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MULTI-STOREYED BUILDING SLAB FOUNDATION SETTLEMENT

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Abstract

The purpose of this article is to consider slab (raft) foundation settlement of multi-storey buildings, to analyse their occurrence and development, and to propose methods and recommendations for their prevention or minimisation. The article considers engineering-geological conditions typical for the Brest south-west microdistrict-1, and proposes a method of levelling uneven deformations of the slab (raft) foundation base.

Keywords: foundation base, foundation settlement, stress-strain state, relative settlement difference, deformation modulus, central and peripheral zones.

ОСАДКИ ПЛИТНЫХ ФУНДАМЕНТОВ МНОГОЭТАЖНЫХ ЗДАНИЙ

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Реферат

Целью данной статьи является рассмотрение осадок плитных фундаментов многоэтажных зданий, анализ их возникновения и развития, а также предложение методов и рекомендаций по их предотвращению или минимизации. В статье рассмотрены инженерно-геологические условия, характерные для ЮЗМР-1 г. Бреста, а также предложен способ выравнивания неравномерных деформаций основания плитного фундамента.

Ключевые слова: основание фундаментов, осадки фундаментов, напряженно-деформированное состояние, относительная разность осадок, модуль деформации, центральная и периферийная зоны.

Introduction

Currently there is an intensive construction of residential multi-storey buildings in the Brest south-west microdistrict-1. The territory of the microdistrict is a wasteland overgrown with shrubs. The landform of the area is flat, the absolute level of which varies from *133.28 m* to *133.98 m*. The geological structure of the territory includes soil formations represented by a vegetation layer with a thickness from *0.1* to *0.4 m*; alluvial and lake-marsh deposits represented by sands of different coarseness: from dusty to medium; sandy loam and loam – weak and medium strength, including weakly peat-covered, with a thickness of up to *1.4 m*; peat and medium peat-covered soils with a thickness of up to *1.0 m*. Beneath alluvial and lake-marsh sediments, lake-alluvial sediments were uncovered, represented by interlaced sands of various sizes from dusty to coarse, sandy loam and loam with plastic, soft-plastic and flowing.

Ground waters are found at a depth of *0.1 – 1.0 m* from the day surface, or at absolute levels of *132.28 – 133.27 m*, their maximum predicted level (according to JSC "Brestproekt") should be taken at the level of *134.5 m* [1].

Taking into account the geological structure of construction sites, when designing the foundations of multi-storey buildings, the characteristics of foundation soils are assumed to be equal to those given in Table 1.

Shallow foundations and driven pile foundations were considered in the option design.

The main variant of foundations for large-panel buildings of different number of storeys (from *5* to *9* storeys) is a solid reinforced concrete slab for the whole building with a height of *500 mm*. The main specificity of this variant is that the soil formations, peats, marshy soils, as well as weak sandy and clayey soils, which cannot be used as foundations without their removal, compaction or consolidation, are embedded from the surface of the site up to the *131.640 m* mark. Taking these factors into account, as well as the adopted depth of the foundation footings, it was necessary to install the sand and gravel pad over the entire thickness of these soils, up to the foundation footing mark. The sand and gravel cushion was poured in layers of *0.2 – 0.3 m* thickness with subsequent compaction of each layer by rollers up to the compaction coefficient K_{com} = *0.95*. Sand cushion thickness was *3.0...4.0 m*.

Table 1 – Characteristics of subgrade soils

Name of soil	Specific weight of soil, kN/m^3	Strength parameters		Deformation modulus *E*, *MPa*
		φ, *deg*	*C*, *kPa*	
Sand and gravel mix	16,0	37	2,0	20,0
Dusty, medium strength sand	10,2	30	4,0	13,0
Dusty, firm sand	10,7	34	5,5	26,0
Fine sand, medium strength	9,8	31	13,0	17,0
Medium sand, medium strength	10,6	37	2,0	43,0

The slab foundation bottom mark is assumed to be *135.400 m* (Project Work Directorate of the Communal Unitary Utilities Enterprise "Brestzhilstroy"). Generally, the foundation slab made of concrete of class C25/30 was built under the house, with separation by expansion joints, within the section.

