Design and Calculation of Cost Effectiveness of Various Types of Foundations in Central Russia

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Abstract

The paper presents design and calculation of cost effectiveness of various types of foundations on the example of the city of Vologda. The evaluation of engineering and geological conditions gets the ability to build the planned buildings on the site and the ability to select the carrier layer base. As the carrier layer can be used sandy loam. Also loam can be used for pile foundation.

Keywords: building foundations, foundation soil, piles, reinforced concrete engineering and geological conditions.

1. Introduction

Engineering and geotechnical surveys were made on the site in Vologda. There were 5 wells with a depth 11 meters, located on the distance of 35, 40, 45, 50 meters. Ground water level is at a depth of 1 m. The layers are deposited unevenly with a focus on SE, therefore possible differential settlement of the building. The top layer of clay gray dusty layered (bandy) with layers of sandy loam with thickness from 3 to 4.5 m. As a result of this calculation this soil is the water-saturated soil, average contractible one and it has design characteristics

\[ R_1 = 90.6 \text{kPa} \quad R_2 = 110.2 \text{kPa} \quad E = 4000 \text{kPa} \quad \varphi = 14^\circ . \]

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The second layer of sandy loam has thickness of 2 to 5 m, average contractible one and it is in tight plastic condition, with the following characteristics \( \varphi = 26^0 \), \( R_s = 349.8 \text{ kPa} \), \( R_b = 436.9 \text{ kPa} \), \( E = 18000 \text{ kPa} \), \( \varphi = 26^0 \). The third layer is a loam. It reaches to the bottom of wells. It is also average contractible and tight plastic condition soil. It has characteristics \( R_s = 430.1 \text{ kPa} \), \( R_b = 486.8 \text{ kPa} \), \( E = 12000 \text{ kPa} \), \( \varphi = 18^0 \).

The evaluation of engineering and geological conditions gets the ability to build the planned buildings on the site and the ability to select the carrier layer base. As the carrier layer can be used sandy loam. Also loam can be used for pile foundation. Building place: Vologda [1-31].

2. Design characteristics of the physical and mechanical properties of soils

The efforts for the foundation of the design loads in the most unfavorable combinations are shown in Table 1.

| Foundation number | Combination 1 | Combination 2 |
|-------------------|--------------|--------------|
|                   | \( N_{0II}, \text{kN} \) | \( M_{0II}, \text{kN}\cdot\text{m} \) | \( T_{0II}, \text{kN} \) | \( N_{0II}, \text{kN} \) | \( M_{0II}, \text{kN}\cdot\text{m} \) | \( T_{0II}, \text{kN} \) |
| 1                 | 1100         | 40           | –             | 1250         | –52          | –             |
| 2                 | 750          | –            | –             | 900          | –            | –             |
| 3                 | 2140         | ±84          | –             | 2400         | ±100         | –             |
| 4                 | 2800         | –220         | –10           | 2940         | –           | –14           |
| 5                 | 1560         | –200         | –12           | 1600         | –240         | –17           |

Fig. 1. The construction of buildings

Design characteristics of the physical and mechanical properties of soils are shown in Tab. 2.
Table 2. Design characteristics of the physical and mechanical properties of soils

| Soil number | Soil description | Unit weight of soil, $\gamma_{soil}$ [kN/m$^3$] | Unit weight of soil solids, $\gamma_{soil, ss}$ [kN/m$^3$] | Porosity coefficient, $e$ | Porosity, $n$ | Unit weight based on weighing the water residue, $\gamma_{w}$ [kN/m$^3$] | Humidity at full water saturation, $W_{sat}$ | Humidity degree, $S_r$ | Plasticity, $I_p$ | Melt flow index, $I_l$ | Relative compressibility coefficient, $m_v$ [m$^3$/kN] |
|-------------|-----------------|-----------------------------------------------|-------------------------------------------------|---------------------|--------------------|-----------------------------------------------|-----------------------------------------------|-----------------|----------------|----------------|----------------|----------------|
| 1           | Clay            | 15.5                                          | 12                                              | 10                  | 18.1               | 14                                            | 14                                            | 26.9            | 0.39           | 0.46           | 0.27           | 2.2×10^{-8} |
| 2           | Sandy loam      | 17.5                                          | 22                                              | 7                   | 20.5               | 26                                            | 10                                            | 26.6            | 0.18           | 0.21           | 0.15           | 2.7×10^{-5} |
| 3           | Loam            | 16.1                                          | 15                                              | 21                  | 19.0               | 18                                            | 28                                            | 26.6            | 0.31           | 0.41           | 0.27           | 4.3×10^{-7} |

