Calculation of bridge piled foundations

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Abstract. Calculation of piled foundations and their beds is carried out according to two groups of limit states. The design of the piled foundation is selected based on the specific conditions of the building site, which are characterized by engineering survey data, constructional aspects of the designed facilities, and design loads acting on the foundation. The paper provides recommendations on calculating the bearing capacity of piled foundation of bridges supported on non-rocky soil, as well as embedded in rocky soil using the values of the reliability coefficient, provided that it is determined by the results of static load tests. Consideration of these recommendations will make it possible to exclude the adoption of excessively complicated solutions for foundations and construction operations, as well as unjustified rise in the cost of construction.

1. Introduction

The work of many scientists and specialists has been devoted to improving the methodology for calculating piled foundation [1-4]. In recent years, scientists of BSTU named after V.G. Shukhov have also been developing new methods of calculation and designing of piled foundations [5,6]. This paper provides recommendations for calculating the bearing capacity of piled foundations of bridges. For calculating piled foundations with a grillage, the sole of which is buried below the calculated ground surface, it is necessary to take into account not only the resistance of the soil to the motion of piles, but also the soil resistance in the sections of the side faces of the grillage that are displaced to the ground. Let us consider these dependencies in more detail.

2. Experimental part

Bed factor on the side face of the foundation slab:

\[ C_Z = K_b Z_1, \]  

wherein \( K_b \) is – proportion factor characterizing the change with the depth of the soil bed factor within the thickness of the grillage, kN / m^4; \( Z_1 \) - depth location of the point for which the soil bed factor to be determined from the calculated ground surface, m. If the upper face of the grillage is located below the calculated ground surface, then the depth \( Z \) to be determined from this face.

Soil bed factor on the side surface of the pile (foundation) element:

\[ C_Z = K_Z, \]  

wherein \( K \) is the proportion factor characterizing changes with depth of the soil bed factor for the soil surrounding the pile, kN / m^4; \( Z \) - depth of the point location for which the soil bed factor is
determined from the calculated ground surface (with the grillage above the ground) or from the grillage sole when it is buried in the ground, m.

Soil bed factor under the sole of the pile (foundation) element:

\[ C_z = \frac{5K_n h_z}{d_n}, \]  

but not less, than:

\[ C_n = \frac{5K_n}{d_n} \]  

wherein \( K_n \) is the proportion factor, characterizing changes with depth of the soil bed factor for the soil located under the sole of the pile (foundation) element, kN / m^4; \( h \) is the depth of the pile soles of the calculated ground surface, m; \( d_n \) is the sole's size of the pile element, m, taken in the case of widening in the lower part to be equal to the largest transverse widening size, and otherwise to be equal to the pile element's diameter. Formula (3) for the values of \( K_n \) shown in Table 1 gives, for the pile elements with a sole having a diameter \( d > 5 \) and located at a depth of \( h_l = 10-15 \) m, the soil bed factor \( C_n \) is close to those used in the calculation of massive foundations of deep meaning. According to formula (4), limiting the minimum value of the soil bed factor \( C_n \), which corresponds to the substitution in formula (3), the value of \( h_l = 10 \) m.

| Soils                                      | \( K \)-factor, kN/m^4 |
|--------------------------------------------|------------------------|
| High plasticity clays and loams (0.75 < \( I_L \) < 1) | 420 to 1820            |
| Soft plasticity clays and loams (0.5 < \( I_L \) < 0.75); plastic sandy loams (0 < \( I_L \) < 1); dusty sands (0.6 < \( e \) < 0.8); low plasticity and semi-solid clays and loams (0 < \( I_L \) < 0.5); solid sandy loams (\( I_L \) < 0); fine sands (0.6 < \( e \) < 0.75); medium-sized sands (0.55 < \( e \) < 0.7) | 3840 to 5760            |
| Solid clays and loams (\( I_L \) < 0); coarse sands (0.55 < \( e \) < 0.7) | 5840 to 9200            |

The values of the proportion factors \( K, K_b, \) and \( K_n \) are taken according to table 2. Their lower values in the table correspond to the highest values of the clay liquidity index \( I_L \) and the porosity coefficient \( e \) of sandy soils indicated in brackets after the name of the soil, and the larger values of these factors are to correspondingly lower values of \( I_L \) and \( e \). At intermediate values of \( I_L \) and \( e \), the values of the \( K, K_b, \) and \( K_n \) factors are taken by interpolation.