Research methodology and results

We have performed calculations of the foundation slab in the engineering-geological conditions specified in Table 1, with the only difference that the layer of flowing loam located at a depth of *5.9...6.9 m*, with a thickness of *1.1* to *1.6 m* in the left section of the house and *1.1...0.2 m* in the right section was taken into account. The calculations were performed using the software packages LIRA-SAPR and PLAXIS 3D, which allow to perform a joint calculation of the system "base-foundation-building" [2, 3, 4].

Isopoles of vertical displacements of the foundation and the character of their development in different sections of the slab are presented in Figures 1 and 2.

a)

b)

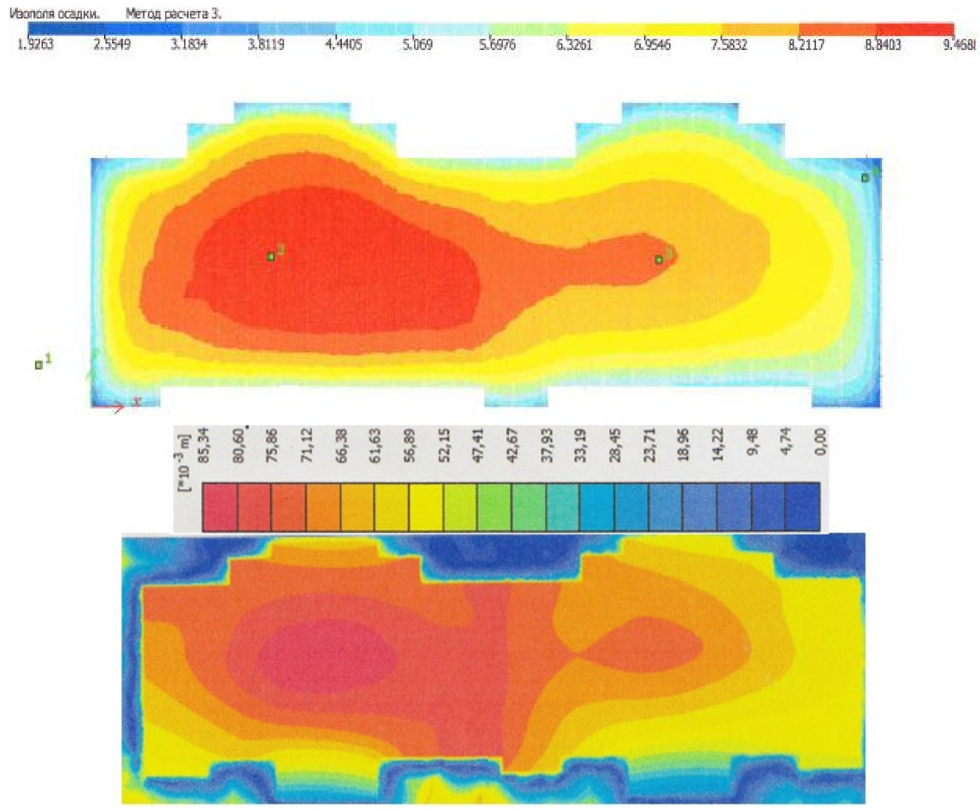

Figure 1 – Isopoles of vertical displacements of the foundations determined by LIRA-SAPR (a) and PLAXIS 3D (b)

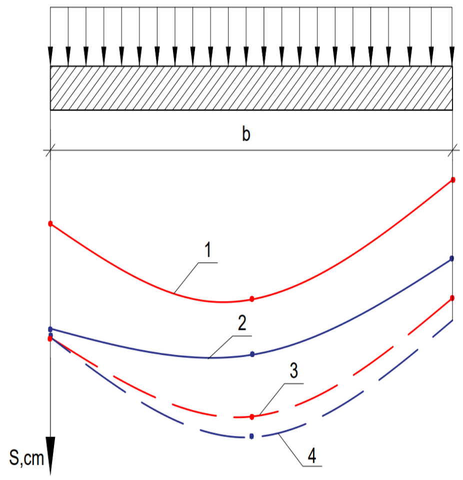

Figure 2 – Character of slab foundations settlement development

1, 2 - foundation slab settlement at the end and in the middle (PC LIRA-SAPR); 3, 4 - the same, respectively, calculated using the PC PLAXIS 3D

The analysis of vertical displacements shows their significant difference in magnitude and trajectories of propagation both in plan and in cross-sections of the slab.