3. Evaluation of geotechnical and hydrogeological conditions and soil properties

Table 3. Definition of additional characteristics of physical and mechanical properties of the soil.

| Soil number | Soil description | Unit weight of the soil, $\gamma_{soil}$ [kN/m$^3$] | Porosity coefficient, $e$ | Porosity, $n$ | Unit weight based on weighing the water residue, $\gamma_{w}$ [kN/m$^3$] | Humidity at full water saturation, $W_{sat}$ | Humidity degree, $S_r$ | Plasticity, $I_p$ | Melt flow index, $I_l$ | Relative compressibility coefficient, $m_v$ [m$^3$/kN] |
|-------------|-----------------|-----------------------------------------------|---------------------|--------------------|-----------------------------------------------|-----------------------------------------------|-----------------|----------------|----------------|----------------|----------------|
| 1.Clay      | 13.02           | 1.066                                         | 0.516               | 8.18               | 0.396                                         | 0.984                                         | 0.19            | 0.632          | 9.8×10^{-6} (-8) | 4.1×10^{-6} (-8) |
| 2.Sandy loam| 17.37           | 0.531                                         | 0.347               | 10.84              | 0.200                                         | 0.901                                         | 0.06            | 0.500          | 5.2×10^{-6} (-8) | 1.1×10^{-6} (-8) |
| 3.Loam      | 14.50           | 0.834                                         | 0.455               | 9.05               | 0.314                                         | 0.989                                         | 0.14            | 0.286          | 5.2×10^{-6} (-8) | 1.1×10^{-6} (-8) |

Determination of the calculated resistance of soil layers and assessment of engineering and geological surveys.

$$R = \frac{\gamma_{soil} \cdot \gamma_{w}}{k} \left[ M_y \cdot k_z \cdot b \cdot \gamma_H + M_q \cdot d_1 \cdot \gamma_H + \left( M_q - 1 \right) \cdot d_h \cdot \gamma_H + M_c \cdot c_{H} \right],$$  \hspace{1cm} (1)

4. The design features of the building and the characteristics of loads

Projected construction consists of prefabricated repair workshop, located in the cell columns 36.0x18.0 m. This building frame type consists of two parts, differing in functionality and height.

The three-story part of the building is arranged with a basement. Exterior brick walls with 0.3m thick. Floors rely
on internal walls and reinforced concrete columns, foundations under which are freestanding. Seven-story building frame consist of columns and floors. The brick walls are constructed on the foundation beams, columns foundations are under-standing. In accordance with paragraph 4 application 4 [3] limit deformation of the foot of foundation of considered structure - the average draft: $S_u=8\text{cm}$, the relative difference between the drafts: $\frac{\Delta S}{L_u}=0.002$;

Given the different heights of individual parts of the building, their rigidity and high-largest burden on the bases, we can expect the development of non-uniform drafts, so between the different parts of the plant must arrange expansion joints. The presence of basement raises the question of waterproofing, construction of which depends on the level of groundwater.

5. Foundation variants

Development of variants spends the most loaded and typical foundation construction.
In this case the most loaded foundation is № 4 $N_{oli}=-2940\text{kN}$; $M_{oli}=0\text{kN*m}$; $T_{oli}=-14\text{kN}$.

5.1. Variant 1. Natural basis foundation

1. Depth foundation determination
Normative depth of freezing in Vologda $d_{fn}=1.5 \text{ m}$, calculated depth of freezing $N_{II}$

$$d_f = k_d d_{fn} = 1.5 \cdot 0.5 = 0.75$$

Because projected building has a basement, located at the level of -2.2 m, the depth of the foundation foot of the level of planning is given by:

$$d = d_b + h_f + 0.05$$

As in our case, the groundwater level to be higher than the depth of the basement floor, tentatively accept:

$$d = d_b + h_f + 0.05 = 3.0 + 0.7 + 0.05 = 3.75\text{m}$$

Accept depth of the foundation foot $d=4.0 \text{ m}$.

