Application of new constructive solutions of high buildings’ zero cycle during building in difficult engineering and geological conditions

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Abstract. Recently, there has been a significant reduction in the number of favorable areas for construction of buildings and structures, which leads to the need to build various facilities in special conditions, so in areas with difficult engineering-geological and mining-geological conditions of construction, which are deteriorating due to natural and man-made factors. It is necessary to assess the possibility of deformation of structures located on foundations with possible uneven deformation in the practice of design and operation. Only with reliable and accurate determination of the stress-strain state of foundation structures and soil mass the service life of buildings and structures can be predicted. Calculations performed with the help of PLAXIS and LIRA programs allowed to analyze the stress-strain state of the soil mass and the stability of the foundations with the same soil base (layer thickness and physical and mechanical properties), loads and boundary conditions: Option I – ordinary solid monolithic reinforced concrete foundation slab; Option II – proposed a solid monolithic reinforced concrete slab with a system of cross beams of different stiffness (patent № 13794). The validity of the theoretical forecast of the behavior of the foundation structure, which interacts with the unevenly deformed base, can not be obtained on the basis of the regulatory framework. The possibility of using a foundation with a system of cross beams of different stiffness in order to increase the reliable operation of high-rise buildings was experimentally and theoretically proved.

1. The problem and its connection with scientific and practical tasks
The thickness of the foundation slab depends on the applied load, the nature of its transmission and the physical and mechanical characteristics of the base soils. Problems of ensuring the reliable operation of “zero cycle” structures, such as groundwork, foundations and aboveground parts of high-rise buildings occupy a special place in their design and construction [1]. The uniqueness of the construction of the foundations of high-rise buildings shows that there is a need for scientific support of design and construction by specialized geotechnical organizations [2].

The choice of construction of the foundation of a high-rise building should be based on technical and economic analysis and is determined by the structural behaviour of the building,
Figure 1. Engineering and geological section.

Figure 2. Plan and type A I option (a) and II option (b) foundations.
soil properties, loads transferred by the building to the foundation, interaction of the building with the soil and surrounding buildings [3].

The territory of Kryvyi Rih is characterized by complex soil construction conditions, where the initial subsidence is very uneven and other deformation soil processes are possible, regardless of the weight of the building, which can suddenly start at any time during the life of buildings. Therefore, in difficult conditions, the high risk and the unpredictability of deformation processes in the foundation soil are much higher than in normal conditions.

2. Analysis of studies and publications
The design of zero-cycle structures in difficult engineering and geological conditions requires improvement of the regulatory framework, modern methods for determining the physical and mechanical characteristics of the underlying foundations, new calculation programs that take into account physical and geometric nonlinearity [4–10].

Today, among the existing types of foundations for high-rise engineering structures, a significant percentage is occupied by raft foundations for work in special conditions, which are characterized, firstly, by deteriorating engineering and geological conditions, and, secondly, by processes with subsidence of foundations caused by natural and man-made conditions of urban

Figure 3. A mosaic of effort $Q_x$, $Q_y$, I option (a) and II option foundations.
Figure 4. A mosaic of effort $M_x$, $M_y$ I option (a) and II option foundations.

areas. Therefore, special foundation structures are needed that can work in such conditions.

When considering the “groundwork – foundation” system, emphasis is placed on the specifics of the properties of reinforced concrete or on the features of the soil foundation. However, the inaccuracy of calculation schemes, shortcomings in the assessment of soil base characteristics and in the behavior of buildings and structures during exploitation lead to the fact that these structures are subject to significant deformations (cracks in structures, shearing and torsional) and go out of service [11–14].

Analysis of existing work on the behaviour of foundation slabs that interact with unevenly deforming foundations shows that there is still no generally accepted method of calculation that allows to take into account the features of deformation of reinforced concrete and soil (under complex load) deformation of the base during the operation of buildings and structures [5–7].

Extensive theoretical and experimental studies of slab foundations by domestic and foreign scientists have led to the development of methods and the creation of calculation programs that allow to study the simultaneous behavior of the foundation with the base [1–5, 11–14].
3. Formulation of the problem
The aim of the study is to solve the problem of choosing an effective zero-cycle design that has increased load-bearing capacity and allows the safe design of multi-storey buildings in special conditions.

