R_{af}A_{af}$ and on the pile tip in the form of force RA. The pile bearing capacity in Fig. 2 is determined according to the equation

$$F = \gamma_t \gamma_c \left(RA + \sum R_{af,i} A_{af,i} \right). \tag{1}$$

The description and values of the term in equation (1) can be found in SP 25.13330.2020, so they are not given in the text of the article.

The design diagram of the pile (Fig. 2) is given to show that it and equation (1) are not applicable to the design of piles in foundations with solid frozen soil and a liquid soil layer above it, as shown in Fig. 3. In the pile limit state, the reaction at the pile tip is equal to $R_{soil}A$, where R_{soil} is the design resistance of the base soil and A is the pile cross-sectional area. The forces $f(x)$ according to Fig. 1 on the length of the pile section c are not taken into account, which gives a reliability reserve for pile operation.

Let us consider the calculation equation for the design diagram in Fig. 3 as applied to the calculations of existing individual piles in solid frozen base soils. The pile ultimate depth in the solid frozen soil in the limiting state is denoted by c. As the solid frozen soil thaws, the values of the members $R_{af,i}$ of equation (1) decrease and at full thawing to the depth $(H-c)$ they are equal to zero. Then, the pile design diagram has a form as shown in Fig. 3. In this case the pile will keep its operating state under the condition $F \leq \gamma_t \gamma_c RA$ in solid frozen soils. Hereafter we will replace R in (1) with R_{soil}.

To prevent lateral offset of the pile tip in the limit state, the pile must enter the permafrost to a depth equal to or greater than 0.5 m, as shown in Fig. 3, as well as according to SP 410.1325800.2018. The friction forces $R_{af,i}$ on the pile length c, as shown in Fig. 1, are neglected, given the low height of the pile penetration into the soil, to the reliability reserve. According to our investigations, the solid frozen soil under the pile tip does not fracture when the load F increases, but the fracture occurs in the pile material. In this case, pile operational safety in bearing capacity depends not on soil strength but on pile material strength R. The calculation equation is $F \leq R \cdot A$. The pile operating time is equal to the time it takes for the foundation soil to thaw to a depth $(H-c)$. For this purpose, the soil thawing depth h must be measured periodically during operation and compared with the permissible pile length $(H-c)$ determined from the condition $F = F_{cr}$. The pile's serviceability in terms of material strength is retained at $F \leq R \cdot A$, where R is the design resistance of the pile material. The problem, however, is to determine the value of H

(taking into account c) at which the pile stability is retained in its longitudinal bending from the operational load on the pile F.

For a building foundation (foundation pile cap) with pile group, the individual piles with more intensive thawing must be monitored. The remaining service life of the structure must then be determined from the condition of the piles according to the pile bearing capacity and the condition of their stability in axial compression. To determine the maximum depth h of the thawed soil layer at time t, the simplest methods that do not need to be described in the article are used. If the pile length H in the existing structure is not known, the value of H can be determined, for example, by the method described in [26, etc.].

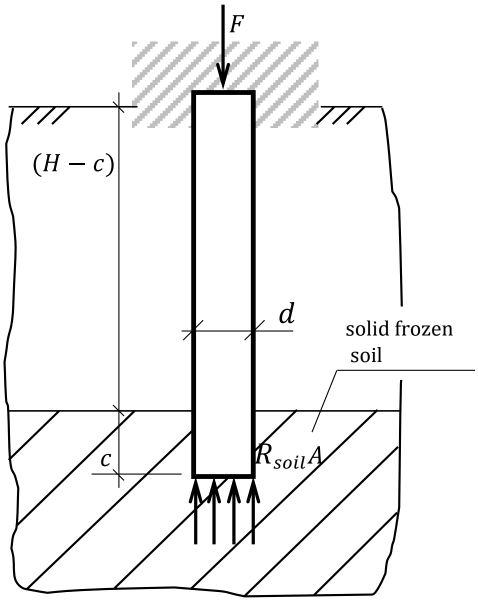

Figure 3. Design diagram of the pile limit state during thawing of the top soil layer to depth $(H-c)$.