2. Determination of the estimated value of the resistance $R$ at laying foundation foot with $b=1 \text{ m}$

$$R = \frac{1 \cdot 12}{1} \cdot \left(0.84 \cdot 1 \cdot 10,84 + 4.37 \cdot 4 \cdot 12,2 + 6.9 \cdot 10\right) = 349.8\kappa\Pi\alpha$$

Unit weight of the soil above foot of foundation:

$$\gamma' = \frac{10.84 \cdot 0.5 + 8.18 \cdot 2 + 18.1 \cdot 1.5}{0.5 + 2 + 1.5} = 12.2\kappa\Pi / \text{m}^3$$

Unit weight of the soil under foot of foundation:

$$\gamma'' = 10.84\kappa\Pi / \text{m}^3$$

3. Area of foundation foot determination:

$$A = \frac{N_{oli}}{R - \gamma \times d} = \frac{2940}{349.8 - 20 \cdot 4.0} = 9.49\text{m}^2$$

4. Foundation sizes determination:
Previous determination of required sizes of foundation foot:

$$b = \sqrt{A} = \sqrt{9.49/2} = 2.18 \text{ m} \Rightarrow l = 4.36 \text{ m}.$$
\[ R = \frac{1.1 \cdot 2}{1} \cdot (0.84 \cdot 1.24 \cdot 10.84 + 4.37 \cdot 4.12.2 + 6.9 \cdot 10) = 364.9 \text{kPa} \]

6. The construction of foundation and the determination of foundation weight \( N_{fII} \) and of weight of the soil on its steps \( N_{gII} \)

Project freestanding column foundation 4.8×2.4 m.

Determination of own foundation weight:
\[ N_{fII} = V \cdot \gamma_{rc} = 15.7 \cdot 25 = 392.1 \text{kN} \]

Soil weight on the foundation steps:
\[ N_{gII} = 30.4 \cdot 16.5 = 501.6 \text{kN} \]

7. The determination of average pressure \( p \) on the foundation foot and the comparison of it with calculated soil resistance \( R \).
\[ P = \frac{N_{dfI} + N_{gI} + N_{fI}}{A} = \frac{2940 + 392.1 + 501.6}{1.2} = 332.8 \text{kPa } \leq 364.9 \text{kPa} \]

8. Checking taken sizes of foundation
\[ p_{\text{max}} = \left( \frac{N_{fI}}{A} \right) \left( 1 + \frac{6 \times e}{b} \right) = \left( \frac{3833.7}{11.52} \right) \times \left( 1 + \frac{0.6 \times 0.019}{4.8} \right) = 340.7 \text{kPa} < 1.2 \times R = 437.9 \text{kPa} ; \]
\[ p_{\text{min}} = \left( \frac{N_{fI}}{A} \right) \left( 1 - \frac{6 \times e}{b} \right) = 324.9 \text{kPa} > 0 ; \]
\[ (p_{\text{max}} + p_{\text{min}}) / 2 = 332.8 \leq R = 364.9 \text{kPa} \]

\( N_{fI} \) - the average value of the efforts on the foot of foundation;

9. The calculation of the strength of the foundation

Calculation of the strength of the foundation material is carried out in the case where a reinforced concrete foundation is an atypical one. When this seek to maximize the strength of the material used in its minimum flow.

For the design of the foundation can be seen that the pyramid punching goes beyond the foot of the basement, so
the check is not performed.

10. Determination of the draft of foundation

\[ \sigma_{zgp} = \gamma' \times d = 48.9 \text{ kN} / \text{m}^2; \]

\[ \sigma_{zp} = \frac{N_H}{A} - \sigma_{zgp} = 332.8 - 48.9 = 283.9 \text{ kN} / \text{m}^2 \]

The thickness of compressible soil is \( H_c = 8.0 \text{ m}. \) The draft:

\[ s = \frac{\beta \cdot \sum \sigma_{zp} \cdot h_i}{E_i} = 0.8 \cdot 1.0 \cdot \left[ \frac{265.5 + 203.0}{18000} + \frac{1132 + 89.4 + 59.6 + 41.2 + 30.1 + 21.6}{12000} \right] = 0.073 \text{ m} = 7.3 \text{ cm} \]

