Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Programme in Construction and Civil Engineering

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Foundation calculation for multi-storey residential building

Thesis 2018

Abstract

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The purpose of the study was to design a foundation for a 9-storey residential building. Initial data was taken from the technical report made by JSC "LenTISIZ". Soil characteristics, foundations and settlements were calculated by Russian and European norms. Differences in the received calculations are insignificant. Also the feasibility study of the designed foundation was made. Calculations showed that the application of the strip foundation is economic.

Keywords: foundation, ground, pile

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1 Introduction

Increasing the economic efficiency of foundations design solutions contributes to the improvement of the methods for their calculation and design. One of the characteristic features of the foundations is the variant nature of their design, when it is necessary to consider several variants of foundations and choose from them the most economically feasible, corresponding to the modern technology of erection and ensuring long-term and safe operation of the constructions, as well as environmental safety of the building environment. In the thesis, two types of the foundations were considered: a shallow foundation and, as an alternative option, a pile foundation.

At the present time, the choice of the most optimal constructive design of foundation is usually carried out by means of a technical and economic comparison of the options for constructing foundations for the following indicators: economic efficiency, material intensity, the need to perform work in a short time, the values of the maximum sediments and unevenness of precipitation, the possibility of performing the works in the winter, etc.

One of the tasks of updating the normative documents and creating an SP instead of SNiP was the convergence of the requirements of Russian norms with the standards of the European Union (Eurocodes). Ensuring practical unity of the systems of technical regulation of construction is a necessity for establishing the development of economic relations between Russian Federation and the European Union in the field of construction.

In this paper, the Russian norms for the design of the SP 22.13330.2011 "Foundations of buildings and structures" Eurocode 7 are considered. The purpose of the study was to design two types of foundations: shallow and, as an alternative, pile. In addition, the feasibility study of the designed foundation was made and the optimal option was chosen.

2 Foundation description

2.1 Shallow foundation

Ratio to depth of width of the foundation base d/b does not exceed 4 in shallow foundations. Load is transferred on the foundation soil mainly through the foundation base. They are erected in pits, previously dug to full depth from the surface of the soil. Usually the depth of laying of these foundations does not exceed 4 to 6 meters [9].

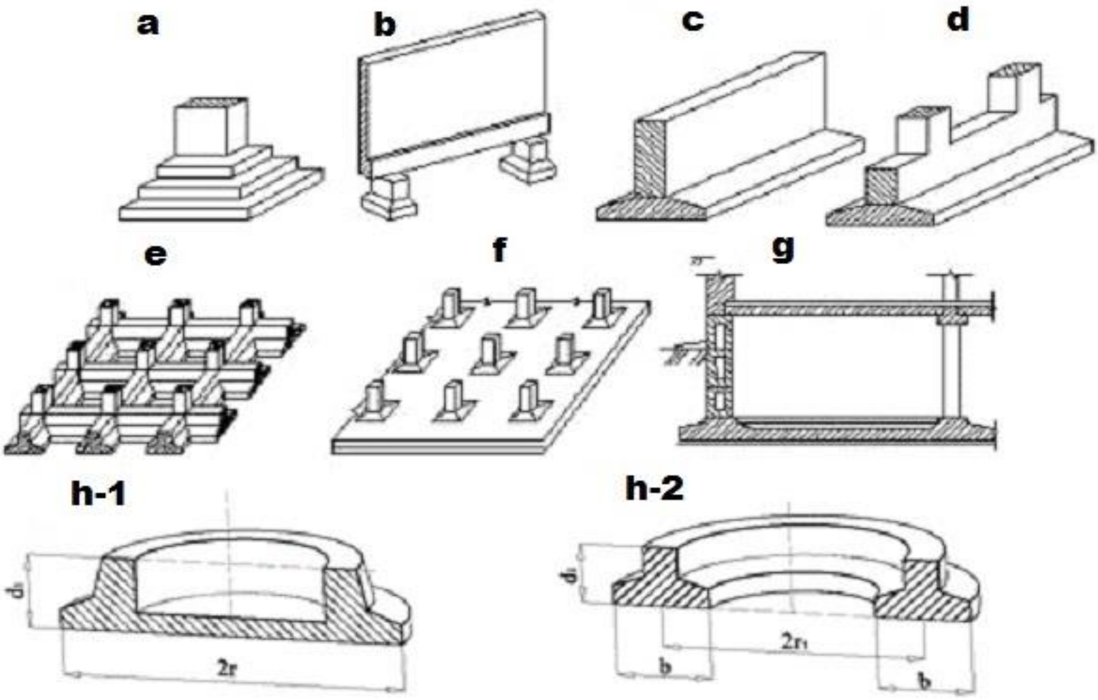
The main types of shallow foundations are: individual (pad foundations), strip foundations, raft (mat) foundation and massive foundation (Figure 1).

Individual foundations usually consist of a column with a square or rectangular pad of concrete and they are used to support a structural column or a wall (Figure 1, a, b). The footing of such foundations can be advanced due to length l and width b.

Strip foundations perceive the load from the individual walls of the building (Figure 1, c, d). In order to reduce the pressure along the footing, strip foundations are developed only in the transverse direction, i.e. on width. Strip foundations for the columns perceive the load from a number of columns (Figure 1, d). To equalize the drawdown of individual columns in a row and the columns in adjacent rows is made in the form of cross bands (Figure 1, d).

Raft foundations are often used under different structures; all the elements of the structure (building) rest on this foundation: walls, columns, pillars, etc. The basic elements of shallow foundation are presented in Figure 2 (with reference to a separate foundation).

.Figure 1. The main types of shallow foundations [3]



a – pad foundation under a column;

b – pad foundation under a wall;

c – strip foundation under a wall;

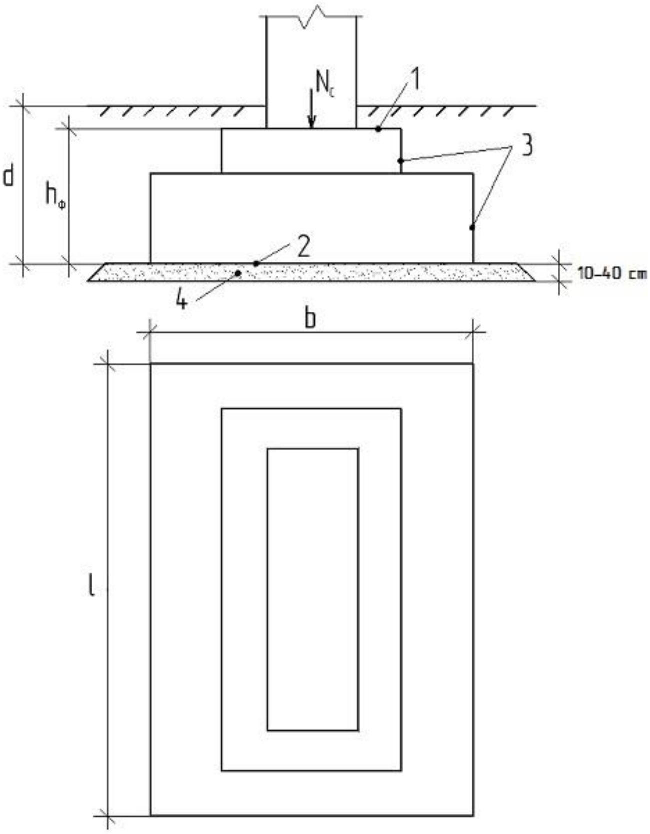
d – strip foundation under columns;

e – strip foundation under a grid of columns;

f,g – mat foundation of a building;

h – circular foundation for a water tower (1 – mat, 2 – ring)

Figure 2. The basic elements of shallow foundations [3]



1 – the upper horizontal plane of foundation is the cut off of foundation;

2 – the footing of foundation;

3 – the lateral surface with vertical ledges;4 - preparation of lean concrete (class B 3,5) or sand medium grain size;

b – the width of foundation footing (the smaller side);

l – the length of foundation footing;

d – foundation depth;

h_f – foundation height.