3. Results and Discussion

Let us consider the design of a pile by the condition of the first kind buckling (form) under axial compression. We take into account the conditions when $F \le F_{cr}$ and the depth of the base thawing soil increases in the upper part of the pile at the stages of operation (in the summertime of the pile operation). Also consider the calculation of the pile length under the same conditions at a given load on the pile at the stage of its design.

The main task of calculation for operational piles in load-bearing structures is to determine their life remaining. When designing the pile, its cross-sectional dimensions and length must be determined according to the design life of the pile. In both cases, the operation of the pile under the described conditions will be limited to the pile buckling in compression, according to the design diagram shown in Fig. 4. The following notations are used: h is the thawed layer height of solid frozen soil, l_0 is the pile design length according to the first kind stability criterion in the longitudinal bending of the pile with the restrained ends [25]. The design diagram of the pile in the buckling analysis (form) takes into account the full restraint of the upper end of the pile in the foundation pile cap. The pile tip is assumed to be elastically restrained (at the level of its length measurement) as a safety margin because the soil is in an intermediate state between liquid thawed soil and permafrost foundation soil. Under such conditions, the soil is exposed to water for a long period of time and its hardness and compressive effect on the pile may be reduced.

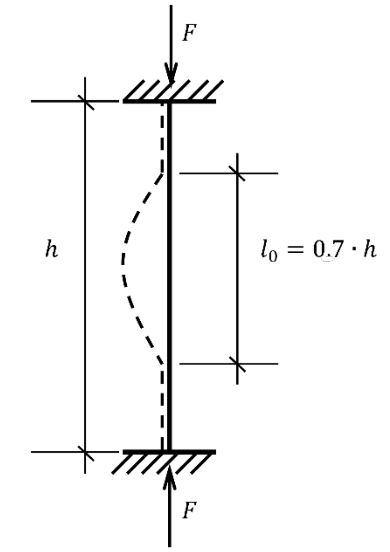

Figure 4. Design diagram of a pile in longitudinal bending operation, h is thawed layer height of the base soil.

Consider the calculation of a pile at the operational stage under axial compression according to the design diagram in Fig. 4. The pile serviceability is determined by the condition $F \le F_{cr}$, where F is the load on the pile and F_{cr} is the critical load in the longitudinal bending of the rod (pile). For example, for reinforced concrete columns (piles) according to [27] we have

$$F_{cr} = \varphi\left(R_b A_b + R_{sc} A_s\right), \quad (2)$$

where R_b, R_{sc} are design compressive resistance of concrete and reinforcement of reinforced concrete pile, A_b, A_s are cross-section areas of concrete and reinforcement, φ is the buckling coefficient of the rod in axial compression. The values of φ for reinforced concrete rod (pile) with restrained ends (Fig. 4) can be determined, for example, according to Table 1 from [27] by the values $l_0 = 0.7h$. The length l_0 is sometimes called the "unbraced length" or "buckling length" of the unrestrained rod [25].

Table 1. Values of coefficients φ for reinforced concrete columns (piles) of circular or square cross-section in compression*.

l_0/d	l_0/b	φ
7	8	1
8.5	10	0.98
10.5	12	0.96
12	14	0.93
14	16	0.89
15.5	18	0.85
17	20	0.81
19	22	0.77
21	24	0.73
22.5	25	0.68
24	28	0.64
26	30	0.59
28	32	0.54
29.5	34	0.49
31	36	0.44
33	38	0.40
34.5	40	0.35

l_0 is design length of the pile, see Fig. 4, d is pile diameter, b is the size of the pile cross-sectional side.

* the effect of sustained load on the bearing capacity due to concrete creep is not taken into account

The design resistance of the pile concrete in axial compression R_b and the design resistance to compression of the pile reinforcement R_{sc} are determined by non-destructive methods at the pile operation stage [28, 29]. At the design stage these characteristics of the materials are determined by SP 63.13330.2018 "Concrete and reinforced concrete structures. General provisions".