The settlement obtained with PLAXIS 3D at the same points is slightly greater than that calculated with LIRA-SAPR. The settlement at points along the perimeter of the foundation is almost always less than the settlement at points along the line passing through the centre of the slab along the long side. It is known that when a load is applied to a flexible slab, its centre gives a settlement *1.24...1.60* times greater than the edges [5]. This is explained by the lawful operation of the foundation and its non-uniform stiffness in the central and peripheral zones of the foundation [6]. Taking this into account, as well as the fact that a significant thickness of the foundation footing is prepared artificially, it is obvious that it is possible to prepare the footing in such a way that its stiffness is different within the foundation spot. The implementation of such a solution contributes to the reduction of settlement differences, i.e. their equalisation: an increase of settlement in the edge zones and its reduction in the centre. Thus, the task is to prepare an artificial foundation with different deformability characteristics. The performed calculations have shown that at a considerable thickness of the sand cushion *(2.0 m...7.0 m)*, from *18 %* to *54 %* of the total foundation settlement is formed at the expense of the artificial foundation. Therefore, cushion thickness and the degree of soil compaction [7], i.e. the coefficient K_{com}, will have a great influence on the relative settlement difference or on the slab deflection. Using the recommendations of [8] the slab foundation settlement under the centre and midpoints of the sides of a rectangular slab can be determined by the formula

$$S = \frac{bPk}{m_B E_m^{red}}, \qquad (1)$$

where P is the average pressure under the foundation footings;

E_m^{red} – average reduced deformation modulus of the base;

$k = k_0$ – coefficient determined from the tables for the basement point under the foundation centre, depending on the ratio of the foundation sides $n=l/b$ and the ratio of the thickness of the removed layer to the foundation half-width $m' = 2H/b$;

$k = k_1$ – same under the centre of the larger side of the foundation;

$k = k_2$ – same under the centre of the smaller side of the foundation;

m_B – coefficient of working conditions of the base, taken for bases with average reduced deformation modulus $E_m^{red} \geq 10\ MPa$ equal to m_B = *1,35* at *10,0 m*, $b <\leq$ *15,0 m*.

The degree of variability of the base compressibility in plan is determined by the formula $\alpha_E = \dfrac{E_{max}^{red}}{E_{min}^{red}}$, (2)

If $\alpha_E \le 1.5$, the foundation is considered to be homogeneous in terms of compressibility. Calculations have shown that α_E determined for the ground conditions of Brest is *1.27*. Therefore, the foundation is homogeneous in terms of compressibility.

Let's denote the foundation settlement under its centre by S_0. Then S_0 will be equal to

$$S_0 = \frac{bPk_0}{m_B E_m^{red}}, \quad (3)$$

The settlement of the foundation under the centre of the larger side of the foundation is equal to