The draft is 7.3 cm and this value less than limit draft \( S_u = 8 \text{ cm}. \)

5.2. Variant 2. The precast reinforced concrete piles foundation.

1. The determination of grillage foot depth.

In determination the depth of the grillage foot guided by the same considerations as in the determination of the depth of the foundation foot, constructed on a natural basis. If there is a basement raft foundation, as a rule, should be placed below the basement floor, and his depth of the foot is given by:

\[ N_{01} \leq \psi R_{b,loc} A_{loc} d_f = d_h + h_{cf} + h_p \]

where \( d_h = 3.0 \text{ m} \) - distance between planning level and basement floor.

\( h_{cf} = 0.30 \text{ m} \) - thickness of basement floor,

The approximate minimum height of grillage can be defined by the formula:

\( h_{pr_{min}} = a_k + 0.2 + t \)

\( d_{pr_{min}} = 0.8 + 0.2 + 0.05 = 1.05 \text{ m} \)

\( d_p = 3.0 + 0.3 + 1.05 = 4.35 \text{ m} \)

level of planning by 4.4 m.

Later in the calculation of the strength of the grillage its height specified.

2. Selecting the type, length and brand of the pile

For these soil conditions will be more rational to choose the hanging piles. Given the depth of the grillage foot, sealing the pile in the grillage and the location of the carrier layer of soil, it is possible to identify the type and length of the pile.

\( L = 3.0 + 1.1 + 2 = 3.15 \text{ m}. \)

Chosen pile brand C5-30: length 5 m, section 30x30, cm; concrete class B20, longitudinal reinforcement section 4\( \Phi \)12. A240.

3. The determination of the bearing capacity of the pile

-In material:

\( R_b = 11500 \text{ kPa}, R_{sc} = 225000 \text{ kPa} \)

\[ F_m = 1 \cdot 1.1 \cdot (11.5 \cdot 0.09 + 225 \cdot 0.00045) \cdot 10^3 = 1136.3 \text{ kN} \]

\[ A_s = \frac{\pi d_{arm}^2}{4} = \frac{3.14 \cdot 0.12^2}{4} = 4.52 \cdot 10^{-4} \text{ m}^2 \]

\( A_{b} = d^2 = 0.3^2 = 0.09 \text{ m}^2\)

\[ N_{pile} = \frac{F_{rm}}{\gamma_k} = \frac{1136.3}{1.4} = 811.6 \text{ kN} \]
- In soil (hanging pile):

\[ F_d = \gamma_c \cdot \left( \gamma_{CR} \cdot R \cdot A + u \sum_{i=1}^{n} \gamma_{cf} \cdot f_i \cdot h_i \right) \]

\[ F_{ds} = 1 \cdot \left[ 1,0 \cdot 3460 \cdot 0,09 + 1,2 \cdot (1,1 \cdot 24 + 1,95 \cdot (43 + 44)) \right] = 546.7 \text{ kN} \]

\[ N_{\text{pile}} = \frac{546.7}{1.4} = 390.5 \text{ kN} \]

Later will use less value of the force of calculated resistance of the pile: \( N_{\text{pile}}^{\text{min}} = 390.5 \text{ kN} \)

4. Approximate determination of the grillage foot area

\( A_r \) – grillage foot area

\( \sigma_r \) – nominal pressure under grillage foot

\[ \sigma_r = \frac{N_{\text{pile}}}{(3d)^2} = \frac{390.5}{(3 \cdot 0.3)^2} = 482.1 \text{ kPa} \], where \( d \) – size of cross pile section

\[ A_r = \frac{1.2 \cdot 2940}{482.1 - 1.1 \cdot 20 \cdot 4.4} = 9.16 \text{ m}^2 \]

4. The determination of pile amount.

\( (N_r + N_g) = \gamma_f \cdot A_r \cdot d_r \cdot \gamma_m = 1.1 \cdot 9.16 \cdot 4.4 \cdot 20 = 886.4 \text{ kN} \)

\[ n_r = \frac{3528 + 886.4}{390.5} = 11.3 \]

Accept 12 piles.

5. Piles placing, grillage construction.

The minimal distance between piles axes is not less 3\( d_c \).