It is possible to plot the dependence of φ on l_0/d or l_0/b from the data in Table 1, or a calculation program can be created.

For the time moment t, let us represent equation (2) as

$$F_{cr}(t)=\varphi(t)\left(R_b A_b+R_{sc} A_s\right). \quad (2')$$

By measuring the depth of thawed solid frozen soil in summertime and revealing the maximal depth of the upper liquid soil layer, we find the value of $h(t)$ at the time t of measurement and, respectively, $l_0(t)=0.7\cdot h(t)$ and the value of $F_{cr}(t)$. The number of measurements h_i during the summertime is anything. It depends on the liability of the pile's operating condition in the structure. The same applies to measurements by years. In all cases, the highest value $h(t)$ from the series of measurements is taken into account.

Using the value of $l_0(t)/d$ from Table 1, find the value of $\varphi(t)$. Using the formula (2') find $F_{cr}(t)$ and compare it with the load F on the pile. At $F \le F_{cr}$, the pile retains its serviceability. Based on the values of $F_{cr}(t)$ at different time values t, a graph is plotted and extrapolated by time (by year). Then the pile operating life to failure at $F=F_{cr}$ is approximated. The value obtained with the passage of short time intervals (years) and measurements $h(t)$ can be refined. The calculation algorithm will be discussed below using a numerical example.

Table 1 shows that the greater l_0, the smaller φ and, consequently, the smaller the value of the critical force $F_{cr}=\varphi\left(R_b A_b+R_{sc} A_s\right)$ by (2). In our problem, l_0 is the height of the thawed layer h of solid frozen soil. We can find $\varphi_{cr}=F\left(R_b A_b+R_{sc} A_s\right)$ from the condition $F \le F_{cr}$. And we can find the value of the thawing soil limit depth l_0 or $h_{\max}$ from Table 1. If, at the operation stage of pile (or building), to measure $h(t)$ values during the first years of operation and to identify $h(t)$ function, it is possible to find the limiting value h_{cr} and correspondingly the value $l_0=0.7\cdot h_{cr}$ by extrapolation of the function for a longer time t. Then use h_{cr} to determine the limit time of the pile or building, thereby preventing an accident or failure of the pile or structure.

The pile stability is high in the first years of operation with small values of h. Further, with increasing values of h it decreases to the point of losing stability. Thus, with an effective pile length, the residual operating time of buildings or structures in terms of the bearing capacity of piles will be determined by the time of reaching the limit pile length according to the calculation scheme of Fig. 3 under the conditions of global warming and the condition of pile stability in the thawed foundation soil layer according to Fig. 4.

Let us show by example the pile calculation method by the stability criterion at the stage of operation. Conditionally consider the pile calculation by the example of an oil pipeline pile in the conditions of the north of the Russian Federation (numerical values in the example are taken conditionally). Let us know the values of the pile diameter $d=0.2$ m with the cross-section area $A_b=0.0314$ m², diameter and reinforcement area of the reinforced concrete pile are respectively equal to $d_s=0.02$ m and $A_s=18.8\cdot 10^{-4}$ m². Concrete and reinforcement compressive resistance characteristics according to SP 63.13330.2018 $R_b=14.5$ MPa, $R_{sc}=210$ MPa. The load on the pile $F=0.42\cdot 10^6\,N.$ If the load F on the pile is not known, and it is impossible to determine it theoretically by calculation, then for reinforced concrete piles of buildings and structures it can be identified by the method described in the invention patent [28].

The oil pipeline section under consideration is located in the permafrost zone. The foundation soils are classified as solid frozen. The length of the pile below the ground surface $H = 8.5$ m, and its lower part should be in the unthawed soil by at least $c = 0.5$ m. It is required to determine the residual pile operating life.

If the pile length under a building or structure is not known from the design documentation, it can be determined using various radar-type devices [24], devices "Spektr-4", "PDS-MG4" [30], the acoustic method [31], etc.