The preliminary dimensions of foundation are from the condition: the actual pressure under the foundation base p must not exceed the design resistance of the ground R, i.e. p≤R. According to this condition foundation is obtained such that the regions of plastic deformations at the base are sufficiently small, Z≤0,25b.

In this way, p = R is a such uniform pressure of foundation on the base, at which the depth of development of the zones of plastic deformation is quite small Z≈0,25b.

The presence of a linear part of the function S = f (p) for the ground in general case is conditional, but considering the single load (built once and for a long time), this assumption is possible for construction practice.

This approach ($z \leq 0,25 \cdot b$), theoretically grounded by N.M. Gersenanov, makes it possible to use the solutions of the theory of linearly deformable medium (LDM) and engineering methods in determining deformations of the base.

The purpose of calculating the bases for deformations is to limit the absolute or relative displacements of foundations and suprafundamental structures to such limits that guarantee the normal operation of the structure and its longevity (due to the appearance of unacceptable deposits, ups, rolls, changes in design levels and structural positions, etc.). It should be noted that the strength and fracture toughness of the foundations themselves and suprafundamental structures are checked by calculation, taking into account the interaction of the structure with the base (resulting forces and deformations).

Calculation of the sediments is carried out by the method of layerwise summation, which allows to take into account the stage of erection of the buildings and the heterogeneity of the base, which is expressed in the change in the depth deformation modulus.

2.2 Pile foundation

Pile foundations are used in cases when the soils of foundation are represented by a high-powered mound, peat, sediments of silt, cohesive soils in a fluid and flow-plastic state, etc. And also pile foundations are used when a building has very heavy, concentrated loads, such as in a high rise structure, bridge, or water tank [3].

Pile foundations are able to take higher loads than spread footings.

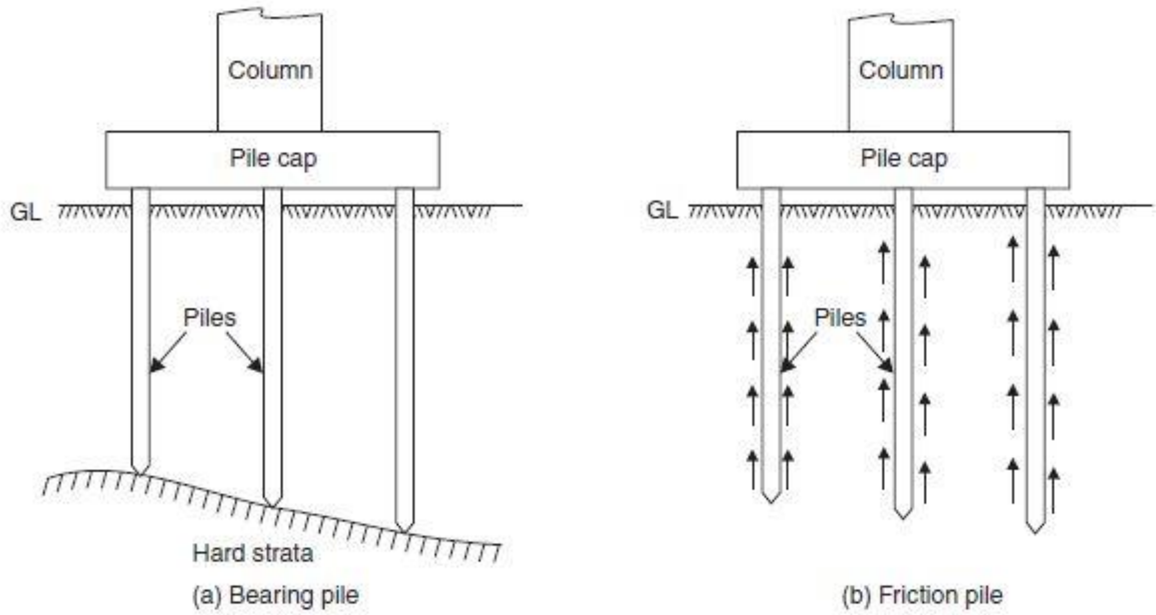
At present, construction is often carried out on weak water-saturated grounds, when the builders use the sites, which were earlier recognized by geologists as unfit for the erection of structures.

The use of pile foundations can also be due to the requirements of increasing stability, reducing the negative impact of rainfall, subsidence of the foundation and heeling of construction.

The scope of pile foundations is determined by engineering-geological conditions and loads transferred to the foundation.

According to the nature of the load transfer to the ground, the piles are divided into two types: end bearing piles and friction piles (Figure 3).

Figure 3. Types of pile foundation [4]



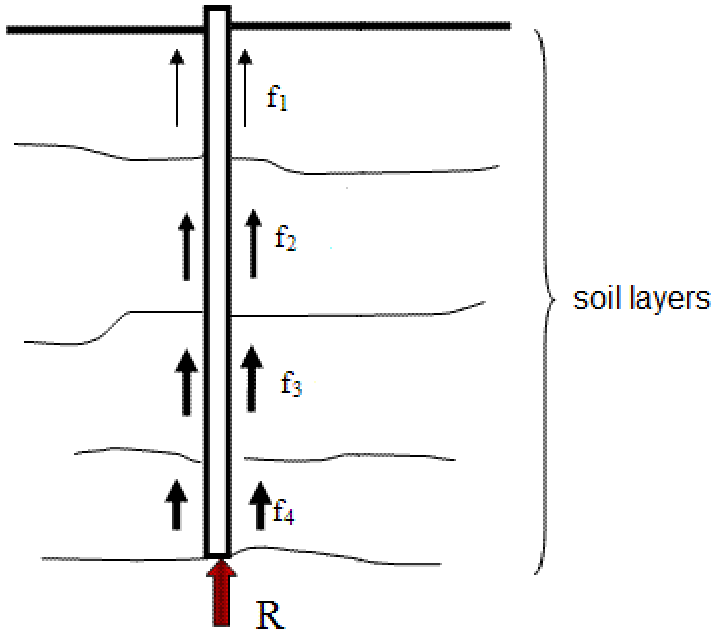
In end bearing piles, the bottom end of the pile rests on a layer of especially strong soil or rock. The load of the building is transferred through the pile onto the strong layer. End bearing piles include all kinds, supported by rocky grounds, and driven piles, in addition, on low-compressible (coarse clastic soils with sandy aggregate of medium density and dense, as well as clays of solid consistency in the water-saturated state with a strain modulus E> 50 MPa) belong to the pile columns. For end bearing piles, the friction along the side surface is not taken into account [10].

The friction pile transfers the load of the building to the soil across the full height of the pile, by friction. So the entire surface of the pile works to transfer the forces to the soil [4].

The friction piles are resting on compressible soils. Under the action of maximum effort, a friction pile receives vertical displacements sufficient to generate frictional forces between the pile and the ground.

For these piles, the load is transmitted both by the side surface of the pile and by its lower end. The bearing capacity of the friction pile is determined by the sum of the resistance of frictional forces along its lateral surface - f, and the resistance at the point –R (Figure 4).

Figure 4. Bearing capacity of the friction pile [4]



The construction of pile foundation is carried out in two stages. Initially, the placement of piles in a grill is made, the dimensions of the grillage are determined. Then, in the second stage, the load acting on the pile is refined and, if necessary, their length and section are changed. Further, following the principle of the design of foundations by the method of successive approximations, the piles are recalculated from 1, taking into account the changed efforts.

The designing of pile foundation begins with a preliminary determination of the dimensions of the grillage and the depth of foundation of the bottom of the grillage.

The depth of the foundation of the bottom of the grillage is assigned based on the following considerations:

- Estimated depth of freezing of soil of base;
- The dimensions of the grillage itself (the scheme of interface with the supra-foundation structure and the pile);
- When assigning the depth of foundation of the grillage are guided by the same considerations as when determining the depth of foundation of the basement foundations erected on a natural basis.