| Soils                                      | \( K \) for piles, kN/m^4 | \( K \) for shells and boring piles \( K_b \) and \( K_n \), kN/m^4 |
|--------------------------------------------|----------------------------|------------------------------------------------------------------|
| High plasticity clays and loams (0.75 < \( I_L \) < 1) | 630 to 2450               | 480 to 1900                                                      |
| Soft plasticity clays and loams (0.5 < \( I_L \) < 0.75); plastic sandy loams (0 < \( I_L \) < 1); dusty sands (0.6 < \( e \) < 0.8); low plasticity and semi-solid clays and loams (0 < \( I_L \) < 0.5); solid sandy loams (\( I_L \) < 0); fine sands (0.6 < \( e \) < 0.75); medium-sized sands (0.55 < \( e \) < 0.7) | 2450 to 4800               | 1900 to 3800                                                      |
| Solid clays and loams (\( I_L \) < 0); coarse sands (0.55 < \( e \) < 0.7) | 7600 to                  | 550 to 920                                                      |
|                                            | 12500                     |                                                                  |
The $K$ and $K_n$ factors for dense sand have been taken 30% higher than the highest values of the corresponding values for this type of soil. If there are several soil layers within the thickness of the grillage and within the depth of the immersion of piles, the values of $K_n$ and $K$ are introduced into the calculation:

$$K_p = \frac{\sum K_i h_i}{h_n},$$

wherein $K_i$ is the value of the proportion factor for the $i$-th soil layer taken in table 2; $h_i$ - thickness of $i$-th soil layer, m; $h_n$ – the depth of the bottom grillage from the calculated ground surface, m. If the top face of the pile cap is located below the calculated ground surface, then the $h_n$ should be understood as a thickness of the plate.

If within the depth

$$h_k = 3,5d + 1,5,$$

counted from the calculated ground surface (when the grillage is located above the soil) or from the sole of the grillage (if immersing it in the soil), there is a single layer of soil, then the given value of $K$ is assumed to be equal to the value corresponding to this soil. In formula (6), the depth $h_k$ and size $d$, equal to the thickness of a square-section pile or the diameter of a circular section, are expressed in meters.

If within the depth $h_k$ there are two soil layers located, then the reduced value

$$K = \frac{K_i h_i (2h_k-h_i)+K_{II}(h_k-h_{II})^2}{h_k^2},$$

and if three soil layers

$$K = K_i h_i [2(h_{III}+h_{II})+h_1] + K_{II} h_{II} (2h_{III}+h_{II}) + K_{III} h_{III},$$

where $h_i$ is the thickness of 1 (upper) soil layer, m; $h_{II}$ and $h_{III}$ — thickness of the II and III soil layers within $h_k$, m; $K_i$, $K_{II}$ and $K_{III}$ - the values of the proportion factors, taken according to table 2 for the soils of these layers.

Estimated width of pile element

$$b_p = K_m (d + 1) K,$$

and pile’s width

$$b_p = K_m (1,5d + 0,5).$$

In formulas (9) and (10): $d$ is the thickness (diameter) of the pile element, m; $K_m$ – factor equal to 0.9 with a round cross-sectional shape of the pile element and 1.0 with a square shape; $K$ is the factor:

$$K = K_1 + \frac{(1-K_1)Z_p}{2d+1}.$$  

In the formula (11): $K_1$ is a factor depending on the number $h_p$ of pile elements in one vertical plane (in one row) parallel to the load; $Z_p$ is average distance in the light (at the level of the calculated ground surface) between pile elements located in the indicated plane, m. The value of $K_1$ is assumed to be equal: for $h_p = 1 K_1 = 1$, for $h_p = 2 K_1 = 0.6$, for $h_p = 3 K_1 = 0.5$, for $h_p > 1 K_1 = 0.45$.

In cases where different numbers of pile elements are located in different vertical planes, the $K$ factor is taken to be similar for all elements and equal to the smaller of the values obtained for these rows. If through the axis of the pile elements it is impossible to draw a vertical plane parallel to the plane of the load, take $K = 1$. In calculating the foundations for the combined action of loads along and across the axis of the bridge, the value of $K$ is taken to be the smaller of the values obtained for each of these directions. In case of support of pile elements on rocky soil, it is allowed in the calculation to take the sole of each pile be loose against transverse displacements and turns, and in case of support of piles on rock (without drilling into it) - fixed against transverse displacements and not fixed against
turns. In this case, the depth $h$ of laying the piles in the soil should be taken equal to the distance from the calculated ground surface (with a grillage located above the soil) or from the sole of the grillage (when it is deepened into the ground) to the bottom of the pile, and if there is widening, to its cross-section with the greatest size.