Let us assume that after $t_1 = 20$ years of operation the soil thawed to a depth of $h_1 = 2$ m, which corresponds to the value of the calculated length of $l_0(20) = 0.7 \cdot 2 = 1.4$ m and $l_0/d = 1.4/0.2 = 7.$ This value of Table 1 corresponds to $\varphi(20) = 1$ and the critical load on the pile

$$F_{cr} = 1 \cdot \left(14.5 \cdot 10^6 \cdot 0.0314 + 210 \cdot 10^6 \cdot 18.8 \cdot 10^{-4}\right) = 0.851 \cdot 10^6 N,$$

which is greater than the load on the pile $F = 0.42 \cdot 10^6 N.$ The pile is in operational condition.

For full $t_2 = 40$ years of pipeline operation the soil has thawed to a depth of $h_2 = 5$ m at $l_0(40) = 0.7 \cdot 5 = 3.5$ m and $l_0/d = 3.5/0.2 = 17.5.$ According to Table 1 we have $\varphi(40) = 0.79$ and

$$F_{cr} = 0.79 \cdot 0.851 \cdot 10^6 = 0.673 \cdot 10^6 N.$$

In this case $F_{cr} > F = 0.42 \cdot 10^6 N,$ the pile is serviceable.

At operation of the pile during $t_3 = 60$ years we have $h_3 = 7$ m at $l_0(60) = 0.7 \cdot 7 = 4.9$ m. At the value of $l_0/d = 4.9/0.2 = 24.5$ according to Table 1 $\varphi(60) = 0.62,$ then we obtain

$$F_{cr} = 0.53 \cdot 10^6 N > F = 0.42 \cdot 10^6 N,$$

the pile is serviceable.

During the pile's operation over the next 70 years, when interpolating the graph $\left(\varphi(t)h(t)\right)$ constructed from several measurements of soil thawing depth $h(t) - F_{cr}(t)$ over the last 60 years, we would have a value of $h_4 = 8$ m and $l_0(70) = 5.6$ m. Then $l_0/d = 5.6/0.2 = 28$ and $\varphi(70) = 0.54$ and $F_{cr} = 0.46 \cdot 10^6 N.$

Taking into account the fact that $F = 0.42 \cdot 10^6 N$ slightly differs from $F_{cr} = 0.46 \cdot 10^6 N,$ and the diagram $h(t) - F_{cr}(t)$ has been built at $t_3 > 60$ years by interpolation, it is unacceptable to operate the pile after 70 years at the soil thawing depth of $h_4 = 8$ m. Thus, according to the condition of oil pipeline support safety, it is necessary to limit the time of its operation by the pile bearing capacity to 60 years.

The above example of a pile calculation according to the stability criterion during the operational phase can be implemented for piles with a square cross-section with side b in a similar way using Table 1.

Consider the pile calculation in compression at the design stage in solid frozen soils in conditions of increasing thawing depth. The dimensions of the cross-section of the pile and its length for a given operation life of an individual pile or of the building (structure) as a whole are sought. The dimensions of the pile cross section are determined by the values of the load on it, the strength of the pile materials and the design requirements for it in accordance with the Codes.

The basis for calculating the length of a pile in the foundation or an individual pile at the design stage under conditions of annual increase in the height h of the upper water layer during thawing of the ground above the solid frozen (rocky) foundation soil is a graph of the growth of $h(t)$ values over time (years). For this purpose, it is necessary to organize observations of the growth of $h(t)$ values over time (in summer periods) in conditions of the construction site or close to them. It is possible to use the available information about the results of observations $h(t)$ in the corresponding control organizations. Let us denote the current increasing height of the liquid soil layer for the time t of observation $h_i(t)$, where i is the number of the year of observation (measurement). Using the set of values $h_i(t)$ and time (years) t, a graph $H(h_i)$ is plotted, for example, using the method of least squares. A function $H(h)$ is selected to describe the graph, by which H values are predicted for the planned lifetime (time) of the pile or structure $H(h)$ according to the project. At this value of the pile length (denote H_{cr}) the critical load F_{cr} must be equal to or greater than the pile load F. For this purpose, the dimensions of the pile cross-section d or b according to the designations in Table 1 are specified.