Calculation of the pile foundation begins with the compilation of a calculation scheme showing the geological section (ground column) with layer marks and also with indicating the consistency of clayey soils, the density of sands, the level of groundwater, the angle of internal friction, adhesion and the modulus of deformation of soils.

The choice of pile length should be assigned depending on ground conditions. On a geological basis it is necessary to estimate the layers of soil that the pile will cut through. It is necessary to assign a layer of soil to which the pile will be buried. A layer of soil is considered as a bearing layer in case it has good building properties. For homogeneous (compressible) soils, the length of the pile is assigned on the basis of the technical and economic comparison.

Hanging piles are buried into the densest layer of soil at 1.5-2.0 m (but not less than 0.5 m in case of coarse-grained, gravel, large and medium-sized sand, clay soils) and not Less than 1.0 m in other rocky soils.

Practice shows that when choosing the length of the pile, it is necessary to be guided by the following considerations: end bearing piles are effective at any length; friction piles are considered effective if their length is 2-3 times the width of the grillage.

Calculation of the bearing capacity of vertically loaded friction piles (friction piles) is usually made only by the strength of the soil, since the strength calculated by the pile material is always higher.

The calculation is carried out according to the first group of limiting states (by bearing capacity).

Pile foundations, bearing capacity F_d of a friction buried pile (square, square with a round cavity, rectangular and hollow, round with diameter up to 0.8 m) and a pile-shell that is not filled with concrete, both working on the compressing pile load, should be defined as the sum of the design resistances of the foundation soils under the lower end of the pile and on its lateral surface.

3 Initial data

The construction area is located in Saint-Petersburg, Russia. The dimensions of the 9-storey building in the axes are 57,96x15,0 m. The structural scheme of the building is a slab system with transverse bearing brick walls. The beginning of the foundation works is in June, in 2019.

Soil investigations were made by JSC “LenTISIZ” on the order of “Delta-te” company. JSC “LenTISIZ” performed the following works:

1. 4 wells were drilled by core boring. The wells are located on the perimeter of the future building;
2. 16 ground samples were taken for laboratory research;
3. Static sounding was made in 4 points on the perimeter of the future construction;
4. A technical report was performed on the basis of investigations [5].

Initial data was taken from the technical report [5].

Engineering survey data is shown on Table 1.

Table 1. Engineering survey data [5]

Well number	Well mark, m	Groundwater level, m	Thickness of soil layers, m			
			1	2	3	4
1	228,3	227,4	1,12	1,47	2,23	not defined
2	227,8	226,7	1,32	1,56	2,43	not defined
3	228,5	227,5	1,22	1,48	2,69	not defined
4	228,8	227,7	1,29	1,46	2,15	not defined
Thickness of a vegetative layer of a ground – 0,1 m						

Table 2 shows the physical properties of the soil in the construction site.

Table 2. Physical properties of the soil in the construction site [5]

Layer number	Layer name	Density, t/m³		Relative humidity		
		Natural	Solid particles	W_0	W_P	W_L
1	Sandy loam	1,682	2,189	15,3%	12,7%	18,5%
2	Small sandy soil	1,722	2,263	17,3%	-	-
3	Sandy loam	1,714	2,264	10,2%	6,9%	11,2%
4	Clay loam	1,711	2,341	12,7%	8,1%	21,2%

The average monthly temperatures for the year for Saint-Petersburg are shown in Table 3.

Table 3. The average monthly temperatures for the year [5]

Month	1	2	3	4	5	6	7	8	9	10	11	12
t°C	-7,8	-7,8	-3,9	3,1	9,8	15,0	17,8	16,0	10,9	4,9	-0,3	-5,0

4 Assessment of engineering and geological conditions of the construction site

4.1 Determination of mechanical soil characteristics

1. Density of dry soil: $\rho_d = \dfrac{\rho}{1+W}$, (1)

where ρ – natural density, *W* – soil moisture;

2. Coefficient of porosity: $e = \dfrac{\rho_s - \rho_d}{\rho_d}$, (2)

where ρ_s – density of soil particles, ρ_s – density of dry soil;

3. Degree of soil moisture: $S_r = \dfrac{W \cdot \rho_s}{e \cdot \rho_w}$; (3)

where *W* – soil moisture, ρ_s – density of dry soil, e – coefficient of porosity, ρ_w – water density;

4. Cohesion intercept (c), angle of internal friction (φ), module of general linear deformability of soil (E_0) were determined for each soil layer;

5. Designed soil resistance:

$$R_0 = \frac{\gamma_{C1}\gamma_{C2}}{k} II \left(M_\gamma b k_z \gamma_{II} + M_q \gamma'_{II} d_1 + \left(M_q - 1 \right) \gamma_{II} d_B + M_C c_{II} \right), \quad (4)$$

where γ_{C1} – coefficient of ground base work; γ_{C2} – coefficient of building work in interaction with the base; *k* – reliability coefficient; M_γ, M_q, M_c– empirical coefficients depended on the design value of the internal friction angle, *b* – minor side of the basement; γ'_{II} – averaged designed value of the specific gravity of the soil lying above the basement footprint; ; γ_{II} – averaged designed value of the specific gravity of the soil lying below the basement footprint; c_{II} – cohesion intercept; d_1 – basement depth.

6. Number of ductility: $I_p = W_l - W_p$, (5)

where W_l – soil moisture at the yield point; W_p – soil moisture at the rolling edge.

7. Liquidity index: $I_L = \frac{W - W_p}{I_p}$, (6)

where *W* – soil moisture; W_p – soil moisture at the rolling edge; I_p – number of ductility.

8. Specific gravity of the soil, taking into account the weighing action of water:

$$\gamma_{sb} = \frac{\gamma_s - \gamma_d}{1+e}, \quad (7)$$

where γ_s – specific gravity of the soil particles; γ_d – specific gravity of the dry soil.

In contrast to SP cohesion intercept (c), angle of internal friction (φ) are calculated by the formulas in Eurocode:

$$tg\varphi = (tg\varphi)_{mean}(1 - k_{n,mean}V_{tg\varphi}); \quad (8)$$

where $(tg\varphi)_{mean} = 0{,}603$ – mean value, $V_{tg\varphi} = 0{,}1$ – coefficient of variation;

$$c = c_{mean}(1 - k_{n,mean}V_c); \quad (9)$$

where $c_{mean} = 3{,}75$ – mean value, $V_c = 0{,}4$ – coefficient of variation.

The values of mechanical soil characteristics determined by SP are shown in Table 4.

Table 4. The values of mechanical soil characteristics

Soil characteristics		Layer name and number			
Layer name		1. Sandy loam	2. Small sandy soil	3. Sandy loam	4. Clay loam
Density	Natural (ρ, t/m^3)	1,682	1,722	1,714	1,711
	Soil particles (ρ_s, t/m^3)	2,189	2,263	2,264	2,341
Specific gravity of the soil (γ, kN/m^3)		16,484	16,876	16,797	16,768
Specific gravity of the soil particles (γ_s, kN/m^3)		21,452	22,177	22,187	22,942
Density of dry soil (ρ_d, t/m^3)		1,463	1,472	1,558	1,514
Specific gravity of the dry soil (γ_d, kN/m^3)		14,337	14,426	15,268	14,837
Coefficient of porosity (e)		0,496	0,537	0,453	0,546
Degree of humidity (S_r)		0,662	0,716	0,500	0,557
Soil deformation module (E, MPa)		28	38	32	25
Cohesion intercept (c, kPa)		17	4	19	34
Angle of internal friction φ, °		27	36	28	23
Designed soil resistance (R_0, kPa)		300	300	300	263,1
Number of ductility (I_p)		5,8%	-	4,3%	13,1%
Liquidity index (I_L)		0,448	-	0,767	0,351
Specific gravity of the soil (γ_{sb}, kN/m^3)		7,655	7,923	8,387	8,371

Values of mechanical soil characteristics determined by SP and Eurocode are the same. Only values of the cohesion intercept and angle of internal friction differ. The difference in these characteristics is negligible and shown in Table 5.