$$S_1 = \frac{bPk_1}{m_B E_m^{red}}, \quad (4)$$

Designing a slab with a width of *15.0 m* and taking into account the location of the internal longitudinal walls and the thickness of the slab, we assume the width of the central zone and the peripheral zones located on either side of its centre to be *5.0 m*. This division into sections is justified by the layout of the buildings. For the large-panel buildings designed in the Brest south-west microdistrict-1, the distance between the axes of the internal longitudinal walls is basically *2.1 m*. The next axis of the longitudinal walls is set at a distance of *2.1 m* to one side and *1.1 m* to the other. Then the total distance between the axes of the outermost longitudinal internal walls is *5.3 m*. In calculations, the distance between the longitudinal internal walls furthest from the centre is assumed to be *5.0 m* wide. Then the edge zones along the length of the slab will also be *5.0 m* wide. Taking into account that the compaction of the sand cushion is carried out until E_0 = *20,0 MPa*, let's assume that exactly this value of modulus should be provided under the central zone of the slab, width *5,0 m*. Then the edge zones should have a modulus of deformation less than E_0. The value of the deformation modulus in the edge zones is denoted by E_1. Then the ratio of the reduced average deformation modulus will be as follows

$$\beta = \frac{E_1^{red}}{E_0^{red}}, \quad (5)$$

From here $E_1^{red} = \beta \cdot E_0^{red}$.

Then the difference in settlement between the points in the middle of the slab and on its edge is equal to

$$S_0 - S_1 = \frac{bP}{m_B}\left(\frac{k_0 E_1^{red} - k_1 E_0^{red}}{E_0^{red} E_1^{red}}\right) = \frac{bP}{m_B E_0^{red}}\left(\frac{k_0\beta - k_1}{\beta}\right), \quad (6)$$

Obviously, the most acceptable slab conditions will be when the difference in settlement is zero.

Then

$$\frac{bP}{m_B E_0^{red}}\left(\frac{k_0\beta - k_1}{\beta}\right) = 0. \quad (7)$$

This expression is zero if $\dfrac{k_0\beta - k_1}{\beta} = 0$.

From here $\beta = \dfrac{k_1}{k_0}$.

According to (5) – $\dfrac{E_1^{red}}{E_0^{red}} = \dfrac{k_1}{k_0}$.

Consequently, the deformation modulus of the soil in the edge zones of the slab in the middle of the long side is equal to $E_1^{red} = \dfrac{k_1}{k_0} E_0^{red}$,

(8)

Thus, by specifying the compaction factor of the sand and gravel mixture and the deformation modulus at a point in the centre of the slab, we obtain the required value of E_1^{red} at the edge zone of the slab in the corresponding section.

Determining k_0 and k_1 according to tables [4] it is possible to determine E_1^{red} for any initial conditions. For more convenient use in practical calculations we have plotted the graphs of change of $E_1^{red} = f\left(k_1/k_0\right)$ (Figure 3). From the graphs we can see that E_1^{red} depends on E_0^{red} and does not depend on the aspect ratio. At values E_0^{red} distinct from those shown in the graphs use interpolation.

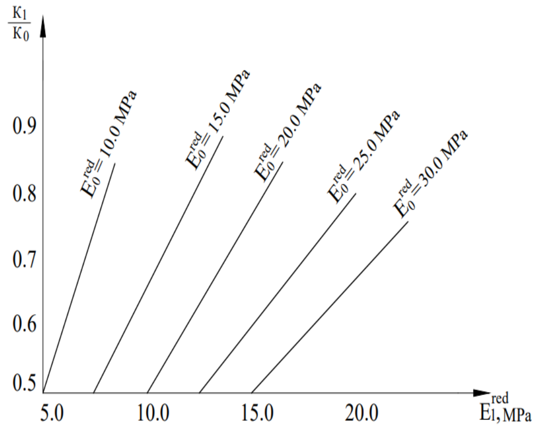

Figure 3 – Variation of E_1^{red} depending on the $\dfrac{k_1}{k_0}$

The values of E_1^{red} and E_0^{red} are taken at the points on the edge of the foundation slab and in its centre. Consequently, along the width of the edge zone (b = *5.0 m*) the deformation modulus will vary from E_1^{red} to E_0^{red}. This can be accounted by keeping in mind the technology of sand and gravel cushion preparation. If the width of the compacted zone for n passes of the roller is *1.7 m* taking into account overlapping of its traces. Then in the area from the edge of the slab to *1.7 m* the modulus of soil deformation should be E_1^{red}.