In calculating the strength and fracture toughness of pile elements, one should take their flexibility by determining the estimated length $l_p$ of the pile, taking into account the degree of resistance to movement of the grillage, due to the layout of the piles in it and the connections with other bridge supports. In addition, each pile is allowed to be considered as a ground-free core rigidly defined at a distance $l_1$ from the sole of the grillage. The value of $l_p$ is determined by the formula:

$$l_1 = l_0 + \frac{2}{\alpha_c},$$  \hspace{1cm} (12)

wherein $l_0$ is the length of the pile section located above the design ground surface, m; $\alpha_c$ is a pile deformation factor, m$^{-1}$.

Pile deformation factor is

$$\alpha_c = \frac{5}{\sqrt{\frac{E}{K_b p}}}$$  \hspace{1cm} (13)

wherein $K$, $b_p$ and $E$ are, respectively, the proportion factor, kN/m$^4$, which characterizes the increase with depth of the soil bed factor on the side surface of the pile, its calculated width, m, and cross-section stiffness, kNm$^2$.

If there are inclined piles in the foundation that prevent the horizontal motion of the grillage in any direction, it is allowed to take $l_p = 0.5...1$ on the flat design scheme of the foundation of inclined piles or only vertical from the number $n_r$ of ground piles according to this scheme (i.e. from the number of rows located perpendicular to the plane of action of the external load) and the degree of uneven distribution of longitudinal forces in the foundation piles, characterized by the ratio $n_N = N_{min}/N_{max}$ of the smallest longitudinal force in the upper section of the piles (positive when compressing and negative when stretching) to the largest one. When supporting foundations on rocks, $\gamma_c = 1$ should be taken.

When calculating the foundation for loads acting jointly along and across the axis of the bridge, the coefficient of operating conditions should be taken equal to the smallest of its values determined for each of these directions. In the case of operation of pile elements for holding ($N_{min} + G < 0$), the following condition must be checked:

$$|N_{min} + G| \leq F_{dn} \frac{\gamma_c}{\gamma_n},$$  \hspace{1cm} (14)

wherein $N_{min}$ is the smallest longitudinal force in the upper section of the pile element, kN; $G$ is the weight of the pile, kN, is determined taking into account hydrostatic weighing, regardless of the type of soil on which the pile rests; $F_{dn}$ is load-bearing capacity of the pile for pulling, kN, determined in accordance with paragraph 4 of SNiP 2.02.03-85; $\gamma_c$ is the coefficient of operating conditions which adopted in accordance with Clause 4 of SNiP 2.02.03-85; $\gamma_n$ is the reliability coefficient taken under any soil conditions and the position of the grillage depending only on the number of piles $h$ in the foundation [7-9].

When calculating the effect of constant loads and effects combined only with a temporary vertical load, soil pressure from the rolling stock to the horizontal lateral load from centrifugal force, the value of the reliability coefficient should be increased by 1.5 times. In the calculation of foundations, in addition to checking the bearing capacity of their foundation, it is necessary to check on the ground as a conditional foundation. When calculating the foundations of piles drilled (embedded) into rock, one should check the bearing capacity of each in the rock. To facilitate the calculation of the deformation coefficient of piles in the soil, use table 3.
Table 3. Values of $\gamma_c$ coefficient.

| Flat foundation layout | $n_z$ | $n_N \leq 0.1$ | $0.1 < n_N \leq 0.3$ | $0.3 < n_N \leq 0.4$ |
|------------------------|------|---------------|----------------|-----------------|
| With only vertical piles | 4    | 1.10          | 1.10           | 1.10            |
|                        | 5-7  | 1.15          | 1.15           | 1.10            |
|                        | $\geq$8 | 1.20      | 1.15           | 1.10            |

When calculating the load-bearing capacity of the ground base of the foundation, you need to check the condition

$$N_{max} + G \leq F_d \frac{\gamma_c}{\gamma_n},$$

wherein $N_{max}$ is the greatest longitudinal force in the upper section of the pile element, kN; $G$ is the weight of the pile element, kN.