Table 5. Cohesion intercept and angle of internal friction determined by SP and Eurocode

Soil characteristics	Layer name and number			
Layer name	1. Sandy loam	2. Small sandy soil	3. Sandy loam	4. Clay loam
Cohesion intercept (SP\ Eurocode)	17 \ 16	4 \ 4	19 \ 19	34 \ 36
Angle of internal friction (SP \ Eurocode)	27 \ 27,5	36 \ 32	28 \ 29	23 \ 20

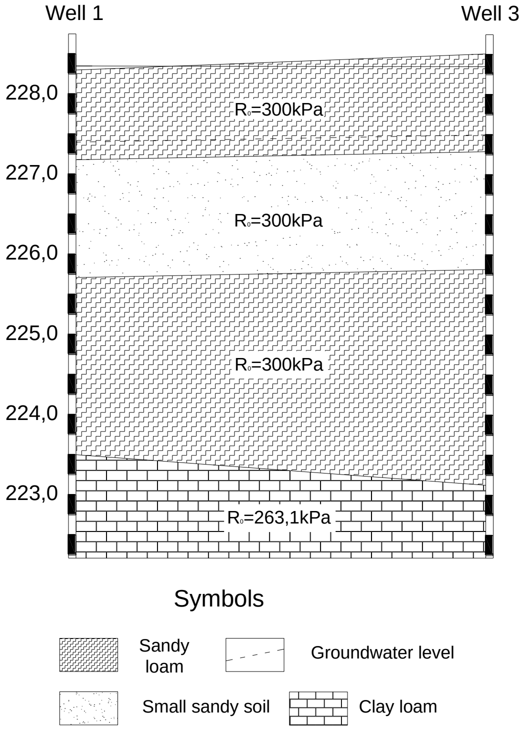
4.2 Drawing of engineering geological sections

The leveling height is calculated as the arithmetic average of the well marks:

$D_l = \Sigma H_{wellhead} / n_{wellhead} = (228,3+227,8+228,5+228,8)/4 = 228,35$ m.

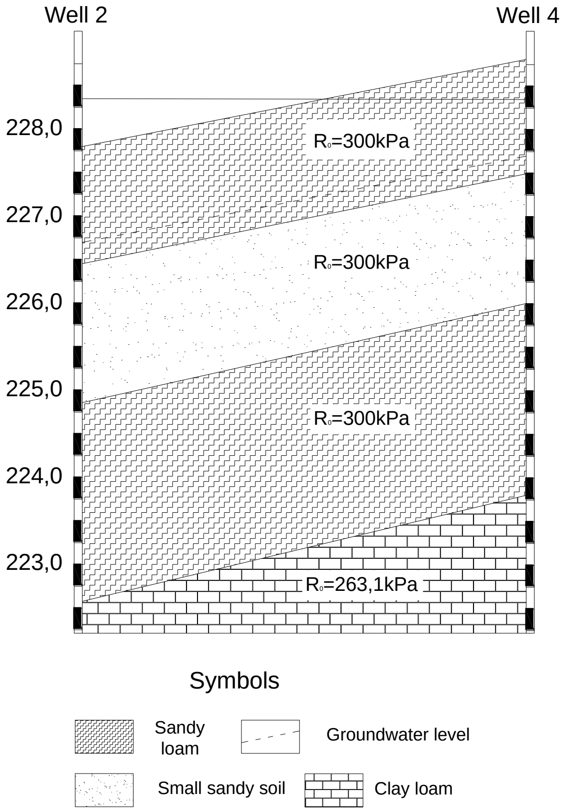
The upper soil layers are sandy loam and small sandy soil. They have similar mechanical characteristics and their designed soil resistances are the same. The geological section constructed on wells 1 and 3 is shown in Figure 3.

Figure 3. The geological section on wells 1 and 3



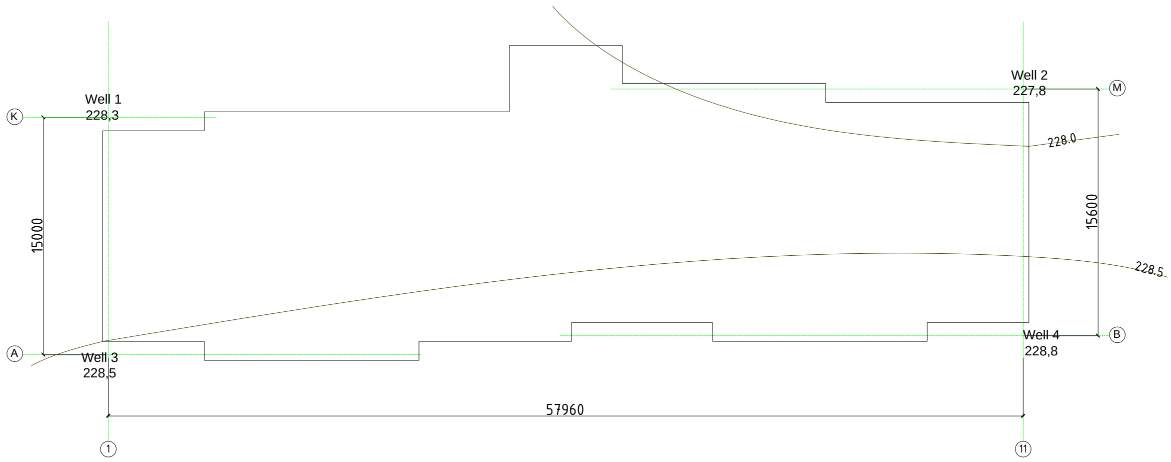
The geological section constructed on wells 2 and 4 is shown in Figure 4.

Figure 4. The geological section on wells 2 and 4



The situational plan with the mapped building and wells is shown in Figure 3. The building outline and axes with distance between them are represented in the figure. Also horizontals passing through the building and wells location with their elevation marks are marked on the plan.

Figure 5. The situational plan



5 Choosing the depth of foundation base

The normative depth of freezing is calculated by the formula:

$$d_{fn} = d\textasciicircum|M_t| \qquad (10)$$

where M_t =-8,1 is sum of average monthly negative temperatures for the winter period;

d_0 = 0,23 m, which depends on the type of soil.

$$d_{fn} = 0{,}23\textasciicircum|-8{,}1|=0{,}65 \text{ m.}$$

The designed depth of freezing is calculated by the formula:

$$d_f = k_h – d_{fn} \qquad (11)$$

where k_h = 0,9 is a coefficient which is taking into account the thermal influence of the building.

$$d_f = 0{,}9 – 0{,}65=0{,}25 \text{ m}$$

The depth of the foundation base is taken from constructive considerations equal to 0,7 m.

6 Load summary

6.1 Load summary in SP

Load calculations on the foundation are shown in Table 6.

Table 6. Load calculations

№	Type of load	Normative load value q_n, kPa	Load reliability coefficient γ_f	Designed load value q, kPa
1	Load from coatings			
	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,2	3,73
	Rockwool slab δ =20 mm (ρ=3,5 kg/m^3)	0,7	1,2	0,84
	Cement-sand grout δ = 20 mm (ρ = 30 kg/m^3)	0,36	1,1	0,40
	4 layers of ruberoid δ =20 mm (ρ=0,3 kg/m^3)	0,006	1,2	0,0072
	Live load:			
	Snow load	1,71	0,7	1,20
	Total:	5,87		6,18
2	Load from floor slabs			
	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,2	3,73
	XPS insulation δ = 0.05 m (ρ = 3.5 kg/m^3)	0,18	1,2	0,22
	Cement-sand grout δ = 20 mm (ρ = 18 kg/m^3)	0,36	1,3	0,47
	Linoleum δ = 0.005 m, (ρ = 18 kg/m^3)	0,09	1,2	0,11
	Partitions load	0,5	1,2	0,60
	Live load:			
	Load from people and equipment	1,5	1,2	1,80
	Total:	5,74		6,93
3	Load from the 1st floor slabs			
	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,2	3,73
	XPS insulation δ = 0.05 m (ρ = 3.5 kg/m^3)	0,18	1,2	0,22

	Cement-sand grout δ = 20 mm (ρ = 18 kg/m^3)	0,36	1,3	0,47
	Linoleum δ = 0.005 m, (ρ = 18 kg/m^3)	0,09	1,2	0,11
	Bitumen δ = 0.005 m, (ρ = 14 kg/m^3)	0,07	1,3	0,09
	Partitions load	0,5	1,2	0,60
	Live load:			
	Load from people and equipment	1,5	1,2	1,80
	Total:	5,81		7,02

Load per meter of the foundation along the axis K is calculated by the formulas:

$$N_{n1} = (\sum q)S_{la} + G_{ow} \qquad (12)$$

$$N_1 = (\sum q)S_{la} + G_{ow} \cdot \gamma_f \qquad (13)$$

where S_{la} is a load area, G_{ow} – own weight of the foundation.