The next roller trace is also equal in width to *1.7 m*. Then the increase in deformation modulus at this section is $0.54(E_0^{red} - E_1)$. The deformation modulus of the soil on the second trace of the roller excavation should be equal to E_1^{red} = *15,4 MPa*. Similar calculations are performed for the third section. Modulus of ground deformation at the third track of the roller penetration is $0.9(E_0^{red} - E_1)$. If the calculations are performed at E_0^{red} = *20,0 MPa*, at the first section the deformation modulus E_1^{red} = *10,0 MPa*; at the second section E_1^{red} = *15,4 MPa*; at the third section – E_1^{red} = *19,0 MPa* (Figure 4).

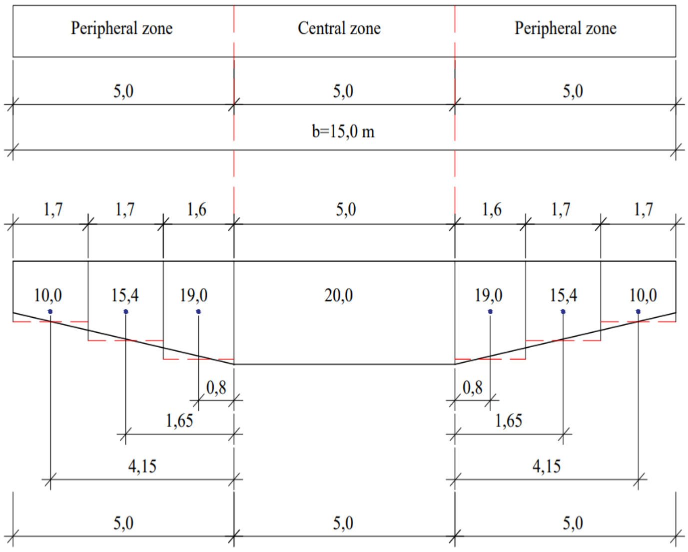

Figure 4 – Scheme deformation modulus E_1 variation in the peripheral zones of a rectangular plate

Foundation slab settlement calculations performed in accordance with the values of E_1, which are recommended for edge zones, showed that the slab settlement at points in the middle of the long sides of the foundation is more uniform and varies from *4.82 cm* to *4.87 cm* for the left section. The settlement at the centre of the slab of the left section is *6.27 cm*. Their magnitude is very important and is limited by the current norms [9]. The relative difference in settlement is *0.0019...0.00187*. For the right section, where the load on the foundation is *22 %* less compared to the left section, the settlement of the extreme points varies from *3.79 cm* to *5.37 cm*. The settlement at the centre of the slab is *5.87 cm*. The relative difference in settlement is *0.0007* and *0.0021*. The settlement of the same foundations without considering the change in deformation modulus for the left section ranged from *3.1 cm* to *6.5 cm* and at the centre *8.1 cm*. The relative deflection is respectively *0.0071* and *0.0025*. For the right section, the settlement is more irregular at the extreme points. They vary from *2.3 cm* to *5.9 cm*. The draught at the centre is *6.8 cm*. The relative difference is *0.006* and *0.0012*. Thus, regulating the degree of compaction of the sand and gravel cushion over the width of the future foundation allows to obtain more uniform settlement and, most importantly, to reduce, and very significantly, the amount of deflections and the relative difference in settlement, which naturally affects the amount of internal forces in the foundation slab.

The design of a slab foundation base to exclude non-uniform settlement is a very rational preparation of an artificial base with appropriate parameters of its deformability, ensuring the presence of minimal non-uniform settlement or completely excluding it.

Conclusion

When designing slab foundations of considerable thickness on artificial foundations, their deformability should be regulated in order to minimise uneven settlement as much as possible.

The proposed method of artificial base construction makes it possible to significantly equalise the foundation slab settlements, reduce their relative difference by 5–8 times without changing the slab height, i.e. without changing its stiffness.

The construction of foundations with an adjustable deformation modulus is possible when using, as foundations, not only artificially laid embankments, but also in case of building foundations on naturally formed basis.

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