For all pile elements based on clay pounds or rock, the weight $G$ should be defined without regard to hydrostatic weighing, and for pile elements based on sandy soils weighing should be taken into account; $F_d$ is the bearing capacity of the base of the pile element, kN, determined in accordance with paragraph 4 of SNiP 2.02.03 - 85; $\gamma_n$ and $\gamma_c$ are coefficients, respectively, the reliability and operating conditions [7]. If the pile elements are based on non-rocky soil and a grillage located above its surface, the value of $\gamma_n$ should be taken depending on the number of piles in the foundation: if $h = 1-5$, then $\gamma_n = 1.75$ (1.6); if $h = 6-10$, then $\gamma_n = 1.65$ (1.5); if $h = 11-20$, then $\gamma_n = 1.55$ (1.4); if $h > 20$, then $\gamma_n = 1.4$ (1.25). The values of the coefficient of reliability given in parentheses are allowed to be used provided that the value of $F_d$ is determined from the test results of piles by static load.

In the calculations of the bearing capacity of foundations from piles supported on non-rocky soil, taking into account one or more loads and effects of braking, horizontal transverse impacts of rolling stock, wind and ice pressure, bulk of ships, temperature changes, it is allowed to determine the value of $\gamma_c$ according to table 3 depending on the presence of piles on the combined action of bending moment $M_h$ and shear force $Q_h$, found by calculation for depth $Z = h$, as well as longitudinal force $N_n = N + G$, where $N$ is the longitudinal force in the upper section of the pile, kN, and $G$ is the weight of the pile, kN, determined without taking into account hydrostatic weighing.

The bearing capacity of a bored pile in the rock $N_n$ is considered to be provided when the following conditions are met:

$$N_n \leq \frac{\gamma_c}{\gamma_n} F_d,$$

wherein $\gamma_c$ and $\gamma_n$ are the operating conditions and reliability coefficients equal to 1.0 and 1.4, respectively;

$F_d$ is the bearing capacity of the pile embedment for compression, taking into account the decreasing effect of the bending moment $M_h$ and the transverse force $Q_h$ on it, kN.

Bearing capacity of pile sealing

$$F_d = \left(\frac{h_{em}}{d_{em}} + 1,5\right)\frac{R_p}{K_g} A K_s,$$

wherein $h_{em}$ is the depth of embedment of the bored pile from the roof of the non-vented rock, m;

$d_{em}$ diameter of the pile in the area embedded in the rock, m;

$R_p$ is the standard (arithmetic mean value) temporary resistance of the rock to uniaxial compression in the water-saturated state, MPa, for the rock located within the depth hem;

$K_g$ - safety factor, taken equal to 1.4;

$A$ is area of supporting the pile on the rock, m<sup>2</sup>;

$K_s$ - coefficient, determined depending on the reduced eccentricity, calculated by the formula

$$\bar{l} = \frac{M_n}{N_n d_x} \left(1 + \frac{2 Q_h}{3 M_h h_3}\right),$$

wherein $M_n$ is the greatest longitudinal bending moment of the pile element, kNm; $N_n$ is the longitudinal force in the upper section of the pile element, kN; $d_x$ is the projection of the pile on the vertical plane, m; $Q_h$ is the sum of all vertical load components, kN; $h_3$ is the depth of embedment of the bored pile from the roof of the non-vented rock, m. 


If value $l > 0.5$, each bearing capacity of rock soil base is allowed to be calculated by formula (14) and additionally check compliance with condition:

$$\frac{6M_t+4Q_s\gamma}{a_s h_3} \leq 0.1 \gamma \cdot n,$$

(19)

The check according to the formulas (16-19) provides for sinking the bottom of the bored pile into non-vented rock (without weak layers) by at least 0.5 m.

The pressure $d$, on the ground along the side surface of the pile elements, which are to be checked at depths determined by formulas (21) and (22), must meet the conditions:

$$\sigma_z \leq \eta_1 \eta_2 \frac{4}{\cos \varphi} (yz \tan \varphi + \xi c),$$

(20)

wherein $\eta_1$ is a coefficient equal to 0.7 in the case of bearing on the support of spacer span structures and 1.0 in other cases; $\eta_2$ is a coefficient taking into account the share of constant load in the total, is determined by the formula (24); $z$ - depth from the calculated surface of the soil (with a grillage located above the soil) or from the sole of the grillage (when deepening it into the ground), m; $\varphi$, $s$ and $\gamma$ are the calculated characteristics (angle of internal friction, degrees; specific adhesion, MPa; specific gravity, kN / m$^3$) of soil; $\xi$ is a coefficient taken equal to 0.3 in the case of bored piles constructed in wells pre-drilled in non-rocky soils and equal to 0.6 in all other cases.