N_{n1}=(5,87+5,74·8+5,81) 3,3+173,5=452,06 kN/m.

N_1=(6,18+6,93·8+7,02) 3,3+173,5·1,3=452,06 kN/m.

Load per meter of the foundation along the axis E is calculated by the formula:

N_{n2}=(5,87+5,74·8+5,81) 4,7+173,5=444.22 kN/m.

N_2=(6,18+6,93·8+7,02) 4,7+173,5·1,3=548,16 kN/m.

Foundation along the axis 1 is not load bearing. So load of the foundation is equal to its own weight:

N_{n3}=173,5 kN/m.

N_3=173,5·1,3=225,55 kN/m.

6.2 Load summary in Eurocode

The characteristic values of actions must be derived using the principles of EN 1990. The values of the actions from the structure must be taken from EN 1991. Actions may be loads applied to the structure or to the soil. Loads may be permanent (e.g. self-weight of structures or soil), variable (e.g. imposed loads on building floors) or accidental (e.g. impact loads). An important principle when dealing with actions is the ‘single-source principle’. This principle states that, if permanent actions arising from the same physical source act simultaneously both favourably and unfavourably, a single factor may be applied to the sum of these actions or to the effect of them [6].

Load reliability coefficients for dead and live loads were taken from Table A 1.3 of the National annex [7] $\gamma_G = 1{,}35$, $\gamma_Q = 1{,}5$. When working in a combination of dead load and live load, the coefficient ξ=0,85 is introduced in accordance with [1,2]. The overall value of the load reliability factor is:

$$\xi \cdot \gamma_G = 0{,}85 \cdot 1{,}35 = 1{,}15$$

Load calculations on the foundation are shown in Table 7.

Table 7. Load calculations

№	Type of load	Normative load value q_n, kPa	Load reliability coefficient γ_G, γ_Q	Designed load value q, kPa
1	Load from coatings			
	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,15	3,58
	Rockwool slab δ =20 mm (ρ=3,5 kg/m^3)	0,7	1,15	0,81
	Cement-sand grout δ = 20 mm (ρ = 30 kg/m^3)	0,36	1,15	0,41
	4 layers of ruberoid δ =20 mm (ρ=0,3 kg/m^3)	0,006	1,15	0,0069
	Live load:			
	Snow load	1,92	1,5	2,88
	Total:	6,10		7,68
2	Load from floor slabs			

	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,15	3,58
	XPS insulation δ = 0.05 m (ρ = 3.5 kg/m^3)	0,18	1,15	0,21
	Cement-sand grout δ = 20 mm (ρ = 18 kg/m^3)	0,36	1,15	0,41
	Linoleum δ = 0.005m, (ρ = 18 kg/m^3)	0,09	1,15	0,10
	Partitions load	0,5	1,15	0,58
	Live load:			
	Load from people and equipment	1,5	1,5	2,25
	Total:	5,74		7,13
3	Load from the 1st floor slabs			
	Dead load:			
	Reinforced concrete slab δ = 0.22 m (ρ = 1415 kg/m^3)	3,11	1,15	3,58
	XPS insulation δ = 0.05 m (ρ = 3.5 kg/m^3)	0,18	1,15	0,21
	Cement-sand grout δ = 20 mm (ρ = 18 kg/m^3)	0,36	1,15	0,41
	Linoleum δ = 0.005 m, (ρ = 18 kg/m^3)	0,09	1,15	0,10
	Bitumen δ = 0.005 m, (ρ = 14 kg/m^3)	0,07	1,15	0,081
	Partitions load	0,5	1,15	0,58
	Live load:			
	Load from people and equipment	1,5	1,5	2,25
	Total:	5,81		7,21

Accidental loads are not taken into account due to their absence.

7 Shallow foundation calculation

7.1 Calculation by SP

7.1.1 Determination of the foundation base width along the axis K

The width of the foundation base is defined by approximation method:

$$A = \frac{N_n}{R_0 - \gamma_{sf} \cdot d} = \frac{360,68}{300 - 22 \cdot 0,7} = 1,3\ m$$

The width of the foundation base is assumed equal to 1,4 m.

Footing sizes are preliminary accepted by 1,4 x 2,38 x 0,4 m. Foundation sizes are preliminary accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

The average pressure below the foundation base (p) should not exceed the design resistance of the soil of the base (R, kPa) determined by formula (4):

$$R = \frac{1,3 \cdot 1,1}{1,1}(0,91 \cdot 1 \cdot 1,4 \cdot 15,9 + 4,64 \cdot 0,7 \cdot 16,48 + 7,14 \cdot 17) = 253,71\ kPa$$

Strength state condition is determined by the formula:

$$P=(N_n+G_{la}+G_f)/A<R \qquad (14)$$

P=(363,58+2,77+13,64)/1,4=271,42 kPa > R=253,71 kPa.

The strength condition is not performed. Therefore the width of the foundation base is increased to 1,6 m.

P=(363,58+2,77+13,64)/1,6=237,49 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is calculated by the formula:

((R-P)/R)*100%=((253,71-237,49)/253,71)*100%=6,4%

The width of the foundation base is increased to 1,8 m.

P=(363,58+2,77+13,64)/1,8=211,11 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is equal:

((R-P)/R)*100%=((253,71-211,11)/253,71)*100%=16,8%

Thus footing sizes is accepted by 1,8 x 2,38 x 0,4 m. And foundation sizes is accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

7.1.2 Determination of the foundation base width along the axis E

The width of the foundation base is defined by approximation method:

$$\mathrm{A} = \frac{N_n}{R_0 - \gamma_{sf} \cdot d} = \frac{444{,}22}{300 - 22 \cdot 0{,}7} = 1{,}56\ m$$

The width of the foundation base is assumed equal to 1,6 m.

Footing sizes are preliminary accepted by 1,6 x 2,38 x 0,4 m. Foundation sizes are preliminary accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

The average pressure below the foundation base (p) should not exceed the design resistance of the soil of the base (R, kPa) determined by formula (4):

$$R = \frac{1{,}3 \cdot 1{,}1}{1{,}1}(0{,}91 \cdot 1 \cdot 1{,}4 \cdot 15{,}9 + 4{,}64 \cdot 0{,}7 \cdot 7{,}7 + 7{,}14 \cdot 17) = 253{,}71\ kPa$$

Strength state condition is determined by the formula:

P=(444,22+2,77+13,64)/1,6=287,89 kPa > R=253,71 kPa.

The strength condition is not performed. Therefore the width of the foundation base is increased to 1,8 m.

P=(444,22+2,77+13,64)/1,8=255,91 kPa > R=253,71 kPa.

The strength condition is not performed. Therefore the width of the foundation base is increased to 2,0 m.

P=(444,22+2,77+13,64)/2,0=230,32 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is calculated by the formula:

((R-P)/R)*100%=((253,71-230,32)/253,71)*100%=9,2%

The width of the foundation base is increased to 2,2 m.