The distance between edge of pile and edge of grillage is not less 5 cm.

In center loaded foundation upper ends of reinforced concrete piles embedded in grillage to 5 cm.

Gratings are reinforced in accordance with the calculation. On top of the piles are usually laid reinforcing mesh.

6. The factual pressure on the pile determination:

Pressure on the pile checking.
Refine grillage weight \( N_r = \gamma_f \cdot A_r \cdot h_g \cdot \gamma_h = 1,1 \cdot 1,1 \cdot 2,4 \cdot 3,6 \cdot 25 = 261,4 \text{kN} \)

Refine soil weight on the steps of the grillage:
\( N_g = \gamma_f \cdot A_g \cdot (d_g - h_g) \cdot \gamma_1 = 1,1 \cdot 2,4 \cdot 3,6 \cdot (4,4 - 1,1) \cdot 15 = 470,5 \text{kN} \)

Pressure on the pile checking.
\[
N_{p\text{max}} = \frac{3528 + 261,1 + 470,5}{12} + \frac{61,6 \cdot 1,5}{6 \cdot 0,5^2 + 6 \cdot 1,5^2} = 355 + 6,16 = 361,2 \text{kN} < 1,2 \cdot 390,5 = 468,6 \text{kN};
\]

\( N_{p\text{min}} = 348.8 \text{kN} > 0 \)

All piles are compressed, the maximum design stress does not exceed the design resistance of the pile.

7. Checking the strength of reinforced concrete grillage under column:

Check the strength of the grillage produce the first limit state, namely punching column punching corner pile, of oblique sections under the action of shear force and the local compression at the ends of the column.

Checking grillage punching column
\[
N \leq (\alpha_1 \cdot (b_c + c_2) + \alpha_2 \cdot (d_c + c_1)) \cdot h_1 \cdot R_{pt},
\]

\[
k_1 = \frac{c_1}{h_1} = \frac{0,95}{1,05} = 0,91 \Rightarrow \alpha = 2,24,
\]

\[
k_2 = \frac{c_2}{h_1} = \frac{0,45}{1,05} = 0,43 \Rightarrow \alpha = 3,77
\]

\[
N_{\text{max}} \leq (2,24 \cdot (0,8 + 0,45) + 3,77 \cdot (0,6 + 0,95)) \cdot 1,05 \cdot 900 = 8168,1 \text{kN}
\]

\[
N = 6 \cdot 552,2 = 3313,2 \text{kN}
\]

\[
N = 3313,2 \text{kN} \leq 8168,1 \text{kN}
\]

Grillage strength punching column is provided.

Checking grillage punching corner pile.

\[
N_{\text{max}} \leq (\beta_1 \cdot (b_{02} + c_{02} / 2) + \beta_2 \cdot (b_{01} + c_{01} / 2)) \cdot h_{01} \cdot R_{pt},
\]

\[
\Rightarrow k_{01} = k_{02} = \frac{c_{01}}{h_{01}} = \frac{0,45}{1,0} = 0,45, \beta = 0,81,
\]

\[
N_{\text{max}} \leq (0,81 \cdot 2 \cdot (0,45 + 0,225)) \cdot 1,0 \cdot 900 = 984,2 \text{kN}
\]

\[
N = 552,2 \text{kN} \leq 984,2 \text{kN}
\]

Grillage strength punching corner pile is provided.

Checking the strength of the local compression
\[
N_{01} \leq \psi R_{b,\text{loc}, A_{\text{loc}}}, \text{where } N_{01} \text{ - calculated normal force in the cross section of the column in crop of grillage},
\]

\[
N_{01} = 1,2 \cdot 2940 = 5784 \text{kN};
\]

\[
\psi R_{b,\text{loc}, A_{\text{loc}}} = 1,0 \cdot 11500 \cdot 2,4 \cdot 3,6 = 99360 \text{kN}
\]

\[
N_{01} = 3528 \text{kN} \leq 99360 \text{kN}
\]

8. Calculation of pile foundation draft

The sizes of the foundation foot conditioned
\[
l_y = l + 2L \cdot \tan \alpha = 3,3 + 2 \cdot 5 \cdot \tan 4,9 = 4,2 \text{m}
\]
\[
b_y = b + 2L \cdot \tan \alpha = 2,1 + 2 \cdot 5 \cdot \tan 4,9 = 3,0 \text{m}
\]