From the content of Fig. 4, we find $l_0 = 0.7H_{cr}$ and set the value of d (or b). According to Table 1, find the value of φ, corresponding to the value of l_0/d, and then by (2) determine the value of F_{cr}. If F_{cr} turns out to be less than the pile load F, it is necessary to increase the values of A_b and A_s in (2). Thus, we increase the value of $(R_b A_b + R_{sc} A_s)$ and consequently the diameter d of the pile. This leads to a decrease in φ, but more to an increase in $(R_b A_b + R_{sc} A_s)$ and hence an increase in F_{cr}. So, if we use the initial data to calculate the pile according to the first example in the article, then with $d = 0.2$ m, $l_0 = 8 \cdot 0.7 = 5.6$ m and $\varphi = 0.54$, we have $F_{cr} = 0.46 \cdot 10^6 N$, which is a little more than $F = 0.42 \cdot 10^6 N$ found in the first example for the reinforced concrete pile and, therefore, can be taken for the project.

Thus, for example, according to the values of t and $h(t)$ in the previous example of calculation of the existing pile in the axis "time – layer height" a graph of dependence $h(t)$ is plotted, which is approximated by some function $H(t)$. The design length of the pile H, taking into account the depth of its lower end into the ground to a depth of $c \geq 0.5$ m, is determined according to the project operating time t_{cr} and the graph of the increasing value of $h(t)$.

4. Conclusions

1. The pile behavior under axial compression in the solid frozen foundation soil at various stages of operation at partial and full layer height thawing of the base soil at different depths $h(t)$ is considered.
2. The design diagrams of the pile in the base soil at various stages of its operation in summertime during thawing of the upper base soil layer are presented.
3. A pile design diagram and calculation algorithm are given, using the pile bearing capacity estimation at the operation stage in the longitudinal bending in the solid frozen soil in summertime as an example.
4. To forecast the piles operating time in pile foundations or individual piles during global warming on the Earth, an algorithm for calculating pile length at the design stage is proposed.
5. A numerical example of calculating the pile operational life in the solid frozen soil of the foundation in an oil pipeline support is given.

References

1. Trofimenko, Y.V., Yakubovich, A.N., Yakubovich, I.A., Shashina, E.V. Modeling of influence of climate change character on the territory of the cryolithozone on the value of risks for the road network. International journal of online and biomedical engineering. 2020. 16 (7). Pp. 65–74. DOI: 10.3991/ijoe.v16i07.14557
2. Vasiliev, A., Drozdov, D., Gravis, A., Malkova, G.V., Nyland, K.E., Streletskiy, D.A. Permafrost degradation in the Western Russian Arctic. Environmental Research Letters. 2020. 15. 045001. DOI: 10.1088/1748-9326/ab6f12