P=(444,22+2,77+13,64)/2,2=209,4 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is equal:

((R-P)/R)*100%=((253,71-209,4)/253,71)*100%=17,5%

Thus footing sizes is accepted by 2,2 x 2,38 x 0,4 m and 2,2 x 1,38 x 0,4 m. And foundation sizes is accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

7.1.3 Determination of the foundation base width along the axis 1

The width of the foundation base is defined by approximation method:

$$\mathrm{A} = \frac{N_n}{R_0 - \gamma_{sf} \cdot d} = \frac{173{,}5}{300 - 22 \cdot 0{,}7} = 0{,}6\ m$$

The width of the foundation base is assumed equal to 0,6 m.

Footing sizes are preliminary accepted by 0,6 x 2,38 x 0,4 m. Foundation sizes are preliminary accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

The average pressure below the foundation base (p) should not exceed the design resistance of the soil of the base (R, kPa) determined by formula (4):

$$R = \frac{1{,}3 \cdot 1{,}1}{1{,}1}(0{,}91 \cdot 1 \cdot 1{,}4 \cdot 15{,}9 + 4{,}64 \cdot 0{,}7 \cdot 7{,}7 + 7{,}14 \cdot 17) = 253{,}71\ kPa$$

Strength state condition is determined by the formula:

P=(173,5+2,77+13,64)/0,6=316,52 kPa > R=253,71 kPa.

The strength condition is not performed. Therefore the width of the foundation base is increased to 0,8 m.

P=(173,5+2,77+13,64)/0,8=237,79 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is calculated by the formula:

((R-P)/R)*100%=((253,71-237,79)/253,71)*100%=6,4%

The width of the foundation base is increased to 1,0 m.

P=(173,5+2,77+13,64)/1,0=189,91 kPa < R=253,71 kPa.

The strength condition is performed. Margin of safety is equal:

$$((R-P)/R)*100\%=((253{,}71-189{,}91)/253{,}71)*100\%=25{,}1\%$$

Thus footing sizes is accepted by 1,0 x 2,38 x 0,4 m. And foundation sizes is accepted by 2,38 x 0,58 x 0,5 m and 1,18 x 0,58 x 0,5 m.

7.1.4 Sediments calculation by the method of layerwise summation

Sediments are calculated by the formula:

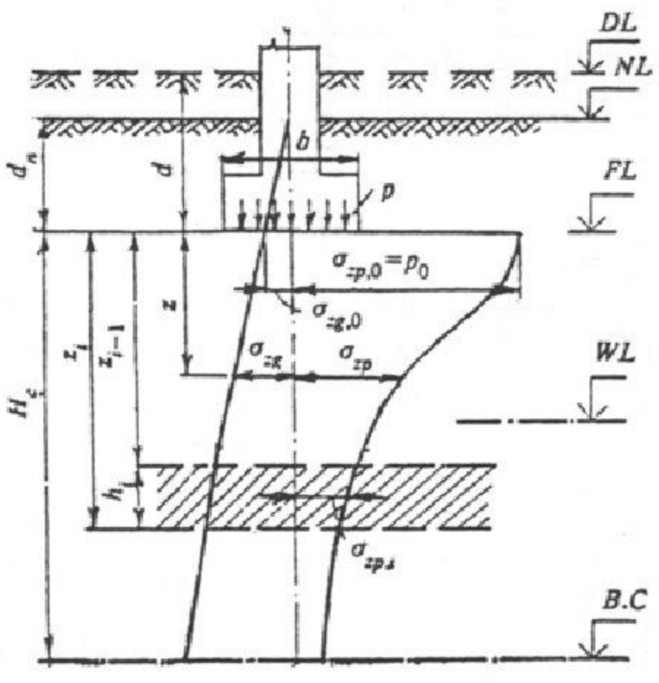
$$S = 0{,}8\sum\frac{\sigma_{zpi}\cdot h_i}{E_{0i}} \leq S_u \qquad (15)$$

where h_i is thickness of layer i;

E_{0i} is module of general linear deformability of layer i.

The scheme of vertical stresses distribution is shown on Figure 5.

Figure 5. The scheme of vertical stresses distribution



where DL – designed layout; NL – natural relief layout; FL – foundation base layout; WL – groundwater layout; BC – lower boundary of the compressible layer; d – foundation depth from designed layout; d_n – foundation depth from natural relief layout; p –average pressure below the foundation base; p_0 – additional pressure below the foundation base; σ_{zg} – additional vertical stress from external load at a depth z from the foundation base; $\sigma_{zg,0}$ – additional vertical stress from external load on the foundation base; σ_{zp} – additional vertical stress from external load at a depth z from the foundation base; $\sigma_{zp,0}$ – additional vertical stress from external load on the foundation base; H_c – depth of the compressible layer.

Settlements are calculated until $\sigma_{zp} \leq 0,2\sigma_{zg}$.

Settlements calculation along the axes K and E is shown on Tables 8-9.

Table 8. Settlements calculation along the axis K

Layer name	z, m	ξ=2z/b	α	σ_{zp}, kPa	σ_{zg}, kPa	$0,2\sigma_{zg}$	E, kPa	S_i, mm
Sandy loam	0	0	1	199,57	11,54	2,31	28	0
	0,3	0,86	0,807	157,07	16,48	3,3	28	1,06
	0,42	1,2	0,644	124,07	18,46	3,7	28	0,43
Small sandy soil	0,72	2,06	0,366	68,66	23,52	4,7	38	0,43
	1,02	2,9	0,233	42,53	28,58	5,7	38	0,27
	1,32	3,8	0,149	26,44	33,64	6,7	38	0,17
	1,62	4,6	0,1065	18,36	38,7	7,7	38	0,12
	1,79	5,1	0,087	14,75	41,57	8,3	38	0,05
Sandy loam	2,09	6,0	0,064	10,53	46,61	9,32	32	0,08
	2,39	6,8	0,050	7,97	51,65	10,33	32	0,06

Table 9. Settlements calculation along the axis E

Layer name	z, m	ξ=2z/b	α	σ_{zp}, kPa	σ_{zg}, kPa	$0,2\sigma_{zg}$	E, kPa	S_i, mm
Sandy loam	0	0	1	197,86	11,54	2,31	28	0
	0,3	0,86	0,807	155,69	16,48	3,3	28	1,33
	0,42	1,2	0,644	122,97	18,46	3,7	28	0,42
Small sandy soil	0,72	2,06	0,366	68,03	23,52	4,7	38	0,43
	1,02	2,9	0,233	42,13	28,58	5,7	38	0,27
	1,32	3,8	0,149	26,19	33,64	6,7	38	0,17
	1,62	4,6	0,1065	18,18	38,7	7,7	38	0,12
	1,79	5,1	0,087	14,6	41,57	8,3	38	0,05
Sandy loam	2,09	6,0	0,064	10,42	46,61	9,32	32	0,08
	2,39	6,8	0,050	7,89	51,65	10,33	32	0,06

7.2 Calculation by Eurocode

The design bearing resistance may be calculated from [1]:

$$R/A' = (\pi + 2)c_u b_c s_c i_c + q \quad (16)$$

where $A' = B' \cdot L'$ – the design effective foundation area; q – overburden or surcharge pressure at the level of the foundation base; b_c – the inclination of the foundation base; s_c – the shape of the foundation; i_c – the inclination of the load, caused by a horizontal load *H*.

The inclination of the foundation base is calculated by the formula [1]:

$$b_c = 1 - 2\alpha/(\pi + 2) \quad (17)$$

where α – the inclination of the foundation base to the horizontal.

The shape of the foundation for rectangular shape is calculated by the formula [1]:

$$s_c = 1 + 0{,}2(B'/L') \quad (18)$$

where B'– the effective foundation width; L' – the effective foundation length.

Foundation width is determined by the formula [1]:

$$B = \frac{E_{d1}}{R_0 - \gamma_{sf} \cdot d} \quad (19)$$

where E_{d1} – normative value of the effects of all the actions; γ_{sf} – averaged value of the specific gravity of foundation materials and ground loads, $\gamma_{sf} = 22\ kN/m^3$; d – foundation depth, $d = 0{,}7\ m$.