Conditional foundation weight
\[
N_y = l_y \cdot b_y \cdot \sum \gamma_i h_i = 3,0 \cdot 4,2 \cdot (18,1 \cdot 1,5 + 8,18 \cdot 2,0 + 10,84 \cdot 2,5 + 9,5 \cdot 3,4) = 1305,4 \text{ kN}
\]
The design resistance of the soil, which is located below the conditional foundation

\[ R = \frac{1.0 \cdot 1.2}{1} \cdot (0.43 \cdot 1.3 \cdot 9.05 + 2.73 \cdot 9.4 \cdot 10.3 + 5.31 \cdot 28) = 509.6 \text{ kPa} \]

Checking the pressure on the ground at the edge of the pile

\[ p_y = \frac{N_y}{l_y \cdot b_y} = \frac{2940 + 1305.4}{4.2 \cdot 3.0} = 336.9 \text{ kPa} \leq R_y = 509.6 \text{ kPa} \]

Determination of foundation draft by layering summation.

\[ \sigma_z = \frac{N_y}{l_y \cdot b_y} = 103.6 \text{ kPa} \]

\[ p_0 = p_y - \sigma_z = 336.9 - 103.6 = 233.3 \text{ kPa} \]

Thickness of compressible layer: \( H_c = 7.0 \text{ m} \)

\[ S = 0.8 \cdot 1.0 \cdot \frac{221.7 + 183.2 + 126 + 80.5 + 56 + 40.9 + 30.4}{12000} = 0.065 \text{ m} \]

Foundation draft 6.5 cm less than the maximum draft of foundations \( S_u = 8 \text{ cm} \)

6. Determination of economic performance variants considered the installation of foundations and the choice of the basic variant.

The cost of each variant can be determined by using the aggregated unit price or unified district unit price. To determine the cost of work for each variant must be installing the volume of individual jobs and the characteristics of their production. Setting the value of each option are compared among themselves the cost and other technical and economic indicators: labor intensity, material consumption, the value of the limit deformation of the base, resulting in determining the most appropriate and cost effective option, which take for further calculations of the foundations of the building or structure for the primary. An exception in this regard may be some cases where the building consists of several structurally distinct volumes assigned to some distance from each other or separated by deformation seams. In such cases, all the bases within the bulk of the buildings are designed for the selected option, and a lightweight construction, where the load is much less, can be taking other types of foundations and types of bases (without feasibility calculations).

| n\text{'}  | Work type          | Work volume | Unit cost | Add [%] | With add | Overall cost |
|----------|--------------------|-------------|-----------|---------|----------|--------------|
| 1        | Soil works         | 177.5 m\text{'} | 3.60      | 7% \( k=1.4 \) | (3.6 \cdot 1.07) \cdot 1.4 = 5.4 | 958.5        |
| 2        | Foundation work    | 15.7 m\text{'} | 44.9      | -       | 44.9     | 704.9        |
| 4        | Concrete work      | 1.3 m\text{'}  | 34.7      | -       | 34.7     | 45.1         |
| 5        | Water work         | 110.9 m\text{'} | 1.8       | -       | 1.8      | 199.6        |
|          | **Total**          | **       | **      | **     | **      | **1908.1**  |
Таблица 6. Pile foundation

| №  | Work type          | Work volume | Unit cost | Add [%] | With add | Overall cost |
|----|--------------------|-------------|-----------|---------|----------|--------------|
| 1  | Soil work          | 148.2 m³    | 3.60      | 7%     | (3.6·1.07)·1.4=5.4 | 800.3        |
| 2  | Grillage work      | 9.5 m³      | 31.1      | -       | 31.1     | 295.5        |
| 3  | Piles work         | 9.72 m³     | 88.4      | -       | 88.4     | 859.3        |
| 4  | Concrete work      | 0.9 m³      | 34.7      | -       | 34.7     | 31.2         |
| 5  | Water work         | 95.3 m³     | 1.8       | -       | 1.8      | 171.5        |
|    |                     |             |           |         |          | Total 2157.8 |

7. Conclusions

As the main variant of taking the natural basis foundation of its favorable economic indicators and indicators of drafts.

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