The object of research is the application of new design solutions of zero-cycle buildings as a modern approach to engineering protection in construction under special conditions.

The subject of research is the elastic-deformed state of the system “groundwork – foundation”.

To achieve this goal the following tasks were solved:

- constructive calculations of two variants of foundations for high-rise buildings were carried out;
- step-by-step modeling of joint work of variants of foundation constructions of high-rise buildings with soil base was performed;
- the development of uneven deformations and the change of the elastically deformed state of the system “groundwork – foundation” under the influence of adverse physical and mechanical processes;

![Figure 5. A mosaic of effort $R_z$, and isopoles of displacements $Z$ I option (a) and II option foundations.](image-url)
Figure 6. Comparison of the results of the calculation of $M_x$ (a) and $Q_x$ (b) 1 option and 2 option foundations.

- the choice of the design method of the zero cycle allowing safe design of high-rise buildings in special construction conditions is substantiated.

4. Presentation of material and results
The results of engineering and geological surveys are necessary for a reasonable choice of types and sizes of foundations and load-bearing structures of underground parts of a high-rise building. They should contain data taking into account the forecast of changes in engineering-geological and hydrogeological conditions and the possible development of harmful processes during the construction and operation of the facility, and also necessary data to assess the impact on the system “basis – foundation” of adverse physical and mechanical processes (figure 1).

The characteristics of soils of natural composition, as well as artificial origin, should be determined, as a rule, on the basis of their direct study in the field or laboratory conditions, taking into account possible changes in soil moisture during construction and operation.
The values of soil characteristics are given as follows:

- normative – $\gamma^n$, $\phi^n$, $c^n$;
- to calculate the design of the base for the first group of limit states – $\gamma_I$, $\phi_I$, $c_I$;
- the same, for the second group of boundary conditions – $\gamma_{II}$, $\phi_{II}$, $c_{II}$.

A comparison of the usual solid monolithic reinforced concrete raft foundation – I option (figure 2), with the proposed solid monolithic reinforced concrete slab with a system of crossed beams of different stiffness – II option (figure 2). Structural dimensions: length $L = 55.2$ m; width $B = 55.2$ m; in the axes: 52.8 m in both directions, the depth of the foundation – 6.4 m, the height of the foundation slab – 1.2 m (option I), from 0.6 to 1.2 m (option II). The foundation is designed for construction on a site with a relief value of the design pressure on the base under the sole $R_0 = 0.2$ MPa.

Figure 7. Comparison of the results of the calculation of $R_z$ (a) and $Z$ (b) 1 option and 2 option foundations.
LIRA software package is a multifunctional software package for calculation, research and design of structures for various purposes [15, 16].

The calculations of the foundations under the raft for the most unfavorable combination of loads were performed, the results of which are given in figure 3, 4, 5.

The analysis of the obtained results of step-by-step modeling of zero-cycle structures shows the possibility of using both option I and option II of the foundation – the maximum subsidence of all models are within acceptable limits according to current regulations [8–10] and are shown in the figure 6, 7.

At the same time, the obtained research results indicate better quantitative results of the II variant of the foundation. Thus, at the stages of modeling with relatively identical total deformations in a conventional slab foundation (option I) there are larger vertical deformation displacements compared to version II of the foundation.

The obtained results are explained by the fact that the increase in the flexibility of the slab due to the inclusion of truncated beams of different stiffness and, accordingly, some increase in displacement contributes to a more uniform redistribution of stresses in the structure and some reduction of contact forces in the soil. The principle of “flexibility” used in this case is a more effective solution of the considered options and gives preference to the proposed option II over the typical option I of the foundation.

The authors propose an improved design solution for slab foundations for the design of high-rise buildings in special conditions [17]. The developed method of estimating the stress-strain state of the “soil – foundation” system under possible load combinations taking into account special design conditions takes into account complex engineering and geological conditions of construction – in forged areas and foundations composed of compressible soils. These stages of modeling were performed in order to monitor the behavior of the foundations (I and II options) in adverse working conditions.