The normative value of the effects of all the actions is calculated by the formula [1]:

$$E_{d1} = (\sum q_n)A + G \quad (20)$$

where $\sum q_n$ – sum of normative load values; A– foundation area; G – own weight.

The inclination of the load, caused by a horizontal load *H* is evaluated by the formula:

$$i_c = \frac{1}{2}(1 + \sqrt{1 - \frac{H}{A\prime \cdot c_u}} \quad (21)$$

where c_u – soil strength in undrained conditions. It is calculated by the formula:

$$c_u = c \cdot \frac{cos\varphi}{1-\frac{1}{3}sin\varphi} + \sigma_0 \frac{sin\varphi}{1-\frac{1}{3}sin\varphi} \quad (22)$$

where $\sigma_0 = \frac{1}{3}\left(\sigma_{z,rp} + 2\sigma_{x,rp}\right)$; $\sigma_{z,rp} = \gamma_{sb} = 7{,}655$; $\sigma_{x,rp} = \frac{\nu}{1-\nu} \cdot \sigma_{z,rp}$; ν – Poisson's coefficient, for sandy loam $\nu = 0{,}3$.

The inequality (23) must be satisfied during for limit states of failure or excessive deformation in the ground [1]:

$$E_d \leq R \quad (23)$$

Where R – design value of the corresponding resistance of the ground calculated by formula 16; E_d – design value of the effects of all the actions.

The design value of the effects of all the actions is determined by the formula [1]:

$$E_d = (\sum q_n)A + G \cdot \gamma_G \quad (24)$$

where γ_G – exposure coefficient, $\gamma_G = 1{,}15$.

7.2.1 Calculation of the foundation base along the axis K

Normative value of the effects of all the actions:

$$E_{d1} = (6{,}1 + 5{,}74 \cdot 8 + 5{,}81) \cdot 3{,}3 + 173{,}5 = 364{,}34\ kN$$

Design value of the effects of all the actions:

$$E_d = (7{,}68 + 7{,}13 \cdot 8 + 7{,}21) \cdot 3{,}3 + 173{,}5 \cdot 1{,}15 = 436{,}89\ kN$$

Foundation width:

$$B = \frac{364{,}34}{300 - 22 \cdot 0{,}7} = 1{,}28\ m$$

Effective foundation width and length are determined from the calculated length: $B' = 1{,}4\ m$, $L' = 2{,}4\ m$.

The design effective foundation area:

$$A' = 1{,}4 \cdot 2{,}4 = 3{,}36\ m^2$$

The shape of the foundation:

$$s_c = 1 + 0{,}2(1{,}4/2{,}4) = 1{,}12$$

As $\alpha = 0°$ so $b_c = 1$.

Values for determining soil strength in undrained conditions:

$$\sigma_{x,rp} = \frac{0{,}3}{1-0{,}3} \cdot 7{,}655 = 3{,}28\ kPa$$

$$\sigma_0 = \frac{1}{3}(7{,}655 + 2 \cdot 3{,}28) = 4{,}74\ kPa$$

Soil strength in undrained conditions:

$$c_u = 16 \cdot \frac{cos27{,}5°}{1 - \frac{1}{3}sin27{,}5°} + 4{,}74 \frac{sin27{,}5°}{1 - \frac{1}{3}sin27{,}5°} = 19{,}36\ kPa$$

The inclination of the load, caused by a horizontal load:

$$i_c = \frac{1}{2}(1 + \sqrt{1 - \frac{60}{3{,}36 \cdot 19{,}36}} = 0{,}64$$

Design value of the corresponding resistance of the ground:

$$R = A'\big((\pi+2)c_u b_c s_c i_c + q\big) = 3{,}36 \cdot \big((\pi+2) \cdot 19{,}36 \cdot 1 \cdot 1{,}12 \cdot 0{,}64 + 71{,}93\big) = 481{,}42\ kN$$

$E_d = 436{,}89 \leq 481{,}42 = R$ so the inequality (23) is satisfied.

7.2.2 Calculation of the foundation base along the axis E

Normative value of the effects of all the actions:

$$E_{d1} = (6,1 + 5,74 \cdot 8 + 5,81) \cdot 4,7 + 173,5 = 445,3\ kN$$

Design value of the effects of all the actions:

$$E_d = (7,68 + 7,13 \cdot 8 + 7,21) \cdot 4,7 + 173,5 \cdot 1,15 = 537,6\ kN$$

Foundation width:

$$B = \frac{445,3}{300 - 22 \cdot 0,7} = 1,56\ m$$

Effective foundation width and length are determined from the calculated length: $B' = 1,6\ m$, $L' = 2,4\ m$.

The design effective foundation area:

$$A' = 1,6 \cdot 2,4 = 3,84\ m^2$$

The shape of the foundation:

$$s_c = 1 + 0,2(1,6/2,4) = 1,13$$

The inclination of the load, caused by a horizontal load:

$$i_c = \frac{1}{2}(1 + \sqrt{1 - \frac{60}{3,84 \cdot 19,36}} = 0,62$$

Design value of the corresponding resistance of the ground:

$$R = 3,84 \cdot \big((\pi + 2) \cdot 19,36 \cdot 1 \cdot 1,13 \cdot 0,62 + 71,93\big) = 544,01\ kN$$

$E_d = 537,6 \leq 544,01 = R$ so the inequality (23) is satisfied.

7.2.3 Calculation of the foundation base along the axis 1

Normative value of the effects of all the actions:

$$E_{d1} = 0 + 173{,}5 = 173{,}5\ kN$$

Design value of the effects of all the actions:

$$E_d = 0 + 173{,}5 \cdot 1{,}15 = 199{,}53\ kN$$

Foundation width:

$$B = \frac{173{,}5}{300 - 22 \cdot 0{,}7} = 0{,}6\ m$$

Effective foundation width and length are determined from the calculated length: $B' = 0{,}6\ m$, $L' = 2{,}4\ m$.

The design effective foundation area:

$$A' = 0{,}6 \cdot 2{,}4 = 1{,}44\ m^2$$

The shape of the foundation:

$$s_c = 1 + 0{,}2(0{,}6/2{,}4) = 1{,}05$$

The inclination of the load, caused by a horizontal load:

$$i_c = \frac{1}{2}(1 + \sqrt{1 - \frac{20}{1{,}44 \cdot 19{,}36}} = 1{,}16$$

Design value of the corresponding resistance of the ground:

$$R = 1{,}44 \cdot \left((\pi + 2) \cdot 19{,}36 \cdot 1 \cdot 1{,}05 \cdot 1{,}16 + 0\right) = 174{,}6\ kN$$

$E_d = 173{,}5 \leq 174{,}6 = R$ so the inequality (23) is satisfied.

$$173{,}5 \leq 174{,}6$$

7.2.4 Settlements calculation

The short-term components of settlement of a foundation, which occur without drainage, was evaluated using the adjusted elasticity method. The values adopted for the stiffness parameters (such as E_m and Poisson's ratio) should in this case represent the undrained behavior [1].

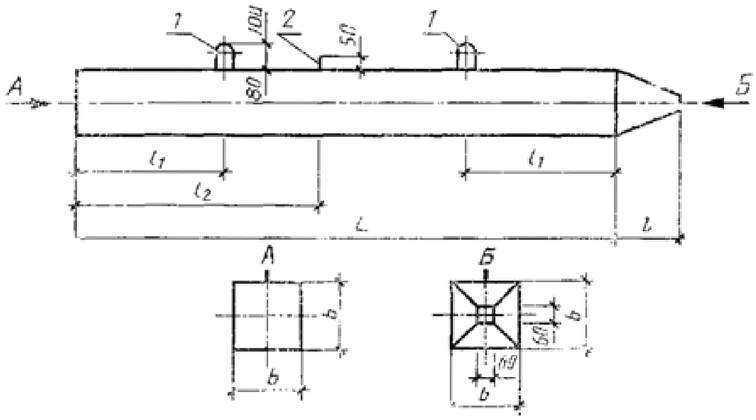
The method of determining settlements in SP is based on the adjusted elasticity method, which is used in Eurocode. Thus settlements determined by SP are equal to the settlements determined by Eurocode.