Verification of condition (20) should be attributed to the calculations for the first group of limiting states, and the calculated soil characteristics are determined according to the joint venture for the design of the foundations of buildings and structures [9]. Moreover, the safety factor for determining the calculated values of the angle of internal friction and specific adhesion should be taken no higher than 1.1 and 1.5, respectively. The calculated value of the specific gravity of the soil should be taken with hydrostatic weighing into account, taking the safety factor equal to 1.0 (it is allowed to take $\gamma = 10$ kN / m$^3$).

For several layers of soil, the values of $\varphi$, $c$ and $\gamma$ are recommended to be taken as the weighted average in the plot of the plot $d_z$, in which these pressures have the same sign.

For driven piles immersed in soil to a depth of more than 10$d$, with the exception of cases when the piles are immersed in silts or clay soils with a refractory or fluid consistency, condition (20) is not checked.

The depths for which the conditions (20) are checked depend on the reduced (dimensionless) depth of laying in the soil of the pile element $h$, determined by the formula:

$$h = \alpha_c h,$$

(21)

Where $\alpha_c$ - coefficient of pile deformation determined by formula (13); $h$ - depth of pile laying in soil.

If $h < 2.5$, condition (20) shall be checked for $z = h/3$ and $z = h$, and if $h > 2.5$,

$$z = 0.85/\alpha_c.$$

(22)

Factor taking into account the proportion of constant load in the total,

$$\eta_z = \frac{M_p+M_t}{nM_p+M_t},$$

(23)

wherein $M_p$ and $M_t$ - moments from external loads, respectively permanent and temporary, kN-m, concerning the axis passing in the level of the lower ends of pile elements through the center of gravity of their section is perpendicular to the power plane; $n$ - coefficient.

In case of calculation of single-row foundations for loads acting in the plane perpendicular to the row, moments $M_p$ and $M_t$ are calculated from horizontal and vertical loads, and in other cases - only from horizontal loads.

Value $n$ is taken depending on reduced pile depth determined by formula (21): at $h < 2.5$, $n = 4.0$; At $h = 5$, $n = 2.5$; In the range $2.5 < h < 5.0$ the value of $n$ is found by linear interpolation. In
calculation of single-row foundations for vertical loads applied outside the row plane, it is necessary to take \( n = 4.0 \) irrespective of \( h \).

3. Conclusions

If the horizontal soil pressures \( \sigma_x \) do not satisfy condition (20), but the bearing capacity of the pile elements on the material is underutilized and the movement of the top support is less than the maximum permissible values, then at the given pile laying depth \( h > 2.5 \), the calculation should be repeated, taking a reduced value of the \( K \) coefficient (tab. 2). With a new value of \( K \), it is necessary to check the strength of the piles according to the material, support displacement and fulfilling the conditions (20).

If the foundation calculation is carried out taking into account the soil resistance by moving the grillage, the following conditions should be checked:

\[
\sigma_n \leq \eta_1 \eta_2 \gamma h_{so} \frac{4 \tan \varphi}{\cos \varphi},
\]

(24)

wherein \( \sigma_n \) is the horizontal pressure on the soil transmitted by the grillage at the level of its sole, MPa; \( \eta_1, \eta_2 \) are the coefficients adopted by the formula (20); when calculating the value of \( \eta_2 \) by the formula (23), one should take \( n = 2.5 \); \( h_{so} \) is the depth of the sole of the grillage from the distance of the soil surface or the thickness of the grillage, if the upper face of the grillage is located below the calculated surface of the slab; \( \varphi \) and \( \gamma \) are the calculated characteristics of the soil surrounding the grillage (angle of internal friction, degrees, and specific gravity, kN/m) indicated in formula (20).

If the horizontal soil pressures \( \sigma_x \) do not satisfy condition (24), but the load-bearing capacity of the pile elements on the material is underutilized and the displacement of the top support is less than the maximum permissible values, the calculation should be repeated using a reduced value of \( K_\delta \) (Table 2).

With a new value of \( K_\delta \), it is necessary to check the strength of the piles according to the material, the displacement of the support and fulfilling the condition (24).

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