Step-by-step modeling of joint interaction of the foundation structure is carried out on a 12-storey residential building with a ground base with the help of the Plaxis software package. This modeling involves determining the elastic-deformed state of the system, taking into account the technological aspects of the construction of the zero cycle of the building – from the device of the slab foundation to its operation [18, 19].

As a result of a detailed analysis of the technology of foundation construction, six calculation schemes (models) of changing the behavior of the foundation slab in accordance with the soil base during the construction of the zero cycle of the building were obtained. Each of the obtained models corresponds to a certain stage:

- stage 1 – the foundation on the project mark;
- stage 2 – backfill (reverse) with compacted soil;
- stage 3 – passing of deformations of the 1st ledge 13.8 m long under the foundation (1/4 of the foundation length);
- stage 4 – passing of deformations of the 2nd ledge 27.6 m long under the foundation (1/2 of the foundation length);
- stage 5 – passing of deformations of the 3rd ledge 41.4 m long under the foundation (3/4 of the foundation length).

The situation was simulated taking into account the deformations on the 1st, 2nd, 3rd ledges (modeling stages № 3 – 5). The developed method of assessing the elastic-deformed state of the system “soil – foundation” under possible combinations of loads, taking into account special design conditions considering complex engineering and geological conditions of construction – in forged areas and foundations composed of compressible soils. These stages of modeling were
Figure 8. 1st stage of modeling I option (a) and II option (b) of foundations.

Figure 9. 1st stage of modeling I option (a) and II option (b) of foundations.
Figure 10. 3rd stage of modeling I option (a) and II option (b) of foundations.

Figure 11. 3rd stage of modeling I option (a) and II option (b) of foundations.
Figure 12. 5th stage of modeling I option (a) and II option (b) of foundations.

Figure 13. 5th stage of modeling I option (a) and II option (b) of foundations.
performed in order to monitor the behavior of the foundation (I and II options) in adverse conditions during exploitation (figure 8, 9, 10, 11, 12, 13).

The simulation results for I and II option of joint work of the foundation structure with the soil base are are shown in the figure 14, 15, 16.

Figure 14. Graphs of the results of the 1st stage of modeling of I option (a) and II option (b) of foundations.

The analysis of the obtained results of step-by-step modeling of zero-cycle structures shows the possibility of using both option I and option II of the foundation – the maximum subsidence of all models are within acceptable limits according to current regulations.

At the same time, the obtained research results indicate better quantitative results of the II variant of the foundation. Thus, at 1-3 stages of modeling with relatively identical total deformations in the usual slab foundation (option I) there are larger vertical deformation
displacements, compared to the II version of the foundation. The stresses during the operation of the option II of the foundation are much lower compared to the option I (according to the graphs):

- at the 1st stage of modeling the maximum stresses (I option) – 0.228623 MN/m²;
- at the 1st stage of modeling the maximum stresses (II option) – 0.213267 MN/m²;
- at the 3rd stage of modeling the maximum stresses (I option) – 0.218836 MN/m²;
- at the 3rd stage of modeling the maximum stresses (II option) – 0.211886 MN/m²;
- at the 5th stage of modeling the maximum stresses (I option) – 0.228248 MN/m²;
- at the 5th stage of modeling the maximum stresses (II option) – 0.228248 MN/m².

Figure 15. Graphs of the results of the 3rd stage of modeling of I option (a) and II option (b) of foundations.
Figure 16. Graphs of the results of the 5th stage of modeling of I option (a) and II option (b) of foundations.

The obtained results can be explained as follows: the flexibility of the slab increases due to the inclusion in the structure of the system of crossed beams of different stiffness and accordingly some increase in displacement contributes to a more uniform redistribution of stresses in the structure and some reduction of contact forces in the soil thickness – that is, to improve the interoperability of the “groundwork – foundation” system.

It should also be noted that the design of the proposed version of the foundation (option II) with a system of intersecting beams of different stiffness, rigidly fixed in the plate, provides the perception of step-like deformations of the base (sealing), which occur as a result of adverse physical and geological processes in the forged areas. This is evidenced by the results of 3-5 stages of modeling – the second version of the foundation has less subsidence and the resulting
effort. That is, in special design conditions, when the design of the zero cycle is subject to additional influences and deformations, the proposed design of the foundation has an advantage in the work.

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