3. Hong, E., Perkins, R., Trainor, S. Thaw settlement hazard of permafrost related to climate warming in Alaska. ARCTIC. 2014. 67(1). Pp. 93–103. DOI: 10.14430/arctic4368
4. Hjort, J., Streletskiy, D., Guy Doré, G., Wu, Q, Bjella, K., Luoto, M. Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment. 2022. 3(1). Pp. 24–38. DOI: 10.1038/s43017-021-00247-8
5. Suter, L., Streletskiy, D., Shiklomanov, N. Assessment of the costs of climate change impacts on critical infrastructure in the Circumpolar Arctic. Polar Geography. 2019. 42(4). Pp. 267–286. DOI: 10.1080/1088937X.2019.1686082
6. Vasiliev, A.A, Gravis, A.G., Gubarkov, A.A., Drozdov, D.S., Korostelev, YU.V., Malkova, G.V., Oblogov, G.E., Ponomareva, O.E., Sadurtdinov, M.R., Streleckaya, I.D., Streleckij D.A., Ustinova, E.V., Shirokov, R.S. Degradaciya merzloty: rezultaty mnogoletnego geokriologicheskogo monitoringa v zapadnom sektore rossijskoj arktiki [Permafrost degradation: results of the long term geocryological monitoring in the western sector of russian arctic]. Kriosfera Zemli. 2020. XXIV(2). Pp. 15–30. (rus)
7. Yakubovich, A.N., Trofimenko, Y.V., Yakubovich, I.A., Shashina, E.V. Assessment of the road transport infrastructure facility functionality loss risk resulting from climate change. 2021. IOP Conf. Ser.: Mater. Sci. Eng. 1159. 012040. DOI: 10.1088/1757-899X/1159/1/012040
8. Glasser, R. The Climate change imperative to transform disaster risk management. International Journal of Disaster Risk Science. 2020. 11. Pp. 152–154. doi.org/10.1007/s13753-020-00248-z
9. Li, M.V., Glyzin, A.V., Bilyushova, T.P. Ideal housing for the north. Architecture and Design: History, Theory, Innovation. 2023. 7. Pp. 166–171. (rus)
10. Wang, G.-S., Yu, Q.-H., You, Y.-H., Zhang, Z., Guo, L., Wang, S.-J., Yu, Y. Problems and countermeasures in construction of transmission line projects in permafrost regions. Sciences in Cold and Arid Regions. 2014. 6(5). Pp. 432–439.
11. Alekseeva, O.I., Balobaev, V.T., Grigoryev, M.N., Makarov, V.N., Chzhan, R.V., Shats, M.M., Shepelev, V.V. 2007. O problemakh gradostroitel'stva v kriolitozone (na primere Yakutska) [On the problems of urban planning in cryolithozone (on the example of Yakutsk)]. Kriosfera Zemli. 2007. 2. Pp. 76–83. (rus)
12. Anisimov, O.A., Belolutskaya, M.A. Otsenka vliyaniya izmeneniya klimata i degradatsii vechnoi merzloty na infrastrukturu v severnykh regionakh Rossii [Assessment of the climate impact change and permafrost degradation on infrastructure in the northern regions of Russia]. Meteorologiya i gidrologiya. 2002. 6. Pp. 15–22. (rus)
13. Anisimov, O.A., Lavrov, S.A. Globalnoe poteplenie i tayanie vechnoi merzloty: otsenka riskov dlya proizvodstvennykh obyektov TEHK [Global warming and permafrost melting: risk assessment for fuel and energy facilities]. Tekhnologii TEHK. 2004. 3. Pp. 78–83. (rus)
14. Solovyev, S.A., Sushev, L.A., Kochkin, A.A., Solovyeva, A.A. Problem of piles structural reliability analysis on the stability criterion in permafrost regions. Building and Reconstruction. 2021. 4. Pp. 3–15. (rus) DOI: 10.33979/2073-7416-2021-96-4-3-16
15. Taimyrskiy telegraf [Taimyr telegraph] [Online]. URL: https://www.ttelegraf.ru. (reference date: 08.01.2023)
16. Wu, Q., Zhang, T. Changes in active layer thickness over the Qinghai- Tibetan Plateau from 1995 to 2007. Journal of Geophysical Research: Atmospheres. 2010. 115. Pp. 1–12.
17. Streletskiy, D., Anisimov, O., Vasiliev, A. Permafrost degradation. Snow and ice-related hazards, risks and disasters. 2015. Pp. 303–344. DOI: 10.1016/B978-0-12-394849-6.00010-X
18. Oberman, N.G. Contemporary permafrost degradation of the European north of Russia. In D. L. Kane, & K. M. Hinkel (Eds.), Proceedings of the Ninth International Conference on Permafrost. Institute of Northern Engineering, University of Alaska Fairbanks. 2008. Pp. 1305–1310.