8 Pile foundation calculation

Clay loam (the 4-th layer) is accepted for the pile foundation. Piles are driven without soil excavating at 1,0 m deeper than the surface of the 4th layer. The length of piles is equal: L = 1,12+1,47+2,23+1,0 =5,82m.

A friction pile of solid square section with longitudinal stressed reinforcement is used. The schematic drawing of the pile is shown on Figure 6.

Figure 6. Schematic pile drawing



where 1 – lifting loops; 2 – pin for fixing the place of stropping.

Accepted pile mark is C6-30 (L= 6 m; l =0,25 m; h= 0,9 m; b =0,3 m; weight – 1380 kg).

The width of grillage is more than pile width on 200 mm. So grillage width is 0,5 m. The height of grilage is accepted 0,5 m. Own grillage weight is $G_{p.gr.}$ = 0,5m • 0,5m • 24kN/m^3 = 6kN/m.

The bearing capacity of the grillage is calculated by the formula:

$$F_d = \gamma_c\ (\gamma_{cr} \bullet R \bullet A + U\sum(\gamma_{cp} \cdot f_i \cdot h_i)); \qquad (25)$$

where $\gamma_c = 1$ is working conditions coefficient;

$\gamma_{cr} = 1$ is working conditions coefficient under the bottom of the pile;

$R = 2100$ kN/m^2 is design resistance of the soil under the pile bottom;

$A = 0{,}09$ m^2 is cross-sectional area of the pile;

$U = 1{,}2$ m is perimeter of the pile;

$\gamma_{cp} = 1$ is working conditions coefficient on the side surface of the pile;

f_i is intensity of the friction force on the side surface of the pile. It is determined for each soil layer. $F_1 = 15{,}5$ kPa; $f_2 =38{,}1$ kPa; $f_3 =8{,}17$ kPa; $f_4 =35{,}5$ kPa.

$$F_d = 1 \bullet (1 \bullet 2100 \bullet 0{,}09+1{,}2(1 \bullet 1{,}2 \cdot 15{,}5+1 \cdot 1{,}49 \bullet 38{,}1+1 \cdot 2{,}38 \bullet 8{,}17+1 \cdot 1{,}0 \cdot 35{,}5)) =345{,}38 \text{ kN}$$

The required pile step along the axis E is calculated by the formula:

$$A=(m_0 \cdot P)/N_{II}=2 \cdot 246{,}7/(548{,}16+6{,}0)=0{,}9 \qquad (26)$$

The pile step is assumed equal to 0,9 m. The number of piles under the wall along axis E is 29.

The required pile step along the axis 1 is calculated by the formula (26):

$$A=\cdot 246{,}7/(225{,}55+6{,}0)=1{,}06$$

The pile step is assumed equal to 1,0 m. Number of piles under the wall along axis 1 is 12.

8.1 Strength check of the soil under the pile bottom

Strength check is carried out on the most loaded section E-E. The pile foundation is reduced to the strip foundation which is equivalent in terms of the effect on the ground. The average angle of internal friction is

$\varphi_{II,mt}=\sum(\varphi_{II}\cdot h_i)/\sum hi=(27\cdot1,12+36\cdot1,47+28\cdot2,23+23\cdot1,0)/(1,12+1,47+2,23+1,0)=28,97°$

The angle of stress dissipation is $\alpha=\varphi_{II,mt}/4=28,97°/4=7,2°$.

The width of the equivalent foundation is equal:

$$B_{eq} = 2tg\alpha\cdot l_p+0,2+b_p = 2tg\alpha\cdot l_p+b_{p.gr.} = 2tg7,2\cdot6,0+0,5=2,02\text{ m.}$$

The design resistance of the soil of the base is calculate by formula (4):

$$R=\frac{1,3\cdot1,1}{1,1}\left[1,06\cdot1\cdot0,3\cdot16,77+5,25\cdot6,0\cdot15,03+7,67\cdot34\right]=961,43kPa$$

Strength state condition is determined by the formula (6):

P=(554,16+6,0+43,2+96,7)/2,02*1=346,56<R=961,43

The strength condition is performed. The margin of safety is calculated by the formula:

((R-P)/R)*100%=((961,43-346,56)/961,43)*100%=64%.

8.2 Sediments calculation by the method of layerwise summation

Sediments are calculated by the formula (15). The scheme of vertical stresses distribution is shown on figure (5). Settlements are calculated until $\sigma_{zp}\leq0,2\sigma_{zg}$.

Settlements calculation along axis E is shown on Table 10.

Table 10. Settlements calculation along the axis E

Layer name	z, m	ξ=2z/b	α	σ_{zp},kPa	σ_{zg}, kPa	0,2σ_{zg}	E, kPa	S_i,mm
Clay loam	0	0	1	256,38	90,18	18,04	25	0
	0,8	0,8	0,881	214,05	103,6	20,72	25	5,48
	1,6	1,6	0,642	147,36	117,02	23,4	25	3,77
	2,4	2,4	0,477	103,09	130,44	26,09	25	2,64
	3,2	3,2	0,374	75,8	143,86	28,77	25	1,94
	4,0	4,0	0,306	57,92	157,28	31,46	25	1,48
	4,8	4,8	0,258	45,39	170,62	34,12	25	1,16
	5,6	5,6	0,223	36,24	184,04	36,81	25	0,93

9 Feasibility study of foundation options

Cost calculations on the construction of strip and pile foundation are shown in Table 11.

Table 11. Cost calculations

Name of works	Unit of measurementt	Amount	The cost of unit	Total cost
1	2	3	4	5
Strip foundation				
1. Removal of the existing subgrade	1000 m^2	0,87	26,79	23,3
2. Earthwork with truck loading and removal	1000 m^3	0,61	4790,65	2922,3
3. Soil development to the dump	1000 m^3	0,14	6033,18	844,65
4. Back filling	1000 m^3	0,14	635,07	88,91
5. Earth compacting	1000 m^3	0,14	742,06	103,89
6. Slabs placement	100 p.	6,0	912,43	5474,58
7. Waterproofing	100 m^2	2,05	368,26	754,93
The total cost for strip foundation is 10 212,56 rub.				
Pile foundation				
1. Removal of the existing subgrade	1000 m^2	0,87	26,79	23,3
2. Earthwork with truck loading and removal	1000 m^3	0,024	4790,65	114,98
3. Soil development to the dump	1000 m^3	0,034	6033,18	205,13
4. Back filling	1000 m^3	0,034	635,07	21,59
5. Earth compacting	1000 m^3	0,034	742,06	25,23
6. Waterproofing	100 m^2	4,2	368,26	1546,69
7. Pile driving	1 m^3	86,4	464,40	40124,16
8. Pile grating production	100 m^3	2,7	57787,79	1560fdd27,03
The total cost for pile foundation is 198 088,11 rub.				

Thus pile foundation is more expensive. So the strip foundation is adopted.

10 Conclusion

The choice of the most optimal constructive design of a foundation is usually carried out by means of a technical and economic comparison of the options for constructing foundations for the following indicators: economic efficiency, material intensity, the need to perform work in a short time, the values of the maximum sediments and unevenness of precipitation, the possibility of performing the works in the winter, etc.

In Eurocode 7 and SP 24.13330.2011 there are similarities of the provisions in geotechnical design by limiting states using partial reliability coefficients. But, despite of the existing general principles and calculations, the design results remain different. Direct use of European norms without taking into account Russia's national characteristics can be irrational and can lead to unpleasant consequences.

Soil characteristics, shallow foundations and settlements were calculated by both norms. Differences in the received calculations are insignificant. Options with shallow and pile foundations were calculated. Arrangements of these foundations in the soil are shown in Appendix 1. The feasibility study of the designed foundation showed that the most optimal option is an application of the strip foundation. Also the plan and sections of shallow foundations were made. Drawings are shown in Appendices 2-4.

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