19. Malkova, G.V. Mean-annual ground temperature monitoring on the steady-state-station “Bolvansky”. Earth's Cryosphere. 2010. 14(3). Pp. 3–14.
20. Wang, F., Li, G., Ma, W., Mu, Y., Zhou, Z., Mao, Y. Permafrost thawing along the China-Russia Crude Oil Pipeline and countermeasures: a case study in Jiagedaqi, Northeast China. Cold Regions Science and Technology. 2018. 155. Pp. 308–313. DOI: 10.1016/J.COLDREGIONS.2018.08.018
21. Streletskiy, D.A., Shiklomanov, N.I., Hatleberg, E. Infrastructure and a changing climate in the Russian Arctic: a geographic impact assessment. Proceedings of the 10th International Conference on Permafrost. 2012. 1. Pp. 407–412.
22. Connon, R., Devoie, E., Hayashi, M., Veness, T., Quinton, W. The influence of shallow taliks on permafrost thaw and active layer dynamics in subarctic Canada. Journal of Geophysical Research: Earth Surface. 2018. 123(2). Pp. 281–297. DOI: 10.1002/2017JF004469
23. Hou, X., Chen, J., Sheng, Y., Rui, P.-F., Liu, Y.-Q., Zhang, S.-H., Dong, T.-C., Gao, J.-W. Field observations of the thermal stability of permafrost under buildings with an underfloor open ventilation space and pile foundations in warm permafrost at high altitudes. Advances in Climate Change Research. 2023. 14 (2). Pp. 267–275. DOI: 10.1016/j.accre.2023.03.004
24. Orlov, V.A., Nechitaeva, V.A., Peterburgskij, D.A. Construction and reconstruction of pipelines in permafrost conditions. Plumbing, Heating and Air Conditioning. 2021. 5(233). Pp. 18-23. – EDN BSILUM. (rus)
25. Smirnov, A.F., Aleksandrov, A.V., Lashchenikov, B. YA., Shaposhnikov, N. N. Stroitelnaya mekhanika. Dinamika i ustoichivost sooruzheniy [Construction mechanics. Dynamics and stability of structures]. Moskva: Stroiizdat, 1984. 415 p. (rus)
26. Skvortsov, D.S., Zhaisambaev, E.A., Derevnin, D.V., Parenkina, O.A. Determination of the length of piles immersed in the soil by the method of an acoustic wave excited in a pile by impact. Russian Journal of Transport Engineering. 2020. 2(7). DOI: 10.15862/13SATS220 (rus)
27. Linovich, L.E. Raschet i konstruirovanie chastej grazhdanskix zdanij [Calculation and design of civil building parts]. Kiev: Budivel`nik, 1972. 664 p. (rus)
28. Utkin, V.S., Sushev, L. A., Solov`ev, S.A. Sposob opredeleniya znacheniya e`kspluatacionnoj nagruzki na zhelezobetonnuyu svayu v sostave zdanij ili sooruzhenij [Method of determining the value of operational load on reinforced concrete pile in buildings or structures]. Patent Russia no 2765358, 2021.
29. Utkin, V.S., Solov`ev, S.A. Sposob izmereniya deformacij, napryazhenij i usilij v armature e`kspluatiruemy`x zhelezobetonny`x konstrukcij [Method of measurement of deformations, stresses and forces in reinforcement of operated reinforced concrete structures]. Patent Russia no 2721892, 2020.
30. Ulybin, A.V., Korenev, V.V. The method of length measurement for hollow steel piles. Construction of Unique Buildings and Structures. 2013. 6(1). Pp. 28-35. (rus). DOI: 10.18720/CUBS.6.5
31. Snezhkov, D. Yu., Leonovich, S.N., Budrevich, N.A. Methodology of testing bored piles by seismo-acoustic and ultrasonic methods. Concrete and Reinforced Concrete. 2022. 2(610). Pp. 20–24. DOI: 10.31659/0005-9889-2022-610-2-20-24

Information about authors:

Vladimir Utkin, *Doctor of Technical Sciences*
E-mail: UtkinVoGTU@mail.ru

Zhanna Kosheleva, *PhD in Technical Sciences*
ORCID: https://orcid.org/0000-0003-2076-4377
E-mail: koshelevazhv@vogu35.ru

Olga Yarygina, *PhD in Technical Sciences*
ORCID: https://orcid.org/0000-0002-2497-5609
E-mail: ola_yarigina@mail.ru

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